Migration of the Ganga river and its implication on hydro-geological potential of Varanasi area, U.P., India

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Borehole data reveals that during Late Quaternary, the Ganga river was non-existent in its present location near Varanasi. Instead, it was flowing further south towards peripheral craton. Himalayan derived grey micaceous sands were being carried by southward flowing rivers beyond the present day water divide of Ganga and mixed with pink arkosic sand brought by northward flowing peninsular rivers. Subsequently, the Ganga shifted to its present position and got incised. Near Varanasi, the Ganga river is flowing along a NW–SE tectonic lineament. The migration of Ganga river is believed to have been in response to basin expansion caused due to Himalayan tectonics during Middle Pleistocene times.

Multi-storied sand bodies generated as a result of channel migration provide excellent aquifers confined by a thick zone of muddy sediments near the surface. Good quality potable water is available at various levels below about 70 m depth in sandy aquifers. Craton derived gravelly coarse-to-medium grained sand forms the main aquifer zones of tens of meter thickness with enormous yield. In contrast, the shallow aquifers made up of recycled interfluve silt and sandy silt occur under unconfined conditions and show water-level fluctuation of a few meters during pre- and post-monsoon periods.

1. Introduction

Formed in response to the Himalayan orogeny, the Indo-Gangetic Plains form the largest alluvial tract in the world. From west to east, it may be divided into four zones namely, Punjab–Rajasthan Alluvial Plains, Gangetic Plain, Bengal Plain and Brahmaputra Plain. Located between 77°–88°E longitudes and 24°–30°N latitudes, the Gangetic Plain occupies the central position in the Indo-Gangetic Foreland Basin System. Depending upon the geographical position and geomorphology, the Ganga Plain is further subdivided into western Gangetic Plain located in Uttar Pradesh and eastern Gangetic Plain located in the state of Bihar. In the western sector, the Yamuna river acts as the axial river up to Allahabad, where it meets Ganga and from there in the eastern part, the Ganga is the axial river and all the rivers coming from Himalaya meet at right angles to it (figure 1A). The Ganga river separates the northern plains formed of Himalayan sediments from the southern plains built up by sediments derived from peninsular India. Sediments derived from Himalayan region are grey in colour comprising silty fine sand containing abundant mica. In contrast, craton derived sediments are pinkish, fine to coarse-grained gravelly sand containing abundant K-feldspars and lacking mica content.

The sediment fill of the Ganga basin is asymmetric decreasing in thickness from north to south. In the piedmont zone in the north the alluvial fill is 3–8 km thick decreasing to about 0.5–1.0 km in the central part and a few hundred to tens of meters thick further south near the craton (Sastri *et al* 1971). The geomorphic setup of the Ganga Plain is believed to have evolved under changing conditions of climate, intra- and extra-basinal

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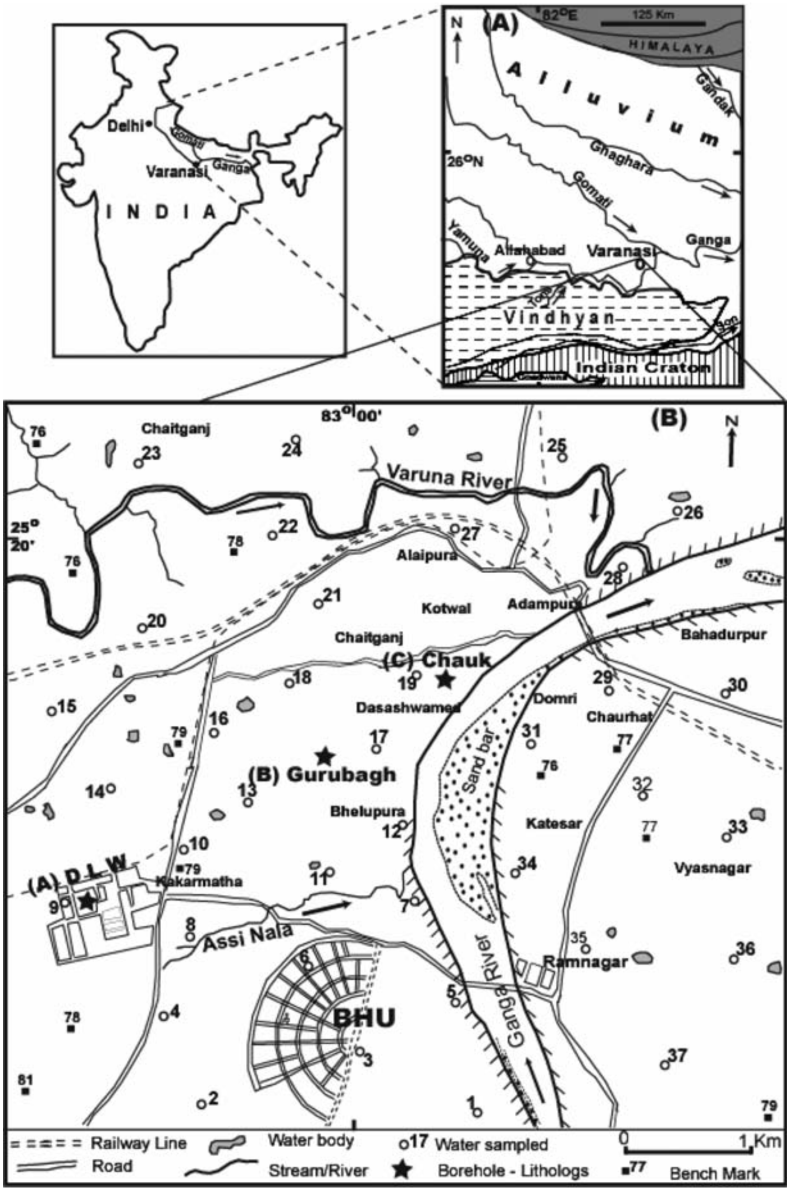

