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Palaeohydrological reconstruction of Siwalik Group in Surai Khola section of west Nepal Himalaya

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ABSTRACT

About 5 km thick Neogene Siwalik Group in the Surai Khola section of west Nepal comprises many fining-upward cycles, which are from several metres to tens of metres thick. However, the Siwalik sequence as a whole reveals a coarsening-upward trend. The palaeohydrological reconstruction of the Siwalik Group was based mainly on two parameters: the sediment grain size and the thickness of individual fining-upward successions. The estimated palaeoflow velocity in the Siwalik Group varies from 0.32 to 4.76 m/s, palaeochannel gradient ranges from 5.29×10^{5} to 9.59×10^{-4} m/m, and palaeodischarge fluctuates from 1 to 10^{4} m^{3}/s, in the stratigraphically upward direction. These palaeohydrological parameters indicate a gradual change in fluvial system, presumably owing to the southward propagation of thrusts.

INTRODUCTION

Palaeohydrological studies of ancient fluvial deposits are carried out mainly for quantifying their hydraulic parameters, which are then used for comparing such deposits with the modern fluvial systems. The palaeohydrological reconstruction of a fluvial system is based on the study of grain size, nature of bedforms, and thickness of a fluvial succession. In this respect, flume experiments and the study of modern depositional systems play a vital role. The palaeohydrological reconstruction of ancient deposits was carried out by Cotter (1971), Steer and Abbott (1984), Bridge and Gordon (1985), Els (1990), and Nakayama (1999). Allen (1965) demonstrated that the mean heights of dunes are proportional to mean water depth. Ethridge and Schumm (1978), Maizels (1983), and Williams (1984) have reviewed the reconstruction methods. In these investigations, Allen (1965), Leeder (1973), and Ethridge and Schumm (1978) worked out on the water depth estimation method for ancient fluvial systems. Leader (1973) as well as Ethridge and Schumm (1978) showed that the thickness of a fining-upward succession in a meandering channel is approximately equal to the bankfull depth. Miall (1996) mentioned that a fining-upward succession is potentially more useful than a dune in determining the palaeohydrological parameters, as the former reflects a longer time and a statistical average of flow parameters. Allen and Homewood (1984) made remarkable palaeohydrological reconstructions of ancient tidal sediments by determining the range of palaeoflow velocity based on the estimated flow depth and bed configuration.

The middle Miocene to lower Pleistocene Siwalik succession comprising the fluvial sediments is extensively distributed in the southern Himalayan foreland. Sedimentation in the basin is thought to be influenced by the Himalayan Neogene tectonics (Parkash et al. 1980; Nakayama and Ulak 1999). The sedimentological studies of the Siwalik Group in the Potwar basin of Pakistan were carried out by Willis (1993a, b), Khan et al. (1997), and Zaleha (1997a, b). These studies included the palaeohydrological reconstructions based on detailed sketches of extensive (hundreds of metres thick) outcrops, but did not deal with the entire Siwalik succession because of a limited number of exposures. The estimated palaeohydrological values showed a progressively increasing trend towards the stratigraphically younger succession of the Siwalik Group in the Potwar Basin (Khan et al. 1997; Zaleha 1997; Willis 1993a, 1993b). The palaeohydrological reconstruction of the entire Siwalik succession from various parts of Nepal (Ulak and Nakayama 2003; Ulak 2002; Ulak and Nakayama 2002; Ulak and Nakayama 2001; Ulak 2001; Ulak and Nakayama 1999) revealed a gradual increase in the palaeoflow velocity towards the stratigraphic top. In Nepal, sedimentological studies on the evolution of the Siwalik fluvial system were carried out by Hisatomi and Tanaka (1994), Ulak and Nakayama (1998), Nakayama and Ulak (1999), and Ulak and Nakayama (2001). These studies showed that the deposition of the Siwalik sediments began with a meandering system and it subsequently changed into a braided system.

This paper focuses on the estimation of palaeohydrological parameters in the entire Siwalik succession of the Surai Khola section in west Nepal. The relationship between the fluctuation of palaeohydrological parameters and the evolution of fluvial system is also discussed.

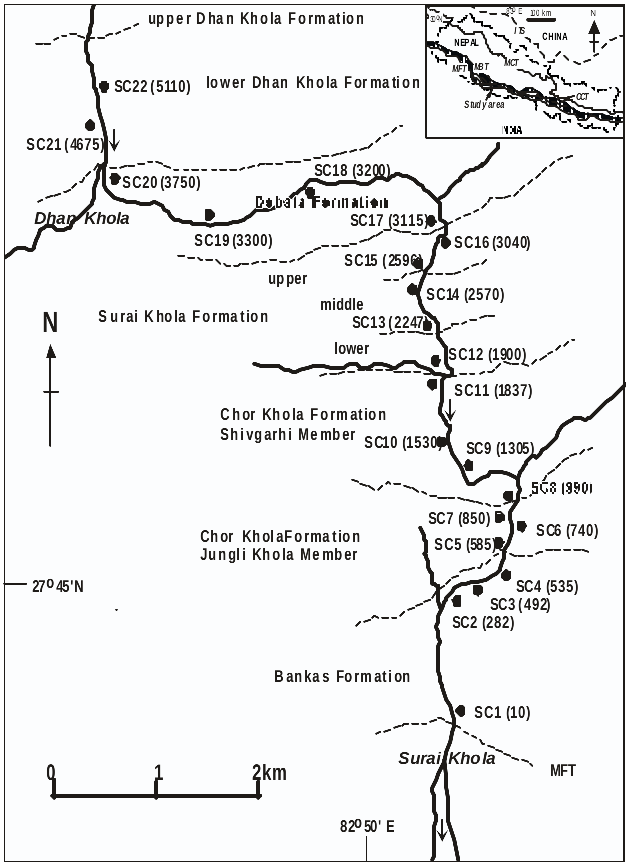


Fig. 1: Geological sketch map of Nepal showing the distribution of the Siwalik Group (shaded) and major tectonic lines, and detailed location map of the Surai Khola section

