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Palaeohydrology of the Siwalik Group along the Bakiya Khola section, central Nepal Himalaya

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ABSTRACT

Middle Miocene to Early Pleistocene fluvial sediments of the Siwalik Group comprises many fining-upward cycles from several to tens of metres thick. It is a foreland basin sediment with a coarsening-upward succession as a whole. The palaeohydrology and evolution of the fluvial depositional system of the group in the Bakiya Khola section of central Nepal was estimated using the grain size analyses, sedimentary structures and thickness of fining-upward cycles. Stratigraphically from older to younger sequence, the velocity and channel gradient of the palaeofluvial system varies from 0.28 m/s to 3.3 m/s and 2.9×10^{-5} to 3.4×10^{-4} m/m, respectively. The progressive changes in palaeovelocity and palaeochannel gradient reflect the southward propagation of thrust activities in the Himalayan front.

INTRODUCTION

Palaeohydrological reconstruction from ancient fluvial deposits is important because it can quantify hydraulic environments of ancient rivers, and facilitate comparison with modern fluvial systems. Methods of hydrological reconstruction of ancient deposits are based on flume experiments and observations of modern depositional systems (Major and Pierson 1992; Major 1996). Palaeohydrology shows the quantitative relationships between the palaeohydrological parameters of the river (e.g. depth, slope, discharge, sediment type) and preserved deposits. There are many case studies of palaeohydrological reconstruction of ancient deposits (e.g. Bridge and Gordon 1985; Cotter 1971; Steer and Abbott 1984; Els 1990; Nakayama 1999). Ethridge and Schumm (1978), Bridge (1978), Maizels (1983), and Williams (1984) have reviewed the methods. In these investigations, Allen (1965), Leeder (1973), and Ethridge and Schumm (1978) lead the important method for estimation of water depth of ancient fluvial systems. Allen (1965) demonstrates that the mean height of dunes is proportional to mean water depth. Leeder (1973) and Ethridge and Schumm (1978) found that the thickness of a fining-upward cycle in meandering channel is approximately equal to the bankfull depth. Miall (1996) mentions that the approach of a fining-upward cycle is potentially more useful because a fining-upward cycle reflects more long-time and statistical average of flow in comparison with dune height. Other notable palaeohydrological reconstruction was performed on the ancient tidal sediments by Allen and Homewood (1984), which determined the range of palaeovelocity based on the supposed flow depth and bed configuration.

The Siwalik Group is a 6 km thick succession of Middle Miocene to Early Pleistocene fluvial sediments, which forms the frontal mountain ranges of the Himalaya. Sedimentation of this foreland basin deposit is thought to be influenced by the Neogene tectonics of the Himalaya (Parkash et al. 1980). Standard stratigraphy of the Siwalik Group has been established in the Potwar Basin of Pakistan on the basis of lithology, vertebrate palaeontology and palaeomagnetism (Johnson et al. 1982; Opdyke et al. 1982). Worldwide climatic changes are recorded in the group, as demonstrated by fossils, and stable isotope analysis (Quade et al. 1989; Harrison et al. 1993; Quade et al. 1995; Cerling et al. 1997).

Detailed sedimentological studies of the Siwalik Group in the Potwar Basin of Pakistan have been carried out by Willis (1993a, 1993b), Khan et al. (1997), and Zaleha (1997a, 1997b). These works included the palaeohydrological reconstructions based on the detail sketches of several hundreds of metres wide outcrops, but did not deal with the entire Siwalik successions because of the limitation of outcrop. In Nepal, such palaeohydrological study on the Siwalik Group is negligible. Ulak and Nakayama (1999), Ulak (2002, in press), Ulak and Nakayama (2002, in press) have estimated palaeohydrology of outcrops along the Surai Khola (Bankas and Chor Khola formations) section, west Nepal and the Chure Khola (Amlekhganj Formation) section, central Nepal. The palaeohydrological study of these sections reveals that the velocity and channel gradient progressively increase from older to younger stratigraphic sequence.

This paper focuses on estimation of the palaeohydrological parameters of the most complete stratigraphic section of the Siwalik Group in Nepal. The relationship between the palaeohydrological change and the Neogene tectonics of the Himalayan uplift is also discussed. The estimation method used in this study can be applicable for any vertical profile data from outcrops with a limited lateral-dimension. It is also suitable for the study of evolutionary change in palaeohydrology. However, in this method estimated values of the palaeohydrological parameters may be less precise in comparison with the values based on large outcrops which provide information of a wider area.

GEOLOGICAL OUTLINE

The Himalaya is the consequence of the intracontinental collision between the Indian and Eurasian plates, producing a succession of southward propagating thrust sheets (Gansser 1964) demarcated by the Main Central Thrust (MCT), Main Boundary Thrust (MBT), and Main Frontal Thrust (MFT) exposed successively from north to south (Fig. 1).

The Siwalik Group was deposited in a foreland basin developed at the southern front of the Himalaya. The sediments were supplied from the rising Himalaya to the north. The Siwalik Group is bounded by the MBT to the north and the MFT to the south. In Nepal, the rocks of Siwalik Group generally dip northward, and exhibit a coarsening upward succession. In most places, the Central Churia Thrust (CCT) or the Main Dun Thrust (MDT) separates the Siwalik Group into the northern and southern belts.

