島根大学地球資源環境学研究報告　20, 41～48 ページ（2001 年 12 月）
Geoscience Rept. Shimane Univ., 20, p.41～48（2001）

Article

Paleohydrological Reconstruction of the Siwalik Group, Surai Khola area along the Kalakati and Bhalubang Sections, West Nepal

Prakash Das Ulak[1] and Katsuhiro Nakayama[2]

Abstract

Paleohydrological reconstructions (channel bed slopes, flow velocity, and bankfull discharge) have been made of the Bankas Formation and the Jungli Khola and Shivgarhi members of the Chor Khola Formation of the Siwalik Group, west Nepal. The succession examined is a stratigraphic thickness of about 1500 m exposed between Kalakati and Bhalubang section. Estimates of channel bed slope, flow velocity, and bankfull discharge have been made based on grain size and bedload thickness. Grain size was determined by conventional petrologic thin section point–counting or by settling tube methodology. Bedload thickness was measured in autogenic fining–upward fluvial successions. During the middle Miocene to lower Pliocene epochs, the paleoslope gradient ranged from 7.06×10^{-4} to 8.28×10^{-4} m/m in the Bankas Formation, from 5.84×10^{-4} to 7.71×10^{-4} m/m in the Jungli Khola Member (Chor Khola Formation), and from 6.32×10^{-4} to 8.71×10^{-4} m/m in the Shivgarhi Member (Chor Khola Formation). Paleovelocities in these three units are estimated to be 0.46 to 0.56 m/s, 0.50 to 0.61 m/s and 0.53 to 0.66 m/s, respectively. Paleodischarge estimates are 0.44×10^{0} to 1.43×10^{3}, 1.12×10^{2} to 3.06×10^{3}, and 1.45×10^{2} to $4.89\times10^{3}\mathrm{m}^{3}/\mathrm{s}$, respectively. Progressive increase in these paleohydrological parameters suggests that uplift of the Himalaya took place during the Neogene.

Introduction

Paleohydrological reconstruction from ancient fluvial deposits is important for quantifying hydraulic environments, and facilitates comparison with modern fluvial systems. Hydrological reconstructions of ancient deposits have been made using flume experiments, coupled with observations of modern depositional systems and their physical parameters. Estimates of parameters such as channel bed slope, flow velocity, and bankfull discharge can now be made on the basis of measurable variables, including grain size and bedload thickness. Bedload thickness measured in outcrop is regarded as the channel paleodepth (flow depth), and grain size can readily be measured by a number of conventional techniques.

The Siwalik Group of Nepal was deposited in a foreland basin south of the Himalaya. Between the middle Miocene to lower Pleistocene, a thickness of about 4 to 6 km of Siwalik sediments were deposited by fluvial systems developed during Himalayan uplift. Stratigraphy of the Siwalik succession in Nepal was established by Auden (1935), Tokuoka *et al*. (1986), Corvinus and Nanda (1994), Sah *et al*. (1994), Dhital *et al*. (1995), Ulak and Nakayama (1998) and others, based on lithological characteristics and grain size. Sedimentological studies in the area show the sediments were deposited from successive meandering and braided systems resulting from upheaval of the Himalaya (Hisatomi and Tanaka, 1994; DeCelles *et al.*, 1998; Ulak and Nakayama, 1998; and Nakayama and Ulak, 1999). Sedimentation was thus strongly influenced by Himalayan uplift and tectonics, and by climatic change through the development of monsoon climate.

Many detailed sedimentological studies have been made of the Siwalik Group in the Potwar basin of Pakistan (e.g. Willis, 1993a, 1993b; Khan *et al.*, 1997; Zaleha, 1997a, 1997b). These studies include paleohydrological estimates, which show that the magnitude of variables such as flow velocity and bankfull discharge gradually increase stratigraphically upward. However, compared to the Potwar Basin, paleohydrological studies of the Siwalik succession in Nepal are few. Ulak and Nakayama (1999) gave the first paleohydrological estimates from Nepal in a study of a small outcrop area in central Nepal.