GEOLOGICAL SETTING

The Himalayan range was formed as a result of the intercontinental collision of the Indian and Asian plates. The collision caused not only compression and folding of sediments, but also breaking up of the Indian crust. As a result, the Himalayan range is composed of a succession of southward-displaced thrust sheets (Gansser 1964). Consequently, the Main Central Thrust (MCT), Main Boundary Thrust (MBT), and Main Frontal Thrust (MFT) are exposed successively from north to south (Fig. 1). The Siwalik Group was deposited in the southern foreland basin of the Himalaya and the sediments were derived from the adjacent mountains in the north. The Siwalik Group is bounded by the MBT in the north and the MFT in the south. The rocks generally dip northwards and comprise an overall coarsening-upward succession.

The Siwalik Group is well exposed in the Surai Khola section of west Nepal. Its lithostratigraphy was established by Corvinus and Nanda (1994) and Dhital et al. (1995). These studies showed that the Siwalik Group comprises the Bankas, Chor Khola, Surai Khola, Dobata, and Dhan Khola Formations in an ascending order (Fig. 1; Table 1). The Bankas Formation (585+ m thick) is composed of fine- to medium-grained greenish grey sandstone (61%) interbedded with bioturbated and variegated mudstone (39%). The Jungli Khola Member (405 m thick) of the Chor Khola Formation is represented by fine- to medium-grained greenish grey sandstone (55%) interbedded with variegated mudstone (45%). The Shivgarhi Member of the Chor Khola Formation (820 m thick) is comprised of coarse-grained sandstone (52%) and grey mudstone (46%) with a few marl beds (2%). The Surai Khola Formation (1310 m thick) is composed of thick-bedded, coarse-grained, "pepper and salt" sandstone. The proportion of grey sandstone (79%) is greater than grey mudstone (21%). The Dobata Formation (750 m thick) is characterised by the interbedding of medium-grained sandstone (23%), grey mudstone (63%), and conglomerate (14%). The Dhan Khola Formation (1,100+ m thick) consists of well-sorted cobble- to pebble-sized conglomerate (70%), mud (27%), and sand beds (3%). Magnetic polarity in this section was measured by Appel et al. (1991) and Rösler et al. (1997). Their study revealed that the deposition of the Siwalik Group in the Surai Khola section began about 13.0 Ma ago.

The Siwalik Group in the Surai Khola area of west Nepal is subdivided into three belts separated by the Rangsing Thrust (RT), Siling Khola Thrust (SKT), and Sit Khola Thrust (ST) from south to north, respectively. Among them, the Rangsing Thrust (Dhital et al. 1995) is correlated with the Central Churia Thrust (CCT; Tokuoka et al. 1986).

Traditionally, the Siwaliks are divided into the Lower, Middle, and Upper Siwaliks (Auden 1935; Gansser 1964). Lithologically, the Bankas Formation and the Jungli Khola Member of the Chor Khola Formations are correlated with the Lower Siwaliks, the Shivgarhi Member of the Chor Khola Formation and the Surai Khola Formation with the Middle Siwaliks, and the Dobata and Dhan Khola Formations with the Upper Siwaliks.

EVOLUTION OF FLUVIAL SYSTEM

Nakayama and Ulak (1999) identified eight facies associations (FA1 to FA8) based on the nature of bedforms, lithology, and bed thickness in the Surai Khola section (Table 1). The study also revealed that the sediments of the Bankas Formation and Jungli Khola Member of the Chor Khola Formation were the products of a fine-grained meandering system, the sediments of the Shivgarhi Member of the Chor Khola Formation and the lower part of the Surai Khola Formation were deposited by a flood flow-dominated fine-grained meandering and flood flow-dominated sandy meandering systems, respectively. The middle and upper parts of the Surai Khola Formation are characterised by the deposits of a braided system whereas the Dobata Formation contains the sediments of an anastomosed system. The sediments of the lower and upper parts of the Dhan Khola Formation were accumulated by a gravelly braided and a debris flow-dominated braided system, respectively.

