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Paleohydrological reconstruction of the Siwalik Group along the Tinau Khola section, west-central Nepal Himalaya

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ABSTRACT

Neogene fluvial sedimentary sequences of the Siwalik Group are extensively accumulated in the southern frontal part of the Himalaya and well exposed in the Tinau Khola section of the west-central Nepal Himalaya. The group reveals a coarsening-upwards succession in general but many fining-upwards fluvial successions on a scale from several to tens of metres is established in each lithological unit. The paleohydrological characteristics have been estimated using thickness of fining-upwards fluvial successions, their grain diameters, and bedforms. The paleohydrology suggests an increase in flow velocity, channel slope gradient, and discharge of the fluvial system. Paleovelocity varies from 0.17 to 5.31 m/s, paleochannel gradient and paleodischarge change from 1.13x10-5 to 7.33x10-4 m/m and 101 to 104 m3/s, respectively towards the stratigraphic top. These progressively changing paleohydrological characteristics reflect the southward propagation of thrusts caused by the upheaval of the Himalaya.

Keywords: Siwalik Group, Himalaya, paleohydrology, fluvial system, thrust activity

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INTRODUCTION

Studies on the paleohydrology of the fluvial deposits are essential in order to quantify the hydraulic conditions of paleoriver system, and facilitate comparison with modern fluvial systems. The paleohydrological reconstruction of the fluvial system is based on the grain size, nature of bedforms, and thickness of the fluvial succession. Methods of hydrological reconstruction of ancient deposits are based on flume experiments and observations of modern depositional systems. The paleohydrological reconstruction of ancient fluvial deposits are studied by Nakayama (1999), Els (1990), Bridge and Gordon (1985), Steer and Abbott (1984), Williams (1984), Maizels (1983), Ethridge and Schumm (1978) and Cotter (1971). In such studies, Allen (1965), Leeder (1973), Ethridge and Schumm (1978) showed the important method of 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) indicate 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 longer-time and statistical average of flow in comparison with dune height. Other significant paleohydrological reconstruction was performed on ancient tidal sediments by Allen and Homewood (1984), which determined the range of paleovelocity based on the supposed flow depth and bed configuration.

Middle Miocene to early Pleistocene fluvial sediments of the Siwalik Group (4-6 km thick; Tokuoka et al. 1990) are widely distributed in the foreland basin on the southern area of the Himalaya. Sedimentation in the Siwalik basin is thought to be influenced by the Neogene tectonics of the Himalaya (Parkash et al. 1980). Stratigraphy of the Siwalik Group has been established in the Potwar basin of Pakistan based on the lithology and paleomagnetism (Johnson et al. 1982; Opdyke et al. 1982).

Studies on the evolution of the fluvial system of the Siwalik Group in the Potwar basin have been carried out by Willis (1993a, b), Khan et al. (1997), and Zaleha (1997a, b). These works also included the paleohydrological reconstructions based on the detail sketches of several hundred metres wide outcrops. The paleohydrology of the Siwalik succession from the Nepal Himalaya has been stuided (Ulak and Nakayama 2003; Ulak 2002; Ulak and Nakayama 2001a; Ulak 2001; Ulak and Nakayama 2001b; Ulak and Nakayama 1999). The evolution of the Neogene fluvial system along the Tinau Khola section was studied by Ulak 2005; Ulak and Nakayama (2001); Ulak and Nakayama (1988) and Hisatomi and Tanaka (1994). They clarify the onset of the Siwalik Group by the meandering river system which then changed into the braided river system 9.9 Ma (~10 Ma).

This paper focuses on estimation of paleohydrological parameters including velocity, channel gradient, discharge of the entire succession of the Siwalik Group along the Tinau Khola section, and on relationship between paleohydrology and evolution of the fluvial system.

Table 1 : Summary of lithostratigraphy (Tokuoka et al. 1990) and evolution of fluvial system (Hisatomi and Tanaka 1994; Ulak and Nakayama 2001) of the Tinau Khola section, west central Nepal Himalaya

Lithological Unit (Tokuoka et al. 1990)	**Thickness (m)**	**Main Lithology**	**Fluvial system** (Ulak and Nakayama 2001)
Deorali Formation#	**450+**	Matrix supported boulder-sized conglomerate	Debris flow-dominated braided system
Chitwan Formation	**200+**	Clast supported cobble-pebble conglomerates	Gravelly braided system
Binai Khola Formation			
Upper Member	**260**	Thick-bedded, grey mudstone interbeds with medium-grained sandstone. (ss>>ms)	Shallow braided system
Middle Member	**1220**	Thick-bedded, very coarse to very coarse grained, "pepper and salt" sandstone with pebbly sandstone.	Deep braided system
Lower Member	**340**	Thick-bedded, coarse-grained, "pepper and sal" sandstone with grey mudstone (ss>ms)	Flood flow-dominated, meandering system
Arung Khola Formation			
Upper Member	**1350**	Medium-grained, grey sandstone with variagated to grey mudstone (ss>ms)	Flood flow-dominated meandering system
Middle Member	**250+**	Fine-grained, grey sandstone with variegated mudstone (ms=ss)	Fine-grained meandering system
Lower Member#	**500+**	Fine-grained, greenish-grey sandstone interbeds with variegated mudstone (ms>>ss)	Fine-grained meandering system

Not exposed in study section. ss:sandstone, ms: mudstone

GEOLOGAL SETTING

The Himalaya is formed as a result of the intercontinental collision between Indian and Asian plates, initiated as early as 65 Ma (Beck et al. 1995). Ongoing collision caused not only compression and folding of the rocks between the two plates, but also breaking up of the Indian crust and forming Himalayan molasses basin in the world's largest terrestrial foreland basin (Burbank et al. 1996). The Himalayan foreland results from subsidence driven by southward-displaced thrusts sheets e.g., Main Central Thrust (MCT), Main Boundary Thrust (MBT), and the Frontal Churia Thrust (FCT) equivalent to the Main Frontal Thrust (MFT) are exposed successively from north to south (Gansser 1964; Fig. 1).

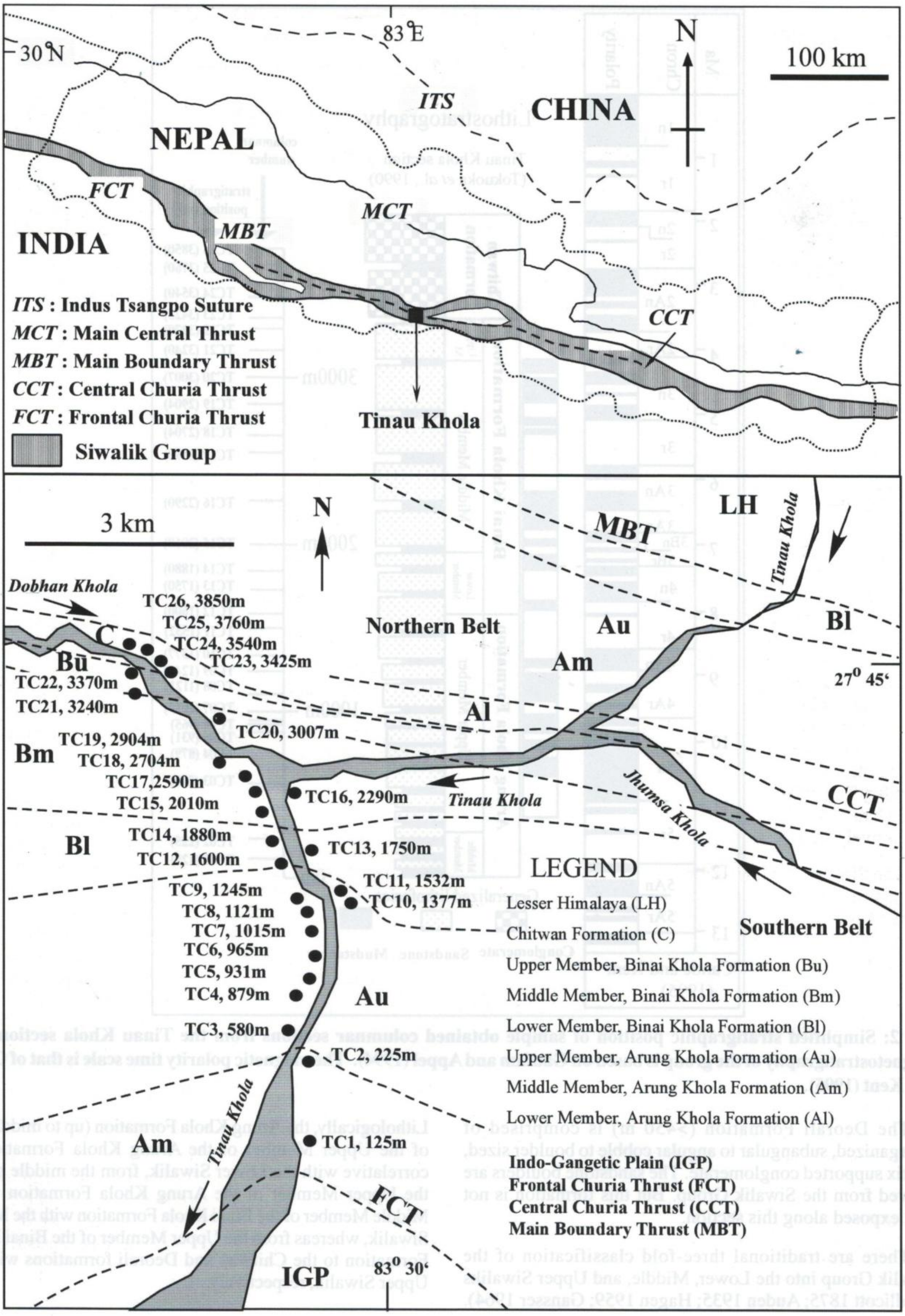
The Siwalik Group was deposited in the foreland basin, situated in the south of the Himalaya and sediments were supplied as a result of rapid upliftment of the Himalaya and sediments carried into the basin by the rivers. The group is bounded from the MBT to the north, separating by the Lesser Himalaya and the MFT to the south by the Indo-Gangetic Plain. In Nepal, the Siwalik Group generally dips northward, and comprises a coarsening upward succession.

