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Marginal fan thick lacustrine sedimentation: Implication for tectonics and/or climatic causes in Kathmandu basin

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ABSTRACT

Very thick gravel deposits are widely distributed from southern marginal to central parts of the Kathmandu basin named as Itaiti Formation. This deposit is more than 120 m thick and deposited around 1 Ma, which is dominated by three types of facies and fans. The first stage fan is widely distributed near the mountain front where sediments aggradation is more active. The third stage fan is the youngest among three fans and is distributed on the present top surface and has covered lacustrine deltaic sequence of the Sunakothi Formation. Seven types of facies elements namely Gms, Gm, Gp, Sp, Sr, Sh, and Fl have been recognized among these three fans. Based on stratigraphic relationship among different geological formations, the first debris flow fans have been spreading over basement rocks and fluvial gravel facies before 1 Ma. This event has played a vital role in the initiation of an ancient lake in the Kathmandu basin. The second and third stage fans originated during the draining stages of the lake. The distal part of the second stage fan and third stage fan is interfingering with the lacustrine delta towards the center of the basin. The first stage debris flow fan was most probably generated by the recent uplift of the Mahabharat range. These gravelly fan deposits and the uppermost Siwalik conglomerate deposits may be synchronous to recent tectonic events throughout the Himalayas. The second and third stage fans have been initiated not only by the tectonics but also by climatic which is indicated by sedimentological and stratigraphic relations among formations.

Keywords: Alluvial fan, lacustrine deltaic, debris-flow, three stages fan, Pleistocene

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INTRODUCTION

Alluvial fans are highly sensitive to climatic and environmental changes, and tectonic activity in any area and/or climatic region. They are very important for sediment produced by mountain catchments and hence may preserve a record of the history of sediment delivery to the fan. Fan morphology plays a vital role in fan depositional processes. The depositional and erosional activity of the fan to changes in process is governed by the critical power relationship between the power required to transport the sediments supplied and the actual transporting power (Bull, 1963, 1977). Sedimentation within the fan body is a consequence of the excess sediment supply whereas excess power, resulting from reduced sediment supply or increased runoff, will lead to erosion. This relationship is only the case of normal conditions. This relation is no longer withstand if the tectonic activity may alter the relief of the source area influencing sediments production or change of the gradients of the fan surface itself.

Alluvial fans are the most widespread depositional landform in front of the Himalayan range. Such types of landforms are bordering the high mountain range and actively subside tectonic continental basins. Such types of fan sediments were deposited in the southern margin of the Kathmandu basin. These fan sediments are very important and have many hidden histories about the origin, and disappearance of the paleo-Kathmandu Lake as well as the evolution of the landforms within the Kathmandu valley. An alluvial fan is generally developed due to the radially spreading of sediments transported events through time is unobstructed. The fan system is controlled by the progressive switching of the sediments transport pathway and resulting depositional lobes. The sediments of alluvial fans are mainly carried by the direct action of gravity and sufficiently steep substrata while the water is a secondary phase (Bull, 1963). Alluvial fan systems have two modes of operation that influence the processes operating on the fan surface and resultant morphology: Aggradational fan process where sediments are deposited on the fan, and degradation in which sediments are eroded from the fan surface. In the simplest terms, excess sediment supply leads to local sediment deposition, therefore, aggradation while excess power in the basin margin will lead to erosion and fan degradation (Allen, 1978). The relationship between the size of the contributing catchment and the size of the fan shows the larger the area of catchment, the greater the potential to store the sediments within it and therefore the more likely decrease in the total amount of sediments delivered to the fan per transport events (Bull, 1963). By contrast, smaller catchments have less potential for sediments storage and are more likely to effectively deliver sediments to the fan surface for any given transport event.

The most important challenge in alluvial fans is to determine whether changes in the fan process have been caused by allogenic factors influencing the fan environments through sediments or water supply or some process-driven thresholds intrinsic to the fan system i.e. autogenic factors. Hence, in this paper, both geological mapping and sedimentological study of lacustrine and fan sediments solve the problems about the role of tectonics and/or climate in the origin and draining of the ancient lake in the southern part of the Kathmandu basin.

GEOLOGY OF THE STUDY AREA

The Kathmandu valley is located in the central Nepal Himalaya, one of the large Quaternary intermontane basins within the Himalayan range. This basin is 25 km wide along N-S and 30 km long along with EW, which covers an area of 650 km^2. The average elevation of this basin is 1300 m and the Bagmati River is the main tributary of the Kathmandu basin. Geotectonically Kathmandu basin is situated on Kathmandu Nappe (Stocklin and Bhattarai, 1977 Rai, 2001). The basement rock at the southern part is comprised of fossiliferous early Paleozoic Tethyan sequence of the Phulchoki Group, which is overlaid on the metamorphosed Bhimphedi Group, while the northern slope of the valley is composed of granite, gneiss, and schist (Fig. 1b). The Kathmandu basin is bounded by the Chandragiri fault in the south and the Kalphu Khola fault in the north (Fig. 1b). This fault-bounded basin is filled up with materials sourced from nearby hills (Fig. 1a). In the northern part sediments, sand and silt are dominant, while in the central and southern part, sand, mud, gravels, and diatomaceous earth with peat occur. The sediments have been broadly divided into three facies: fluviodeltaic in the northern, fluvio-lacustrine in the southern and central, and alluvial fan in the southern margin (Fig. 1a).