Figure 1. **(A)** Geomorphic cum geological map of a part of central Ganga Plain showing major rivers and their source areas located in the Himalaya and peninsular India respectively. **(B)** Geomorphological map based on 1974 SOI toposheet in 1: 50,000 scale, of Varanasi area showing drainage pattern, incised Ganga river flowing to north, ponds and location of boreholes and dug wells within Varanasi city.

tectonics and sea-level induced base-level changes (Singh 1996; Shukla *et al* 2001; Shukla and Bora 2003; Tandon *et al* 2006). River systems responded to all those changes and evolved differentially in time and space.

Systematic studies based on the surface outcrops are underway to understand the geomorphic response to various allo-and-autocyclic processes in the Ganga Plain. The present study based on extensive field surveys and data collected in boreholes provides new information regarding the Ganga river valley and aquifer development around Varanasi. Boreholes drilled within Varanasi city have been analyzed to understand the subsurface stratigraphic architecture and its significance in groundwater potential. Grain-size analysis of sand horizons helped delineate the sand bodies and to interpret them in terms of depositional environment, provenance and palaeochannel patterns. Comment has also been made on the channel behaviour of the Ganga river in response to varying climate and tectonics through time.

2. Geomorphology of Varanasi area

Based on 1974 SOI toposheets of 1:50,000 scale, a geomorphic map of Varanasi has been prepared and ground checks were made in and

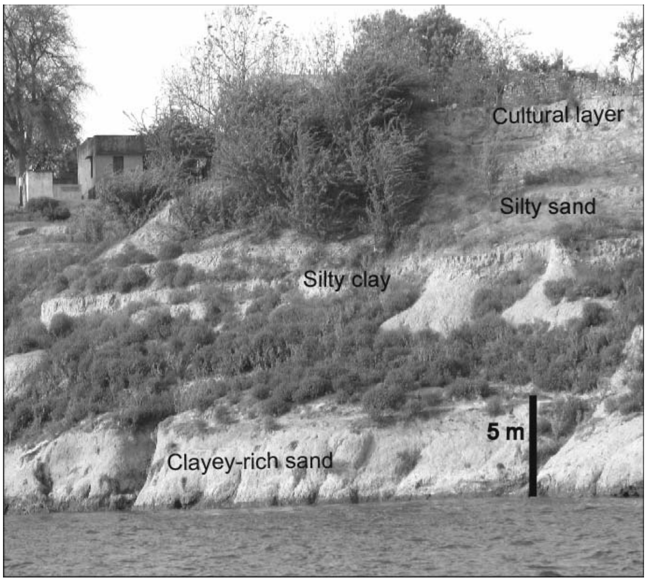

Figure 2. Close-up of the cliff section on eastern bank of the Ganga river near Ramnagar. The section is about 20 m high and made up of repetitive units of clay, silt and sand mixed in different proportions to form transitional lithologies.