Paleohydrological studies of the Siwalik Group are essential for reconstruction of the hydraulic environment and thus examination of the relationship between upheaval of the Himalaya and climatic change. As another step in filling the gap in our knowledge of paleohydrological conditions in the Nepal Siwalik succession, we here focus on the paleohydrology of the Siwalik Group in the Surai Khola area the Kalakati–Bhalubang section, west Nepal.

Geological Setting

The Siwalik Group of the Surai Khola area is lithologically divided into the Bankas, Chor Khola, Surai Khola, Dobata, and Dhan Khola formations, from bottom to top (Dhital *et al.*, 1995). The Chor Khola Formation is subdivided into the Jungli Khola and Shivgarhi members, in ascending order (Fig. 1). The Rangsing Khola Thrust (RT) and Siling Khola Thrust (ST) separate the Siwalik Group in

---

[1] Department of Geology, Tri–Chandra Campus, Tribhuvan University, Kathmandu, Nepal

[2] Department of Geoscience, Shimane University, Matsue 690–8504, Japan

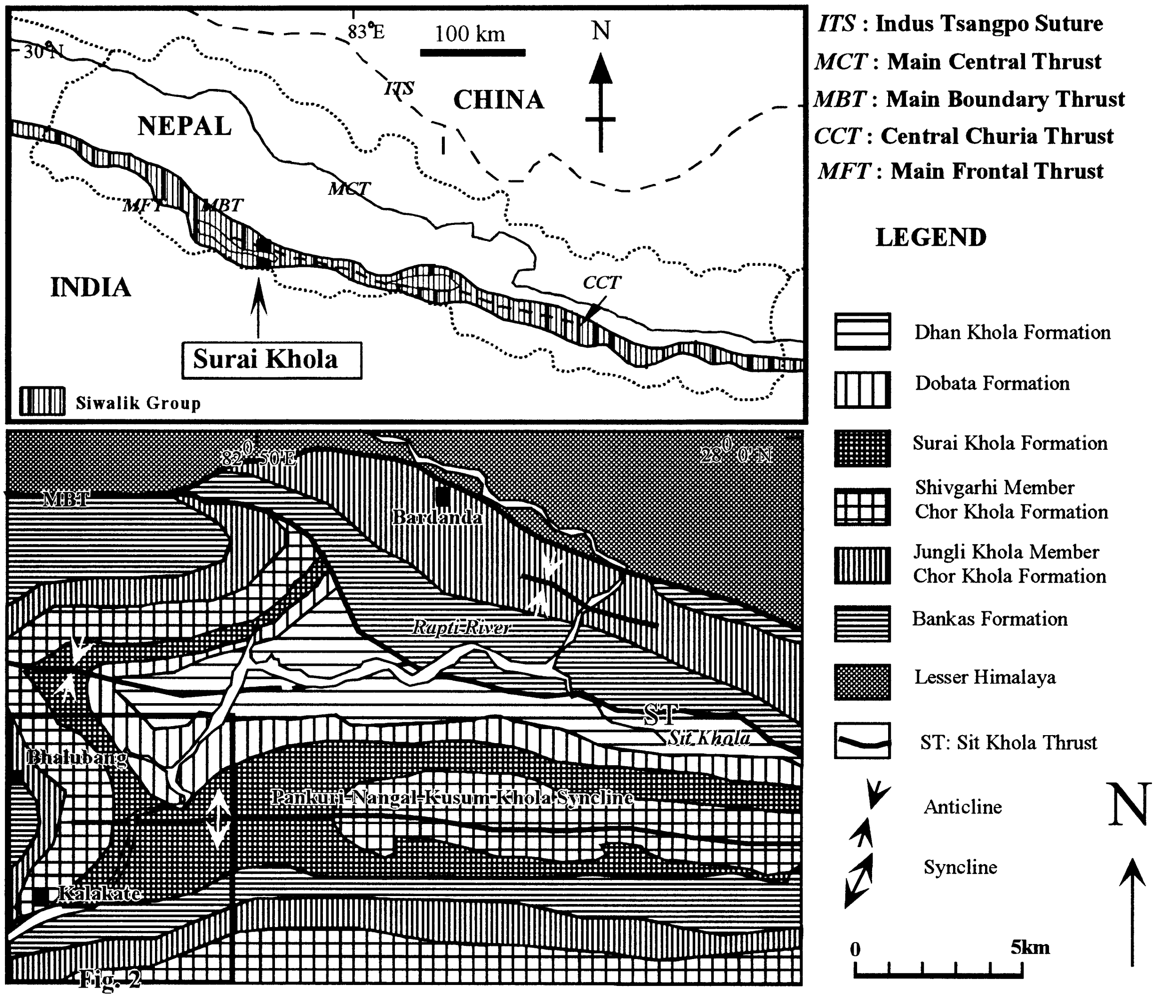

Fig. 1: Geological map of the Surai Khola area, western Nepal (after Dhital *et al*., 1995).

the Surai Khola area into three belts.

The Bankas Formation is about 680 m thick in the studied section but the thickness is about 585 m in its type locality. It is identified by dominance of bioturbated and variegated mudstone beds over fine-grained, greenish-grey to brownish grey sandstone beds. The ratio of mudstone to sandstone is about 55:45. The Jungli Khola Member (about 550 m thick) of the Chor Khola Formation is characterized by fine-to medium-grained, light grey sandstone, and variegated mudstone. Sandstone to mudstone ratio is about 55:45. The Shivgarhi Member (Chor Khola Formation) is about 275 m thick in this area, and is typified by alternating beds of medium- to coarse-grained, light grey, "pepper & salt" sandstone and variegated mudstone, in the ratio 62:38. The Surai Khola Formation consists