Table 1: Established lithostratigraphy (Dhital et al. 1995) and evolution of the fluvial system (Nakayama and Ulak 1999) of the Surai Khola area, west Nepal

Lithological Unit Facies association	Thickness (m)	Main Lithology	Dominant lithofacies*	Architectural element**	Fluvial system
Dhan Khola Formation		Matrix supported boulder-sized conglomerate	Gcm, Gmm	SG, GB	Debris flow-dominated braided system
upper (FA8)	1,100+		Gmg	DA	
lower (FA7)		Clast supported, cobble-pebble conglomerates	Gp, Gt	GB, SB	Gravelly braided system
			Gh	DA, HO	
Dobata Formation		Thick bedded, grey mudstone interbeds with medium-grained sandstone.	St, Sp	DA, FF	Anastomosed system
(FA6)	750		Fms, Sr	SB, LA	
Surai Khola Formation					
upper (FA5)	480	Thick bedded, very coarse-grained, "pepper and salt" sandstone with pebbly sandstone.	St, Sr, Sp	SB, DA	Shallow braided system
			Ss, Gp, Gt		
middle (FA4)	470	Thick bedded, coarse-grained, pepper and salt sandstone with grey mudstone	St, Sp, Sh	LA, HO	Deep braided system
			Ss	FF	
lower (FA3)	360	Medium-grained sandstone interbedded with grey mudstones.	St, Sr, Sp	DA, LA,	Flood flow-dominated, meandering system
			Ss, Sh	FF, SB	
Chor Khola Formation					
Shivgarhi M. (FA2)	820	Medium-grained, grey sandstone with variegated to grey mudstone	St, Sr, Fl	LA, FF, SB	Flood flow-dominated meandering system
			Fm, Fr, P	DA	
Jungli Khola M. (FA1)	410	Fine-grained, grey sandstone with variegated mudstone	Fl, P, Sr	FF, SB, LA	Fine-grained meandering system
			Fm, Fsm	DA, LS	
Bankas Formation		Fine-grained, greenish grey sandstone interbeds with variegated mudstone	P, Fr, Fm	FF, SB, LA	Fine-grained meandering system
(FA1)	585+		Fl, Fsm	LS	

*Classification from Miall (1996). ** CH recognised in all facies associations.

Nakayama and Ulak (1999) recognised six stages during the deposition of the Siwalik Group. Three of the stages were controlled by thrust activities; i.e., the onset of deposition of the Siwalik Group by the MCT, the development of gravelly facies in the lower part of the Dhan Khola Formation by the MBT, and the initiation of debris flow facies in the upper part of the Dhan Khola Formation by the CCT.

PALAEOHYDROLOGICAL RECONSTRUCTION

Representative lithological columnar sections and their facies associations in the Surai Khola section were given by Nakayama and Ulak (1999). Samples for grain size analysis were collected from the bottom of the fining-upward successions on a scale from several metres to tens of metres, and some were sampled from the middle portion of the successions (Fig. 2). The bottom of a fining-upward succession is suitable for palaeohydrological estimation. Though some outsized clasts were observed at the bottom of some successions, they were not included in the study. Forty-seven sand samples were obtained from twenty-two sections. Each fining-upward succession generally comprises the bed load fluvial deposits of stratified sand and gravel as well as the suspended load of muddy material.

Grain size analysis

Since the consolidation of samples widely varied from strongly lithified to loosely packed, grain size was measured from thin sections and a settling tube (Tamura and Nakayama 1993). The thin section method was used for the stratigraphically lower 20 samples: from SC01a to SC13f of the Bankas and Chor Khola Formations, and the settling tube method was applied for stratigraphically upper 17 samples: from SC14a to SC22a (the Surai Khola Formation, the Dobata Formation, and the lower part of the Dhan Khola Formation).

The longest apparent dimension of more than 200 grains was measured in one thin section, and their statistical measures (50% of dimension, and 95% of dimension, mean diameter, and 95% of grain size distribution) were obtained. A comparison of the thin section grain size values of two samples (SC14a and SC15a) with those obtained from the settling tube for the same samples did not show any significant difference.

The bed load sediments from any stratigraphic record exhibit a variation in grain size. Palaeohydrological reconstructions have been carried out using various representative grain parameters. It is generally assumed that the largest clast on the bed primarily controls the entrainment

