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Small-amplitude lake-level fluctuations recorded in aggrading deltaic deposits of the Upper Pleistocene Thimi and Gokarna formations, Kathmandu Valley, Nepal

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ABSTRACT

Small-amplitude lake-level fluctuations have been recognized from the aggrading delta-plain deposits in the lower parts of the Thimi and Gokarna formations, Kathmandu Valley, Nepal. The delta-plain deposits consist of gravelly sand beds of fluvial channel origin (coarse-sediment interval) and alternation of fine to very fine sand and sandy silt beds (fine-sediment interval). Wave-generated structures occur in the sand beds of the fine-sediment intervals.

The vertical and lateral facies changes suggest that the deposition of a set of coarse- and fine-sediment intervals associated with prograding delta front deposits was controlled by a lake-level rise and fall sequence superimposed on a long-term lake-level rise trend. The aggradation of fluvial sediments occurred during a lake-level rise period with sufficient sediment supply to fill a newly created accommodation space on the delta plain. The observation of wave-generated structures in an overlying fine-sediment interval suggests that the delta plain was subsequently inundated due to further lake-level rise, exceeding the sedimentation rate. Subsequent delta progradation occurred during a lake-level stabilized phase after a lake-level fall. The small-amplitude lake-level changes are thought to be attributable to seasonal wet and dry cycles, as inferred based on the presence of peculiar aggrading delta successions, implying that lake-level fluctuations may have occurred over short time scales, and on the results of a previous palaeopalynological study in which a moist palaeoclimate was inferred in the lower part of the Gokarna Formation in particular.

INTRODUCTION

The Kathmandu Valley is an intermontane basin in the Lesser Himalayan Belt and is filled with fluvio-lacustrine sediments of Plio-Pleistocene age (Yoshida and Gautam 1988). The top of the basin fill succession is made up of several terraces of lacustrine-delta deposits (Akiba 1980; Natori et al. 1980; Yamanaka 1982; Sakai et al. 2000). Marginal areas of terraces in the central region of the basin consist of several Gilbert-type delta successions (Sakai et al. 2000). This implies that terrace formations were associated with lake-level rises, which may have occurred due to basin plugging at the outlet as a result of mass movement such as landslides (Sakai et al. 2000).

In the basinward margin of the Gokarna and Thimi terraces, sand beds exhibiting wave-generated sedimentary structures were discovered in the aggrading delta-plain deposits. Wave-generated structures have previously been reported from subaqueous depositional environments such as nearshore and delta front of large recent and ancient lakes (e.g. Dam and Surlyk 1993; Greenwood and Sherman 1986; Martel and Gibling 1991). Frequently appeared sand beds with wave-generated structures in the delta-plain deposits suggest periodical inundations of the delta-plain environment. In this paper, we describe the depositional facies and their lateral and vertical variation in the terrace sediments, and discuss delta aggradation processes and the possible origin of lake-level fluctuations that induced the formation of wave-generated structures in the aggrading delta-plain successions.

GEOLOGIC SETTING

The Kathmandu Valley-fill sediments cover the Kathmandu Complex (Stöcklin and Bhattarai 1980) of the Paleozoic sedimentary rocks and Precambrian gneiss (e.g. Dongol 1985; Rai et al. 1997; Yoshida and Igarashi 1984) (Fig. 1), and consist of more than 600 m of fluvio-lacustrine sediments (e.g. Moribayashi and Maruo 1980; Katel et al. 1996). The upper extent of these deposits forms several depositional terraces (Fig. 2), named Patan (1,300–1,320 m), Thimi (1,330–1,340 m) and Gokarna (1,350–1,390 m) terraces, distributed in the central part of the basin, and Boregaon (1,410–1,430 m), Chapagaon (1,440–1,460 m) and Pyangaon