This basin is filled with a very thick (upto 550 m) sequence of lacustrine and fluvial deposits of the Plio-Pleistocene age (Yoshida and Igarashi 1984, Moribayashi and Mauro 1980). First, significant works have been carried out by Yoshida and Igarashi (1984), Yoshida and Gautam (1988), Dangol (1985, Sah et al. (1995), and Sakai (2001). Yoshida and Igarashi (1984) first established a lithostratigraphic unit; the Lukundol Formation, which was the older lake sediments covered by three fluvial terraces namely; the Chapagaon, Boregaon, and Pyangaon terraces. According to them, the lake became narrow and shifted toward the north due to the upheaval of the Mahabharat range. They proposed the units such as the Gokarna, Thimi, and Patan Formations, which belonged to their younger stage deposits. Sakai et al. (2001) reported that these formations belonged to the fluvio-deltaic deposits. Sah et al. (1995) proposed six stratigraphic units for the whole basin-fill sediments, i.e. Tarebhir, Lukundol, Sunakothi, Tokha, Kalimati, and Thimi Formations. Sakai (2001) proposed different stratigraphic units in the south, central and northern parts of the basin. Paudel (2014), Paudel and Sakai (2008 and 2009) explored lithological variation found from south to north of the basin based on geological mapping including texture and composition of the sediments. The redefined stratigraphic names are the Tarebhir, Lukundol, Itaiti, Kalimati, Sunakothi Formations, and Terrace gravel deposits in the ascending order.

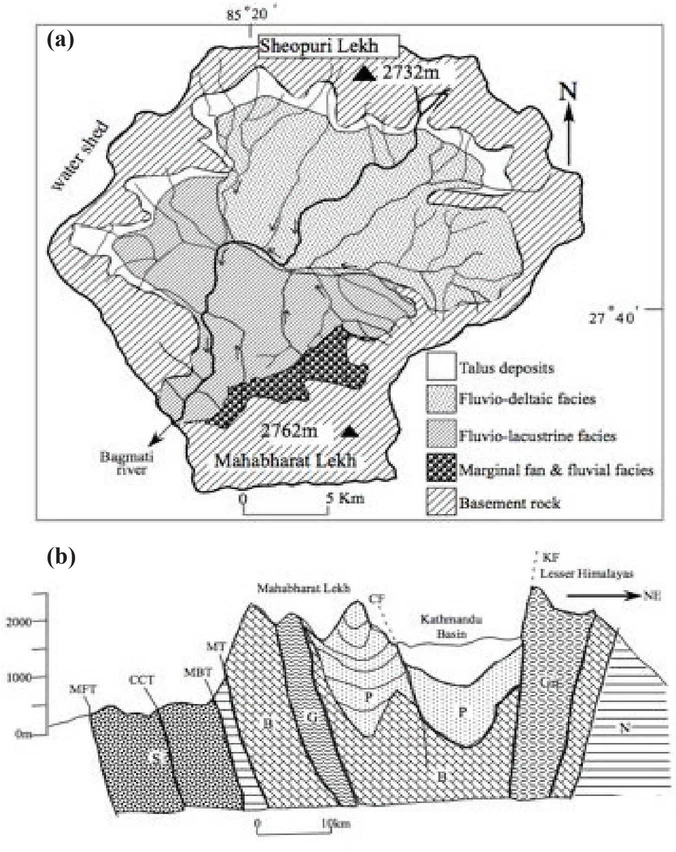

Fig. 1: (a) Simplified lithofacies map of Kathmandu valley showing different facies within the basin-filled sediments. The arrows show the present flow direction of the rivers, (b) A schematic geological cross section in the Central Nepal Himalaya (modified after Stocklin and Bhattarai, 1977. S: Siwalik Group, B: Bhimphedi Group, P: Phulchoki Group, N: Nawakot Group, G: Granite, Gn: Gneiss, K: Kathmandu Complex, MFT: Main Frontal Thrust, CCT: Central Churiya Thrust, MBT: Main Boundary Thrust, MT: Mahabharat Thrust, MCT: Main Central Thrust.

RESULTS

Stratigraphy and depositional setting of gravel deposits

The Kathmandu valley is located in the mid-land zone of central Nepal and its basin floor is filled by Plio-Pleistocene fluvio-lacustrine terrestrial deposits. The source of these sediments is the surrounding mountain range composed of different rock types. Sedimentary characteristics indicate four types of unconsolidated successions that are identified within the basin. These are before lake succession (Fluvial and fan setting), during lake succession, draining stage lake succession, and finally fluvial succession. These four sets are stratigraphically named as Tarebhir, Lukundol, Kalimati, and Itaiti Formations (Sakai 2001). Further, Paudel and Sakai (2008, 2009) redefined the stratigraphy based on detailed sedimentological study and mapped as Tarebhir, Lukundol, Kalimati, Sunakoth, Itaiti Fan, and terrace gravel deposits. Very thick gravel beds distributed in the southern part and stratigraphically underlying, overlying and interfingering with different geological formations (Fig. 2). These gravel units are lacking to describe based on the stratigraphic relationship until now. In this section, gravel sequences that are distributed within the different formations during different times are included and described based on the similarity of their depositional settings and stratigraphic relations. Based on these criteria gravel deposits are divided into three depositional settings: prelake stage gravel, Gravel in lacustrine and deltaic settings, and stream-dominated gravel fan setting during and after the lake period.

Prelake stage gravels setting

This stage is the first stage and occurred before 1 Ma. Stratigraphically this setting is defined by the Tarebhir Formation, and the proximal part of the Itaiti Formation (Sakai, 2001; Paudel and Sakai, 2008). Stratigraphically the depositional age of this gravel is the oldest gravel sequence and is distributed in the southern marginal part of the basin. The base in the southern marginal part of the basin is composed of coarse grain granitic and gneissic clasts of fluvial origin. Based on stratigraphic relation to the basement rock underlying the basal gravel it was deposited by the Protobagmati river flowing from north to south before 1 Ma (before the lake). Contact relationships between them have been showing erosional. This unit outcrops on the surface over an area approximately 1.5 km long and less than 1 km in width in the southernmost part of the basin. To the center (north) the basal conglomerates are intercalated with fluvial micaceous sand and silts beds. These sandstone and siltstone beds are very thin and lenticular in shape. Further toward the center, these conglomerate passes into thick predominantly fluviatile, sands-dominated sequences. Based on imbrications of the clasts and sedimentary structures, it shows sediments were transported from the Shivapuri range in the north by the Protobagmati river before the origin of the lake.