around Varanasi to locate water bodies and natural drainage pattern (figure 1). After confluence of the Yamuna with the Ganga river at Allahabad, the Ganga river acts as the axial river and flows ESE followed by a northwardly trend near Varanasi to Saidpur (figure 1A). Within this stretch the Ganga river has a narrow valley (3–8 km) bordered by 6–20 m high continuous sedimentary bluffs present on both the sides. At Varanasi, the Ganga river has the narrowest valley which is just 1–2 km wide, though the active channel is only about 1 km wide and is totally confined between the cliff walls (Shukla 2006) (figure 1B). Because of incision, the river channel shows entrenched meanders of 8–10 km wavelength. Varanasi is located on the western cut side of the meander bend on an escarpment which is 8–17 m high. At this spot, the Ganga meanders flows NNW and shows development of a huge point bar (2 km long and 0.70 km wide) attached to the eastern bank represented by 10–20 m high cliff. Escarpments formed due to incision of Upland Terrace Surfaces (Older Alluvium) are made up of beds of fine sand, yellowish buff silt, grey clayey silt and differentially ferrugenized silty clay (figure 2). Near Varanasi along the eastern bank of the Ganga river at Ramnagar, the cliff section has been IRSL dated between 47 ± 12 Ka near the base and 7 ± 1 Ka near the top (Srivastava *et al* 2003). The cliff surfaces are degraded by gulleying activity and presently contributing cannibalized sediments to the Ganga river. On the surface it shows existence of abandoned channels, meander scars and ephemeral to semi-permanent ponds of tens to a few hundred meter extension (cf. Singh *et al* 1999). When compared with the report of Prinsep 1822, incorporated in Choudhary (2005), it becomes clear that within a time-span of about 150 years, ponds have decreased in size and number up to more than fifty per cent. Ground checks reveal that excessive siltation during rains and human interventions filling the ponds with garbage and encroachment have been responsible for such degradation.

The drainage system of Varanasi environs is mainly controlled by Varuna river and Assi Nala (Khan *et al* 1988). Both the tributaries join the Ganga river from the city side on the western bank. Varuna river valley is less than 0.5 km wide and the banks are fairly high and scoured on either side. Because of encroachment, the Assi Nala is now converted into a drain though the valley at places is more than 100 m wide (figure 1B).

At Varanasi, the Ganga river carries a mixed sediment load derived both from Himalaya and peninsular craton including Vindhyan rocks (figure 1A). From the craton side sediment is being carried by many tributaries meeting from south with Yamuna river before its confluence with the Ganga river at Allahabad. However, Tons river meets the Ganga between Allahabad and Varanasi (figure 1A). The sand is fine-to-medium grained and grey coloured with appreciable mica content. Sand is deposited mainly as point bars flanked by narrow flood plains confined to river valley. Wherever the river valley is wide, dissected valley terrace (T_1) (Newer Alluvium) (Shukla *et al* 2001; Srivastava *et al* 2003) is also developed and exhibits features like ponds, abandoned channels and meander scars.

3. Alluvial fill in Varanasi

Three boreholes drilled by private agencies for groundwater extraction south of the Ganga river to various depths mainly to tap potable water within the Varanasi city have been studied for sediment and water characteristics (figures 1B, 3). Drilling was done by direct rotary method by private agencies hired by Banaras Hindu University (BHU), Diesel Locomotive Works (DLW) and Jal Nigam, Varanasi. Sediment samples were systematically collected at intervals of three meters. The nature of muddy units was documented at the drilling centers. Because of outstanding contrast in grain size among the sand fraction of the samples, sand horizons were subjected to grain-size analysis using single phi scale, and various statistical parameters of Folk and Wards (1957) were calculated. Based on grain-size, comprehensive lithologs are prepared