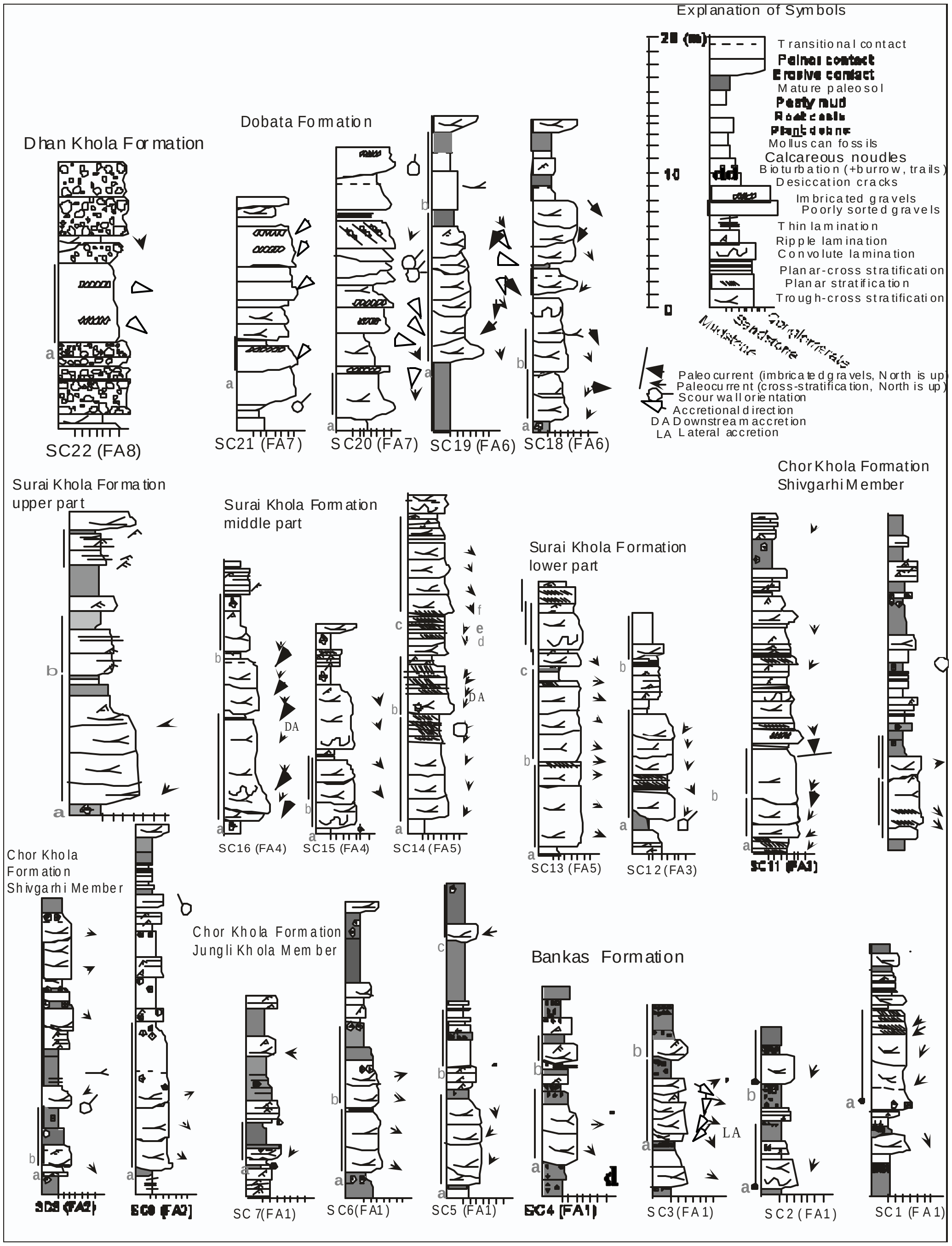


Fig. 2: Columnar sections and sampling points of the Surai Khola section

characteristics. Maizels (1983) reviewed the representative grain size in fluvial gravely deposits, and recommended the 95% of the whole grain size distribution (D_{95}) as the representative value. Allen and Homewood (1984) adopted the mean grain size (D_{50}) for palaeohydrological reconstruction, but there was no hydraulic justification for its use. Hence, D_{95} of each sample is taken as the representative grain size in this study (Table 2).

Because of a wide variation in consolidation and grain size, it is impossible to apply a unique method of palaeohydrological estimation to the entire Siwalik succession. From the experimental work and data from natural streams, measures of stream competence can be 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 the grain below this size can easily form visible-sized bedforms. Table 1 shows that only SC21a and SC22a samples are gravelly, and hence their grains are larger than the critical size. The remaining samples are sandy. Allen and Homewood

Table 2: Summary of the palaeohydrology of the Siwalik Group of the Surai Khola section, central Nepal