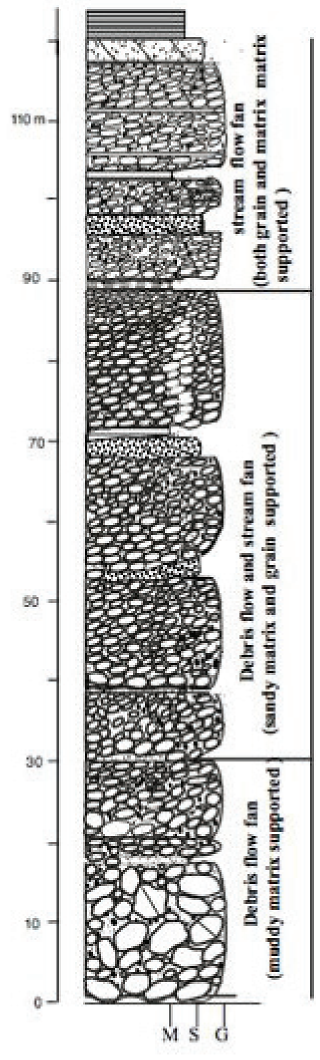

Fig. 2: A detailed lithostratigraphy of the fan sediments in the southern part of the basin. M: mud, S: sand and G: gravel.

Debris flow-dominated fan gravels occurred above this basal fluvial gravel sequence at the southern margin of the basin (Fig. 2). The composition of the fan gravel is drastically changed to metasandstone and some carbonate pebble and boulders. Gravels are poorly sorted, pebbles are irregularly arranged and without preferred orientation, and some clasts are vertically oriented and fracture surface (Fig. 3A). Such types of characteristics indicate sediments are cohesive debris flow fan deposits and their composition indicated they are not transported from the north as previous fluvial gravel. Morphologically, this fan shows different lobes which were frequently spreading from the right and left sides of the present Bagmati river outlet at the southern marginal part of the basin. There are usually down fan decreases in mean grain size, bed thickness, and channel depth and down fan increases in sediments sorting. Fan head area contains the localized accumulation of poorly sorted angular and coarse gravels with clasts being grain to matrix-supported. Internal stratification is poorly developed.

Gravel in lacustrine and delta stag setting

Many types of gravel beds have been distributed either above the marginal lake sediments of Lukundol or interbedded with deltaic Sunakothi sediments, which are included within this setting (Fig. 3; 4C,D). Besides this, some pebbly fluvial gravels and micaceous coarse sand beds are interbedded within the marginal facies of the Lukundol Formation. These gravel and sand beds which are interbedded in Lukundol on the southern part of the basin are completely fluvial gravel transported from the northern mountain of the Kathmandu basin. Although fan gravel beds are not intercalated, very few numbers of diamictite beds in the middle- and upper-part show debris flow from the south rarely occurred during the depositional period of marginal Lukundol Formation. Clasts of the diamictite are mainly composed of metasandstone and limestone but they did not contain granitic composition. Hence, there is no sign of fan gravel deposits from the southern mountain range of the Kathmandu basin during marginal lake deposits of the Lukundol depositional period. The Kalimati Formation consists of massive to very thin-laminated black

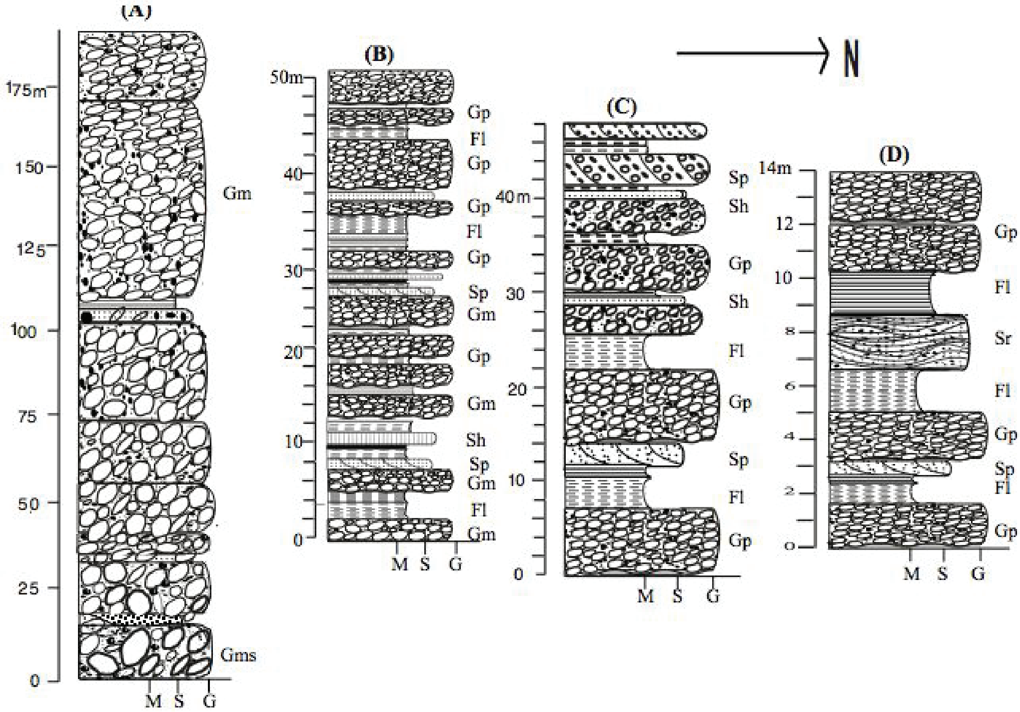

Fig. 3: Geologic columns of different facies from southern margin to center (North) (A) Debris flow dominated fan, (B) Debris flow and stream dominated fan, (D) Stream dominated fan. Abbreviates Gms, Gm,Gp, Sp, Sh,Sr and Sr are different facies units for detailed see Table 1.

and grey silt and mud beds, parallel laminated very fine sand, and diatomaceous mud. Thin sand beds with small-scale cross-bedding and ripples are intercalated between the mud beds of Kalimati and the outcrops are exposed around the southern part. These sedimentary structures and composition of sand beds is expressing very small stream activity performing from the south during proper lake sediments of the Kalimati depositional period. Occasionally, thin to thick beds of gravel are interbedded with sandy and muddy beds of the deltaic sequence of the Sunakothi Fm continues from the south to the central part of the basin.