The Siwalik Group is also well exposed in the Arung Khola-Tinau Khola area, west-central Nepal Himalaya. The lithostratigraphy of the Siwalik Group along the Arung Khola-Tinau Khola has been established by Tokuoka et al. (1986, 1988, 1990) and comprises the Arung Khola, Binai Khola, Chitwan and Deorali formations, in ascending order based on increasing grain size and lithology (Fig.1; Table 1). The Arung Khola and Binai Khola formations are subdivided into the Lower, Middle and Upper members based on thickness of the mudstone and sandstone beds as well as their proportion.

The Lower Member of the Arung Khola Formation, *Al* (500+m) consists of bioturbated and variegated mudstone alternating with fine- to very fine-grained, calcareous sandstone, with a ratio of mudstone and sandstone 65:35. The Middle Member, *Am* (250 m) is characterized by variegated mudstone and fine- to medium-grained sandstone, in proportion of 57:43. The Upper Member, *Au* (1,350 m) is represented by fine- to coarse-grained, calcareous sandstone alternating with mudstone of ratio sandstone and mudstone about 70:30.

The Lower Member of the Binai Khola Formation, *Bl* (340 m) is composed of thick bedded, medium- to coarse-grained, grey sandstone and dark grey mudstone. Conglomerate beds are frequently found with sandstone beds in the upper part of the member. The ratio of sandstone, mudstone and conglomerate are about 72:25:3. The Middle Member, *Bm* (1,220 m) is composed of thick bedded, coarse-grained "pepper and salt" sandstone alternating with dark grey mudstone, having 52:16:32 ratio of sandstone, mudstone and conglomerate. The Upper Member, *Bu* (260 m) is identified by coarse- to very coarse-grained sandstone beds subordinate with lenses of conglomerate beds, with proportion of sandstone, mudstone and conglomerate about 45:16:39. Most of the clasts in conglomerate is composed of the Lesser Himalayan rocks.

The Chitwan Formation (>200 m) comprises of well-sorted, clast supported, semi-consolidated conglomerates with lenses of sands and muds, with ratio of is 71:29. The clasts are rounded to subrounded in pebble-sized, consist of quartzite, sandstone, shale and limestone clasts from the Lesser Himalayan rocks.


30°N
83°E
N
100 km
ITS
CHINA
NEPAL
FCT
MCT
MBT
INDIA
CCT
ITS : Indus Tsangpo Suture
MCT : Main Central Thrust
MBT : Main Boundary Thrust
CCT : Central Churia Thrust
FCT : Frontal Churia Thrust
Siwalik Group
Tinau Khola
3 km
N
LH
MBT
Tinau Khola
Dobhan Khola
TC26, 3850m
TC25, 3760m
TC24, 3540m
TC23, 3425m
C
Bu
TC22, 3370m
TC21, 3240m
Northern Belt
Au
Am
Bl
27° 45‘
Al
TC20, 3007m
TC19, 2904m
TC18, 2704m
Bm
TC17,2590m
TC15, 2010m
TC16, 2290m
Tinau Khola
Jhumsa Khola
CCT
Bl
TC14, 1880m
TC12, 1600m
TC13, 1750m
LEGEND
TC9, 1245m
TC11, 1532m
TC10, 1377m
TC8, 1121m
TC7, 1015m
TC6, 965m
TC5, 931m
TC4, 879m
Southern Belt
Au
TC3, 580m
TC2, 225m
Lesser Himalaya (LH)
Chitwan Formation (C)
Upper Member, Binai Khola Formation (Bu)
Middle Member, Binai Khola Formation (Bm)
Lower Member, Binai Khola Formation (Bl)
Upper Member, Arung Khola Formation (Au)
Middle Member, Arung Khola Formation (Am)
Lower Member, Arung Khola Formation (Al)
Am
Tinau Khola
TC1, 125m
Indo-Gangetic Plain (IGP)
Frontal Churia Thrust (FCT)
Central Churia Thrust (CCT)
Main Boundary Thrust (MBT)
FCT
IGP
83° 30‘