The Siwalik Group is well exposed in the Bakiya Khola area of central Nepal. The lithostratigraphy of this area was formally established by Sah et al. (1994) and Ulak and Nakayama (1998). The Siwalik Group comprises of the Rapti, Amlekhganj, Churia Khola, and Churia Mai formations, in the ascending order. The Rapti and Amlekhganj formations are subdivided into the Lower, Middle, and Upper members respectively (Fig. 2). The Rapti Formation (>1,100 m) is composed of very fine- to medium-grained, grey sandstones and bioturbated, variegated mudstones. In the Lower Member of the Rapti Formation, the proportion of mudstone is greater than sandstone, in the Middle Member, sandstones and mudstones are present in roughly equal proportions, and the Upper Member comprises mainly fine- to coarse-grained sandstone beds with associated dark grey to variegated mudstone. The Amlekhganj Formation (3,050 m) is characterised by coarse- to very coarse-grained "pepper and salt" sandstones. The Upper Member of this formation includes pebbly sandstones. The Churia Khola Formation (1,100 m) comprises cobble- to pebble-sized conglomerates, in which clasts are mostly of quartzite and limestone from the Lesser Himalaya. The Churia Mai Formation (>500 m) consists of poorly sorted boulder-sized conglomerates, with subordinate dark grey mudstones. Presence of boulder-sized sandstone clasts derived from the Siwalik Group itself (mainly the Rapti Formation) is characteristic of this formation.

Nakayama and Ulak (1999) interpreted that the Rapti Formation and the Lower Member of the Amlekhganj Formation are the deposits of meandering river system, the Middle and Upper members of the Amlekhganj Formation are deposits of sandy braided river system, whereas the Churia Khola Formation is deposited by gravelly braided river system, and the Churia Mai Formation is the deposit of a debris flow-dominated braided river system.

Whereas the southern belt contains all the four formations of the Siwalik Group, the northern belt contains only the Rapti and Amlekhganj formations. Magnetostratigraphic work by Harrison et al. (1993) shows that deposition of the Siwalik Group in the Bakiya Khola section began before 11 Ma. The Siwalik Group is also traditionally divided into the Lower, Middle, and Upper Siwaliks (Medlicott 1875; Auden 1935). Lithologically, the Lower and Middle members of the Rapti Formation are correlative with the Lower Siwalik, the Upper Member of the Rapti Formation, and the Lower and Middle members of the Amlekhganj Formation with the Middle Siwalik, and The Upper Member of the Amlekhganj Formation and Churia Khola, and Churia Mai formations with the Upper Siwalik, respectively (Table 1).

Nakayama and Ulak (1999) recognised five stages of evolution of fluvial system during the deposition of the Siwalik Group. They inferred that three of the five stages were controlled by thrust activities: (i) the thrusting along the MCT was responsible for the onset of the deposition of the Siwalik Group, (ii) the MBT was responsible for the deposition of the gravelly facies of the Churia Khola Formation, and (iii) the CCT was responsible for the deposition of the debris flow facies of the Churia Mai Formation.

SAMPLING

Representative lithological columnar sections and interpretation of the Siwalik Group along the Bakiya Khola is given by Nakayama and Ulak (1999). Samples for grain size analysis were basically collected from the bottom of the fining-upward cycles on a scale from several to tens of metres, and some were sampled from the middle position of the cycles. The bottom of the fining-upward cycle is generally considered suitable sampling position for palaeohydrological estimation. Out sized clasts are observed in the bottom part of some cycles, however, samples fro analysis do not include such clasts. Sampling locations, their stratigraphic position, and corresponding columnar sections are shown in Figs. 1, 2, and 3, respectively. A total of 19 (C01 to C19) different sections were investigated, collecting 30 samples for palaeohydrological analysis.

The stratified sandstone and gravel beds belonging to each fining-upward cycle generally comprises of bedload sediments whereas the muddy sequence represents the sediments deposited by suspended load. Measurement of bedload deposit thickness and sampling position from the bottom of the fining-upward cycles, and the description of sedimentary structures were used for palaeohydrological estimation (Fig. 3).