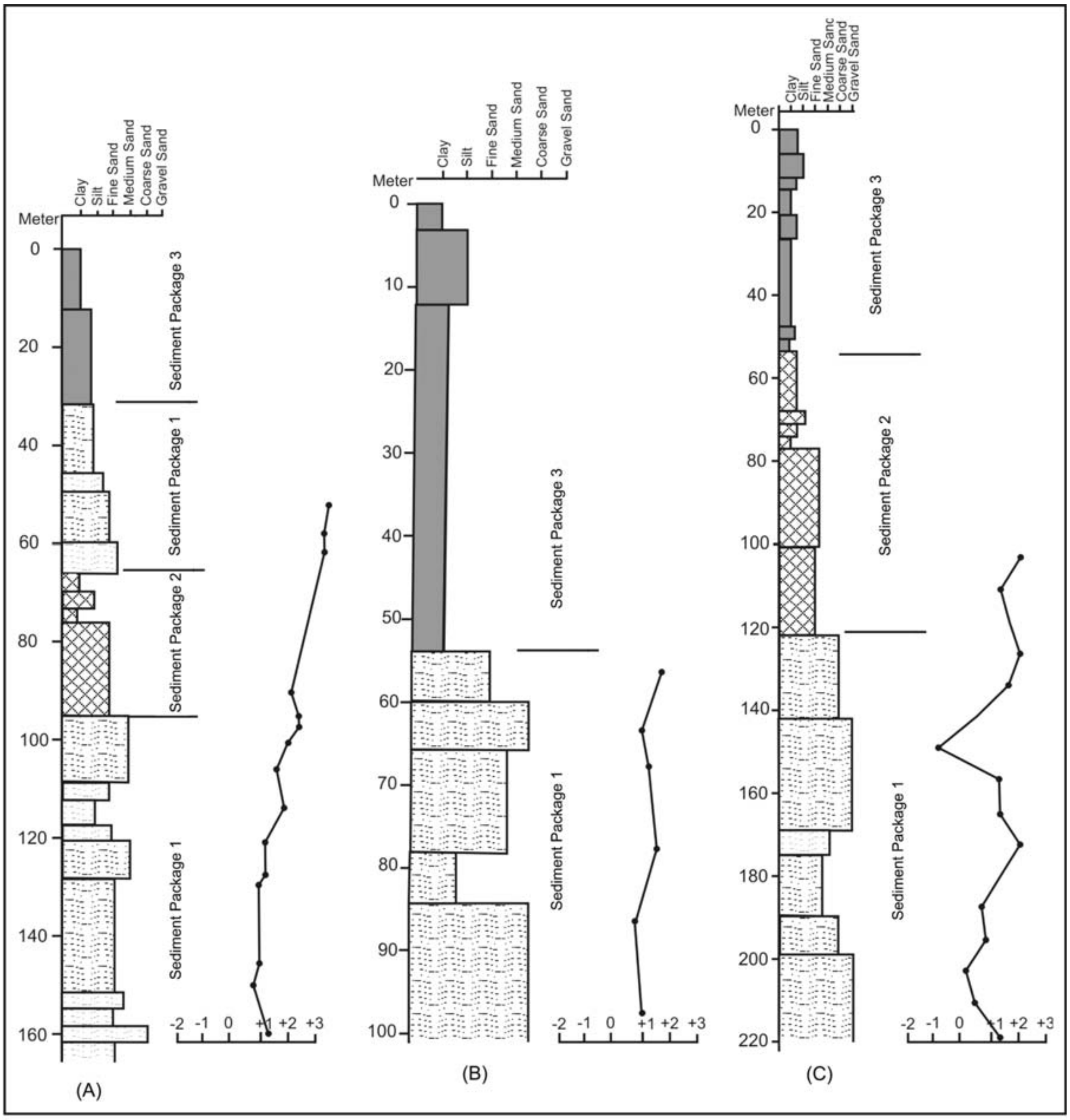

Figure 3. Lithologs showing subsurface stratigraphy and grain-size variations in phi-scale as encountered in boreholes drilled at DLW **(A)**, Gurubagh **(B)** and Chauk-Thana **(C)** in Varanasi. In DLW and Chauk-Thana boreholes, sediment derived from both peninsular (sediment package 1) and Himalayan sources (sediment package 2) are super-imposed, while Gurubagh profile is devoid of Himalayan sediments. Peninsular sands are medium-to-coarse grained, while sands sourced from the Himalayas are medium-to-fine grained. Channel belt and channel-bar events demarcated by increased grain-size are present in both the sedimentary packages 1 and 2. The sandy packages in all the three boreholes are capped by fine-grained sediment package 3.

to understand the nature of the sand bodies and their vertical and lateral behaviour (figure 3).

Starting from south to north three boreholes dug at DLW, Gurubagh and Chauk-Thana, were analyzed for the purpose of the study (figure 3). DLW is the southernmost bore hole (figure 3A) located about 3.5 km away from the Ganga river having a depth of little more than 160 m (figure 1B). The Gurubagh well is placed about 1.5 km away from the river channel and goes to a depth of 102 m (figure 3B). Chauk-Thana site is located about 500 m away from the Ganga river channel on Upland Terrace Surface (figure 1B). The borehole of Chauk-Thana is the deepest, penetrating down to 222 m depth (figure 3C). All these boreholes show a systematic change of stratigraphic records in terms of sand body thickness, grain size and relative percentage of sand-mud units through time. Based on the nature of sand to mud horizons, three fundamental sedimentary packages have been recognized and a tentative correlation is attempted amongst the three boreholes.

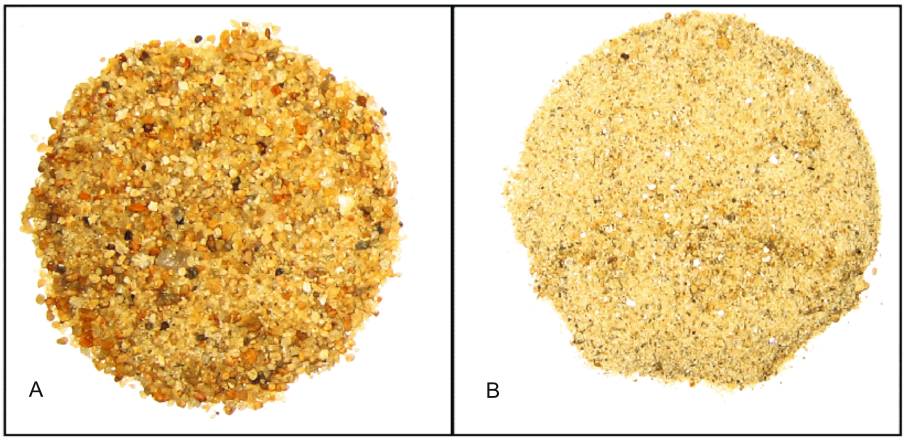

Figure 4. **(A)** Coarse-grained pink arkosic sand recovered from Chauk-Thana borehole at about 150 m depth representing sediment package 1; **(B)** fine-to-medium grained micaceous grey coloured greywacke sand recovered from 75 m depth from the DLW borehole representing sediment package 2.