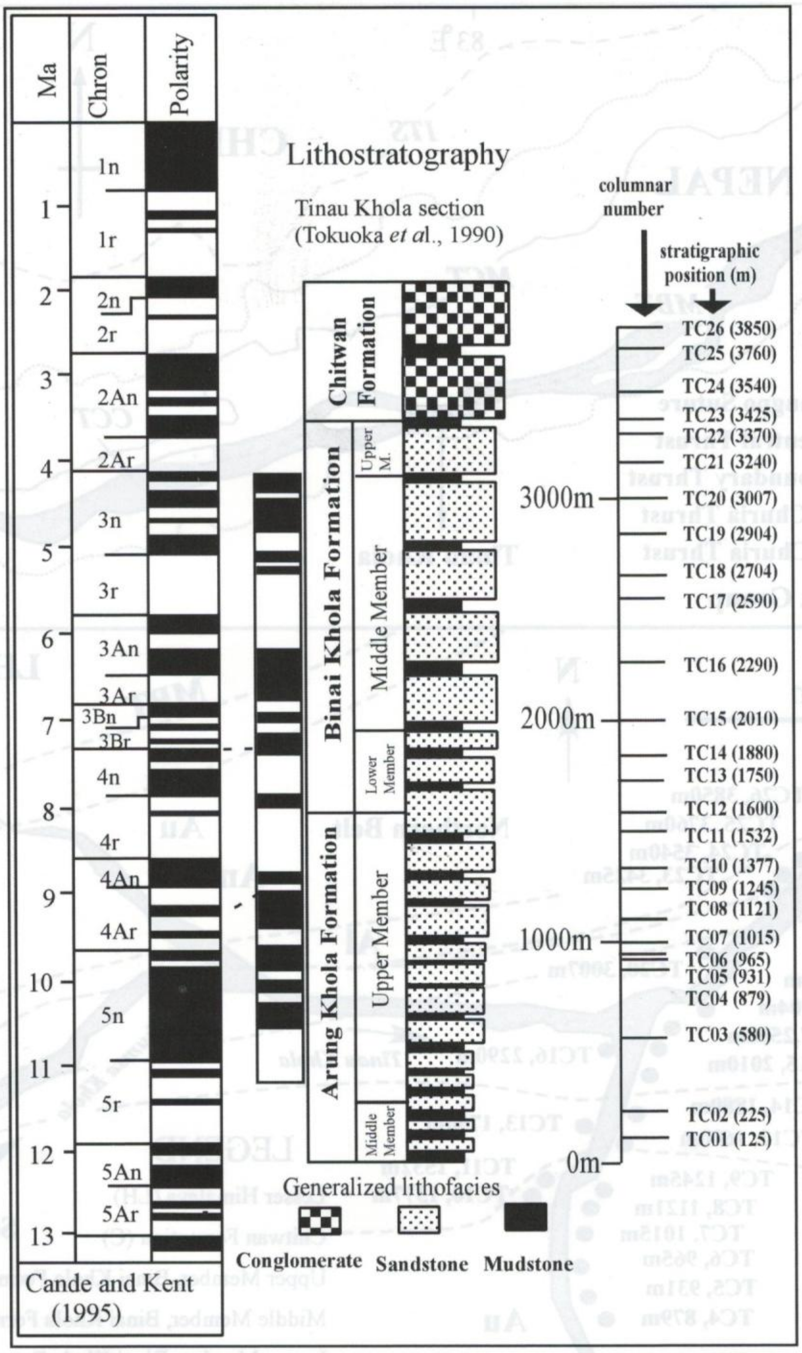


Fig. 2: Simplified stratigraphic position of sample obtained columnar sections from the Tinau Khola section. The magnetostratigraphy of the group is based on Gautam and Appel (1994). The magnetic polarity time scale is that of Cande and Kent (1995).

The Deorali Formation (>450 m) is comprised of disorganized, subangular to angular cobble to boulder sized, matrix supported conglomerate. The sandstone boulders are derived from the Siwalik Group. But this formation is not well exposed along this section.

There are traditional three-fold classification of the Siwalik Group into the Lower, Middle, and Upper Siwaliks (Medlicott 1875; Auden 1935; Hagen 1959; Gansser 1964). Lithologically, the Arung Khola Formation (up to middle part of the Upper Member of the Arung Khola Formation) is correlative with the Lower Siwalik, from the middle part of the Upper Member of the Arung Khola Formation to the Middle Member of the Binai Khola Formation with the Middle Siwalik, whereas from the Upper Member of the Binai Khola Formation to the Chitwan and Deorali formations with the Upper Siwalik, respectively.

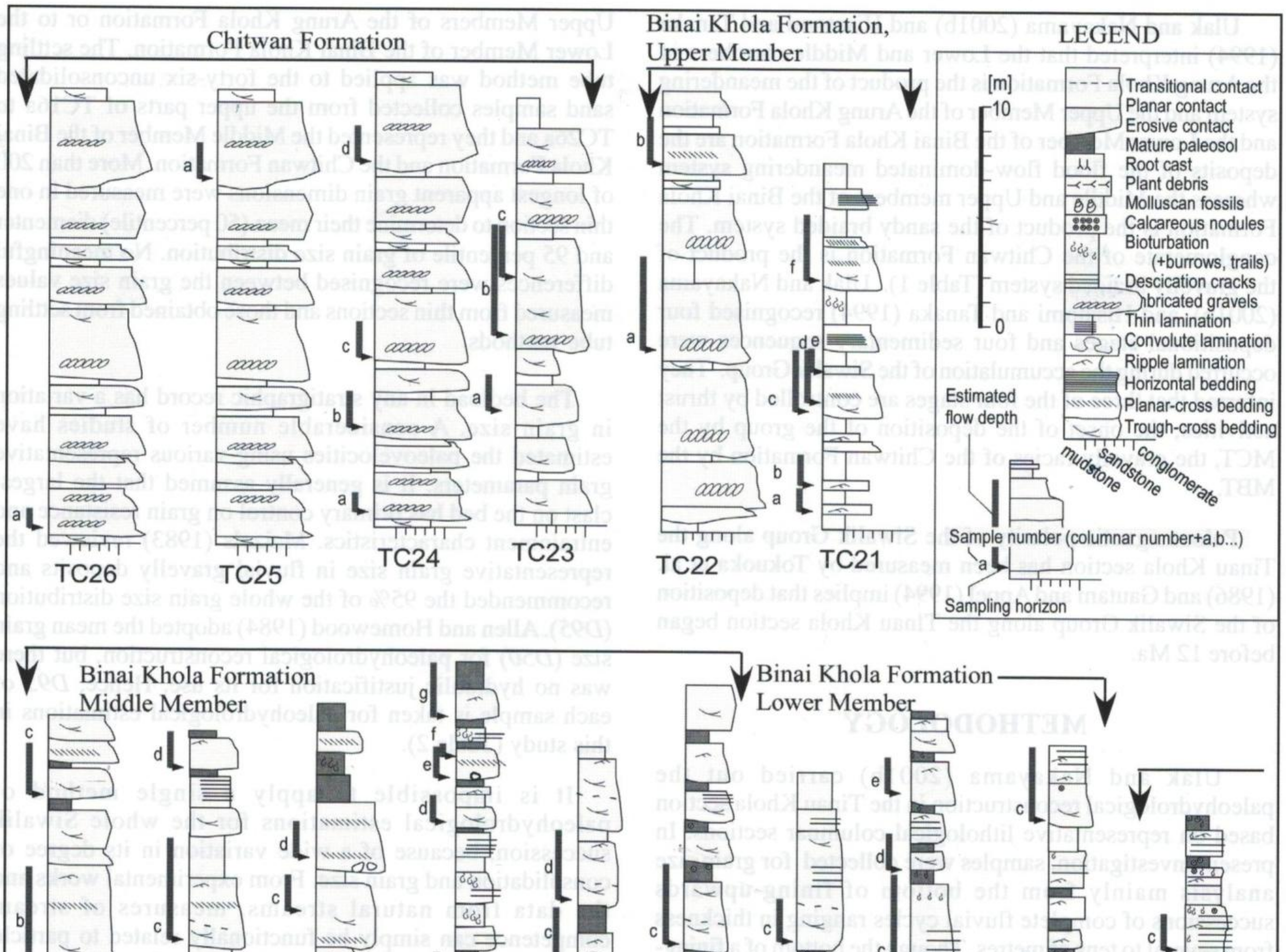


Fig. 3: Columnar log sections and sampling points of the Tinau Khola section, west-central Nepal Himalaya

Ulak and Nakayama (2001b) and Hisatomi and Tanaka (1994) interpreted that the Lower and Middle members of the Arung Khola Formation is the product of the meandering system and the Upper Member of the Arung Khola Formation and the Lower Member of the Binai Khola Formation are the deposits of the flood flow-dominated meandering system whereas the Middle and Upper members of the Binai Khola Formation is the product of the sandy braided system. The conglomerate of the Chitwan Formation is the product of the gravelly braided system (Table 1). Ulak and Nakayama (2001b), and Hisatomi and Tanaka (1994) recognised four depositional stages and four sedimentary sequences were occurred during the accumulation of the Siwalik Group. They inferred that three of the four stages are controlled by thrust activities; the onset of the deposition of the group by the MCT, the gravelly facies of the Chitwan Formation by the MBT.

Paloemagnetic polarity of the Siwalik Group along the Tinau Khola section has been measured by Tokuoka et al. (1986) and Gautam and Appel (1994) implies that deposition of the Siwalik Group along the Tinau Khola section began before 12 Ma.

METHODOLOGY

Ulak and Nakayama (2001b) carried out the paleohydrological reconstruction in the Tinau Khola section based on representative lithological columnar sections. In present investigation, samples were collected for grain size analysis mainly from the bottom of fining-upwards successions of complete fluvial cycles ranging in thickness from several to tens of metres. Though the bottom of a fining-upward succession is suitable for sampling, some samples were also taken from its middle part. Occasionally there were some out-sized clasts at the bottom of some successions and the samples do not include such clasts. Sampling locations, their stratigraphic position, and location of each columnar section are shown in Figs. 2 and 3.

Each fining-upwards succession generally comprises bedload in the form of stratified sands and gravels at the bottom and suspended load of muddy material at the top. Measurement of bedload thickness and sampling position from the bottom of a fining-upwards cycle, and the description of sedimentary structures were carried out for paleohydrological estimations (Fig. 3). For this purpose, ninety-four samples were collected from twenty-six sections (TC01 to TC26) in this study.