Stratigraphy			Bedding	Sample	Grain size (mm)		Depth	Paleovelocity (m/s)					Paleoslope	Paleodischarge
				No	D_{50}	D_{95}	d_c (m)	U_{cr}	U_{rd}	U_{up}	V_c	AV	(m/m)	(m^3/s)
Upper Siwalik	Dhan Khola Fm		HB	SC22a	9.90	19.78	3.1				3.93	3.93	$5.87x10^{-4}$	$6.69x10^{3}$
			PCB	SC21a	0.84	1.78	3.1				4.76	4.76	$5.29x10^{-5}$	$8.99x10^{4}$
	Dobata Fm.		PCB	SC20a	0.36	0.69	2.4	0.34	0.74	0.67		0.72	7.44x10-4	6.79x102
			TCB	SC19b	0.17	0.23	1.8	0.23	0.60	0.63		0.62	2.70x10-4	3.39x102
			TCB	SC19a	0.52	0.99	1.2	0.18	1.02	0.39		0.60	1.20x10-4	1.28x102
			TCB	SC18b	0.22	0.51	1.9	0.19	0.73	0.77		0.58	1.90x10-4	3.87x102
			TCB	SC18a	0.17	0.25	2.7	0.20	0.70	0.54		0.59	2.70x10-4	9.01x102
			TCB	SC17c	0.11	0.23	1.9	0.19	0.53	0.44		0.47	1.90x10-4	3.87x102
			RL	SC17b	0.09	0.56	0.4	0.15	0.31	0.23		0.37	4.00x10-5	9.04x100
			TCB	SC17a	0.16	0.72	5.7	0.21	0.77	0.40		0.52	5.70x10-4	5.46x103
Middle Siwalik	Surai Khola Fm.	upper	TCB	SC16b	0.15	0.35	0.8	0.17	0.50	0.42		0.45	8.00x10-5	4.81x101
			TCB	SC16a	0.90	0.31	1.2	0.18	1.34	0.37		0.69	1.20x10-4	1.28x102
		middle	TCB	SC15b	0.42	0.91	5.5	0.26	1.24	3.12		2.49	8.25x10-4	5.08x103
			TCB	SC15a	0.33	0.65	2.5	0.24	0.95	1.79		1.51	3.75x10-4	7.49x102
			TCB	SC14c	0.60	1.14	3.6	0.25	1.38	2.32		2.01	5.40x10-4	1.80x103
			PCB	SC14b	0.56	1.15	1.7	0.21	1.15	1.35		1.21	2.21x10-4	2.96x102
			TCB	SC14a	0.61	1.29	2.1	0.27	1.25	1.58		1.47	4.28x10-4	4.92x102
		lower	RL	SC13f	0.15	0.30	0.4	0.21	0.41	0.43		0.64	8.16x10-5	9.04x100
			PCB	SC13e	0.19	0.26	0.8	0.24	0.56	0.76		0.63	1.63x10-4	4.81x101
			RL	SC13d	0.84	1.82	0.7	0.23	1.14	0.68		0.68	1.42x10-4	3.48x101
			TCB	SC13c	0.60	1.36	1.5	0.26	1.15	1.23		1.20	3.06x10-4	2.19x102
			RL	SC13b	0.19	0.39	0.6	0.23	0.52	0.60		0.83	1.22x10-4	2.40x101
			PCB	SC13a	0.37	0.78	0.9	0.24	0.80	0.83		0.81	1.84x10-4	6.38x101
			TCB	SC12b	0.42	0.96	2.1	0.27	1.04	1.58		1.40	4.28x10-4	4.92x102
			TCB	SC12a	0.72	1.55	1.3	0.25	1.22	1.10		1.14	2.65x10-4	1.55x101
	Chor Khola Fm.	Shivgarhi M.	PCB	SC11b	0.14	0.31	0.7	0.23	0.46	0.68		0.53	1.43x10-4	3.48x101
			PCB	SC11a	0.21	0.41	1.2	0.25	0.65	1.04		0.78	2.49x10-4	1.28x102
			TCB	SC10d	0.14	0.27	1.6	0.26	0.57	1.29		1.05	3.26x10-4	2.55x102
			RL	SC10c	0.14	0.26	0.5	0.22	0.42	0.52		0.32	1.02x10-4	1.55x101
			PCB	SC10b	0.25	0.50	2.7	0.28	0.84	1.89		1.19	5.51x10-4	9.01x102
			TCB	SC10a	0.28	0.57	0.7	0.23	0.65	0.68		0.67	1.43x10-4	3.48x101
			RL	SC09b	0.17	0.29	0.9	0.24	0.54	0.83		0.39	1.84x10-4	6.38x101
			TCB	SC09a	0.19	0.36	0.4	0.21	0.46	0.43		0.44	8.16x10-5	9.04x100
			TCB	SC08a	0.38	0.67	4.7	0.30	1.16	2.80		2.25	9.59x10-4	3.43x103
Lower Siwalik		Jungli Khola M.	RL	SC07a	0.28	0.46	0.9	0.24	0.69	0.83		0.47	1.87x10-4	6.38x101
			TBC	SC06b	0.39	0.73	0.4	0.21	0.66	0.43		0.50	8.16x10-5	9.04x102
			TCB	SC06a	0.52	0.99	3.5	0.29	1.28	2.28		1.94	7.14x10-4	1.69x103
			TCB	SC05c	0.32	0.78	1.8	0.26	0.87	1.41		1.23	3.67x10-4	3.39x102
			TCB	SC05b	0.20	0.44	2.7	0.28	0.76	1.89		1.51	5.51x10-4	9.01x102
			TCB	SC05a	0.68	1.46	0.9	0.24	1.09	0.83		0.92	1.84x10-4	6.38x101
	Bankas Fm		TCB	SC04b	0.14	0.25	1.7	0.26	0.56	1.35		1.09	3.47x10-4	2.95x102
			TCB	SC04a	0.15	0.30	4.1	0.29	0.71	2.54		1.93	8.36x10-4	2.47x103
			RL	SC03b	0.48	0.98	2.7	0.28	1.17	1.89		0.72	5.51x10-4	9.01x102
			TCB	SC03a	0.13	0.25	2.4	0.28	0.58	1.74		1.35	4.90x10-4	6.78x102
			TCB	SC02b	0.14	0.31	2.2	0.27	0.61	1.63		1.29	4.49x10-4	5.50x102
			TCB	SC02a	0.18	0.30	1.7	0.26	0.65	1.35		1.12	3.49x10-4	2.95x102
			RL	SC01a	0.40	0.81	1.6	0.26	0.95	1.29		0.61	3.26x10-4	2.55x102

(1984) developed palaeohydrological methods for sandy sediments, and the Maning-Limerious method was recommended by Maizels (1983) for gravely sediments. Ethridge and Schumm (1978) recommended two methods for a sandy fluvial system based on the palaeochannel dimension. Apparent sedimentary structures (bedforms) are observable in the entire succession of the Surai Khola. However, the measurement of channel dimension is frequently difficult. The method of Allen and Homewood (1984) is adopted here, which restricts palaeohydrological values in terms of bedforms. The method of Allen and Homewood (1984) was developed originally for the tidal sediments, and Masuda and Nakayama (1988) and Nakayama (1997) slightly modified it for both tidal and fluvial sediments, and this converted method is adopted in this study. While applying the Maning-Limerious method, the slope gradients were estimated from the grain size instead of the actual measured values because of outcrop limitations. The estimation methods adopted in this paper need simply grain size and flow depth. The uppermost part of the Siwalik Group, i.e., the upper part of the Dhan Khola Formation, is excluded, as it is dominated by poorly sorted and non-stratified conglomerates to which this method is inapplicable.

Palaeoflow depth

The thickness of fining-upward succession is used for estimating the palaeoflow depth. Most of the samples were obtained from the bottoms of fining-upward successions, so that the bed load channel depth is concordant with the flow depth in this study. This is the extended application of the bankfull flow estimation in a meandering channel (Ethridge and Schumm 1978; Bridge 1978).