These gravels are clast supported and sandy matrix with crude horizontal stratification and minor interbedded sand beds. Most deposits are clast supported with a sandy matrix (Fig. 4C). Sand beds show cross-lamination. In some outcrops, pebbly gravel beds are sandwiched between rhythmic mud beds. This indicates the fan gravels were deposited up to the prodelta region of the Sunakothi Fm.

Stream-dominated gravel setting

Very thick to thin beds of gravels, which are stratigraphically overlying above the Sunakothi deltaic sequence from south to central part are explained by this setting. Sakai (2001) included all gravel sequences above the Lukundol Fm as Itaiti fan gravel. Later, Paudel and Sakai (2008, 2014) showed the proximal and distal parts of the Itaiti Fm in their geological map. In this paper, gravel sequences, which are overlying on the deltaic Sunakothi Fm and widely distributed in the south to the central part and younger than the other settings are defined by this setting (Fig. 3). The origin of this setting is linked to the disappearance of the ancient paleo-lake. It makes different terraces from the south to the central part of the basin. Gravel and sand beds with some intercalation of mud towards the distal part are mainly composed of pebble to cobble size gravels. The organization of the clast and arrangement of the materials of the different grain sizes is rather good, showing the layer of clasts of different sizes and also interbedded sand and mud beds. Horizontal layers show good imbrications of the clasts; cross-bedded gravels and sand are prominent. More or less everywhere this sequence started from thin beds of coarse sand than the overlying by gravel.

This gravelly sequence is often intercalated by a very thin bed of carbonaceous mud and sand beds. Both fining and coarsening upward sequences are observed within the different outcrops. Very good planar cross-bedded gravel shows clear imbrications (Fig. 4E). In some localities, the gravel beds show strong scouring in the silty clay of the underlying deltaic sediments of the Sunakothi Fm. It is well exposed in the Champi and Chapagaon Sunakothi, Thecho area. At the central part of the basin toward the south from ring-road 2 to 3 m thick sheet gravel has erosionally covered the Sunakothi and Kalimati Formation (Fm). The composition of the clasts is metasandstone and quartzite.

One remarkable point about this setting is its contact relation between the different formations. Previously, the whole gravel sequence is considered as the alluvial fan by Sakai (2001), but this study reveals that the gravelly sequence is overlying only on the Sunakothi Fm on the southern part.