Grain size analyses

As the consolidation of samples widely varied (from strongly lithified to loosely packed), their grain size was estimated either from thin sections (for strongly lithified sandstones) or using a settling tube. Thin sections were prepared from the lower fifty-two samples collected from TC01a to TC15c and they belong either to the Middle and Upper Members of the Arung Khola Formation or to the Lower Member of the Binai Khola Formation. The settling tube method was applied to the forty-six unconsolidated sand samples collected from the upper parts of TC16a to TC26a and they represented the Middle Member of the Binai Khola Formation and the Chitwan Formation. More than 200 of longest apparent grain dimensions were measured in one thin section to determine their mean (50 percentile) diamenter and 95 percentile of grain size distribution. No meaningful differences were recognised between the grain size values measured from thin sections and those obtained from settling tube methods.

The bedload in any stratigraphic record has a variation in grain size. A considerable number of studies have estimated the paleovelocities using various representative grain parameters. It is generally assumed that the largest 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 the 95% of the whole grain size distribution (*D95*). Allen and Homewood (1984) adopted the mean grain size (*D50*) for paleohydrological reconstruction, but there was no hydraulic justification for its use. Hence, *D95* of each sample is taken for paleohydrological estimations in this study (Table 2).

It is impossible to apply a single method of paleohydrological estimations for the whole Siwalik succession, because of a wide variation in its degree of consolidation and grain size. From experimental works and the data from natural streams, measures of stream competence can simply 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 TC23a to TC26a samples are gravelly and hence larger than this critical size, and other samples are sandy. Basically the method used by Allen and Homewood (1984) for sandy sediments, and Manning-Limerinous method recommended by Maizels (1983) for gravelly sediments were utilised in this study. Ethridge and Schumm (1978) recommended the two methods for sandy fluvial system, based on the paleochannel dimension. Apparent sedimentary structures (bedforms) are observable in a whole succession along the Tinau Khola section, however, the measurement of channel dimension is frequently difficult. So, the method of Allen and Homewood (1984) was adopted which restricts paleohydrological 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, and this converted method was adopted in this study. While applying the Manning-Limerinous method, the slope gradients were estimated from the grain size instead of the actual measured values because of outcrop limitations.

Table 2: Palaeohydrological parameters of the Siwalik Group from the Tinau Khola section, west-central Nepal Himalaya

		Grain size		**Palaeohydrolgical parameters**						
		D_{50}	D_{95}	Depth	*Ucr*	*Urd*	*Upd*	Velocity	Gradient	Discharge
Bedding	Sample	(mm)	(mm)	(m)	(m/s)	(m/s)	(m/s)	(m/s)	(m/m)	(m^3/s)
Chitwan Formation										
HB	TC26a	13.625	27.129	6.30	****	****	****	5.31	3.96E-04	1.22E+04
HB	TC25a	8.414	18.672	4.30	****	****	****	4.65	4.00E-04	1.16E+04
PB	TC24d	0.389	0.845	1.90	0.30	0.45	0.66	0.52	1.38E-04	3.87E+02
TB	TC24c	0.719	1.527	1.10	0.32	3.27	0.79	1.61	3.18E-04	1.04E+02
PB	TC24b	0.379	0.723	0.90	0.26	0.46	0.54	0.49	2.67E-04	6.38E+01
TB	TC24a	2.057	5.671	3.70	0.68	0.65	1.35	1.12	2.97E-04	1.93E+03
Upper Member, Binai Khola Formation										
TB	TC23c	0.199	0.405	3.20	0.27	0.27	0.53	0.45	5.63E-05	1.36E+03
TB	TC23b	0.513	1.234	4.90	0.36	0.61	0.93	0.82	6.12E-05	3.79E+03
TB	TC23a	0.145	0.268	2.70	0.25	0.18	0.33	0.28	5.93E-05	9.02E+02
RL	TC22b	0.289	0.502	1.90	0.28	0.92	0.57	0.60	1.16E-04	3.87E+02
TB	TC22a	0.699	1.389	1.70	0.34	0.91	0.87	0.88	2.06E-04	2.96E+02
Middle Member, Binai Khola Formation										
RL	TC21f	0.159	0.302	1.90	0.22	0.45	0.42	0.33	7.37E-05	3.87E+02
TB	TC21e	0.216	0.405	1.80	0.25	0.20	0.37	0.32	1.00E-04	3.39E+02
TB	TC21d	0.228	0.442	2.90	0.26	0.80	0.56	0.64	6.21E-05	1.07E+03
TB	TC21c	0.633	1.398	3.90	0.35	1.13	0.99	1.04	7.44E-05	2.19E+03
RL	TC21b	0.175	0.312	1.70	0.23	0.64	0.43	0.43	9.41E-05	2.96E+02
RL	TC21a	0.204	0.401	0.90	0.22	0.19	0.40	0.20	1.89E-04	6.38E+01
RL	TC20c	0.076	0.187	4.80	0.20	0.17	0.36	0.19	1.88E-05	3.61E+03
TB	TC20b	0.321	0.612	1.90	0.27	0.77	0.60	0.66	1.11E-04	3.87E+02
TB	TC20a	0.101	0.208	6.10	0.23	1.17	0.43	0.68	1.80E-05	6.43E+03
PB	TC19d	0.392	0.786	1.40	0.27	0.17	0.62	0.32	1.57E-04	1.85E+02
PB	TC19c	0.447	0.926	5.20	0.35	0.30	0.67	0.42	5.19E-05	4.37E+02
PB	TC19b	0.184	0.387	2.50	0.25	1.04	0.49	0.86	6.80E-05	7.49E+02
TB	TC19a	0.813	1.678	2.70	0.39	0.75	1.04	0.82	1.44E-04	9.02E+02
RL	TC18g	0.105	0.201	2.40	0.20	0.50	0.36	0.35	4.58E-05	6.79E+02
TB	TC18f	0.348	0.676	1.60	0.29	0.95	0.60	0.72	1.56E-04	2.55E+02
RL	TC18e	0.191	0.412	2.10	0.25	0.75	0.48	0.50	8.10E-05	4.92E+02
RL	TC18d	0.156	0.301	1.30	0.20	0.40	0.38	0.30	1.00E-04	1.55E+02
TB	TC18c	0.152	0.298	0.80	0.19	0.56	0.33	0.41	1.63E-04	4.81E+01
TB	TC18b	0.231	0.437	2.60	0.26	0.43	0.55	0.51	6.92E-05	8.23E+02
PB	TC18a	0.135	0.291	2.40	0.23	0.19	0.31	0.23	5.83E-05	6.79E+02
TB	TC17e	0.295	0.592	6.10	0.30	1.05	0.74	0.84	3.11E-03	6.43E+03
TB	TC17d	0.606	1.203	4.80	0.38	0.46	0.77	0.67	6.67E-05	3.61E+03
PB	TC17c	0.161	0.145	0.70	0.20	0.27	0.33	0.29	2.14E-04	3.48E+01
TB	TC17b	0.578	1.188	2.50	0.34	0.55	0.86	0.76	1.20E-04	7.49E+02
PB	TC17a	0.314	0.678	3.40	0.29	0.73	0.68	0.71	6.18E-05	1.57E+03
RL	TC16d	0.054	0.123	1.80	0.17	0.17	0.24	0.17	4.44E-05	3.39E+02
TB	TC16c	0.408	0.808	5.10	0.33	0.85	0.84	0.67	4.90E-05	4.17E+03
RL	TC16b	0.213	0.423	1.20	0.23	0.40	0.44	0.31	1.42E-04	1.28E+02
RL	TC16a	0.375	0.675	2.90	0.29	1.81	0.72	1.05	7.24E-05	1.07E+03
Lower Member, Binai Khola Formation										
TB	TC15c	0.246	0.459	5.20	0.29	0.90	0.65	0.53	3.65E-05	4.37E+03
TB	TC15b	0.282	0.561	2.90	0.27	1.10	0.62	0.50	6.55E-05	1.07E+03
RL	TC15a	0.086	0.176	0.60	0.15	0.28	0.23	0.22	1.50E-04	2.40E+01
TB	TC14c	0.188	0.389	1.40	0.23	0.47	0.43	0.36	2.10E-04	1.85E+02
TB	TC14b	0.125	0.254	1.90	0.24	0.40	0.38	0.33	8.42E-05	3.87E+02
TB	TC14a	0.201	0.401	2.40	0.26	0.84	0.50	0.42	7.50E-05	6.79E+02
RL	TC13e	0.181	0.356	2.30	0.20	0.69	0.47	0.44	4.78E-05	6.13E+02
TB	TC13d	0.109	0.204	1.50	1.90	0.64	0.33	0.85	7.33E-04	2.19E+02
RL	TC13c	0.022	0.076	4.10	0.15	0.20	0.19	0.17	1.22E-05	2.47E+03
TB	TC13b	0.277	0.519	1.40	0.25	0.50	0.52	0.43	1.36E-04	1.85E+02
RL	TC13a	0.197	0.390	1.30	0.23	0.58	0.43	0.40	1.31E-04	1.55E+02