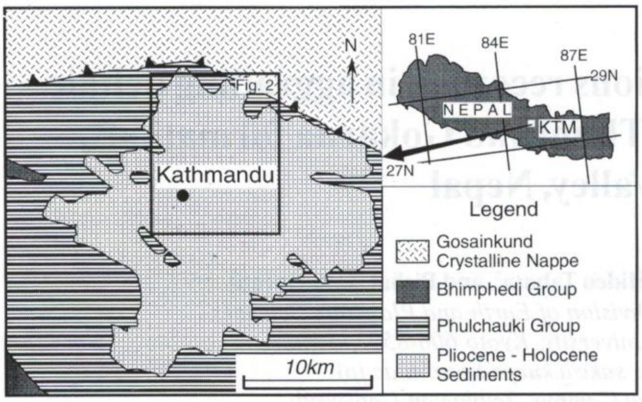

Fig. 1: Location and simplified geological map of the Kathmandu Valley

(1,480–1,520 m) terraces, confined in the southern part of the basin (Yoshida and Igarashi 1984). Terrace sediments around the basin center have been stratigraphically defined using appropriate terrace names (Gokarna, Thimi, and Patan formations). The depositional periods of these formations have been evaluated by means of ^{14}C age measurements; -28 kyr (Gokarna Formation), 28-24 kyr (Thimi Formation) and 19-11 kyr (Patan Formation) (e.g. Yonechi 1973; Yoshida and Igarashi 1984). However Gajurel (1998) obtained older age data than the upper limit of the Gokarna Formation (45 and 43 kyr) from the Thimi terrace sediments at Thimi quarry, suggesting that stratigraphic relationship between the Thimi and Gokarna formations should be reconsidered based on detail stratigraphic and chronological studies (Gautam et al. 2001).

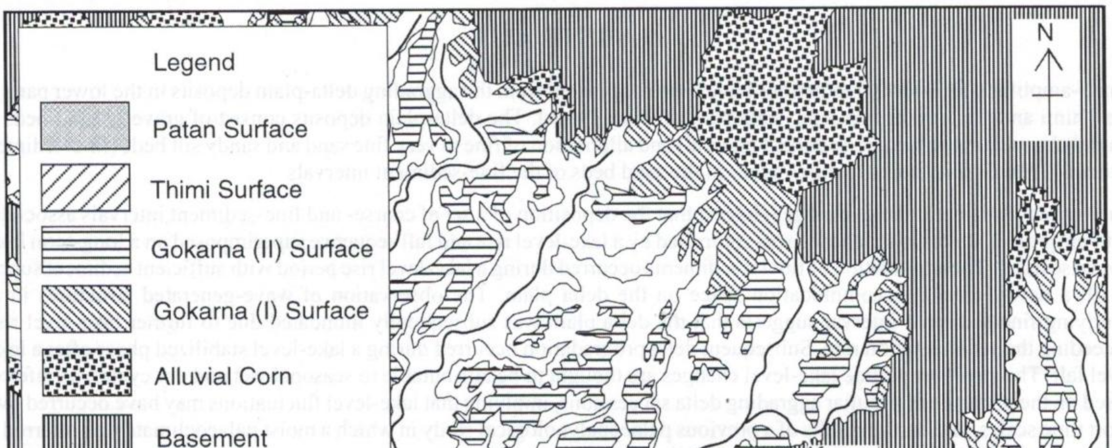

Fig. 2: Terrace surface classification map of area indicated in Fig. 1 and locations of columnar sections shown in Fig. 3 and 5. TIA: Tribhuvan International Airport.

The main study sites (Locs. 1-10) are located to the east of Kathmandu City (Fig. 2). Locations 1-8 correspond to the marginal areas of the Thimi Terrace around Tribhuvan International Airport, where broad lateral facies changes and the stacking patterns of the delta deposits can be described. Location 9 and 10 (Fig. 2) correspond to the marginal regions of the Gokarna Terrace around Kapan, where the lateral facies changes between the delta-plain and delta-front deposits in aggrading delta successions can be observed directly at outcrops.

DEPOSITIONAL ENVIRONMENT OF STUDIED SECTIONS

We applied facies analysis method (cf. Walker 1984; Walker and James 1992) for the interpretation of terrace sediments in the study area. The findings were that (1) the sections at Locs. 1-10 consist mainly of sand and silt beds of delta-plain, delta-front and prodelta origin; and (2) braided channel deposits (Patan Formation) that fill incised valleys truncating the underlying Thimi Formation and form small alluvial fans, are identified at Loc. 1 and 3. (Fig. 3). Only the delta successions of the lower parts of the Thimi and Gokarna formations, the focus of this study, are described below.

Delta-plain deposit

This facies is characterized by trough cross-stratified or parallel laminated gravelly sand beds, and alternating beds of fine to very fine sand and sandy silt, referred to here as coarse-sediment and fine-sediment intervals, respectively. The coarse-sediment intervals are up to 3 m thick, and the individual cross-laminated beds are up to 0.3 m thick. The bases of the intervals indicate minor erosion surfaces, and the tops of the intervals are partly truncated by overlying fine-sediment intervals. Tracing the coarse-sediment intervals to the downstream direction, they tend to incline and continue into delta-front deposits (described below) with decrease in thickness.

The fine-sediment intervals are up to 0.5 m thick. The sand beds in these intervals, up to 0.3 m thick themselves (commonly 0.1 m thick), exhibit wave-ripple, current-ripple and climbing-ripple laminations, and hummocky cross-stratifications (Harms et al. 1975; Dott and Bourgeois 1982; Cheel and Leckie 1992) (Fig. 4). The base and top boundaries of the fine-sediment intervals are sharp. Abundant muscovite flakes occur in both the sand and sandy silt beds. The fine-sediment intervals also continue into delta-front deposits with no distinct facies boundary.