of thick-bedded, coarse-grained to pebbly sandstone with "pepper & salt" appearance, and associated dark grey mudstone. The proportions of sandstone, mudstone and conglomerate are 71:21:8. The Dobata Formation is characterized by presence of thick-bedded, dark grey fossiliferous mudstone, sandstone and conglomerate, with respective ratios of 63:23:14. The largely conglomeratic Dhan Khola Formation is composed of well-sorted, moderately indurated pebble-to cobble-sized gravel beds in its lower part, and poorly sorted beds with boulder-sized Siwalik-derived sandstone clasts in the upper part. Conglomerate, sandstone and mudstone proportions are about 70:27:3, respectively.

The Siwalik sediments are well exposed between the Rangsing Khola Thrust (RT) in the south and the Siling Khola Thrust (ST) in the north. Paleomagnetic polarity shows that deposition in the Surai Khola area took place between 13 Ma and 1 Ma (Appel *et al.*, 1991 and Rösler *et al.*, 1997). Among the five formations of the Surai Khola area, only the Bankas and Chor Khola Formations are well exposed in the Kalakati–Bhalubang section.

Sedimentology

The evolution of the fluvial system of the Siwalik Group of the Surai Khola area based on facies association was studied by Nakayama and Ulak (1999). Brief lithofacies definitions are given in Table 1. The Bankas Formation and

Table 1. Facies associations of the Siwalik Group (after Nakayama and Ulak, 1999).

Facies association	Dominant lithofacies types*	Characteristic architectural element**	Stratigraphic Units Dhital et al. 1995	Interpretation
FA1	P, Fr, Fm, Fl, Fsm	FF, SB, LA > LS	Bankas F. Jungli Khola M. (Chor Khola F.)	Fine-grained meandering system (with pigment paleosols)
FA2	Fl, Fr, P, Sr, Fm, Fsm	FF, SB, LA, > DA, LS	Shivgarhi M. (Chor Khola F.)	Food flow-dominated fine-grained meandering system

*Classification from Miall(1977, 1996). ** CH recognised in all facies associations. Classification from Miall (1985, 1996).