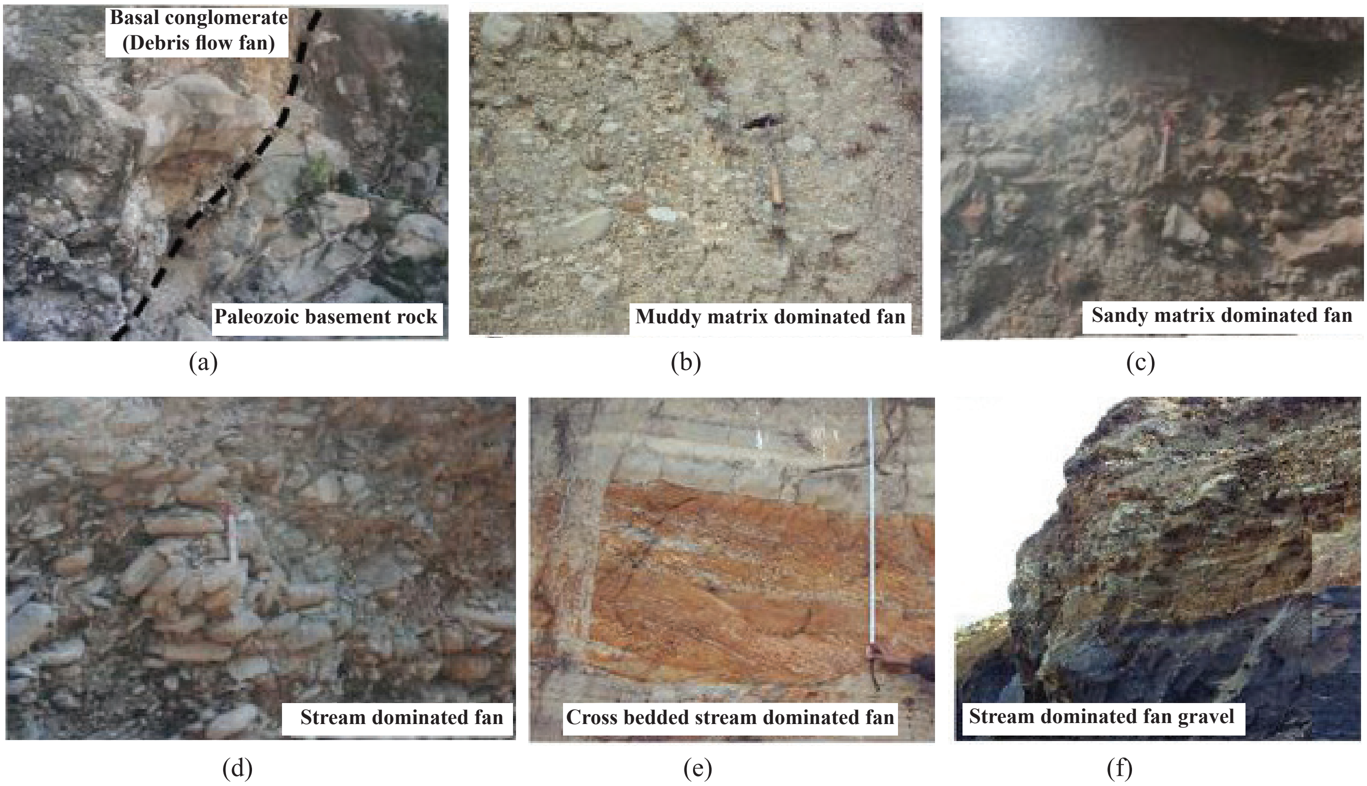

Fig. 4: Photograph showing different facies (a) Photograph of matrix supported gravels overlying on basement rocks (debrisflow fan sediments), (b) Muddy matrix supported, unorganized gravel of debris flow fan of stage 1st, (c) Sandy matrix clast supported, very crude stratification debris flow-stream fan 2nd stage, (d) Clast supported, imbricate, sandy matrix gravel with stratification of 2nd stage distal fan sediments, (e) Planar cross stratified gravel of stream dominated 3rd stage fan fan, (f) Stream dominated 3rd stage fan above deltaic facies of Sunakothi Fm. Deltaic sequence shows coarsening upward sequence indicate progradation of delta toward basin center.

DISCUSSION

Sedimentary processes and resultant facies

The distinctive setting, forms, and hydraulic condition of alluvial fans yield a set of distinctive processes and facies assemblage are shown in Table 1. Two basic types of processes called primary and secondary are operating within the alluvial fan morphology ((Blair et al., 1994). Primary processes are those that actively transport sediments from the drainage basin to the fan site. Sediments are more angular, poorly sorted, and coarse-grained which indicates the sediments originated from rock-fall, rockslide, and rock avalanches. Other processes may include colluvial slide, debris flow, and sheet flood. Primary processes are generally promoted to construct the large fan or aggradation of the fan surface. So, the primary processes are an important role in the evolution and stratigraphy of the fan in a very short period.

This study shows that the primary processes are operating in the following ways: sediment gravity flow generated by the collapse of bedrocks cliff in the drainage basin at the southern margin of the basin (Fig. 4A). The second type is sediment gravity flow generated by destabilization of colluvial slope in the drainage basin and the third is fluid gravity flow generated by destabilization of colluvial slope in the drainage basin.

Secondary processes are responsible for removal or modifying in-situ sediments previously deposited on the fan by primary processes. They include overland flow. It is typically worked to remove, erosion and degradation of the fan. The three facies associations within three different stages have been identified in the gravelly sequences of the study area (Fig. 3). The stratigraphic relationship among the three stages or associations and their distribution is shown in Figure 5 and their summary interpretation is shown in Figure 7.

First stage fan (Debris flow dominated)

It is a first and old stage fan that is composed of matrix-supported very hard clast. Very poorly sorted boulder gravel, which is harder than other matrixes supported clast at the contact between basal gravel and basement rock is fractured (Fig. 2A, 4A). Mainly, this stage is composed of lithofacies Gms (Table 1) while toward a few distances down fan facies Sh is intercalated. Such sedimentological characteristics show the possibility of strong energy acted during the sedimentation process (Fig. 2A). The most obvious reason for it is a catastrophic emplacement by mass flow such as fluvial floods or gravity flow. The flow energy must have been very high to

Table 1: Facies code, sedimentary structure and their interpretation of different gravel fan distributed in the southern part of the Kathmandu Basin (on the basis of Miall concept 1975).

Facies code	Lithofacies	Sedimentary structure	Interpretation	Name of the setting
Gms	Good matrix supported crudely stratified , good sorting gravel	Poorly sorted clast and matrix.	Debrisflow, subaerial deposits	First stage fan Proximal 2nd stage fan
Gm	Massive and crudely bedded gravel	Horizontal bedding Imbrication	Stream flow and sheet flow	2nd stage fan Proximal 3rd stage fan
Gp	Thin stratified or lense shape, matrix or grain supported loose gravels	Well graded, cross-bedded, lense shape	Stream flow and channel flow	Distal 2nd stage and 3rd stage fan
Sp	Sand medium to coarse	Planar cross-bed	Lower flow regime & sandwave	Distal 2rd stage & 3rd stage fan
Sr	Sand very fine to coarse	Ripple of various types	Lower flow regime	3rd stage fan
Sh	Sand very fine to coarse	Horizontal lamination	Planar sand bed, upper & lower flow regime	3rd stage fan
Fl	Sand, silt & mud	Fine lamination Very small ripple	Overbank & wanning flood deposits	3rd stage fan

carry such a large size clast. Most of the clast composition is similar to the southern mountain rock known as metasandstone. Based on the composition of the clasts source of debris flow was from the south or southeast of the basin.

There are mainly two types of lateral sequences within the Itaiti gravel (Paudel and Sakai, 2008). In this study, Itaiti gravel sequences are defined by a very thick gravel sequence that overlies above the basement rock, the Tarebhir Fm at the southern margin is included and interpreted as the debris-flow gravel, which was originated before 1 Ma. Hence, the Proximal gravel beds above the basement rocks and the Tarebhir Fm are matrix-supported gravel that commonly lacks internal structure, and the clasts imbrication are generally ascribed to high viscosity mass flow process commonly known as debris flow origin. The poorly organized, a high value of mean particle size and bed thickness ratio indicates it might be possible that the water moving in shallow channel choked with sediments debris causing poor layering in the gravel beds of the proximal part of the basin (Fig. 4B).

2nd stage fan (Debris and streamflow)

The 2nd stage fan is made up of thick monotonous gravel to frequent intercalation of thin beds of sand and mud. The sand and mud beds are not thicker and laterally continuous as gravel. The gravel beds are mainly divided into two types: the proximal part at the base are debris flow nature and the distal part are subrounded to angular, clast-supported with sandy matrix and thin lens of sand (rarely planar cross-bedding) or the mud beds (Fig. 3; 4C,D). They show mostly crude parallel stratification. The clasts are up to the boulder and the basal surface is concave, erosional, or sometimes sharp (Fig. 4). The above characteristic features of gravel are in agreement with Miall's (1977) concept about the lithofacies code Gm (Table 1). Such types of gravel were formed during the high discharge events in a shallow braided river. Consequently, these fan facies can be interpreted to be mixed deposits of debris and streamflow origin.