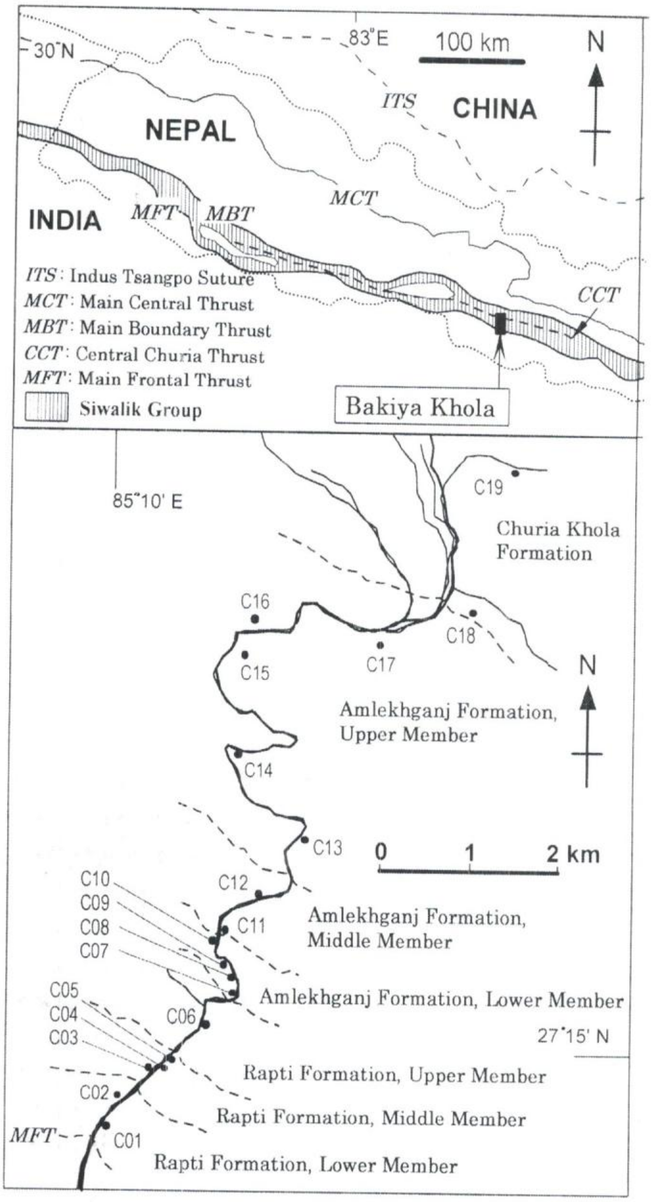

Fig. 1: Geological sketch map of Nepal showing the distribution of the Siwalik Group (shaded) and major tectonic lines, and detailed location map of the Bakiya Khola section, central Nepal.

GRAIN SIZE ANALYSES

Grain size analyses were carried out following the procedure of Tucker (1988) and using the settling velocity tube and thin sections as the consolidation of samples widely varied from strongly lithified to loosely packed. The thin section method was applied to stratigraphically lower 20 samples (sample No. C01a to C12b), and the sieving method was applied to the upper 12 samples (sample No. C12a to C19a). In thin sections, the longest dimensions of each of the 200 selected grains were measured using image analyses program (Scion Image). Based on the longest dimension of each grain, mean diameter (50% dimension) and 95% of grain size distribution (95% of dimension) were calculated.

Harrel and Erikson (1979) proposed the conversion equations from values of a thin section method to ones of a settling velocity method. The values were compared in this study by two methods, on the same samples of C12a and C12b (Fig. 4). Meaningful difference between the values by two methods are not recognised, hence conversion equations were not used for other samples.

Generally, bedload in any stratigraphic record has variation in grain size. It is assumed that the largest size clast on the bed has primary control on grain resistance, and entrainment characteristics. Maizels (1983) reviewed the representative grain size in fluvial gravelly deposits, and recommended 95% of the whole grain size distribution (D_{95}) for the palaeohydrology. Allen and Homewood (1984) used mean grain size (D_{50}) for palaeohydrological reconstruction, but there was no hydraulic justification for its use. In the present study D_{95} of each sample is adopted for palaeohydrological estimation (Table 1).

PALAEOHYDROLOGY

It is very difficult to apply a unique method for palaeohydrological estimation on the whole Siwalik succession because of wide variation in consolidation and grain size. From experimental work and data from natural streams, measures of stream competence are simply functionally related to particle size where particles are larger than 5-8 mm in diameter (Maizels 1983). Below this size, viscous forces begin to become effective rather than inertial forces, and also grain below this size can easily form visible-sized bedforms. Table 1 shows that only samples C18a and C19a are gravelly, larger size than the above criteria, the other samples are of smaller (sand sized grains). The method by Allen and Homewood (1984) was used for sandy sediments, and Manning-Limer method recommended by Maizels (1983) was used for gravelly sediments. Ethridge and Schumm (1978) recommended the two methods for sandy fluvial system, based on the palaeochannel dimension. Sedimentary structures (bedforms) are observable in a whole succession along the Bakiya Khola, however, the measurement of channel dimension is mostly difficult. The method of Allen and Homewood (1984) was adopted, which restricts palaeohydrological values in terms of bedforms. The method of Allen and Homewood (1984) is originally for the tidal sediments, and Masuda and Nakayama (1988) and Nakayama (1997) slightly modified it for both tidal and the fluvial sediments, which was used in this study. In Manning-Lemer method, the estimated slope values calculated from the grain size were used instead of actual measured values because of the outcrop limitation. The palaeohydrological estimation methods used in this paper need only grain size and flow depth as parameters. The uppermost part of the Siwalik Group, the Churia Mai Formation was not investigated because the formation is dominated by poorly sorted and non-stratified conglomerates to which these methods are not applicable.

Table 1: Summary of the palaeohydrology of the Siwalik Group of the Bakiya Khola section, central Nepal.