the Jungli Khola Member of the Chor Khola Formation are interpreted as the products of fine-grained meandering systems. This assessment is based on the predominance of bioturbated, variegated and thick-bedded mudstone beds, by the presence of pigmented paleosols and calcareous nodules, and by the abundance of trace fossils in fine-grained sandstone beds. Occurrence of crevasse splay deposits is identified by the rippled and sheet-like geometry of sandstone interbedded within mudstone beds. Lateral accreted fine-to medium-grained, cross-stratified sandstones within mudstone beds represent the bedload of meandering channels. Similarly, the Shivgarhi Member of the Chor Khola Formation was deposited by a flood flow-dominated fine-grained meandering system. Coarse-grained sandstones with lateral accretion architecture reflect the bedload of the meandering channels, whereas accumulations of multiple thin-bedded muddy sandstone beds formed by successive flood flow. Climbing ripples within beds reflect gradual change in flood flow velocity. Vertical lithological variability and flat depositional surfaces are susceptible to small changes in depositional processes. However, deposition may have taken place during flood events.

Paleohydrological Studies

Methodology

Grain size

Samples for grain size were generally collected from lowermost parts of autogenic fining upward successions. Over-sized clasts in the lowermost parts of these successions were interpreted as channel lags. Such horizons and thin (less than 1.5 m) sandstone beds in the fining-upward successions were not sampled. Sampling locations are shown in Fig. 2.

Lithified sediments were examined in thin section using an optical microscope. Apparent long axes of grains of more than 200 grains were measured in each thin section. The mean of the measured axes is taken as the mean diameter (D_m) for the sample (Clastic Sediment Research Group, 1983). This method was applied to almost all samples from the Bankas Formation and the Jungli Khola Member of the Chor Khola Formation, which are basically calcareous mudstone and sandstone.

Settling tube analysis was used for friable and medium- to coarse-grained sandy sediments. Mean diameter (D_m) was calculated using a computer program developed by Tamura & Nakayama (1993). The program uses Gibbs' formula (Gibbs *et al.*,1971) and moment methods (Friedman & Johnson, 1982). This technique was mainly used for samples from the Shivgarhi Member of the Chor Khola Formation.

For apparently similar samples, calculated D_m values

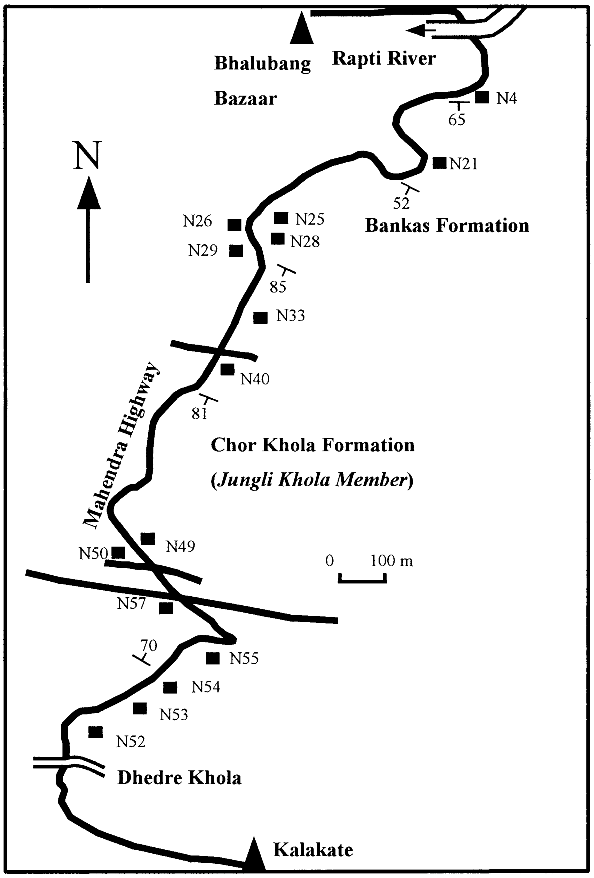

Fig. 2: Route map along the Kalakati-Bhalubang section and sampling locations.

Table 2. Decompacted thicknesses of lithological units in the Siwalik Group, Surai Khola area. Star (*) indicates exposed in the study section.