Lower Mamber, binai Khola Formation

Table 2: (Continued)

		Grain size		Palaeohydrolgical parameters							
		D_{50}	D_{95}	*Depth*	*Ucr*	*Urd*	*Upd*	*V*	*Velocity*	*Gradient*	*Discharge*
Bedding	Sample	(mm)	(mm)	(m)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)	(m/m)	(m^3/s)
Upper Member, Arung Khola Formation											
RL	TC12c	0.143	0.287	2.10	0.22	0.57	0.41	****	0.40	6.67E-05	4.92E+02
RL	TC12b	0.124	0.256	1.50	0.19	0.66	0.35	****	0.43	7.33E-05	2.19E+02
PB	TC12a	0.229	0.445	5.20	0.28	0.63	0.63	****	0.63	3.46E-05	4.37E+03
PB	TC11c	0.142	0.278	1.70	0.14	0.62	0.39	****	0.54	3.53E-05	2.96E+02
RL	TC11b	0.149	0.301	0.90	0.21	0.56	0.34	****	0.39	1.78E-04	6.38E+01
TB	TC11a	0.321	0.656	3.10	0.30	0.46	0.67	****	0.53	7.42E-04	1.26E+03
TB	TC10e	0.343	0.659	4.10	0.31	0.51	0.74	****	0.59	5.61E-05	2.47E+03
PB	TC10d	0.399	0.813	0.20	0.20	0.24	0.32	****	0.26	1.22E-04	1.70E+00
TB	TC10c	0.043	0.103	1.80	0.16	0.46	0.22	****	0.38	3.89E-05	3.39E+02
TB	TC10b	0.018	0.036	3.10	0.14	0.22	0.16	****	0.20	1.61E-05	1.26E+03
TB	TC10a	0.092	0.190	1.70	0.18	0.70	0.31	****	0.57	5.88E-05	2.96E+02
RL	TC09e	0.242	0.476	1.90	0.25	0.55	0.52	****	0.40	9.47E-05	3.87E+02
PB	TC09d	0.225	0.445	2.20	0.25	0.55	0.52	****	0.54	7.73E-05	5.50E+02
TB	TC09c	0.252	0.499	2.70	0.26	0.60	0.57	****	0.59	6.67E-05	9.02E+02
RL	TC09b	0.213	0.431	0.40	0.19	0.37	0.31	****	0.28	4.25E-04	9.04E+00
RL	TC09a	0.027	0.427	3.20	0.14	0.29	0.20	****	0.22	1.56E-05	1.36E+03
TB	TC08b	0.236	0.490	2.10	0.27	0.43	0.53	****	0.46	1.00E-04	4.92E+02
TB	TC08a	0.186	0.389	1.20	0.22	0.65	0.40	****	0.57	1.33E-04	1.28E+02
TB	TC07c	0.072	0.151	3.20	0.19	0.81	0.32	****	0.64	2.81E-05	1.36E+03
TB	TC07b	0.241	0.486	5.30	0.29	0.67	0.65	****	0.66	3.40E-05	4.58E+03
TB	TC07a	0.378	0.765	1.10	0.27	0.40	0.57	****	0.45	2.18E-04	1.04E+02
RL	TC06d	0.051	0.111	0.80	0.14	0.59	0.19	****	0.36	8.75E-05	4.81E+01
RL	TC06c	0.258	0.523	1.10	0.23	0.49	0.47	****	0.36	1.64E-04	1.04E+02
RL	TC06b	0.111	0.243	1.50	0.19	0.64	0.33	****	0.42	7.33E-05	2.19E+02
TB	TC06a	0.250	0.543	2.70	0.26	0.60	0.58	****	0.59	6.67E-05	9.02E+02
RL	TC05c	0.149	0.289	2.60	0.23	0.65	0.44	****	0.44	5.38E-05	8.23E+02
RL	TC05b	0.103	0.193	1.40	0.19	0.62	0.32	****	0.40	7.86E-05	1.85E+02
RL	TC05a	0.138	0.278	0.90	0.18	0.54	0.33	****	0.36	1.33E-04	6.38E+01
RL	TC04b	0.101	0.221	0.70	0.17	0.52	0.26	****	0.34	1.57E-04	3.48E+01
RL	TC04a	0.065	0.132	0.60	0.14	0.55	0.20	****	0.34	1.33E-05	2.40E+01
RL	TC03d	0.067	0.123	0.70	0.14	0.58	0.21	****	0.36	1.14E-04	3.48E+01
RL	TC03c	0.084	0.154	0.80	0.16	0.57	0.25	****	0.36	1.13E-05	4.81E+01
RL	TC03b	0.095	0.203	1.50	0.18	0.67	0.31	****	0.43	6.67E-05	2.19E+02
TB	TC03a	0.089	0.187	0.20	0.13	0.37	0.15	****	0.30	5.00E-04	1.70E+00
Middle Member, Arung Khola Formation											
RL	TC02e	0.117	0.256	0.30	0.14	0.39	0.21	****	0.27	3.33E-04	4.52E+00
RL	TC02d	0.169	0.321	1.40	0.18	0.59	0.41	****	0.38	7.14E-05	1.85E+02
RL	TC02c	0.238	0.456	2.90	0.20	0.56	0.57	****	0.38	3.45E-05	1.07E+03
RL	TC02b	0.099	0.211	2.10	0.19	0.70	0.34	****	0.44	4.76E-05	4.92E+02
RL	TC02a	0.339	0.609	3.20	0.30	0.70	0.70	****	0.50	7.19E-05	1.36E+03
RL	TC01b	0.153	0.298	2.30	0.20	0.91	0.43	****	0.56	4.78E-05	6.13E+02
RL	TC01a	0.130	0.254	2.60	0.25	0.29	0.41	****	0.27	6.15E-05	8.23E+02

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 (*$0.15mm>D_{95}$*).*

The estimation methods adopted in this paper needed simply grain size and flow depth.

Paleoflow depth

Thickness between the top of bedload beds and sampling horizon is used for paleoflow depth. Most of the samples were obtained from the bottom 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 accretion architecture are recognised in TC02, TC06, and TC09 (Ulak and Nakayama 2001b). The estimation method of bankfull flow depth in meandering channel is directly applied to these three localities. Other fining-upward cycles in this study have no apparent evidence of deposits of meandering channel. The bedload thickness in simple upward-fining cycle can be considered to roughly indicate the bankfull flow depth.

Ethridge and Schumm (1978) indicates the coefficient of 0.585/0.9 for converting from bedload thickness to paleoflow depth. However, the coefficient was not used because the estimation in this study applied to all fining-upwards might not have such preciseness. The decompacted thickness was not calculated because all measured thickness were of bedload sand and gravel in which the compaction should 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 paleohydrological evolution.

Paleohydrology 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 1967; Yalin 1972), k is von Karman's constant, d is the flow depth in meter, and z_0 is the roughness length in meter. Values of k and z_0 (after Allen and Homewood 1984) are 0.4 and 0.0004, and were used in this study. U_{cr} is calculated from the shear stress for threshold (U_{cr}) which are directly related to grain diameter (Fig. 7 in Miller et al. 1977). Similarly, U_{rd} and U_{up} can be obtained by 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 in equation (1). The value of *k* was as 0.4 in both equations, and values for z_o were 0.0006 and 0.001 for in equations (2) and (3), respectively.