3.1 *Sediment package 1*

The sediment package 1 is 35–105 m thick forming the bulk of the sedimentary succession of the three boreholes (figure 3). It is characterized by medium-to-coarse grained sand ($M_Z = 1.20–0.52$) which is often gravelly, orthoclase-rich, pink in colour, sand almost devoid of any mica content (figures 3, 4A). Though, dark coloured heavy minerals calcrete, rock fragments (mainly quartzite) are also present. Based on mineral content, the sand can be classed as arkosic sand similar to craton derived sand brought by modern rivers flowing from south to north. The framework grains are subangular to sub-rounded, moderately to poorly sorted (0.41–1.53), mostly negatively to positively skewed ($Sk_I = -0.24–0.21$) and generally platy to leptikurtic ($K_G = 0.88–1.35$). However, some of the sand bodies encountered at the shallower levels are clearly fine-grained ($Mz = 2.1–2.23$) and moderately-to-well sorted (0.79–0.45).

3.2 *Sediment package 2*

The sediment package 2 is nearly 30–60 m thick and composed of micaceous, fine-to-medium grained sand ($Mz = 2.32–1.96$) containing feldspars, rock fragments, mica and dark coloured heavy minerals (figures 3, 4B). The mica (Muscovite) is in abundance and its percentage increases further upward in the sand succession. This grey coloured sand can be better classed as greywacke sand, which is similar to sand brought by the present day Himalayan rivers including the Ganga river. The overall character of the sand is well sorted (0.69–0.42), near symmetrical leptikurtic to mesokurtic ($K_G = 1.4–1.0$).

Sometimes, this package shows a mixed lithology whereby craton derived pink arkosic sand is intermixed with Himalayan derived gray sand showing orthoclase, rock fragments, plagioclase and abundant mica (figure 3C). In such cases grain-size becomes medium-grained sand ($Mz = 1.2–1.8$) with poor to moderate sorting (1.0–0.68), negatively to symmetrically skewed ($Sk_I = -0.003–0.25$) and lepti- to mesokurtic ($K_G = 1.1–0.98$) in character. Thick package in different boreholes show fining upward character in which sandy horizons are succeeded by thickly developed silt-mud units.

3.3 *Sediment package 3*

Sediment package 3 is 30–60 m thick and in all the boreholes caps the underlying sandy deposits (figure 3). The package is characterized by interlayering of gray-black clay, buff silt and yellowish gray fine sand units. Quite often, sediments are mixed together to form an array of transitional lithologies (figure 2). In general, units are poorly sorted, almost completely mottled, differentially ferrugenized and extensively calcretized. In all the three boreholes this sedimentary package shows coarsening upward character exhibited by the presence of 4–9 m thick silt and sandy silt units at the upper levels.

4. Description and correlation of boreholes

4.1 *DLW borehole*

In the DLW borehole all the three sediment packages are developed. In general, sedimentary succession is sand dominated and shows very characteristic patterns whereby individual multi-storied sand bodies are separated by thin silt and clayey silt horizons. The sediment package 1 starts at about 160 m and continues to about 95 m level where a drastic change in composition of sand units is noticed (figure 3A). Within the sediment package 1, two multi-storied complexes are separated by about 5 m thick silt unit at 115 m level. In the lower complex (160–115 m levels) smaller depositional cycles starting with clean coarse-to-medium sand and ending with fine sand can be seen. Whereas, the samples of the second sand layer occurring above 115 m is characterized by medium-to-coarse sand without any fine-grained unit embedded in it (figure 3A).

The sediment package 2 occurring between 95 and 65 m levels is 30 m thick and fining upwards where top 9 m of the sand body is represented by interbedded clay-silt horizon. Muddy units also contain flaky mica and fine sand similar to the underlying sand, ferruginous nodules and plant fragments (figure 3A).

At 65 m, the sediment package 1 repeats in the succession probably with marked erosion of underlying sediments. It is characterized by a sudden increase in grain-size at the base and a clearly fining upward trend where top few meters is represented by silt. This sand succession incorporates mud pieces containing mica flakes eroded from top of the sediment package 2 which is composed of Himalayan derived grey micaceous sand to mud content. Above 30 m in the profile, the succession is made up of fine-grained sedimentary package 3 showing mottling, calcretization and anthropogenic signatures at the top (figure 3A).