The cross-lamination and coarse-grained sediments indicate that the coarse-sediment intervals were deposited under strong unidirectional current conditions, that is, fluvial-flow origin on the delta plain. The fine-sediment intervals, in which wave-generated sedimentary structures such as wave-ripple lamination and hummocky cross-stratification are common, are expected to have accumulated at a time when the delta-plain environment was temporally inundated. Because fine-sediment intervals indicate subaqueous deposition, they should be contained in the prodelta or lake-floor deposits. Inundation of the delta plain was, however, temporal event in a long-term delta aggradation phase, hence, we recognize the intervals as "inundated delta-plain deposit".

Delta-front deposit

This facies is characterized by tabular cross-stratified medium to coarse sand beds and interbedded fine to very fine sand and sandy silt beds in an interval up to 10 m thick. Individual sand units in the tabular cross-stratified beds are up to 50 cm thick (average 5 cm) and are massive or exhibit reverse or normal grading and parallel laminations. Facies thicker than 5 m contain slump structures (e.g. lower section at Loc. 5). Wave-ripple laminations and hummocky cross-stratifications are also recognized in this facies, and are commonly found in the upper section of the interval within the top 5 m of the facies. Several sand beds extend from coarse-sediment intervals of the delta-plain and are commonly thinner than that on the delta-plain. Most fine-sediment intervals also continue from the delta-plain facies without changing thickness and internal sedimentary structures.

Wave-generated sedimentary structures are a good indicator of subaqueous deposition. The sedimentary features, massive, reverse or normal grading, and slumped beds, indicate that sediment transport occurred mainly via gravity processes (cf. Middleton and Hampton 1976). The large-scale cross-stratified sand beds, their depositional process and interfingering relationship with the lateral equivalent delta-plain deposits suggest that this facies is of delta-front origin. The character of the fine-sediment intervals suggests that suspension-fallout sedimentation is dominant both on the delta-plain and delta-front when the delta-plain environment was submerged.

Prodelta deposit

Of all the studied sections (the lower parts of the Thimi and Gokarna formations), distinct prodelta deposits can only be observed at Loc. 1 and 4. This facies consists of alternating sand and sandy silt beds in an interval of about 1 m thick. Interbedded sand is commonly a continuation of the overlying cross-laminated sand of delta-front deposits, characterized by parallel and climbing-ripple laminations and a tendency to thin away from the foot of the delta-front slope. Wave-ripple laminations are also observed in the sand beds.

Finer sediments, dominant in this facies, suggest deposition from suspension under a hydrologically calm environment. These features and the nature of the overlying facies (delta-front deposit) suggest that this facies is of prodelta origin. The interbedded sand layers exhibit indicators of intermittent sediment supply from the delta-front environment as traction or suspended load.