Formal stratigraphic units	Measured thickness (m)	Decompacted thickness (m)	Expansion ratio (Ep)
Dhan Khola Formation	1,100	****	1.000
Dobata Formation	750	770	1.029
Surai Khola Formation			
upper part	480	500	1.047
middle part	470	500	1.057
lower part	360	380	1.055
Chor Khola Formation*			
Shivgarhi Member	820	860	1.055
Jungli Khola Member	410	440	1.068
Bankas Formation*	590	630	1.072

derived by the two methods differed by 12 – 15%. Consequently, five pilot samples of friable sandy sediments analysis previously measured by settling tube were artificially cemented so that thin sections could be made and point–counted. The thin section D_m values were consistently greater than D_m values derived by settling tube, but all fell within 10%. Because the D_m values measured using settling tube methodology are inherently more reliable, all D_m values derived from thin sections were consequently reduced by 10% to compensate for methodological bias.

Decompaction

Measured bedload thickness (T_m) was used to estimate channel paleodepth. However, many of the samples examined are indurated, and have thus been compacted. Present bed thicknesses are therefore not equivalent to bed thickness at time of deposition. Consequently, decompacted thickness (T_d) must be calculated if paleohydrologic estimates are to be accurate.

Decompaction was calculated from the southern belt, where the complete section is well exposed. The method used was that of Allen & Allen (1990). Decompacted thickness was calculated for each formal stratigraphic unit using the equation:

$$y'_2 - y'_1 = (y_2 - y_1)\left\{ \left(\frac{\phi_0}{c}\right)^{-cy_1} - \left(\frac{\phi_0}{c}\right)^{-cy_2} \right\} + \left\{ 1 - \left(\frac{\phi_0}{c}\right)^{-cy_2} \right\} \quad (1)$$

where, y_2 and y_1 are the lower and upper depths of the present layer, y'_2 and y'_1 are the equivalents for the decompacted layer, (ϕ_0 and c represent surface porosity, porosity–depth coefficient (km^{-1}),and decompacted values when y'_1=0.

The expansion ratio (E_p) for each stratigraphic unit is given by:

$$E_p = \frac{y'_2 - y'_1}{y_2 - y_1} \quad (2)$$

The decompacted thickness (T_d) of each fining upward succession is then calculated:

$$T_d = E_P \cdot T_m \quad (3)$$

Decompaction rates (expansion rates) of the individual lithological units of the Siwalik Group in the Surai Khola area (Table 2) range between 1.086 and 1.000, using equations 1, 2 and 3.

Paleoslope

The range of paleoslope of the channels at each sampling horizon was estimated. All estimates were based on sandstones with trough–and planar–cross stratification or (lower) plane stratification which may have formed dunes under subcritical flow (Froude number; $Fr<1$). The value of Se is calculated using the equation of DuBoys (1879) and Costa (1983).

$$Se = \frac{0.163?\,(10^3 D)^{1.213}}{\gamma g d} \quad (4)$$

where, γ is the water density (1,000 kg/m^3), g is acceleration due to gravity (9.8 m/s^2), d is the flow depth in meters, and D is the grain diameter in meters. For the Bankas and Chor Khola Formations of the Siwalik Group, which are basically composed of shaley sandstone to sandstone, D_m was used in the equation for D.

Sc is estimated as the slope gradient that attains critical flow at a Froude number (Fr) of 1. Maximum slope gradient Sc can be estimated using the following equation modified from Blair & McPherson (1994):

$$S_c = \frac{n^2 g}{\sqrt[3]{T_d}} \quad (5)$$

where, g and T_d are the same as in equation (5), and n is the Manning roughness coefficient. Manning roughness varies depending on the bottom materials. The value of n is determined based on grain diameter using the Strickler method (Bray, 1979).

$$n = 0.041?\sqrt[6]{D_m} \quad (6)$$

Unique individual values of paleoslope gradient (S) were estimated using an equation modified from Els (1990), which is appropriate for sandy fluvial systems:

$$S = \frac{\tau}{\gamma g T_d} \quad (7)$$

in which g, and T_d are as in equations (6) and (7). τ is the shear stress in N/m^2, which can be obtained from the diagram of Miller *et al*. (1977).