As lateral accretion architectures are recognised in SC03, the estimation method of bankfull flow depth in meandering channel is directly applied here. Other fining-upward successions in this study have no apparent evidence of meandering channel deposits. However, the described columnar sections have the same order of thickness as those of fining-upward successions ranging from several metres to tens meters. Hence, the bed load channel depth in a simple fining-upward succession can be considered to roughly indicate the bankfull flow depth.

Ethridge and Schumm (1978) specify the coefficient of 0.585/0.9 for converting from bed load thickness to palaeoflow depth. This value is not used in this study because the estimations applied to all fining-upward successions may not have such preciseness. The decompacted thickness is not calculated either, because all the measured thicknesses in this study include bed load sand and gravel in which the compaction must be negligible. Above these, there can be some imprecision for the estimation of flow depth. Nonetheless, the estimated values are considered to be accurate enough to discuss the palaeohydrological evolution.

Palaeohydrology of sandy bed load

The method of Allen and Homewood (1984) provides the depth-mean velocity 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 as given below:

$$U_{cr} = \frac{u_{cr}}{k}\ln\left(\frac{d}{ez_0}\right) \text{.......................................(1)}$$

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 metre, and z_0 is the roughness length in metre.

Using 0.4 and 0.0004 for e and z_0, according to Allen and Homewood (1984), u_{cr} is calculated from the shear stress for threshold (u_r), which is directly related to grain diameter (Miller et al. 1977). Similarly, U_{rd} and U_{up} are obtained from the following equations:

$$U_{rd} = \frac{u_{rd}}{k}\ln\left(\frac{d}{ez_0}\right) \text{....................................(2)}$$

$$U_{up} = \frac{u_{up}}{k}\ln\left(\frac{d}{ez_0}\right) \text{....................................(3)}$$

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 the same as in (1).

Here, 0.4 was used for e in both equations, and 0.0006 and 0.001 were used for z_o in equations (2) and (3), respectively. Three velocity values for each sample were calculated, and a unique velocity value (V) was estimated based on these three values and bedform configurations. Firstly, the relationship between bedforms and bedding structures was worked out. Planar cross-bedding and trough cross-bedding are formed by the accumulation of 2D dunes and 3D dunes, respectively. Ripple lamination is formed by ripples. Secondly, the relationship between the grain size and bedform was evaluated. Relatively small grains (less than about 0.15 mm in diameter) never form dunes, while relatively coarse grains (larger than about 0.8 mm in diameter) never form ripples. Both ripples and dunes can occur in sediments with the grain diameter between these sizes. Thirdly, the velocity range was restricted using bedform type, that is, 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 a relatively slower velocity of the range between U_{rd} (or U_{cr}) and U_{up}, while 3D dunes are formed in a relatively faster velocity of this range.

Each equation and its applicable grain range and bedform are explained in the note of Table 1.

The palaeochannel gradient for critical flow (S_c) condition was estimated as follows:

$$S_c = \frac{t_{cr}}{g \cdot d_c} \text{..(4)}$$

where g is the specific weight of water taken as 1000 kg/m^3 and d is used for critical flow depth (d_c) .

The simplest equation for discharge (Q) is:

$$Q = VA \text{..(5)}$$

where V is mean velocity, and A is cross-sectional area of flow.

However, since the channel width required for determining the cross-sectional area (*A*) was difficult to measure on ancient sediments exposed in a limited area, the estimation of discharge was based on the depth and grain size of the sandy materials (Kellerhals 1967):

$$Q = 70.2dc^2.D_m{}^{0.3} \quad \text{.................................(6)}$$

Palaeohydrology for gravely bed load

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

$$t_{cr} = 0.056(g_s - g)D \quad \text{..............................(7)}$$

where g_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.

Then, the channel gradient for critical flow condition was obtained from equations (4) and (7):

$$S_c = \frac{0.092D_{95}}{d_c} \quad \text{..(8)}$$

The palaeoflow velocity for critical flow condition was calculated according to the Manning-Limerious equation:

$$\overline{V_c} = \frac{\sqrt[3]{d_c{}^2.}}{\sqrt{S_c}} \cdot \frac{1.16 + 2.0\log\left(\dfrac{d_c}{D_{95}}\right)}{0.113\sqrt[6]{d_c}} \quad \text{.............(9)}$$

where $\overline{V_c}$ is the critical mean flow velocity.

The adopted value of as a unique velocity value V is given in Table 2.

The determination of palaeodischarge for sand and gravel deposits was carried out using the following Manning-Limerious equation (Maizels 1983):

$$Q = \frac{\overline{V_c}}{S_c} \quad \text{...(10)}$$

where Q is the discharge, $\overline{V_c}$ is the critical mean flow velocity, and S_c is the palaeochannel gradient for critical flow.