4.2 *Gurubagh borehole*

In 102 m deep borehole, silt-clay (sediment package 3) outranks the sand (sedimentary package 1) though the succession is fining upwards (figure 3B). Beginning from the base to 54 m level, the sequence is sand dominated, and two sand bodies occurring at 102–84 m and 78–54 m levels respectively are separated by a 6 m thick grey clayey silty unit which contains minute calcrete fragments. The second sand body which is 24 m thick can be further identified into two depositional events separated by 6 m thick coarse sand unit occurring at 66 m level.

Between 54 and 12 m levels the sequence is essentially made up of brownish buff sticky mud that becomes silty towards upper-levels (sediment package 3). Near the top of the sequence a 9 m thick clayey silt horizon occurs which in turn is capped by a 3 m thick anthropogenic soil horizon at the surface (figure 3B).

4.3 *Chauk-Thana borehole*

In this borehole starting from 222 m at the base to 78 m level sequence is represented by sand without any silt-mud units (figure 3C). However, within the sandy succession two distinct sediment packages 1 and 2 are identified. They are comparable to sediment packages 1 and 2 respectively of the DLW borehole. Within this sandy succession, individual sand bodies are demarcated by sudden increase in grain-size at the base and progressive decrease in grain-size upwards. Such two sand bodies beginning with granular coarse sand at base and terminating with fine-medium-grained sand near the top have been recognized between 222 m–171 m and 171 m–120 m levels within the sedimentary package 1 (figure 3C).

At 120 m level starts the sediment package 2, which at 78 m level is succeeded by a 9 m thick (78–69 m levels) interbedded succession of buff sticky mud and micaceous silt-sand units containing dispersed clay content. Further up from 59 m level succession is made up of sediment package 3 which near the top becomes silt-rich (figure 3C).

5. Sedimentation pattern of alluvial fill

The borehole data furnish information regarding palaeochannel patterns and processes of sedimentation. All the three borehole successions are clearly fining upwards capped by 30–60 m thick silt-mud rich sediment package 3 (figure 3). The sandy sediment packages 1 and 2 also demonstrate systematic decrease in grain-size from lower to upper stratigraphic levels. Based on grain-size and thickness, the channel and channel belt events are discernible throughout the succession. Within the sediment package 1 (figures 3, 4A), channel belt events are 30–50 m thick. Marked by gravelly-coarse sand at the base and capped by 5–6 m thick silt-fine sand units, they lack muddy material. Such two to three channel belt events are discernible in all the three boreholes (figure 3). Smaller 7–10 m thick fining upward cycles may represent individual channel – bar events within the channel belts. Thus multi-storied character and general absence of muddy facies of over bank nature may imply sedimentation by multi-channel rivers (braided rivers) (Miall 1996; Shukla *et al* 2001). It seems that channels were larger in dimension and free to migrate laterally eroding any intervening muddy units of over bank origin (figure 5). However, the braided character of the palaeochannels carrying medium to coarse (rarely gravelly) sand may be attributed to high sediment/water ratio and higher slope gradient near the source

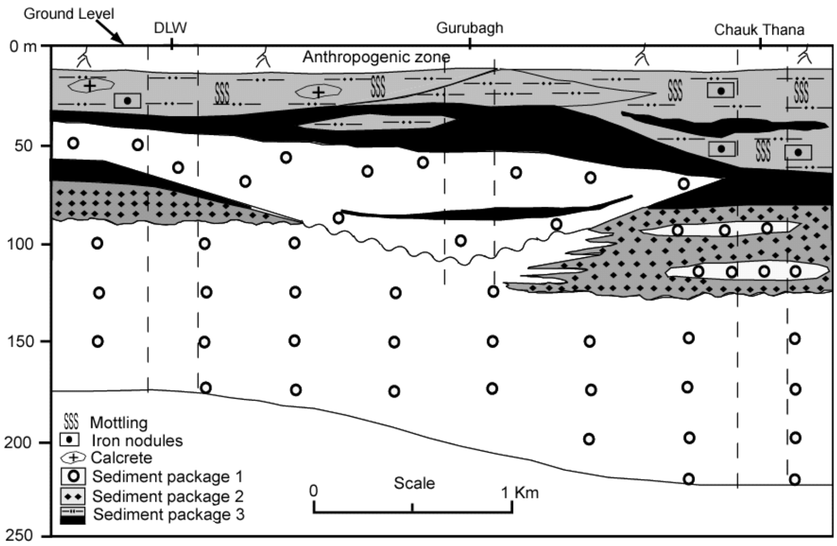

Figure 5. Subsurface architecture extrapolated from borehole data shows that thick and laterally persistent sandy succession of peninsular origin (sediment package 1) are overlain by sands of Himalayan source (sediment package 2) which in turn is deeply eroded by sediment package 1 near Gurubagh. Up to about 70 m depth aquifers are in unconfined condition whereas, below this depth a thick sandy succession is present forming semi-confined to confined aquifer conditions with enormous yields of good water.