Stratigraphic position		Sample number	Bedding	Grain size (mm)		Flow depth (m)	Palaeovelocity (m/s)						Palaeochannel gradient (m/m)
				50%	95%						adopted		
				D_m	D_{95}	$d (d_c)$	V_c	U_{cr}	U_{rd}	U_{up}	V		S_c
Churia Khola F.	Upper Siwalik	C19a	HB	18.68	42.35	11.6	3.33	----	----	----	3.33	1)	3.36E-04
		C18a	HB	9.74	21.14	6.4	2.39		----	----	2.39	1)	3.04E-04
Amlekhganj F.		C17b	PCB	0.71	1.35	3.6	----	0.55	----	1.07	0.72	2)	2.07E-04
		C17a	TCB	1.10	2.68	7.7	----	0.93	----	1.74	1.47	3)	2.27E-04
(Upper M.)		C16a	TCB	1.12	2.03	4.3	----	0.74	----	1.36	1.15	3)	2.93E-04
		C15a	TCB	0.80	1.70	4.8	----	0.67	----	1.27	1.07	3)	2.11E-04
		C14a	TCB	0.78	1.79	12.0	----	0.76	----	1.53	1.28	3)	8.99E-05
		C13a	TCB	0.37	0.82	6.3	----	0.42	----	0.93	0.76	3)	6.02E-05
Amlekhganj F.	Middle Siwalik	C12d	TCB	0.88	2.18	6.8	----	0.81	----	1.54	1.29	3)	2.02E-04
		C12c	PCB	0.21	0.35	2.1	----	0.26	0.47	0.63	0.52	4)	9.25E-05
(Middle M.)		C12b	TCB	0.43	0.86	5.4	----	0.42	----	0.92	0.75	3)	7.27E-05
		C12a	TCB	0.52	0.98	5.4	----	0.45	----	0.98	0.81	3)	8.16E-05
		C11b	TCB	0.22	0.63	2.9	----	0.34	0.40	0.88	0.72	5)	1.05E-04
		C11a	TCB	0.32	0.78	4.1	----	0.39	0.40	0.84	0.69	5)	8.80E-05
Amlekhganj F.		C10b	PCB	0.22	0.39	1.0	----	0.25	0.38	0.55	0.44	4)	2.08E-04
		C10a	TCB	0.28	0.64	6.5	----	0.38	0.46	1.03	0.84	5)	4.75E-05
(Lower M.)		C09b	TCB	0.24	0.52	6.0	----	0.35	0.49	0.96	0.81	5)	4.36E-05
		C09a	TCB	0.50	0.90	9.9	----	0.46	----	1.05	0.85	3)	4.13E-05
		C08a	TCB	0.37	0.70	2.7	----	0.36	0.38	0.83	0.68	5)	1.22E-04
		C07a	TCB	0.29	0.42	4.5	----	0.31	0.51	0.82	0.71	5)	4.95E-05
Rapti F.		C06c	RL	0.13	0.26	0.6	----	0.20	0.39	0.39	0.29	6)	2.64E-04
(Upper M.)		C06b	TCB	0.22	0.33	3.0	----	0.27	0.51	0.67	0.62	5)	6.23E-05
		C06a	TCB	0.24	0.37	4.8	----	0.30	0.54	0.78	0.70	5)	4.21E-05
Rapti F.	Lower Siwalik	C05a	TCB	0.11	0.21	1.2	----	0.21	0.50	0.43	0.45	5)	1.17E-04
(Middle M.)		C04a	TCB	0.12	0.27	3.8	----	0.26	0.58	0.63	0.61	5)	4.25E-05
		C03b	TCB	0.15	0.24	3.3	----	0.25	0.59	0.58	0.58	5)	4.54E-05
		C03a	TCB	0.17	0.29	5.9	----	0.28	0.61	0.72	0.68	5)	2.90E-05
Rapti F.		C02b	TCB	0.11	0.19	1.2	----	0.20	0.52	0.41	0.45	5)	1.10E-04
(Lower M.)		C02a	TCB	0.076	0.20	1.7	----	0.21	0.55	0.46	0.49	5)	7.94E-05
		C01a	RL	0.052	0.093	3.5	----	0.20	----	0.37	0.28	7)	2.92E-05

Bedding: HB: horizontal bedding, TCB: trough-cross bedding, PCB: planar-cross bedding, RL: ripple lamiation, D_m: median diameter, D_{95}: 95th percentile of grain size distribution, d (d_c): estimated channel depth (critical flow depth), V_c: critical flow velocity for gravels, U: depth-mean velocity for sand (U_{cr}: threshold of particle movement, U_{rd}: for ripple-dune transition, U_{up}: for upper plane bed transition from ripples or dunes), S_c: palaeochannel gradient for critical flow condition, V: estimated palaeovelocity values in this paper, see text in detail. 1) $V=V_c$ (for gravels), 2) $V=(2U_{cr}+U_{up})/3$ for PCB of relative coarse grains (D_{95}>0.8mm), 3) $V=(U_{cr}+2U_{up})/3$ for TCB of relative coarse grains, 4) $V=(2U_{rd}+U_{up})/3$ for PCB of relative medium-sized grains (0.8mm>D_{95}≥0.15mm), 5) $V=(U_{rd}+2U_{up})/3$ for TCB of relative medium-sized grains, 6) $V=(U_{cr}+U_{rd})/2$ for RL of relative medium-sized grains, 7) $V=(U_{cr}+U_{up})/2$ for RL of relative small grains (0.15mm>D_{95}). F-Formation, M-Member.