RESULTS

The palaeoflow velocity, palaeochannel gradient, and palaeodischarge range from 0.61 to 1.35 m/s, 3.26x10^{-4} to 8.36x10^{-4} m/m, and 2.55x10^{2} to 2.47x10^{3} m^3/s, respectively in the Bankas Formation, whereas in the Jungli Khola Member of the Chor Khola Formation they vary respectively from 0.47 to 1.94 m/s, 8.16x10^{-5} to 7.14x10^{-4} m/m, and 6.38x10^{1} to 1.69x10^{3} m^3/s. The Shivgarhi Member of the Chor Khola Formation shows a range of palaeoflow velocity, palaeochannel gradient, and palaeodischarge from 0.39 to 2.25 m/s, 8.16x10^{-5} to 9.59x10^{-4} m/m, and 9.04x10^{0} to 3.43x10^{3} m^3/s, respectively. The Surai Khola, Dobata, and Dhan Khola Formations exhibit a range of palaeoflow velocity from 0.45 to 2.49 m/s, 0.37 to 0.72 m/s, and 3.93 to 4.47 m/s, respectively. Similarly, the palaeochannel gradient ranges from 8.00x10^{-5} to 1.20x10^{-4} m/m, 4.00x10^{-5} to 9.04x10^{-4}, and 5.29x10^{-5} to 5.87x10^{-4} m/m, respectively. The palaeodischarge in the Surai Khola, Dobata, and Dhan Khola Formations ranges from 4.81x10^{1} to 1.28x10^{2} m^3/s, 9.04x10^{0} to 5.46x10^{3} m^3/s, and 6.69x10^{3} to 8.99x10^{4} m^3/s, respectively.

EVOLUTION OF FLUVIAL SYSTEM

Figure 3 and Table 4 depict the evolution of fluvial system in the Surai Khola section, where palaeoflow velocity, palaeochannel gradient, and palaeodischarge gradually increase in the stratigraphically upward direction. The upper part of the Dhan Khola Formation was inferred to be accumulated from a debris flow-dominated fan system controlled by the CCT (Nakayama and Ulak 1999). Blair and McPherson (1994) indicated that a debris flow-dominated fan system exhibits a steep slope gradient (more than 1.5 degrees or 0.026 m/m). This slope value is much steeper than any estimated slope value in this study.

Nakayama and Ulak (1999) classified the fluvial system in the Siwalik Group of the study area into the following 6 stages: the meandering system (Stage 1), flood flow-dominated meandering system (Stage 2), sandy braided system (Stage 3), anastomosed system (Stage 4), gravely braided system (Stage 5), and debris flow-dominated braided system (Stage 6). They also concluded that the inception of Stage 1, Stage 5, and Stage 6 were controlled by the MCT, MBT, and CCT, respectively. Two drastic palaeohydrological changes in this area coincide with the inception of Stage 5 and Stage 6. That is, the palaeohydrological changes presumably reflect the southward propagation of thrusts. Stage 2, 3, 4, 5, and 6 initiated about 9.5, 6.5, 4.0, 2.5, and 1.0 Ma ago, respectively.

DISCUSSION AND CONCLUSION

In the Siwaliks of the Surai Khola section, palaeoflow estimations were made for both sandy and gravelly sediments. This section mainly exhibits a progressively increasing trend of palaeohydrological parameters towards the stratigraphic top, indicating a progressive change in the fluvial regime as well as in the rate of sedimentation (Table 3). In this section, palaeochannel gradient varies from 5.29x10^{-5} to 9.59x10^{-4} m/m, palaeovelocity ranges from 0.32 to 4.76 m/s, and palaeodischarge ranges from 10^{0} to 10^{4} m^3/s. These

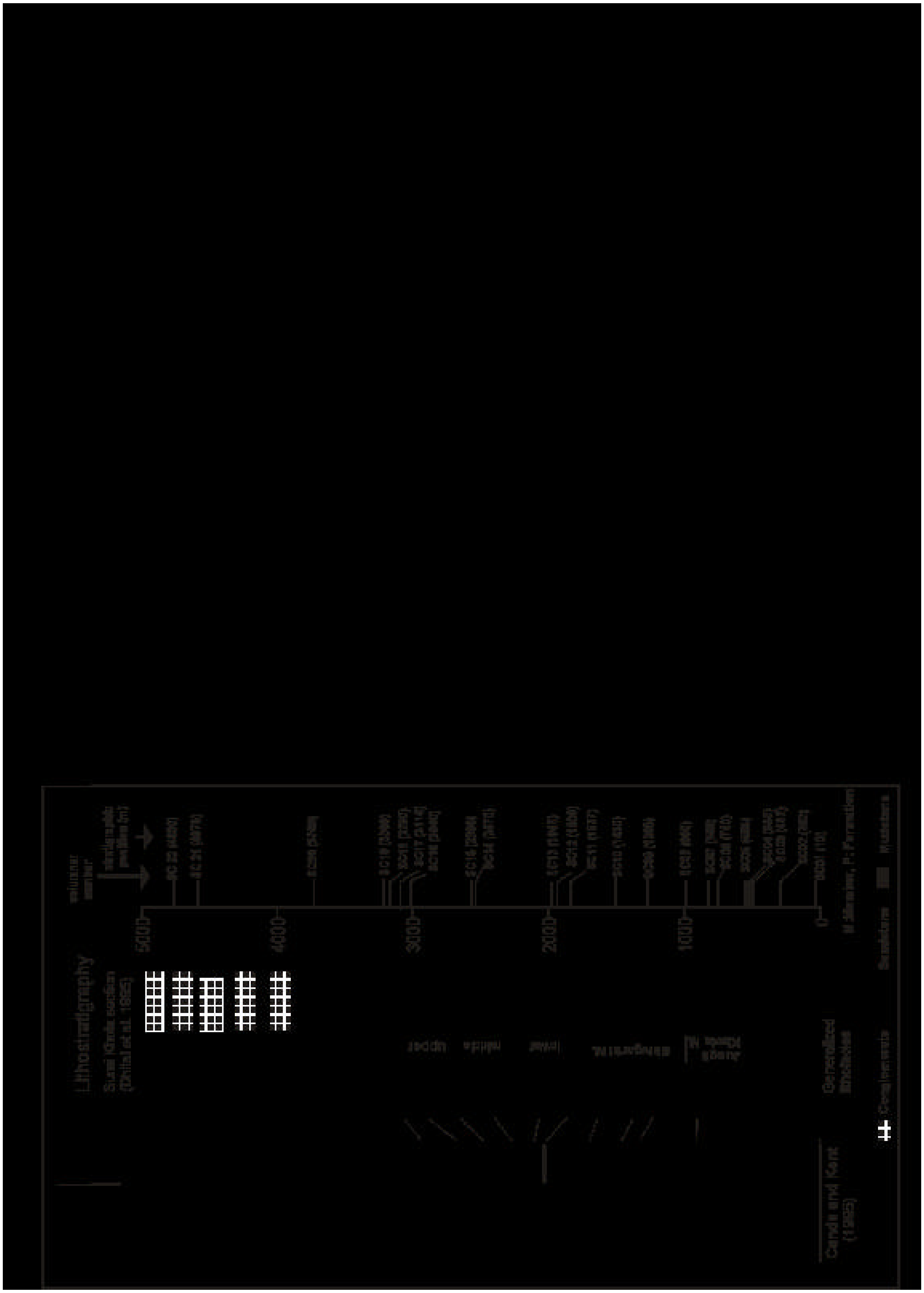
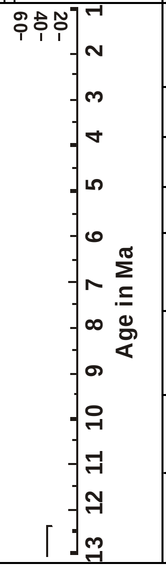