terrain. Poor to moderate sorting, near symmetrical to negative skewness and dominantly platy-to-leptikurtic behaviour of the sand horizons also support the nearness of the source terrain and high energy conditions of the transporting medium (Folk and Wards 1957). It is to be pointed out that the sediment source of peninsular craton comprising sedimentary rocks of Vindhyan (Singh 2006), Gondwana basin and metamorphic suite of the Bundelkhand granites, is located just about 50–70 km away from Varanasi (figure 1A).

In contrast, the sediment package 2 characterized by Himalayan derived medium-grained greywacke sand is 30 m and 60 m thick in DLW and Chauk-Thana boreholes respectively (figure 3, 4B). The Chauk-Thana succession however, shows a mixed lithology implying that rivers coming from south and north were interacting. Nevertheless, in each case sandy succession is capped by about 10 m thick muddy units with intervening silt horizons containing mica present in the underlying sand units, plant material and charcoal pieces and characteristically lack calcrete. Such muddy units may represent sedimentation by suspension fall out on over bank areas associated with the channels (Shukla and Singh 2004). Therefore, abundance of muddy over bank sediments and relatively low sand to mud ratio may imply sinuous (meandering) channel pattern (Bridge 1985; Miall 1996). Localized occurrence of Himalayan derived sediments in two boreholes; smaller thickness and lensoid geometry of sand horizons corroborate this interpretation (figure 5). Low sediment/water ratio, low-gradient far away from the Himalayan source may have promoted the meandering channel pattern of the rivers (figure 1A). Relatively well sorted character, smaller grain-size and symmetrically skewed, lepti- to mesokurtic sands point to a prolonged transport away from the source under fluctuating energy conditions (Folk and Wards 1957).

Subsequently the channel belts were aggraded by interfluve processes producing thick silt-rich sediment package 3 during Upper Pleistocene (Singh *et al* 1999; Srivastava *et al* 2003) (figures 3, 5). With time, the sediments would have been churned by animal and plant activity and diagenetically modified producing calcrete and ferruginous nodules under differing climatic conditions.

6. Discussion

6.1 *Forcing on sedimentation*

In Varanasi, the SE flowing Ganga river takes an abrupt swing and flows to NNW direction (figure 1). It is incised and unlike to other places where cliff development is seen only on southern bank of the rivers and northern sides are gently sloping, near Varanasi, cliffs are present on both sides of the channel (figure 1B). The nature of the Ganga river is meandering with huge point bar development as compared to adjacent areas where it is braided with mid-channel bars (Singh *et al* 2007). In this part it shows the narrowest valley with distorted meanders confined between high cliff walls of interfluve deposits (Older Alluvium) running for several kilometers (figures 1B, 2). The meanders have straight margins on the eastern side and are free looping on the western part of the valley. Boreholes and dug wells on either side across the Ganga river demonstrate that on Varanasi side craton derived pink arkosic sand occurs at a depth of 30–60 m, whereas in Ramnagar it is encountered at a depth of 15–20 m only with a fine-grained cover at the top (sediment package 3). These features may suggest to a possible lineament control on the river course near Varanasi. The Ramnagar side may represent the upthrown block with a possible throw of several meters. This is also manifested by intense gulleying activity in and around Ramnagar along the Ganga river channel.

Tectonic control on river channels of Ganga Plain has been satisfactorily demonstrated. The incised courses of rivers in the Ganga Plain follow the lineaments oriented in NW-SE and W-E directions (Singh *et al* 1996). These weak zones conform the structural style of the Himalaya and believed to have tectonically active through Quaternary times controlling sedimentation and alluvial fill of the Ganga Plain (Sastri *et al* 1971).

The information gathered from three boreholes within Varanasi city reveals an interesting scenario of the subsurface alluvial stratigraphy. In DLW borehole, a 30 m thick Himalayan sand unit (sediment package 2) is sandwiched between thick sequences of arkosic sand of peninsular origin (sediment package 1 in figures 3A, 5). Similar succession is encountered in Chauk-Thana borehole, where about a 40 m thick (120–77 m level) zone of mixed pink arkosic and micaceous greywacke sand is present at the upper stratigraphic level below the muddy succession (figure 3C). In Gurubagh borehole however, the succession is made up of only craton derived arkosic sand followed by thick (60 m) muddy succession (figures 3B, 5). The subsurface architecture extrapolated with the help of the borehole data indicates a deep erosion of Himalayan derived sediments by overlying channels bringing peninsular sediments near Gurubagh. After the channel activity ceased, the valley was filled with thick muddy deposits. This situation led to the development of confined aquifer conditions in the deeper levels of the alluvial stratigraphy (figure 5).