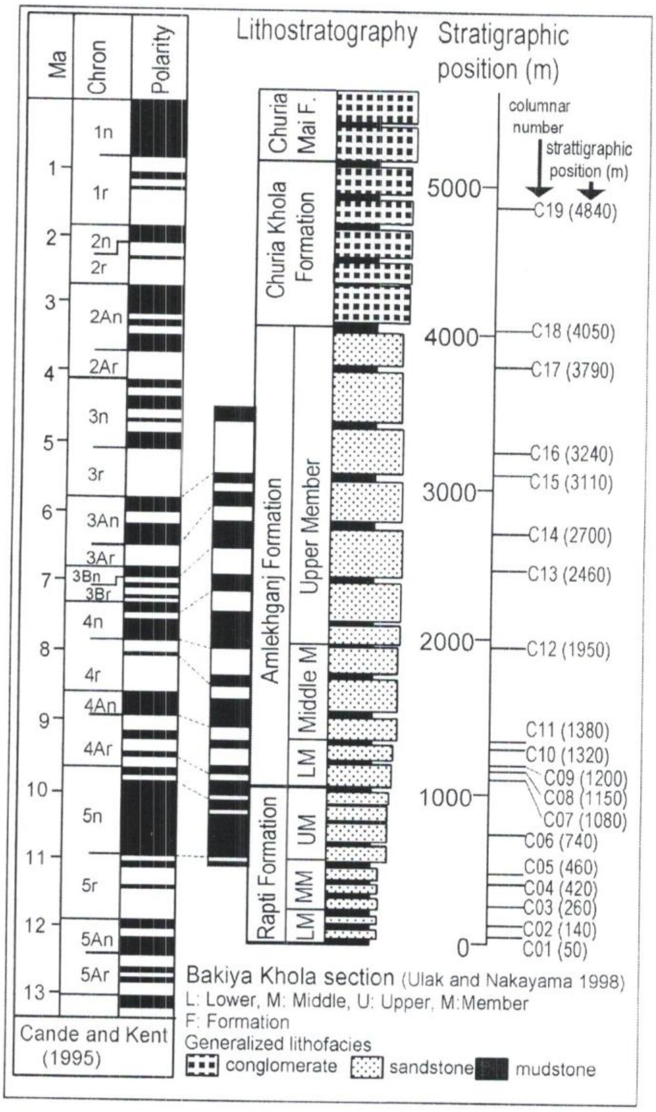

Fig. 2: Simplified stratigraphic logs of the Bakiya Khola section, and stratigraphic position of sample obtained columnar sections. The magnetostratigraphy of the group is based on Harrison et al. (1993). The magnetic polarity time scale is that of Cande and Kent (1995).

Palaeoflow Depth

The thickness of the beds formed by bedload is used for palaeoflow depth. Most of the samples were obtained from the bottoms of the fining-upward cycles, so that bedload thickness is frequently concordant with flow depth in this study. This is the extended application of the bankfull flow estimation in meandering channel (Ethridge and Schumm 1978; Bridge 1978).

Lateral accretionary architectures are recognised in stratigraphic sections C02, C06, and C09 (Nakayama and Ulak, 1999), and therefore the estimation method of bankfull flow depth in meandering channel is directly applicable. Other fining-upward cycles in this study have no direct evidence of deposits of meandering channel, however, all of them show the same order thickness of fining upward cycles ranging from several to tens of meters. Thus, bedload thickness in simple upward-fining cycle is considered to roughly indicate the bankfull flow depth. However, the estimated bankfull depth of braided channels may give serious underestimate.

Ethridge and Schumm (1978) use coefficient of 0.585/0.9 to convert the bedload thickness to palaeoflow depth. In this study, this coefficient was not used because the estimation of the fining-upwards cycles may not have such preciseness. In this study, the decompacted thickness was not calculated either, because all the sediments are bedload sand and gravel in which the compaction must have been negligible. Despite the possibility of imprecision for estimation of flow depth, however, the final estimated palaeohydrological values must be sufficient to discuss the evolutional change of palaeohydrology.

Palaeohydrology for Sandy Bedload

The method by Allen and Homewood (1984) provides the depth-mean velocities for the threshold of sediment movement (U_{cr}), ripple-dune transition (U_{rd}), and transition to upper plane bed from ripples and dunes (U_{up}) based on the flow depth and grain size:

$$U_{cr} = \frac{u_{cr}}{\kappa} \ln\left(\frac{d}{ez_0}\right) \tag{1}$$

where, u_{cr} is the shear velocity for the threshold of sediment movement (Vanoni 1964; Yalin 1972), k is von Karman's constant, d is the flow depth in meter, and z_0 is the roughness length in meter. The value used for k is 0.4 and 0.0004 for z_0, following Allen and Homewood (1984). u_{cr} is calculated from the shear stress for threshold (t_{cr}) which is directly related to grain diameter and grain Reynolds number (Miller et al. 1977). Similarly, U_{rd} and U_{up} are obtained by using following equations:

$$U_{rd} = \frac{u_{rd}}{\kappa} \ln\left(\frac{d}{ez_0}\right) \tag{2}$$

$$U_{up} = \frac{u_{up}}{\kappa} \ln\left(\frac{d}{ez_0}\right) \tag{3}$$

where, u_{rd} is the shear velocity for ripple-dune transition (Vanoni 1974), and u_{up} is the shear velocity for upper plane bed transition from ripples and dunes (Bagnold 1966). Other symbols are same as in equation (1). The value for k is used 0.4 in both the equations, and 0.0006 and 0.001 for z_0 in equations (2) and (3), respectively.