Age of the Tarebhir (Pliocene), Lukundol, and Sunakothi (Pleistocene) Fm have differed from each other. Based on the sedimentological study, Paudel (2014) argued that the proximal part of the gravel is an alluvial fan of the Itaiti Fm while toward the basin center is the terrace gravel deposits, which are not related to Itaiti Fm proposed by Sakai 2001. Based on the texture and stratification of gravel deposited within the middle and upper part of the Tarebhir Fm, distal part of the Itaiti Fm, and intercalated gravel beds within the Sunakothi Fm on which the youngest gravel deposits above the Sunakothi Fm are deposited by the activity of stream (Table 1).

The wedge of sand beds in gravel beds is frequently observed toward the distal area (Fig. 4). Such types of couplets were happening due to the high flow of stream carried pebble to cobble size gravels as well as coarse sand in suspension. The gravels were transported as bedload deposits and sand was deposited when the velocity of the stream became gradually low.

3rd stage fan (Braided stream dominated)

This is the last stage gravel fan deposit that overlies above the Sunakothi deltaic sequence. The characteristic features of this deltaic sequence are the poorly sorted, well-organized and imbricated, and planar stratification composed of sandy matrix (Fig. 4E,F). Two types of the base of the gravel beds frequently occur. Essentially, the planar basal surface and lateral continuity of the gravel above deltaic Sunakothi Fm indicate that these sediments were deposited as sheet flood deposits. The scoured base with sand or mud is frequently occurred, and mostly they are sharp base. Some localities usually observed repetition of gravel, sand and mud beds. Irregular contact between the gravels and the lower part of the sand beds usually occurs, which indicates protruding pebbles and hollows in the gravel surface. Also, horizontal stratification of sand beds implied upper flow regime plane bed condition. It is argued that prograding of the fan towards the deltaic sequence is based on frequent coarsening and fining upward sequence.

Fluvio-lacustrine and fan facies relationship

Individual sedimentation units in their measured sections within the study area have one to several facies units (Table 1). The most commonly observed types in fan facies are muddy matrix-supported poorly graded gravel, graded and stratified gravel/sand/mud units, in which the gravel beds are either sharply overlain by sands or mud beds, or gradually decrease in clast size and content toward the sands/mud division. The gravel divisions are generally thicker than the sand/mud division within the fan units, which is laterally changed in the sedimentation processes. The relationship between these bed types and individual facies could be determined by vertical facies transitions in several beds from the south to the central part of the basin (Fig. 3, 6). The facies sequence is tripartite, and consists of massive and clast-supported gravel beds with muddy or sandy matrix in the southern marginal part (Fig. 4), sand-matrix-rich and normally graded gravels, and stratified gravelly sand in the middle part, and thinly stratified or laminated and cross-laminated sand in the upper part (Fig. 2). The facies sequence can be regarded as an idealized depositional sequence produced by composite sediment flow that comprises a debris flow, stream flow, and intermediate flow condition between them (Fig. 5, 6). Li and Yuan (1983), Davies (1986, 1990), Wan and Wang (1994), and Major (1997) show that a debris flow usually consists of many surges or roll waves before deposition occurs. Each sediments surge should aside deposits of earlier surges, spreads out, and leaves a deposit that is thinner and longer than the surge itself. However, the cumulative deposit thickness produced by a series of surges may greatly exceed the average flow thickness. Deposits of earlier surges do not consolidate before the arrival of later surges, resulting in an amalgamation of many surge layers into a single massive layer (Major, 1997). In this way, the marginal part of the thick debris flow fan was becoming enlarged and covered laterally the earlier Pliocene fluvial deposits of the Tarebhir Fm. This event had been playing a crucial role in the origin of an ancient lake in the southern part of the Kathmandu basin.

Age, sedimentation processes, and stratigraphic relationship of the basal gravel among the Tarebhir Fm (Pliocene), Lukundol Fm (Pleistocene), and Sunakothi Fm (Late Pleistocene) have differed from each other. The sedimentological study reveals that the proximal part of the gravel is debris flow dominated alluvial fan of the Itaiti Fm, while toward the basin center it is stream-dominated fan gravel deposits which is not related to the Itaiti Fm proposed by Sakai (2001) that is strongly manifested by the stratigraphic relationship in the lower and upper sequences (Fig. 6). In the southern periphery of the basin, Pliocene fluvial gravel of Tarebhir Fm is directly overlaid by debris flow deposits (Fig. 4A) from the southern Mahabharat range. As a result of this debris flow, the Protobagmati river started damming which initiated the origin of the marginal lake. Gradually marginal lacustrine sediments were extended over the southern part of the basin. There are many gravel and

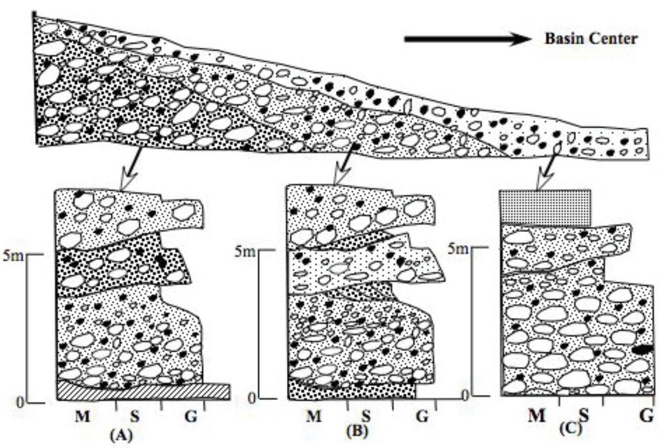

Fig. 5: Three representative bed types common in the Lower sequence (the lower sequence (bed type A), the middle sequence (bed type B), and the upper sequence (bed type C. They are composed of relatively thick gravel beds overlain by thin sandstone beds.