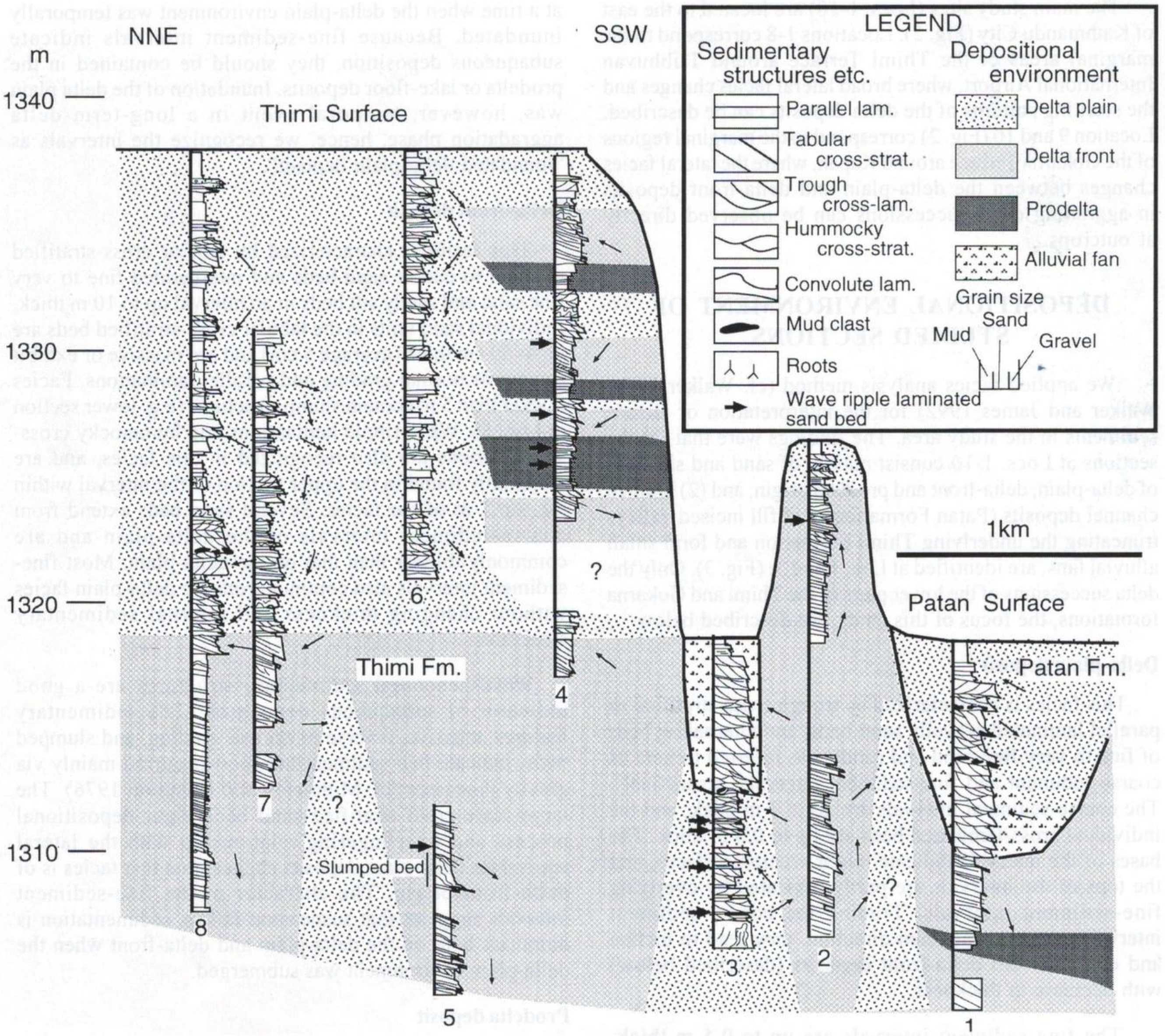

Fig. 3: Columnar sections of the Thimi Formation recorded in this study. Long arrows indicate palaeoflow directions (up = north).

LATERAL AND VERTICAL FACIES CHANGE

Broad facies change

A broad lateral variation of delta facies in the Thimi Formation sections (Fig. 3), suggests that delta aggradation occurred in a limited area during the early phase of deposition of the lower part of the Thimi Formation prior to the delta progradation phase. The section at Loc. 3 consists of only delta-plain deposits. The dominant palaeoflow direction, as determined from cross laminations, is toward WNW; the cross sections shown in Fig. 3 is taken subperpendicular to the major sediment supply path in this area. To the north and south of Loc. 3 (Loc. 2 and 5), thick delta-front deposits appear at the same elevation with the Loc. 3 delta-plain deposits. The delta progradation directions at Locs. 2 and 5 are toward the north and south, respectively (Fig. 3), indicating that delta lobes other than that observed at Loc. 3 may be present to the south of Loc. 2 and north of Loc. 5.

The facies relationship between the aggrading delta-plain and thick delta-front deposits cannot be observed directly in the outcrops of the Thimi Formation. However, the Loc. 9 example provides a clue to understanding this relationship (Fig. 5). As stated below, the Loc. 9 aggrading delta succession exhibits temporal delta progradation and includes