Paleovelocity

Several equations are available for calculation of paleovelocity. Firstly, we estimated paleovelocity mainly from paleoslope and grain diameter, using the equation of Els (1990).

$$S_c = \frac{\sqrt[3]{T_d^2} \cdot \sqrt{S}}{n} \quad (8)$$

where V is the mean velocity of flow. Other symbols are as defined above.

Secondly, we estimated paleovelocity range using the methodology of Allen and Homewood (1984) and Nakayama (1997). This method provides the velocities for the threshold of sediment movement (V_{cr}), ripple–dune transition (V_{rd}), and dune–plane bed transition (V_{dp}) based on the flow depth and grain size.

$$V_{cr} = \frac{u_{cr}}{\kappa} \ln\left(\frac{h}{e z_0}\right) \tag{9}$$

where, ucr is the shear velocity for the threshold of sediment movement (Vanoni, 1964; Yalin, 1972), κ is von Karman's constant, h is the flow depth in meter, and z_0 is the roughness length in metres. We adopted values of 0.4 and 0.0004 for κ and z_0, following Allen and Homewood (1984), and used T_d for h. V_{rd} and V_{dp} are obtained by the following equations:

$$V_{rd} = \frac{u_{rd}}{\kappa} \ln\left(\frac{h}{e z_0}\right) \tag{10}$$

$$V_{dp} = \frac{u_{dp}}{\kappa} \ln\left(\frac{h}{e z_0}\right) \tag{11}$$

where u_{rd} is the shear velocity for ripple–dune transition (Vanoni, 1974), and u_{dp} is the shear velocity for dune–(upper) plane bed transition (Bagnold, 1966). Other symbols are as in equation (9). We used a value of 0.4 for κ in both equations, and 0.0006 and 0.001 for z_0 in equations (10) and (11), respectively.

Paleodischarge

The simplest equation for discharge (Q) is:

$$Q = VA \tag{12}$$

where, V is mean velocity and A is the cross–sectional area of flow. However, since the channel width value required for determining A cannot be measured in these outcrops, other methods of estimating discharge are useful. We estimated discharge as a function of depth.

$$Q_1 = 70.2\, T_d^{2.5} D_m^{0.3} \tag{13}$$

$$Q_2 = 82.3\, T_d^{2.41} \tag{14}$$

Equation (13) is modified from Kellerhals (1967), and equation (14) is based on Parker (1979).

Results

Mean grain diameters (D_m) in the study area show considerable overlap, but in general increase gradually stratigraphically upward. Measured grain size ranges from 1.91×10^{-4}m to 3.98×10^{-4}m in the Bankas Formation, varies between 1.88×10^{-4}m and 4.39×10^{-4}m in the Jungli Khola Member of the Chor Khola Formation, and reaches 2.72×10^{-4}m to 6.18×10^{-4}m in the Shivgarhi Member. For estimation of the paleoslope (using equations 4, 5 and 7), minimum slope values (Se) range from 7.46×10^{-7} to 1.55×10^{-6}, 1.92×10^{-7} to 6.06×10^{-7} and 2.75×10^{-7} to 9.44×10^{-7}m/m, respectively. Similarly, maximum slope (Sc) ranges vary from 5.90×10^{-6} to 8.71×10^{-6}, 3.43×10^{-6} to 6.34×10^{-6}, and 3.81×10^{-6} to 8.66×10^{-6}m/m, in sequence. Paleoslope values (S) range from 7.06×10^{-4} to 8.28×10^{-4}m/m. 5.84×10^{-4} to 7.71×10^{-4}m/m and 6.32×10^{-4} to 8.71×10^{-4}m/m, respectively. Using equation 8 for paleovelocity estimation also yields progressive increase upward, from a range of 0.46 to 0.56 (Bankas Formation), to 0.50 to 0.61 (Jungli Khola Member of the Chor Khola Formation), to 0.53 to 0.66 m/s (Shivgarhi Member of the Chor Khola Formation). Similarly, from equations 9, 10 and 11, the threshold of sediment movement (V_{cr}) increases upward from 0.25 to 0.37 m/s, ripple–dune transition (V_{rd}) increases from 0.48 to 0.74 m/s, and dune–plane bed transition (V_{dp}) increases from 0.48 to 0.84 m/s. Paleodischarge (Q) was estimated from equations 13 and 14. The estimates range from 0.44×10^{0} to 1.43×10^{3}m^3/s 1.61×10^{2} to 3.06×10^{3}m^3/s and 1.45×10^{2} to 4.89×10^{3}m^3/s in the Bankas Formation, Jungli Khola and Shivgarhi members of the Chor Khola Formation, respectively (Fig. 3, Tables 3 and 4).