The borehole information also suggests that during Quaternary, the Ganga river was not incised and was free to migrate laterally on the surface. It was flowing away from its present incised position further towards south. The Himalayan rivers bringing the micaceous greywacke sand were reaching beyond Varanasi city further towards peninsular craton in the south probably under increased water budget conditions. They were interacting with NE flowing southern rivers bringing pink arkosic sand from craton side near Varanasi (figure 5). This led to mixing and superposition of sediments derived from two different sources across the zone of present day water divide of Ganga. Subsequently, probably in response to enhanced tectonics of craton in the south, the Ganga river migrated to north, occupied its present position and got incised. This led southern rivers to reach up to Varanasi depositing again the craton derived sand over the Himalayan sediments (figure 5). Similar deductions based on borehole data have been made for Ganga river by Singh and Bajpai (1989) for the Kanpur region.

The rivers draining different source areas were mostly multi-channel type and of moderate size, producing up to 50 m thick sediment packages (figure 3). However, the individual channels within a channel belt were 5–10 m deep. The rivers were not incised and were free to migrate over vast flood plain areas. Such a situation where muddy sediments are removed due to channel migration may favour the development of semi-to-unconfined aquifers (figure 5). Sediment character indicates that channels may have enough water and energy to transport medium-to-coarse grained gravelly sand up to a considerable distance. The climate may have been more humid, and tectonics more intense than today releasing coarser clastics from the source areas. As evidenced by the fining upward character of the borehole profiles, it seems that with continued sedimentation coincident probably with subdued source tectonics coupled with reduced water budget, the rivers aggraded and valleys were filled by fine-grained sediments by vertical accretion processes. The sediments were later modified by diagenetic processes. Srivastava *et al* (2003) dated such sediments in the cliff section of Ramnagar between 47 and 7 Ka (figures 1B, 2). It has been demonstrated that around 47 Ka was a humid phase while the time period between 7 and 3 Ka was a phase of marked aridity in the Ganga Plain (Srivastava *et al* 2003; Shukla 2008).

6.2 *Hydro-geological potential*

The process of sedimentation had the commanding role on the evolution of alluvial fill and aquifer development near Varanasi. Borehole information reveals that the subsurface stratigraphy is dominated by laterally persistent multi-storied sand bodies capped by thick muddy succession near the top (figure 3). The nature of occurrence and availability of groundwater is directly related to relative thickness of sand and clay zones. Sand layers form the most important aquifers in the study area and their potentiality obviously increases with increase in its degree of assortment.

The alternating sand and clay layers have created a multi-tiered aquifer system (figure 5).

Monitoring of dug wells shows that the near surface groundwater occurs under water-table conditions. The general slope of the water-table is from north to south in Varnasi environs. The average hydraulic gradient of the study area is 0.356 m/km which indicates porous nature of near surface formations of the area (Pandey 1993). The general water-table elevations (MSL) indicate that the Ganga and Varuna rivers being deeply incised are gaining rivers. It is observed that some perched water-table zones are also present where water level is very shallow. In the western part of Varanasi city, water level is deep as compared to eastern part of the city.

The shallow bore wells (hand pumps) and dug wells puncturing unconfined aquifers at about 25–40 m depth have water-level fluctuations from 8.51 m to 11.25 m. Such unconfined aquifers are made up of recycled interfluve silt and silty sand forming lensoid units capped by relatively thin and impersistent mud layers showing calcrete development (figures 2, 3).

The deep wells penetrating below 60–70 m have enormous yield of 45,000 lph to 220,500 lph. Good quality potable water is available from coarse-grained deep sandy aquifers. These aquifers are made up of craton derived pink arkosic sand (sediment package 1) or the mixture sedimentary package 1 and 2 (Himalayan gray sand) (figures 3, 4). Because of thick cover of fine-grained material (sediment package 3) near the top, these aquifers occur in semi-confined to confined conditions. Differential erosion of the sand horizons by succeeding channel events within a sedimentary package may promote to semi-confined conditions of the aquifers (figure 5). The total thickness of the good water yielding sand strata varies from 20 to 80 m or more in tube wells occurring at an average depth of about 100 m (cf. Bilas 1980) (figure 3).

Because of intensive pumping of water due to fast urbanization, the water level in Varanasi shows a lowering trend. The average fall of groundwater-level in last fifteen years is about 1.43 m (Sinha 2003). In general, the ground water of Varanasi city is of good quality and except nitrate (NO_3) (Raju *et al* 2008), all the dissolved solids are within the permissible limit of IS (1991).

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