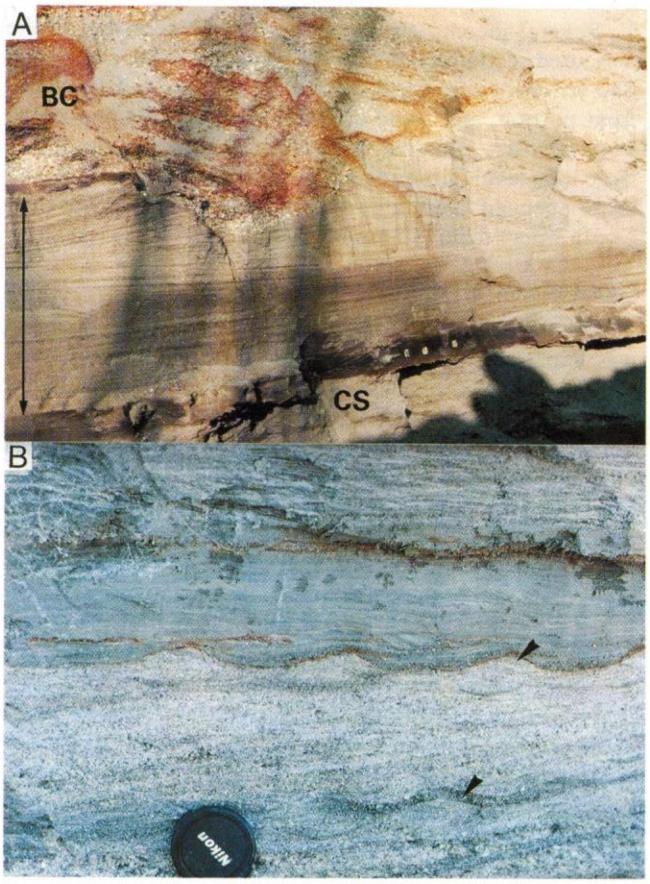

Fig. 4: Wave-generated sedimentary structures of the lower parts of the Thimi and Gokarna formations. (A) Hummocky cross-stratified sand bed at Loc. 3 (arrowed interval). This bed is truncated by braided channel fill deposits of small alluvial fan origin (Patan Formation). Outcrop is 1 m high. (B) Typical wave-ripple laminations (arrowed points) found at an arrowed point of Fig. 6C. Scale is 5 cm in diameter. BC: Braided channel-fill deposit of alluvial-fan origin, CS: Coarse-sediment interval.

only thin delta-front deposits (less than 2 m). This implies that most of the sediment was trapped on the delta-plain in a period of lake-level rise.

In the case of the Thimi Formation, delta progradation is expected to have occurred as the lake-level stabilized. This is supported by the elevation of the tops of the thick delta-front deposits, which are at almost the same level in all sections except for the terrace margin (Loc. 2) where overlying delta deposits prograded further over underlying delta margin, and Loc. 1 and 3 where overlying alluvial fan deposits truncate the Thimi Formation (Fig. 3).

Facies change in aggrading delta deposits

As stated above, the delta-plain deposits of both the Thimi and Gokarna formations consist of alternating coarse- and fine-sediment intervals. A typical sequence has the following features: The coarse-sediment interval has an almost flat base and top where it overlies the fine-sediment interval and flat-topped delta-front deposits (Fig. 6A and B), and tends to thin toward the transition to delta-front facies. The overlying fine-sediment interval is also of constant thickness, and extends from the delta-plain environment to the delta-front environment (Fig. 6A and C). The fine-sediment interval is then overlain by delta-front deposit in the inclined delta-front region (Fig. 6C). The delta-front deposit has a flat top and exhibits a short sequence of delta progradation. This deposit is then overlain by the next coarse-sediment interval (Fig. 6C). There are relatively few complete successions as described above, and the continuity of thinner fine-sediment intervals is poor (Fig. 6A). Some such intervals are traceable only in the delta-plain environment, and others have limited continuity only in the delta-front deposits. In some sequences, delta-front deposits are not recognizable.

DISCUSSION

Accumulation process for coarse- and fine-sediment intervals

The vertical and lateral facies changes stated above suggest that the delta-plain environment was periodically submerged as a result of small lake-level rises (Fig. 7). The coarse-sediment interval is expected to have begun to accumulate following a delta progradation phase (Fig. 7A and B). The lateral facies change of the coarse-sediment intervals into delta-front deposits with little progradation implies that sediment accumulation occurred with rising lake-level, the rate of which was synchronized with the sedimentation rate (Fig. 7B). The overlying fine-sediment interval is inferred to have been deposited when the delta-plain environment was completely submerged due to further lake-level rise at a rate exceeding the sedimentation rate (Fig. 7C). Lateral equivalent shoreline sediments of the fine-sediment intervals have not been discovered, and might be truncated by subsequent fluvial processes. The lake-level rise amplitude is evaluated as being up to 9 m based on the presence of wave-generated sedimentary structures in the upper 5 m of the thick delta-front deposits and the maximum thickness of a couplet of the coarse- and fine-sediment intervals (4 m). The presence of overlying flat-topped delta front deposits is indicative of subsequent deposition during a period of stable lake-level following lake-level fall (Fig. 7D). The amplitude of the fall is difficult to evaluate, however it is thought to be smaller than the previous lake-level rise because most of the previously deposited sediments are preserved. The coarse-sediment interval formation of the following set may have been initiated in conjunction with subsequent lake-level rise.