Discussion and Conclusions

Paleohydrological estimates from the Siwalik Group in the Kalakati–Bhalubang section in the Surai Khola area show upward increments in paleoslope, paleovelocity and paleodischarge. Our paleohydrological reconstruction shows that paleoslope (S) values vary from 5.84×10^{-4} to 8.71×10^{-4} m/m, paleovelocity (V) ranges from 0.46 to 0.66 m/s, and paleodischarge (Q) gradually increases from 0.44×10^{0} to 4.89×10^{3}m^3/s, from the Bankas Formation to the Chor Khola Formation.

The paleohydrological values derived from our study area in the Siwalik Group in Nepal are comparable with those reported from the Siwalik Group in the Potwar basin of Pakistan. Estimated paleoslope (S) in the Chinji Formation (Lower Siwalik) and the upper part of the Nagri Formation (Middle Siwalik) in the Potwar Basin ranges from 6.40×10^{-5} to 8.00×10^{-5}m/m, whereas paleovelocity (V)varies between 0.53 and 0.76 m/s, and paleodischarge (Q) from 1.70×10^{2} to 3.60×10^{3}m^3/s (Willis, 1993b). Zaleha (1997b) gave paleoslope (S), paleovelocity (V) paleodischarge (Q) estimates of 2.80×10^{-5} to 5.5×10^{-5} m/m, 0.48 to 0.65 m/s, and 7.20×10^{2} to $\times$ 6.91×10^{3}m^3/s, respectively. Other estimates of paleoslope (S), paleovelocity (V) and paleodischarge (Q) from that area are 4.70×10^{-5}m/m, 0.61 m/s and 9.67×10^{2} m^3/s, respectively (Khan *et al*., 1997).

Paleohydrological estimates of the paleoslope gradient (S), paleovelocity (V), and paleodischarge (Q) for the Amlekhganj Formation (Middle Siwalik) in central Nepal are 1.21×10^{-5} to 1.88×10^{-5}m/m, 0.47 to 0.78 m/s, 3.16×10^{-5} to 1.41×10^{-5}m^3/s, respectively (Ulak & Nakayama, 1999). These values are greater than those determined for the Lower Siwalik Group in the present study area, suggesting progressive increase towards stratigraphic top.

The relationship between paleohydrology, rate of sedimentation and characteristic fluvial style of the Siwalik Group in the Surai Khola area is illustrated in Fig. 4. The style of the fluvial system from fine–grained meandering to flood–flow dominated after deposition of the Shivgarhi Member of the Chor Khola Formation (Nakayama & Ulak, 1999). Similarly, the rate of sedimentation increases after deposition of the Shivgarhi Member (Appel *et al.*, 1991).

Table 3. Paleohydrological estimates from the Kalakati– Bhalubang section, Surai Khola, west Nepal.