Three velocities were calculated on each sample, and the unique velocity (V) was estimated based on these three values and bedform configurations. Planar-cross bedding and trough-cross bedding are formed by migrating 2D dunes

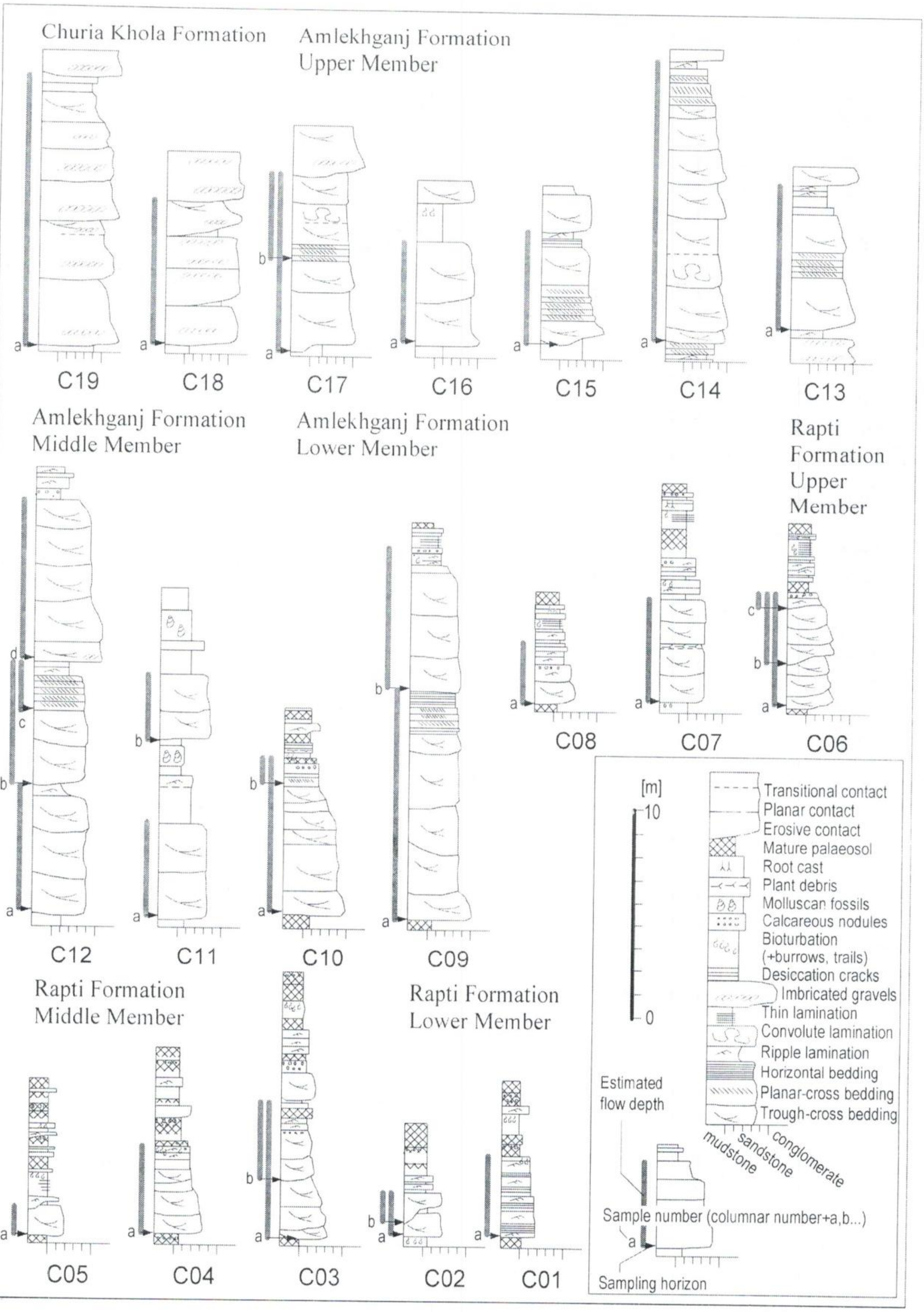

Fig. 3: Coloumnar log sections and sampling points of the Bakiya Khola section. Palaeocurrents of C02-03, C05-09, and C11-C18 are described in Fig. 4 of Nakayama and Ulak (1999). Location of columnar sections are shown in Fig. 1.

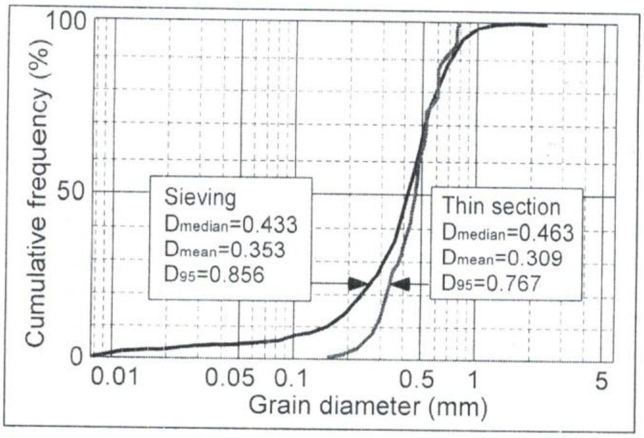

Fig. 4: Comparison between thin section and sieved methods

and 3D dunes, respectively, and ripple laminations are formed by ripples. Small grains with less than about 0.15 mm in diameter never form dunes, and relatively coarse grains, larger than about 0.8 mm in diameter never form ripples. Both ripples and dunes can occur in sediments with diameter from 0.15 to 0.8 mm. The determination of velocity range using bedform type is difficult. 2D dunes and 3D dunes occur under the flow between U_{rd} and U_{up}, and ripples occur under the flow between U_{cr} and U_{rd}. Further, 2D dunes are formed in relatively slower velocity of the range between U_{rd} (or U_{cr}) and U_{up}, while 3D dunes are formed in relatively faster velocity. Seven equations were used to determine the unique velocity value. Each equation and its applicable grain range and bedform is explained in Table 1.