The duration of each fluctuation is expected to be less than 100 years based on the delta stacking pattern itself which was formed in a longer time period than each cycle, and other area examples indicating rapid lake-level rise in dammed lakes. In the dammed lakes of the temperate climate

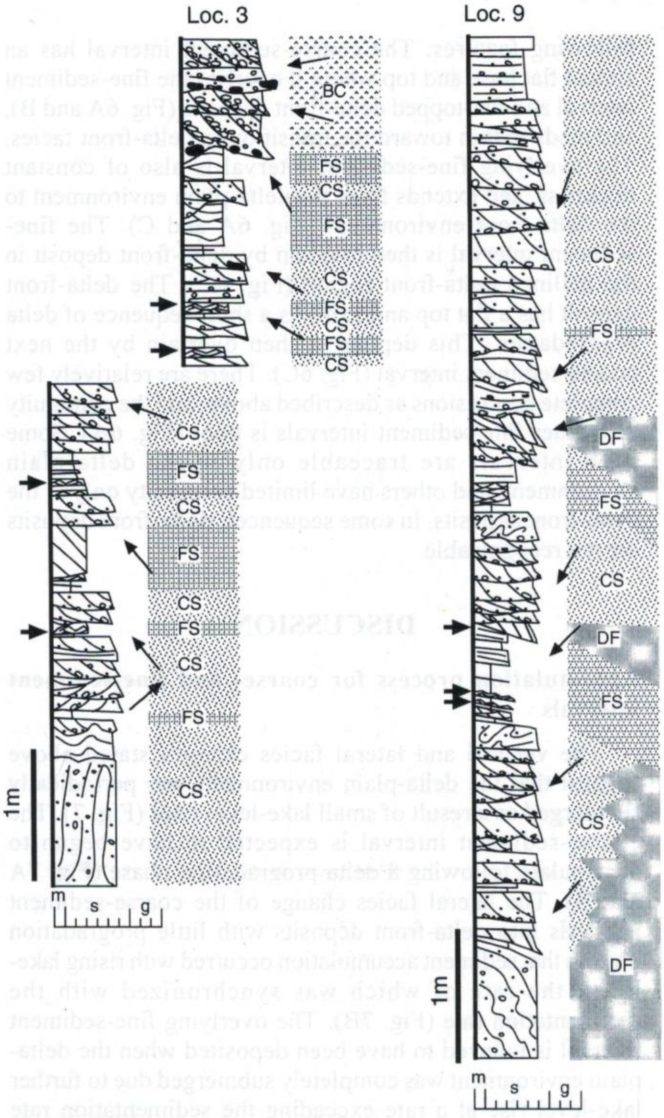

Fig. 5: Columnar sections from Loc. 3 and 9. Long and short arrows indicate palaeoflow directions (up = north) and wave-ripple laminated sand beds, respectively. CS: Coarse-sediment interval, FS: Fine-sediment interval, DF: Delta-front deposit, m: mud, s: sand, g: gravel.

condition, several tens of meters lake-level rise after plug formation occur during several tens of years in some cases. It is exemplified by a New Zealand caldera lake (Lake Taupo) dammed by volcanic eruption and having area similar to the Kathmandu Valley, where ca. 130 m of lake-level rise during about 20 years are estimated (Riggs et al. 2001). In such type of lakes, sediment accumulation occurs only under sufficient sediment supply to form aggrading or backstepping delta and lake floor deposits without distinct progradation (e.g. Fig. 6 in Manville 2001). From the similarity of stacking pattern of the strata, about 10–20 m of delta aggradation in limited area in both the Thimi and Gokarna formations is thought to be formed in a short time period, probably time scale similar to the New Zealand case.

Several incomplete successions were recorded in the measured sections (Fig. 5 and 6); some sets have very thin fine-sediment intervals that are recognized only in the delta-front portion, and some do not include prograding delta-front deposits. This may be attributable to erosion due to large lake-level falls, preventing sediment preservation, and lower sedimentation rates due to the migration of the river mouth where delta progradation occurs.

Cause of lake-level fluctuation

Sakai T. et al. (2000) suggested that basin outlet plugging was important in the formation of the lake in Kathmandu Valley. Once the plug is formed, the lake behaves like a hydrologically closed lake (cf. Talbot and Allen 1992), such as the Dead Sea and Salt Lake. Until the lake-level reaches the plug level, which determines the upper limit of the lake-level rise, lake-level fluctuation in the plugged basin may be controlled by tectonics, climate change affecting evaporation and rain fall, infiltration (Talbot and Allen 1992) and water input due to other lake bursts from the surrounding basins. In the case of the Gokarna and Thimi formations, tectonic effects may be less important because the terrace surfaces are characterized by almost flat topography in the entire study area, and there is no fault and fold that deform strata in the area. Infiltration, an important factor in basins such as those with carbonate sediment basements or other high-permeability basements, also seems to have a negligible influence on the lake-level change, as evidence by the thick silt beds that constitute the major part of the basin fill sediments (Katel et al. 1996).