Three velocity values were calculated for each sample, and then estimated the unique velocity value (*V*) based on these three values and bedform configurations. First, the relation between bedforms and bedding structures must be confirmed. Planar-cross bedding and trough-cross bedding are formed by accumulation of 2D dunes and 3D dunes, respectively. Second, the relation between grain size and bedform is also important. Relative 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 of which grain diameter is between these sizes. Third, the velocity range using bedform types, 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 relatively slower velocity of the range between U_{rd} (or U_{cr}) and U_{up}, while 3D dunes are formed in relative faster velocity of this range. Each equation and its applicable grain range and bedform is explained in the note of Table 2. For the determination of the velocity Fig. 4 has been used.

Paleochannel gradient for critical flow (S_c) condition was 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. d_c is critical flow depth, and was replaced by d in the present study.

Paleodischarge for sandy bedload

The simplest equation for discharge (*Q*) is:

$$Q = VA \tag{5}$$

where, *V* is mean velocity, and *A* is cross-sectional area of flow. However, since the channel width necessary for determining cross sectional area (*A*) is difficult on ancient sediments outcropped in a limited area, other method of estimating discharge is useful. Estimation of the discharge in this study was based on the depth and grain size for the sandy materials (Kellerhals, 1967).

$$Q = 70.2d_c^{\,2}.D_m^{\,0.3} \tag{6}$$

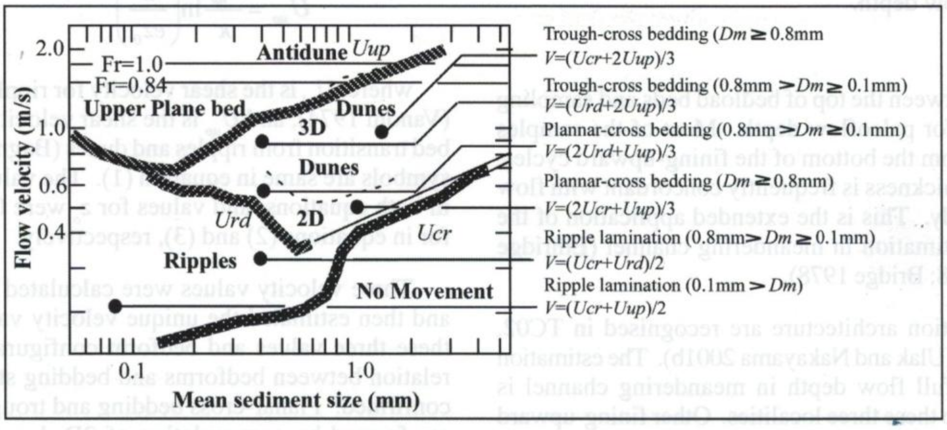


Fig. 4: Estimating equations for sandy samples on a bedform phase diagram. *Vcr*: critical flow velocity for gravels, U: depth-mean velocity for sand (*Ucr*: threshold of particle movement. *Urd*: for ripple-dune transition, *Uup*: for upper plane bed transition from ripplr or dune)

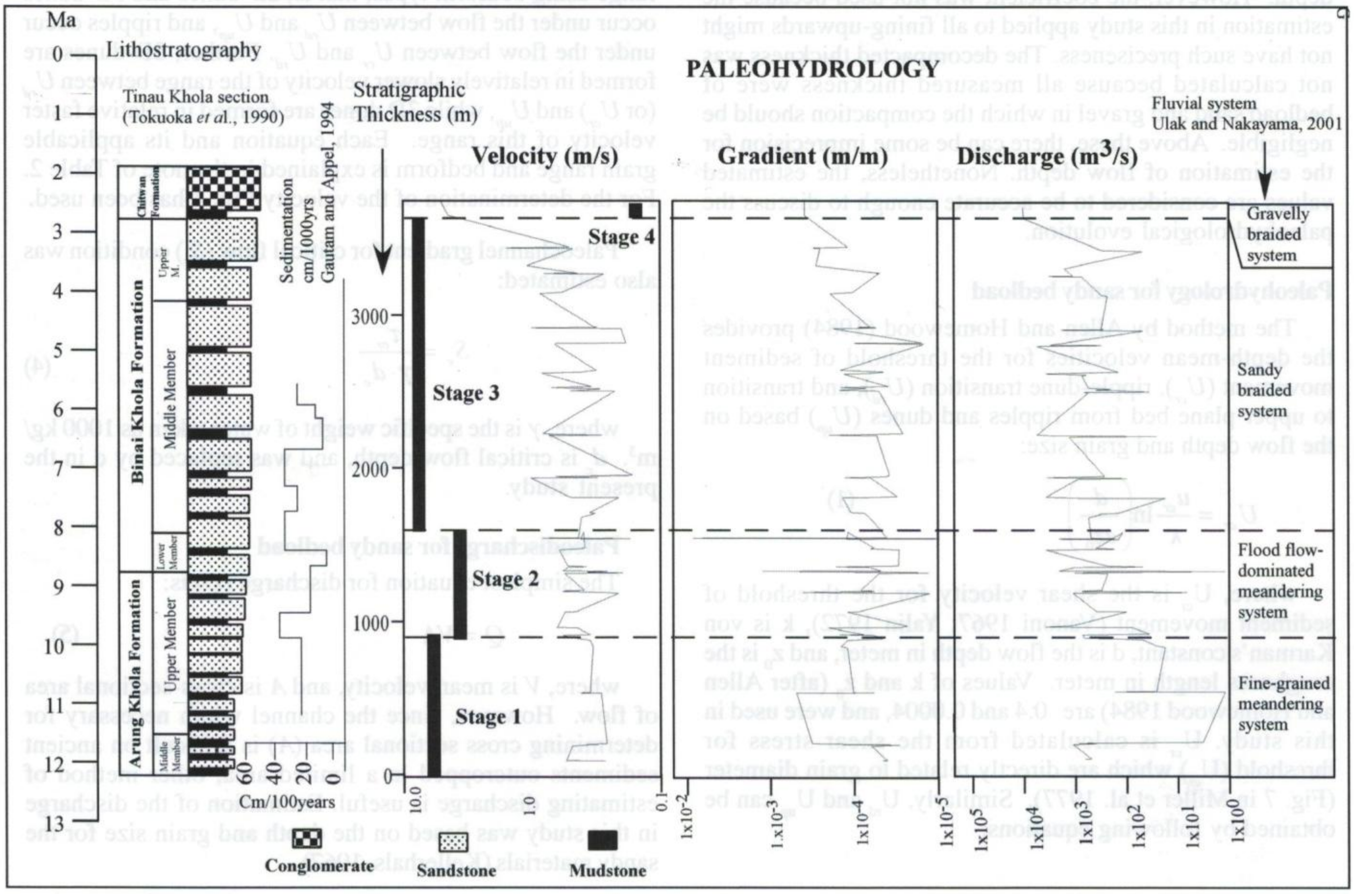


Fig. 5: Relation between sedimentation rate, paleohydrology change in fluvial system along the Tinau Khola section, west-central Nepal Himalaya

Table 3: Summary of palaeohydrological parameters of Siwalik Group from the Tinau Khola section

Stratigrahy	Grain size (mm)				Velocity (m/s)		Gradient (m/m)		Discharge (m^3/s)		Fluvial system
	(D_m)		(D_{95})		(V)		(S)		(Q)		**Ulak and Nakayama 2001**
Chitwan	0.38	13.63	0.72	27.1	0.49	5.31	1.38E-04	4.00E-04	6.38E+01	1.22E+04	Gravelly braided system
Binai Khola Formation											
Upper	0.145	0.699	0.268	1.389	0.28	0.88	5.63E-05	2.06E-04	2.96E+02	3.79E+03	Sandy braided system
Middle	0.054	0.813	0.123	1.678	0.17	1.05	1.80E-05	1.89E-04	3.48E+01	6.43E+03	
Lower	0.022	0.282	0.076	0.561	0.17	0.85	1.22E-05	7.33E-04	2.40E+01	4.37E+03	Flood flow-dominated meandering system
Arung Khola Formation											
Upper	0.051	0.399	0.103	0.765	0.20	0.66	1.13E-05	7.42E-04	1.70E+00	4.58E+03	Flood flow-dominated meandering system
Middle	0.117	0.339	0.211	0.609	0.27	0.56	3.45E-05	3.33E-04	4.52E+00	1.36E+03	Meandering system

Paleohydrology for gravelly bedload

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

$$\tau_{cr} = 0.056(\gamma_s - \gamma)D \tag{7}$$

where, γ_s is the specific weight of clast taken as 2650 kg/m³. D is the size of bed roughness element, for which D_{95} is used. Then channel gradient for critical flow condition was obtained from equations (4) and (7):

$$S_c = \frac{0.092D_{95}}{d_c} \tag{8}$$

Paleoflow velocity for critical flow condition can be calculated according to the Manning-Limerinos equation:

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

where is the critical mean flow velocity, and adopted as the unique velocity value V in Table 2.