Fig. 3: Simplified stratigraphic logs of the Surai Khola section, and stratigraphic position of sample obtained columnar sections. The magnetostratigraphy of the group is based on Appel et al. (1991). The magnetic polarity time scale is that of Cande and Kent (1995).

Table 3: Summary of the palaeohydrology and its relation to the rate of sedimentation and evolution of the fluvial system

Lithostratigraphy Dhital et al. 1995		Fluvial system Nakayama and Ulak 1999	Sedimentation rate (mm/yr) Appel et al. 1991	Paleohydrology		
				Velocity (m/s)	Gradient (m/m)	Paleodischarge (m^3/s)
Dhan Khola Fm		Debris flow-dominated braided system		3.93 to 4.76	5.29×10^{-5} to 5.87×10^{-4}	6.69×10^{3} to 8.99×10^{4}
		Gravelly braided system				
Dobata Fm		Anastomosed system		0.37 to 0.72	4.00×10^{-5} to 7.44×10^{-4}	9.04×10^{0} to 7.44×10^{3}
Surai Khola Fm	upper	Sandy braided system		0.45 to 0.69	8.00×10^{-5} to 1.20×10^{-4}	4.81×10^{1} to 1.28×10^{2}
	middle			1.21 to 2.49	2.21×10^{-4} to 8.25×10^{-4}	2.96×10^{2} to 5.28×10^{3}
	lower	Sandy meandering system		0.63 to 1.40	8.16×10^{-5} to 4.28×10^{-4}	9.04×10^{1} to 4.92×10^{2}
Chor Khola Fm	Shivgarhi M	Flood flow-dominated meandering system		0.39 to 2.25	8.16×10^{-5} to 9.59×10^{-4}	9.04×10^{0} to 3.43×10^{3}
	Jungli Khola M			0.47 to 1.94	8.16×10^{-5} to 7.14×10^{-4}	6.38×10^{1} to 1.69×10^{3}
Bankas Fm		Fine-grained meandering system with pigment paleosol		0.61 to 1.35	3.26×10^{-4} to 8.36×10^{-4}	2.55×10^{2} to 2.47×10^{3}

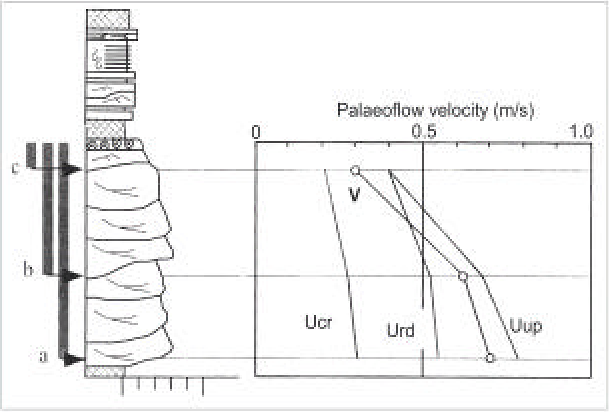


Fig. 4: Variation of palaeoflow velocity in one complete fining upward succession.

estimates suggest that the fluvial systems grew progressively larger due to the southward propagation of the MCT, MBT, and CCT.

In some cases, the palaeoflow velocities decrease upwards (Fig. 4), which may reflect the changing velocities from thalweg to point (side) bar. Since only two factors (grains size and bed load channel depth) were used, and other factors such as channel shape, sorting of deposition, and suspended load were not considered, this study is suitable mainly for depicting the evolutional change of the Siwalik fluvial system.

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