We were unable to confidently identify the cause of short-term small-amplitude lake-level changes, however climate changes seem to be the important control factor. Yoshida and Igarashi (1984) reconstructed the lower Gokarna phase climate conditions by means of palaeopalynological analysis. Based on this study, they recognized the presence of tropical evergreen lower mountain forests (900–1,800 m elevation) suggesting a mild and moist climate for this period. This condition is similar to or slightly cooler than the modern Kathmandu Valley climate condition. The Thimi phase climate has not been reconstructed. However, lake area spreading in the Tarim Basin of the Tibetan Plateau was recognized around 26 kyr (Fig. 2; Yan et al. 1997) implying possibility of temporal increase in southwestern monsoon activity affecting even to the north of the Himalayan Mountains during the Thimi phase.

Modern Kathmandu Valley is situated near the transition between warm temperate and subtropical climate conditions. The annual climatic cycle is characterized by a wet season that continues from June to early September, and a dry season. The increment of water supply during the wet season introduced by 300–400 mm rainfall per month has the potential to cause a lake-level rise of a few meters if the basin outlet were plugged, sufficient to inundate a delta-plain environment. In the dammed lake stated above, 5–9 m of lake-level rise in a year, which is sufficient to delta-plain inundation, has been estimated (Riggs et al. 2001). We now