Paleodischarge for gravelly bedload

Paleodischarge of sands and gravel deposits were calculated using the Manning-Limerinos equation (Maizels 1983) as below:

$$Q = \frac{\overline{V_c}}{S_c} \tag{10}$$

RESULTS

Using above formulas, the estimated gradient, velocity, and discharge are summarised in Fig. 5 and Tables 2 and 3. Measured slope gradients vary from 1.13x10-5 to 7.33x10-4 m/m, velocities range from 0.17 to 5.31 m/s, whereas the paleodischarge shows a ranges of 101 to 104 m^3/s. The paleovelocity ranges from 0.27 to 0.56 m/s, paleoslope gradient changes from 3.45x10-5 to 3.33x10-4 m/m, and the paleodischarge from 4.52x101 to 1.36x103 m^3/s in the Middle Member of the Arung Khola Formation. The paleohydrological parameters vary from 0.20 to 0.66 m/s (velocity), 1.13x10-5 to 7.42x10-4 m/m (slope gradient), and 1.70x101 to 4.58x103 m^3/s in the Upper Member of the Arung Khola Formation. In the Lower Member of the Binai Khola Formation, the paleovelocity ranges from 0.17 to 0.85 m/s, the paleochannel gradient and paleodischarge vary from 1.22x10-5 to 7.33x10-4 m/m, and 2.40x101 to 4.37x103 m^3/s, respectively whereas in the Middle and Upper Members of the Binai Khola Formation, the paleovelocity, paleochannel gradient, and Paleoslope change from 0.17 to 1.05 m/s, 1.80x10-5 to 2.06x10-4 m/m, and 3.48x101 to 6.48x103 m^3/s, respectively. The paleohydrological parameters in the Chitwan Formation range from 0.49 to 5.31 m/s, 1.38x10-4 to 4.00x10-4 m/m, and 6.38x101 to 1.22x104 m^3/s as the velocity, channel gradient, and discharge respectively.

Evolution of fluvial system and estimated paleohydrology

Fig. 5 indicates the evolution of paleohydrology within the stratigraphic framework. Both paleoflow velocity, paleochannel gradient, and paleodischarge are gradually increasing stratigraphically towards. The method in this study was applied within a stratigraphic range between the Arung Khola Formation and the Chitwan Formation. The sediments of the Deorali Formation were not exposed in the study section.

Blair and McPherson (1994) indicated that debris flow-dominated fan systems had steep slope gradients of more than 1.5 degrees (0.026 m/m). This slope value is much steeper than any estimated slope values in this study.

Ulak and Nakayama (2001b) summarised the evolutional pattern of the Siwaliks from the Tinau Khola area into the following four stages from bottom to top respectively: meandering system (stage 1), flood flow-dominated meandering system (stage 2), sandy braided system (stage 3), and gravelly braided system (stage 4). They also concluded that the inception of stage 1 and stage 4 was controlled by the MCT and MBT, respectively. Two dratic paleohydrological changes in this study coincide with the inception stages 3 and 4 (Table 3). That is, paleohydrological changes presumably reflect the southward progradation of thrusts. Stages 2, 3, and 4, initiated about 9.9 Ma, 8.2 Ma, and 2.5 Ma ago, respectively.

DISCUSSIONS

The estimation method in this study covers both sandy and gravelly sediments, and it is also applicable to the outcrops with limited lateral dimension. Further, the method can analyse the flow constitution using multiple samples from a fining-upwards cycle.

The estimation in this study is convenient, however, it might have had some problems in precision. Here, only two numeral factors (viz., grain size and bed load thickness) were used and they do not address other factors such as channel shape, sorting of deposition, and material in suspension. The method also suffers from the limitations due to the unavailability of the fining-upwards successions in the Middle Member of the Binai Khola Formation.

The paleohydrology of the Siwalik Group in Pakistan was studied based on channel aggradational patterns and channel dimensions described in hundred-meter wide outcrops (Willis 1993b; Zaleha 1997b; Khan et al. 1997). The estimated values must be much more precise than those obtained in this study. Present method is suitable only for deciphering the evolutional changes in the Siwalik fluvial system.

CONCLUSIONS

The paleohydrological estimations for the Siwalik Group in Nepal gradually increase paleohydrological parameter values from lower to upper Siwalik members. Paleochannel gradient varies from $1.13\text{x}10^{-5}$ to $7.33\text{x}10^{-4}$ m/m, paleovelocity ranges from 0.17 m/s to 5.31 m/s and paleodischarge changes from and 10^{1} to 10^{4} m^{3}/s. These estimations suggest that fluvial systems grew progressively larger due to southward progradation of thrust activity. The estimation method applied in this study is widely applicable, and suitable for analysing the evolutional changes of fluvial system.

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REFERENCES

Allen, J. R. L., 1965, The sedimentology and paleogeograhy of the Old Red Sandstone of Anglesey, North Wales: Yorks. Geol. Soc. Proceedings, v. 35, pp. 139–185.

Allen, P. A. and Homewood, P., 1984, Evolution and mechanics of a Miocene tidal sandwave. Sedimentology, v. 31, pp. 63–81.

Auden, J. B., 1935, Transverses in the Himalaya. Records of the Geological Survey of India v. 69, pp. 123–167.

Bagnold, R. A., 1966, An approach to the sediment transport problem from general physics. Professional Paper of US Geological Survey, v. 422-I, pp. I1–I37.

Beck, R. A., Burbank, D. W., Sercombe, W. J., Riley, G. W., Barndt, J. R., Aftal, J., Khan, A. M., Jurgen, H., Metje, Cheema, A., Shafique, N. A., Lawrence, R. D., and Khan, M.A., 1995, Stratigraphic evidence for early collision between southwest India and Asia: Nature, v. 373, pp. 55–58.

Blair, T. C. and McPherson, J. G., 1994, Alluvial fans and their natural distinction from rivers based on morphology, hydraulic processes, sedimentary processes, and facies assemblages. Journal Sedimentary Research, v. A64, pp. 450–489.

Bridge, J. S. and Gordon, E. A., 1985, Quantitative reconstructions of ancient river systems in the Oneonta Formation, Catskill Magnafacies. In The Catskill Delta, (eds D. Woodrow and W. Sevon), pp. 163–181. Special paper of the Geological Society of America no. 201.

Bridge, J. S., 1978, Paleohydraulic interpretation using mathematical models of contemporary flow and sedimentation meandering channels. In Fluvial Sedimentology, (ed A. D. Miall), pp. 723–742. Canadian Society of Petroleum Geology, Memoir no. 5.

Burbank, D. W., Beck, R. A., and Mulder, T., 1996, The Himalayan foreland basin, (eds., in Yin, A., and Harrison, M.,), The tectonic evolution of Asia: New York, Cambridge University Press, World and Regional Geology Series, pp. 149–188.

Cande, S. C. and Kent, D. V., 1995, Revised calibration of the geomagnetic polarity time scale for the Late Cretaceous and Cenozoic. Journal Geophysics Research v. 100, pp. 6093–6095.

Cotter, E., 1971, Paleoflow characteristics of a late Cretaceous River in Utah from analysis of sedimentary structures in the Ferron Sandstone. Journal of Sedimentary Petrology, v. 41, pp.129–138.

Els, B. G., 1990, Determination of some paleohydralic parameters for a fluvial Witwatersrand succession. South African Journal of Geology, v. 93, pp. 531–537.