Palaeochannel gradient for critical flow (S_c) condition is also estimated:

$$S_c = \frac{\tau_{cr}}{\gamma \cdot d_c} \tag{4}$$

where, γ is the specific weight of water taken as 1000 kg/m^3 and d_c is used for critical flow depth.

Palaeohydrology for Gravelly Bedload

In the case of gravel clasts at high Reynolds number, the critical tractive force (= shear stress of threshold: t_{cr}) is obtained using the following equation (Shields 1936; Graf 1971):

$$\tau_{cr} = 0.056(\gamma_s - \gamma)D \tag{5}$$

where, γ_s is the specific weight of clast taken as 2650 kg/m^3. D is the size of bed roughness element, for which D_{95} is used. Channel gradient for critical flow condition is obtained from equations (4) and (5):

$$S_c = \frac{0.092 D_{95}}{d_c} \tag{6}$$

Palaeoflow velocity for critical flow condition can be calculated according to the Manning-Limer equation:

$$\bar{V}_c = \frac{\sqrt[3]{d_c^{\,2}}}{\sqrt{S_c}} \cdot \frac{1.16 + 2.0 \log\left(\dfrac{d_c}{D_{95}}\right)}{0.113\sqrt[6]{d_c}} \tag{7}$$

where, $\bar{V}_c$ is the critical mean flow velocity, and unique velocity $\bar{V}_c$ value V was adopted in Table 1.

DISCUSSION

Application and Limitation

The method used in this study is applicable to both sandy and gravelly sediments, and is also applicable to the outcrops with limited lateral-dimension. Further, the method can analyse the flow conditions using multiple samples from a fining-upward cycle. Fig. 5 depicts the example of C06. The palaeoflow velocities decrease upward, which reflect the flow velocities from the thalweg to the upper point (side) bar surface. This method was also used by Masuda and Nakayama (1988).

There are some limitations in the method used in this study because only two numeral factors of grains size and bedload thickness are used, and parameters about the channel shape, sorting of deposition, suspension material (sediment-laden water) are not considered. As the fining-upward cycles are used in this method, which are the typical lithofacies of most rock units of Siwaliks, the Middle Member of the Amlekhganj Formation could not be analysed as they do not contain the ideal fining-upward cycles.

The palaeohydrology in the Siwalik Group of Pakistan has been studied based on channel aggradational pattern and channel dimension described in the hundred metre wide outcrops (Willis 1993b; Zaleha 1997b; Khan et al. 1997). These estimated values may be more precise than the values in this study. There may be some problems while comparing the palaeohydrology of the Pakistan Siwalik, and those of the present study area due to different methodology and precision. However, methods in this study are suitable for determining the evolutionary changes of fluvial system through the Siwalik succession.

EVOLUTION OF FLUVIAL SYSTEM AND ESTIMATION OF PALAEOHYDROLOGICAL VALUES

Changes in the palaeohydrology within the stratigraphic framework are depicted in Fig. 6. Both palaeoflow velocity and palaeochannel gradient exhibit an increase in the upward stratigraphic units.

The depositional system of the Churia Mai Formation has been interpreted as the debris flow-dominated fan system, with its piedmont line formed by the CCT (Nakayama and Ulak 1999). Blair and McPherson (1994) indicated that debris flow-dominated fan system have steep slope gradient,

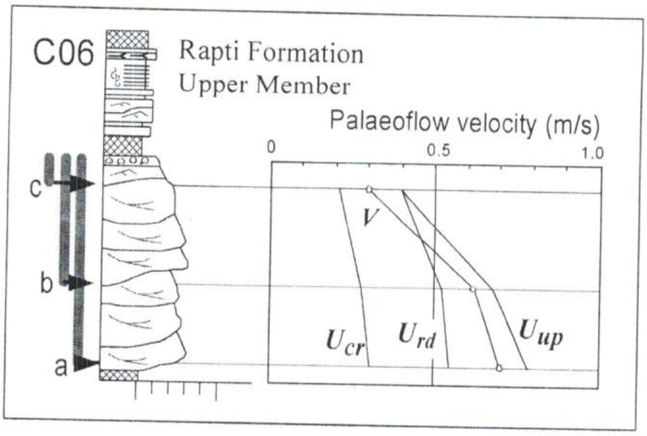

Fig. 5: Variation of palaeoflow velocity in one fining-upward cycle (C06). Variation must reflect the constitution of a channel flow. Marks in log section see Fig. 3.

more than 1.5° (0.026 m/m). This slope value is much steeper than any estimated slope values in this study. Two prominent changes in palaeohydrology are recognised at the formation boundaries among the Amlekhganj, Churia Khola, and Churia Mai formations.