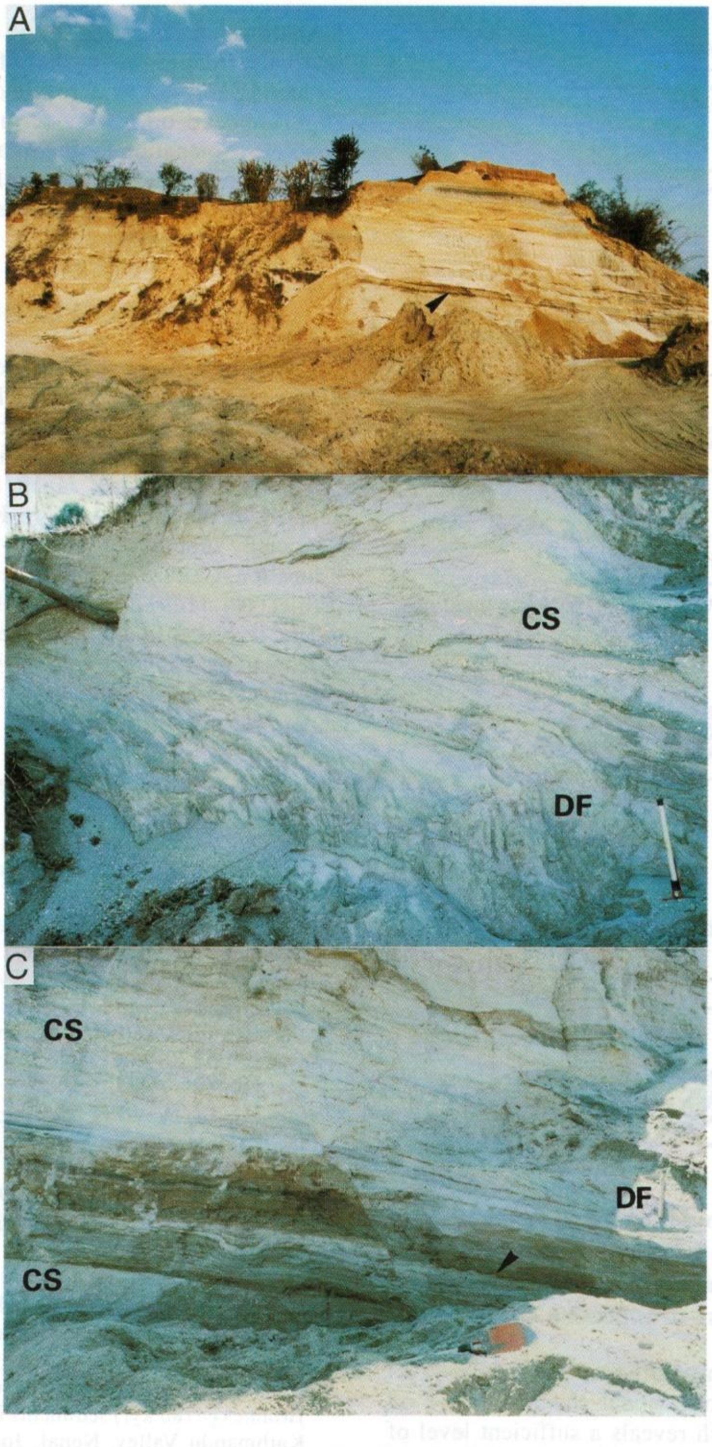

Fig. 6: Outcrop photographs of aggrading delta deposits at Loc. 9 and 10. (A) Outcrop view of Loc. 10. Arrowed interval represents a fine-sediment interval traceable from delta-plain to delta-front deposits. Other thin fine-sediment intervals with poor continuity (thin brown layers) are also recognized at this site. The outcrop is 15 m high. (B) Delta-front deposits and an overlying coarse-sediment interval in the Gokarna Formation at Loc. 9. Alternating fine sand and silt beds near the top of the photograph correspond to those in Fig. 6C. The scale is 60 cm long. (C) A fine-sediment interval (thick brown part), overlying fluvial channel-fill deposits of coarse-sediment interval and overlain by delta-front deposits. These deposits are then overlain by other coarse-sediment interval. The brown part in the upper part of the photograph is other fine-sediment interval. The outcrop is 2 m high. Close-up photograph around the arrow is shown in Fig. 4B. BC: Braided channel-fill deposit of alluvial-fan origin, CS: Coarse-sediment interval, FS: Fine-sediment interval, DF: Delta-front deposit.

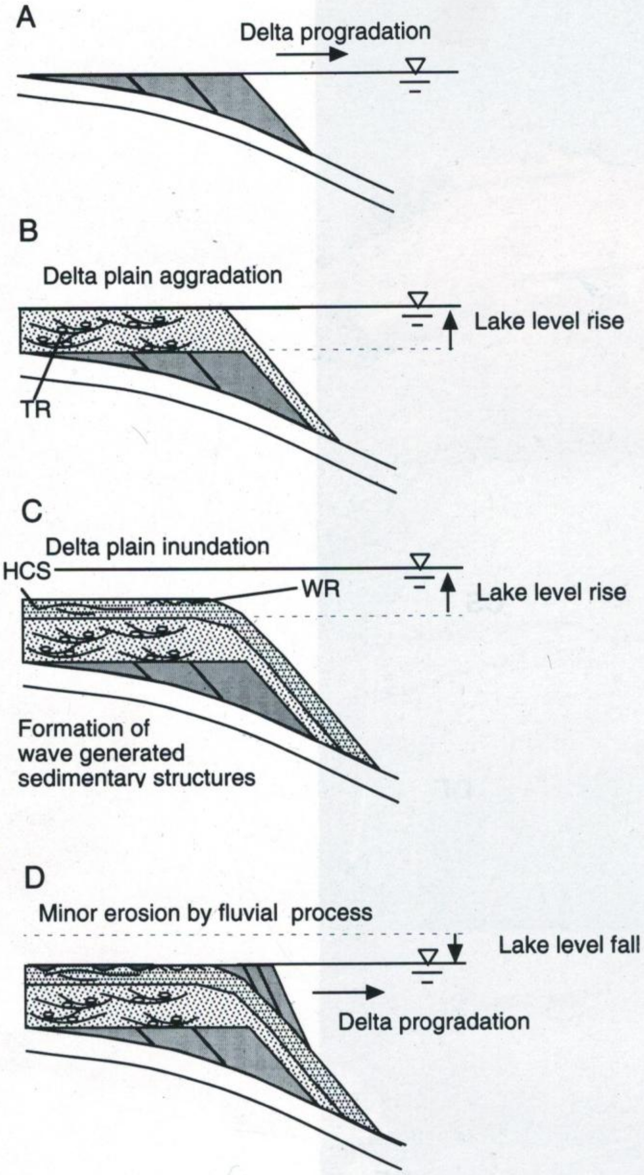

Fig. 7: Model of delta accumulation based on the study of lower parts of the Thimi and Gokarna formations. HCS: Hummocky cross-stratification, WR: Wave-ripple lamination, TR: Trough cross-stratification

believe that the short-term small-amplitude lake-level fluctuations occurred due to seasonal changes, based on climate reconstruction, which reveals a sufficient level of moisture, together with possibility of high rate of lake-level rise. Further chronological studies and pollen analysis will provide detailed information regarding the climatic condition during the deposition of these formations.

CONCLUDING REMARKS

Small-amplitude lake-level fluctuations have been recognized from the aggrading delta-plain deposits in the marginal areas of the lower parts of the Thimi and Gokarna formations. A complete set of coarse- and fine-sediment intervals with prograding delta-front deposits is interpreted as having formed as a result of lake-level rise and fall superimposed on a long-term lake-level rise trend. A concrete explanation for the small lake-level fluctuations is yet to be proposed, however climatic conditions such as seasonal wet and dry cycles, may be important factors for the lake-level change.

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