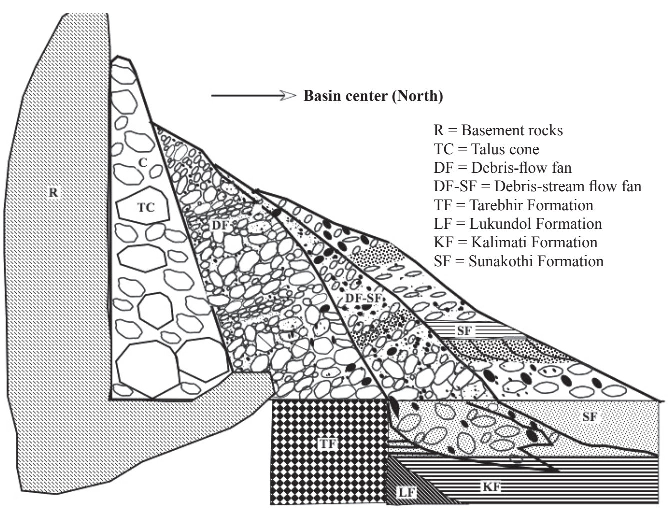

Fig. 6: A schematic diagram representing three different fan types, and relationship and distribution among them. As the fan built upward and outward the older fan stages were progressively overlaid by younger, second and third stages fan.

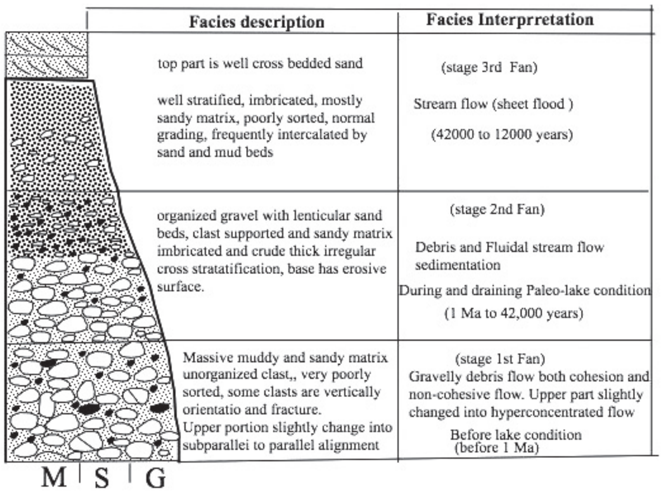

Fig. 7: Facies sequence obtained by the summary within individual sedimentation units. Abbreviations: M- mud, S- sand, and G- gravel.

sand beds within the marginal lake sequences with granitic composition, and this granitic clast was transported from the northern Shivapuri range of the Kathmandu basin. Based on the composition of clasts and sedimentary structures indicate that they are of fluvial origin and not linked to the alluvial fan materials from the south. It is seeming that there was a cessation of fan activity during the deposition of the marginal lake sediments.

Stratigraphic sequences and their distribution slightly vary toward the basin centre from the basin margin. More than forty meters thick muddy and sandy sequence erosionally covered the lacustrine facies of the Kalimati Fm and this muddy and sandy sequence is river-dominated delta facies (Paudel, 2014). Delta facies is not only composed of muddy and sandy facies, but it also contains interbedded gravel facies throughout the study area. Gravel beds are grain to matrix-supported, poorly sorted with sandy matrix. The size of the clasts is not larger than the proximal part of the Itaiti gravel but the stratification of the gravel is distinguishable. The thickness of the gravel bed is 1 to 2 m. and is mostly lenticular in shape.

The sandy and muddy sediments of the Sunakothi Fm show lacustrine delta prograding from the southern part of the Kathmandu basin. Thick to thin beds of gravel with the erosional surface to sharp contact between sandy sequence indicates the activity of stream flow and channel flow deposits during the formation of delta front deposit. The cross-bedded and well-graded gravel beds support the activity of the channel during the deposition period of the delta.

The distal part at the top surface from south to ring road gravels shows a considerable reduction of the clast size and better organization of gravel toward the centre of the basin (around Adhikarigaon at Champi). The gravel beds are more stratified, clasts are highly imbricated. Repetition of the continuous fining-upward sequence and paleocurrent, which has not drastically changed within the gravelly sequence also supports the gravelly braided river channel deposits. It might be possible that the repetition of the continuous fining upward sequence in this fan indicates the decrease in energy leading to the recession of the fan toward the centre.

Control of sedimentary processes

Fan sedimentation is mainly influenced by three extrinsic variables: tectonics, climate, and sea or lake level fluctuation, with the latter two potentially dependent upon each other and upon tectonics. In addition, sedimentation is affected by processes inherent to the depositional system, which act independently of the extrinsic variables. The climatic changes influence the development of alluvial fans by inducing variability in the magnitude and frequency of fluvial processes that alter alluvial fan morphology. Lustig (1965) suggested that the locus of deposition was shifted down the fan, deep fan head trenching at the fan apex, and greater estimated tractive force inactive channels on the fan surface area due to the climatic influences rather than tectonics in the fan system. Many researchers (Bull, 1977; Drew, 1973; Mc Pherson and Hirst, 1972) proposed the influence of fans by tectonic uplift or activity in the basin margin. The role of tectonics in the development of fan is considered in terms of fan entrenchment, fan segmentation and sedimentology, shape, and thickness of alluvial fan. The active basin margin areas like the Kathmandu basin tectonics play a vital role in providing a huge volume of sediments to construct the fan.