Earlier Nakayama and Ulak (1999) worked out the evolutionary history of the fluvial system of the Siwalik Group in this study area. They identified five stages of evolution of the fluvial system. From older to younger stages, they are: (i) meandering system (stage 1), (ii) flood flow-dominated meandering system (stage 2), (iii) sandy braided system (stage 3), (iv) gravelly braided system (stage 4), and (v) debris flow-dominated braided system (stage 5). They also concluded that the inception of stage 1, stage 4, and stage 5 were controlled by the activity of the MCT, MBT, and CCT, respectively. Two prominent palaeohydrological changes observed in the present study coincide with the

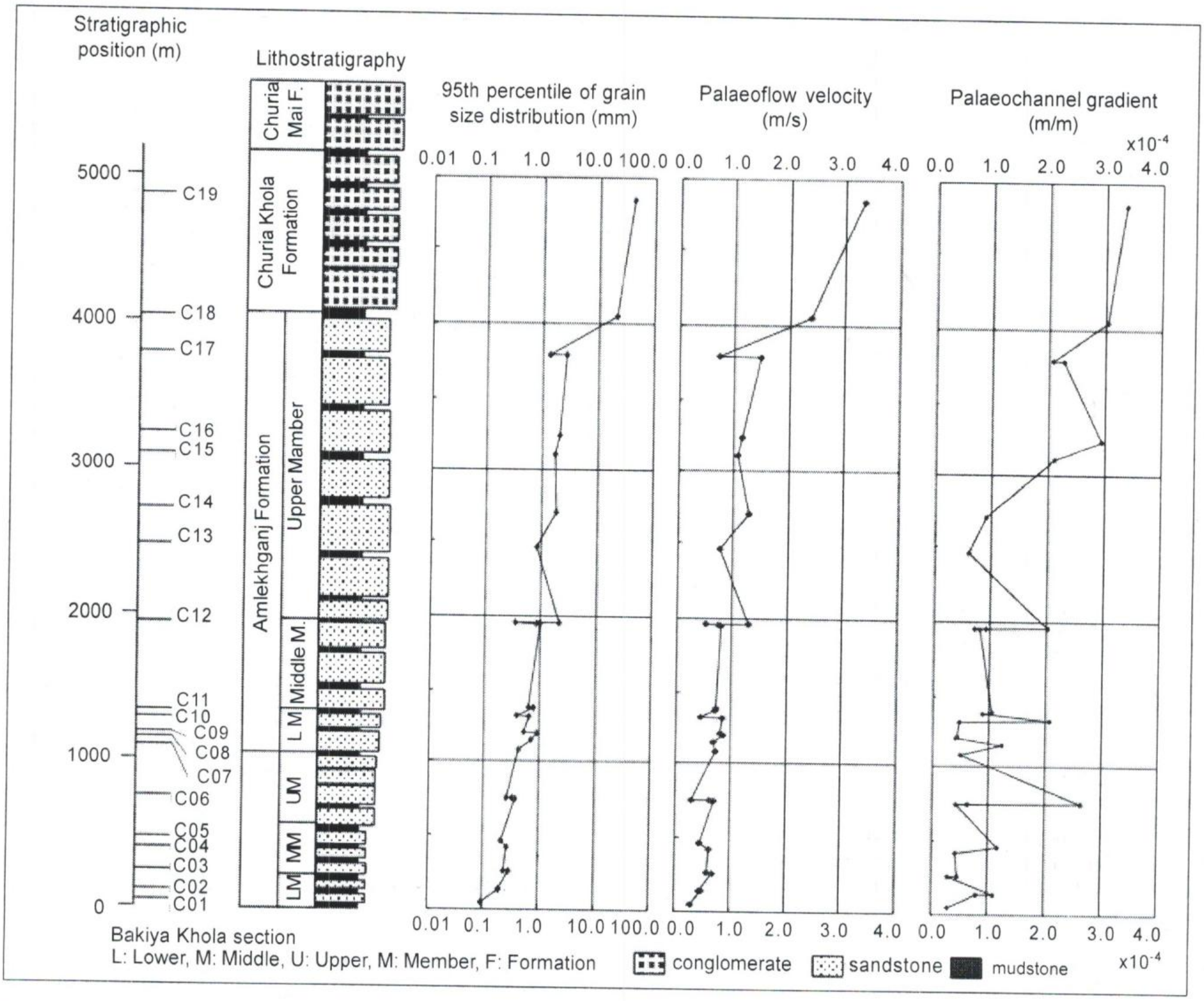

Fig. 6: Stratigraphic change in palaeohydrological estimations in the Bakiya Khola section. Individual data are listed in Table 1.

stage 4 and stage 5, respectively. The palaeohydrological changes and the corresponding fluvial system change both reflect the consequences of activity along the MBT and CCT.

CONCLUSION

Palaeohydrological estimations for the Siwalik Group in Nepal show a gradual increase in flow velocity and channel gradient from older to younger stratigraphic units. Palaeochannel gradient varies from 2.9×10^{-5} m/m to 3.4×10^{-4} m/m, and palaeovelocity ranges from 0.28 m/s to 3.3 m/s. These estimates suggest that fluvial system grew progressively larger due to southward progradation of thrust activity. The palaeohydrological estimation method of this study is widely applicable, and suitable for analysing the evolutional change of fluvial system, but has some limitations in precision.

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