Ethridge, F. G. and Schumm, S. H., 1978, Reconstructing paleochannel morphologic and flow characteristics: methodology, limitations and assessment. In: Fluvial

Sedimentology, (ed., A. D. Miall), pp. 703–721. Canadian Society of Petroleum Geology, Memoir no. 5.

Gansser, A., 1964, *Geology of Himalayas*. London: Interscience, 289 p.

Gautam, P., and Appel, E., 1994, Magnetic polarity stratigraphy of Siwalik Group sediments of Tinau Khola Section in west Nepal. Geophysics Jour. Int., v. 117, pp. 223–234.

Graf, W. H., 1971, *Hydraulics of Sediment Transport*. New York: McGraw-Hill, 509 pp.

Hagen, T., 1959, *Report on the Geological Survey of Nepal* (preliminary re-connaissance). Denkschr. Schweiz. naturf. Gesell., v. 86 (1), pp. 1-185.

Hisatomi, K. and Tanaka, S., 1994, Climatic and environmental changes at 9 and 7.5 Ma in the Churia (Siwalik) Group, West Central Nepal. Himalayan Geology. Wadia Institute for the Himalayan Geology, India, v. 15, pp. 161–180.

Johnson, N. M., Opdyke, N. D., Johnson, G. D., Lindsay, E. H. and Tahirkheli, R. A. K., 1982, Magnetic polarity stratigraphy and ages of Siwalik Group rocks of the Potwar, Pakistan. Paleogeography, Paleoclimatology and Paleoecology, v. 37, pp. 17–42.

Kellerhals, R., 1967, Stable channels with gravel-paved beds. Jour. Waterways Harbors Division, American Society Civil Engineers, v. 93, pp. 63–84.

Khan, I. A., Bridge, J. S., Kappelman, J. and Wilson, R., 1997, Evolution of Miocene fluvial environments, eastern Potwar Plateau, northern Pakistan. Sedimentology, v. 44, pp. 221–251.

Leeder, M. R., 1973, Fluvial fining upwards cycles and the magnitude of paleochannels. Geological Magazine, v. 110, pp. 489-502.

Maizels, J. K., 1983, Paleovelocity and paleodischarge determination for coarse gravel deposits. In Background to Paleohydrology (ed., K. J. Gregory), pp. 103–139. John Wiley, New York. Masuda, F. and Nakayama, N., 1988. Calculation of paleotidal current velocity. Journal of Sedimentological Society of Japan, v. 29, pp. 1-8 (in Japanese with English abstract).

Meddlicott, H. B., 1875, Note on the geology of Nepal. Records of the Geological Survey of India, v. 8, pp. 93–101.

Miall, A. D., 1996, *The Geology of Fluvial Deposits.* Springer-Verlag Berlin 582p.

Miller, W. J., Mccave, I. N. and Komar, P. D., 1977, Threshold of sediment motion under unidirectional currents. Sedimentology, v. 34, pp. 507–527.

Nakayama, K. and Ulak, P. D., 1999, Evolution of fluvial style in the Siwalik Group in the foothills of the Nepal Himalaya. Sedimentary Geology, v. 125, pp. 205–224.

Nakayama, K., 1997, Unidirectional to bidirectional subtidal sandwaves influenced by gradually decreasing steady flow velocity. Geological Magazine, v. 134, pp. 557–661.

Nakayama, K., 1999, Sand and mud-dominated alluvial fan deposits of the Miocene Seto Porcelain clay Formation, Japan. In Fluvial Sedimentology VI (eds., N. D. Smith and J. Roger), pp. 393–407. International Association of Sedimentology, Special Publication 28.

Opdyke, N. D., Johnson, G. D., Lindsay, E. H. and Tarhikheli, R. A. K., 1982, Paleomagnetism of the Middle Siwalik formations of northern Pakistan and rotation of the Salt Range Decollement. Paleogeography Paleoclimatology and Paleoecology, v. 37, pp. 1–15.

Parkash, B., Sharma, R. P. and Roy, A. K., 1980, The Siwalik Group (molasse) sediments shed by collision of continental plates. Sedimentary Geology, v. 25, pp. 127–159.

Shields, A., 1936, Anwendung der Ahnlichkeitsmechanik und der Turbulenzforschung auf die Geschiebebewegung: Mitteilungen der Preuss. Berlin: Versuchanst Wasserbau Schiffbau, 26 p.

Steer, L. B. and Abbott, P. L., 1984, Paleohydrology of the Eocene Ballena Gravels, San Diego County, California. Sedimentary Geology, v. 38, pp. 181–216.

Tokuoka, T., Takayasu, K., Hisatomi, K., Yamasaki, H., Tanaka, S., Konomatsu, M., Sah R. B., and Roy, S. M., 1990, Stratigraphy and Geologic Structures of the Churia (Siwalik) Group in the Tinau Khola-Binai Khola area, west central Nepal. Memoirs Faculty of Science, Shimane University, Japan, v. 24, pp. 71–88.

Tokuoka, T., Takayasu, K., Yoshida, M., and Hisatomi, K., 1986, The Churia (Siwalik) Group of the Arung Khola area, West Central Nepal. Memories Faculty of Science, Shimane University, Japan, v. 22, pp. 135–210.

Tokuoka, T., Takeda, S., Yoshida, M., and Upreti, B. N., 1988, The Churia (Siwalik) Group in the western part of the Arung Khola area, west central Nepal. Memories Faculty Science, Shimane University, Japan, v. 22, pp. 131–140.

Ulak P. D., 2002, Paleohydrology of the Siwalik Group along the Bakiya Khola section, central Nepal Himalaya. Jour. Nepal Geol. Soc., v. 26, pp. 49–58.

Ulak, P. D. and Nakayama, K., 1998, Lithostratigraphy and evolution of the fluvial system in the Siwalik Group, Surai Khola, central Nepal. Bull. Depart. Geol., Tribhuvan Univ., v. 6, pp. 1–14.

Ulak, P. D., 2001, Paleohydrolgy of the Siwalik Group, Surai Khola area along Kalakate-Bhalubang section, West Nepal. Bull. Department of Geology, v. 8, pp. 49–60.

Ulak, P. D., 2005, Paleohydrology of the Siwalik Group along the Surai Khola west Nepal. Jour. Nepal Geol. Soc., v. 31, pp. 33–42.

Ulak, P. D. and Nakayama, K., 2001a, Paleohydrological Reconstruction of the Siwalik Group, Surai Khola area along the Kalakate-Bhalubang sections, west Nepal. Geological Report, Shimane University, Japan. v. 20, pp. 41–48.

Ulak, P. D., and Nakayama, K., 2001b, Neogene fluvial system of the Siwalik Group along the Tinau Khola section, west-central Nepal. Jour. Nepal Geol. Soc., v. 25, pp. 111–122.

Ulak, P. D., and Nakayama, K., 2003, Paleohydrology of the Neogene Siwalik Group along Bakiya Khola area, central Nepal. Himalayan Geology, Wadia Institute of Himalayan Geology, India. v. 24 (1), pp. 23–34.

Vanoni, V. A., 1974, Factors determining bedforms in alluvial channels. Proceedings of American Society of Civil Engineers, v. 100, pp. 363–377.

Williams, G. P., 1984, Paleohydrology equations for rivers. In Development and applications of geomorphology (eds., J. E. Costa and P. J. Fleisher), . Springer-Verlag, Berlin, pp. 343–367.

Willis, B., 1993a, Ancient river systems in the Himalayan foredeep, Chinji village area, northern Pakistan. Sedimentary Geology, v. 88, pp. 1-76.

Willis, B., 1993b, Evolution of Miocene fluvial systems in the Himalayan foredeep through a two kilometer-thick succession in northern Pakistan. Sedimentary Geology, v. 88, pp. 77–121.

Yalin, M. S., 1972, *Mechanics of Sediment Transport*. New York: Pergamon Press, 290 p.

Zaleha, M. J., 1997a, Fluvial and lacustrine paleoenvironments of the Miocene Siwalik Group, northern Pakistan. Sedimentology, v. 44, pp. 349–368.

Zaleha, M. J., 1997b, Intra- and extrabasinal controls on fluvial deposition in the Miocene Indo-Gangetic foreland basin, northern Pakistan. Sedimentology, v. 44, pp. 369–390.