Integrated analysis of different sedimentological pieces of evidence such as texture, structure, lithology, the slope of the terrain, paleocurrent of the sediments, probable processes of deposition, facies, and vertical and lateral facies changes, etc. are becoming common criteria as an attempt to interpret for the causes of sedimentation either tectonics or climatic dominant or both. Evidence from stratigraphic records including distribution of certain types of sediments and climatically driven change in lake level recorded in lacustrine-alluvial fan interbedding are important clues for interpretation. Often coarse fluvial channel and bar deposits and detrital overbank can be interpreted in terms of local climate or local tectonic influences. This section focuses on the lithology, texture, and structure of clastic deposits in the alluvial fan-lacustrine system to determine whether they contain any useful information regarding climatic or tectonics.

If the rate of tectonics uplift during the deposition period is greater than the flow of the stream deposition then the fan sediments deposited closer to the mountain range is more concentrated and very thick-bedded. However, the rate of tectonic uplift is not as significant as the flow of the stream depositing the sediments this result in a more spread-out flatter alluvial fan which has a greater distance from mountain range (Fig. 6). The proximal part of the fan sequence within the study area is thicker and same time clasts are coarser than the distal part which indicates tectonic activity had played a significant role during the deposition of the sediments. Such a huge volume of clastic sediments is only possible if they are especially prominent where the uplift of the southern mountain region provides a continuous supply of fresh debris from steep slope mountains. Bull (1977) argued that the tectonically active region has an abundance of an alluvial fan while in the tectonically stable area pediment is the dominant landform. Such types of pediment landform did not develop in the southern part of the Kathmandu basin.

Two phases of events are dominated by the development of alluvial fans under the influence of tectonic uplift and climate. First, the fan is shown by the deposition of adjacent to the mountain front. Second, the area of deposition is shifted further down fan direction due to stream channel activity by climatic influences. The sedimentary facies of the study area manifested those depositional environmental changes from proximal to the distal part where fluvial influences were more pronounced in the sediments and sedimentary structures were preserved within the down fan direction.

The role of basin margin tectonics within the intermountain basin has a significant wide accommodation space for the huge amount of sediments deposition. The thick clastic detrital sequence and their wider distribution from the south and north to the central part of the Kathmandu basin indicate that a wide accommodation space was available before the deposition of these sediments. This wide space was most probably the result of the higher rate of upliftment of the Mahabharata Range in the south and the Shivapuri Range in the north. The thick sandy/muddy part of the fluviolacustrine sequences, which are dipping toward the centre at the southern margin, and thick fluvial gravel beds within the sandy sequence showing the paleocurrent direction from south and southeast indicate that the rate of upliftment of the Mahabharat range in the south was infrequent. On the other hand, thick fluvial sandy and gravelly sediments within the deltaic Formations show greater runoff and the large volume of sediments yielded due to greater relief and elevated precipitation at the time of deposition. Moreover, repetition of fine and coarse sediments indicates a seasonal high to low amount of precipitation rate within the Kathmandu basin during the deposition of these sediments.

There are some common arguments about the influence of both tectonics and climate within the deposition of fan sediments in the southern part of the Kathmandu basin. Based on a sedimentological study of gravel sequences from the southern margin to the central part different gravelly facies have been identified. The basal part of the basin margin gravel beds is mostly clasts supported and muddy matrix-supported debris flow deposits. The muddy matrix within the debris flow probably enhances the mobility of the debris flow by lubricating frictional clast's interaction. Such types of muddy matrix most probably have been supplied by grinding of the boulders obtained from basin margin tectonics. The clast-supported sandy matrix gravel sequence is distributed in the distal part of the basin margin. The matrix of the gravel beds is mainly composed of sandy materials, which are poorly sorted and granular coarse sand. The scoured base surface is more common above sandy or muddy beds. Such type of facies is suggestive of cohesionless debris flow dominated by frictional grain interaction. Lack of inverse grading and imbrications of clast is probably due to suppression of clast collision and activity of stream.

Fine-grained mud beds are frequently interbedded between gravel and sand beds toward the basin center in the southern part of the Kathmandu basin. It is suggested that such types of sequences are most probably deposited due to the waning stage of sheet flood or water flow or dewatering of the debris flow or reworking of surficial deposits by sheet wash during torrential rain. It might be possible that the surface was inundated during some period due to heavy flooding events. Such kinds of fine-grain sediments were deposited by suspension processes. Thick units forming the sequence boundaries indicate a long period of fan abandonment and slow suspension sedimentation.

CONCLUSIONS

Thick sedimentary sequences have many hidden histories about the types and process of sedimentation and its linkage to climatic and tectonics of the recent geological time within the central Nepal Himalaya. Based on a detailed geological survey and sedimentological study of the gravelly sequence and its relationship to the fluvio-lacustrine sequences, it is concluded that there are three stages of fan sediments that have been deposited during different geological times and processes. The first stage fan originated from a debris flow mechanism that mostly covered the basement rocks and fluvial gravel sediments deposited before 1 Ma. Huge volume and various sizes of the clasts with fine matrix most probably have been supplied by grinding of the boulders obtained from basin margin tectonics. The first stage fan is mainly composed of gravel facies of Gms and rarely Gm. Second and third-stage fans are composed of various types of gravel and sand facies (Gms, Gm, Gp, Sp, Sr, Sh, and Fl). Stratigraphically, the second stage fan is overlying on the marginal lake of Lukundol Fm while the third stage fan is covered widely in the southern part of the basin and laterally second stage fan interfingering with lacustrine deltaic facies of Sunakoth Fm. It is suggested that the second and third stage fan sediments were deposited up to the delta front and prodeltaic region of the Sunakothi Fm.

Sedimentological evidence of second and third-stage fans implied rather a debris flow processes, pronounced stream activity during deposition is clarified by clast supported sandy matrix gravel sequence, repetition of couplets of gravel-sand-mud sequences on the distal part of basin margin. The matrix of the gravel beds is mainly composed of sandy materials, which are poorly sorted coarse sand. The scoured base surface is more common above sandy or muddy beds. Lack of inverse grading and imbrications of clasts is probably due to suppression of clasts collision and activity of stream. Hence, high precipitation and runoff were adequately happening since the first debris flow fan deposit was initiated by basin margin tectonics.

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