Sample	Grain	Water	Decomp.	Paleoslope			Paleovelocity				Paleodischarge	
				Minimum	Maximum			Sediment movement	ripple-dune	dune-plane bed		
Number	size	depth	thickness	*Se*	*Sc*	*S*	*V*	*Vcr*	*Vrd*	*Vdpb*	Q_1	Q_2
	(m)	(m)	(m)	(m/m)	(m/m)	(m/m)	(m/s)	(m/s)	(m/s)	(m/s)	(m^3/s)	(m3/s)
Shivgarhi Member, Chor Khola Formation												
N52	$2.72x10^{-4}$	3.40	3.63	$9.44x10^{-7}$	$5.40x10^{-6}$	$7.05x10^{-4}$	0.53	0.28	0.57	0.63	$1.50x10^{2}$	$1.84x10^{3}$
N53	$6.18x10^{-4}$	4.10	4.38	$3.60x10^{-7}$	$8.66x10^{-6}$	$8.70x10^{-4}$	0.66	0.37	0.43	0.81	$3.07x10^{2}$	$2.89x10^{3}$
N54	$4.00x10^{-4}$	3.20	3.42	$4.13x10^{-7}$	$7.72x10^{-6}$	$8.19x10^{-4}$	0.57	0.32	0.43	0.76	$1.45x10^{2}$	$159x10^{3}$
N55	$3.32x10^{-4}$	3.50	3.74	$8.96x10^{-7}$	$6.10x10^{-6}$	$7.46x10^{-4}$	0.55	0.29	0.50	0.70	$1.72x10^{2}$	$1.98x10^{3}$
N57	$2.93x10^{-4}$	5.10	5.45	$2.75x10^{-7}$	$3.80x10^{-6}$	$6.32x10^{-4}$	0.57	0.31	0.55	0.71	$4.23x10^{2}$	$4.89x10^{3}$
Jungli Khola Member, Chor Khola Formation												
N50	$2.19x10^{-4}$	3.10	3.31	$1.92x10^{-7}$	$5.08x10^{-6}$	$6.76x10^{-4}$	0.50	0.26	0.58	0.56	$1.12x10^{2}$	$1.47x10^{3}$
N49	$4.39x10^{-4}$	4.20	4.49	$6.06x10^{-7}$	$6.34x10^{-6}$	$7.71x10^{-4}$	0.61	0.33	0.50	0.84	$2.94x10^{2}$	3.06x103
N40	$1.88x10^{-4}$	4.20	4.43	$4.94x10^{-7}$	$3.43x10^{-6}$	$5.84x10^{-4}$	0.51	0.27	0.74	0.55	$2.21x10^{2}$	2.97x103
Bankas Foramation												
N33	$3.98x10^{-4}$	3.10	3.27	$7.46x10^{-7}$	$8.04x10^{-6}$	$8.28x10^{-4}$	0.56	0.31	0.50	0.75	$1.30x10^{2}$	$1.43x10^{3}$
N29	$2.66x10^{-4}$	3.10	3.27	$1.02x10^{-6}$	$5.90x10^{-6}$	$7.24x10^{-4}$	0.51	0.27	0.57	0.61	$1.15x10^{2}$	$1.43x10^{3}$
N28	$2.03x10^{-4}$	2.30	2.43	$9.91x10^{-7}$	$6.58x10^{-6}$	$7.31x10^{-4}$	0.46	0.26	0.61	0.50	$5.00x10^{1}$	$6.97x10^{2}$
N26	$2.27x10^{-4}$	2.50	2.64	$1.04x10^{-6}$	$6.54x10^{-6}$	$7.38x10^{-4}$	0.48	0.27	0.56	0.54	$6.40x10^{1}$	$8.52x10^{2}$
N25	$2.83x10^{-4}$	2.20	2.32	$1.55x10^{-6}$	$8.71x10^{-6}$	$8.28x10^{-4}$	0.49	0.27	0.48	0.59	$5.00x10^{1}$	$6.26x10^{2}$
N21	$1.91x10^{-4}$	2.20	2.32	$9.62x10^{-7}$	$6.61x10^{-6}$	$7.27x10^{-4}$	0.46	0.26	0.66	0.48	$4.40x10^{1}$	$6.26x10^{2}$
N4	$1.94x10^{-4}$	2.40	2.57	$8.84x10^{-7}$	$6.02x10^{-6}$	$7.06x10^{-4}$	0.47	0.25	0.63	0.49	$0.57x10^{0}$	$8.02x10^{2}$

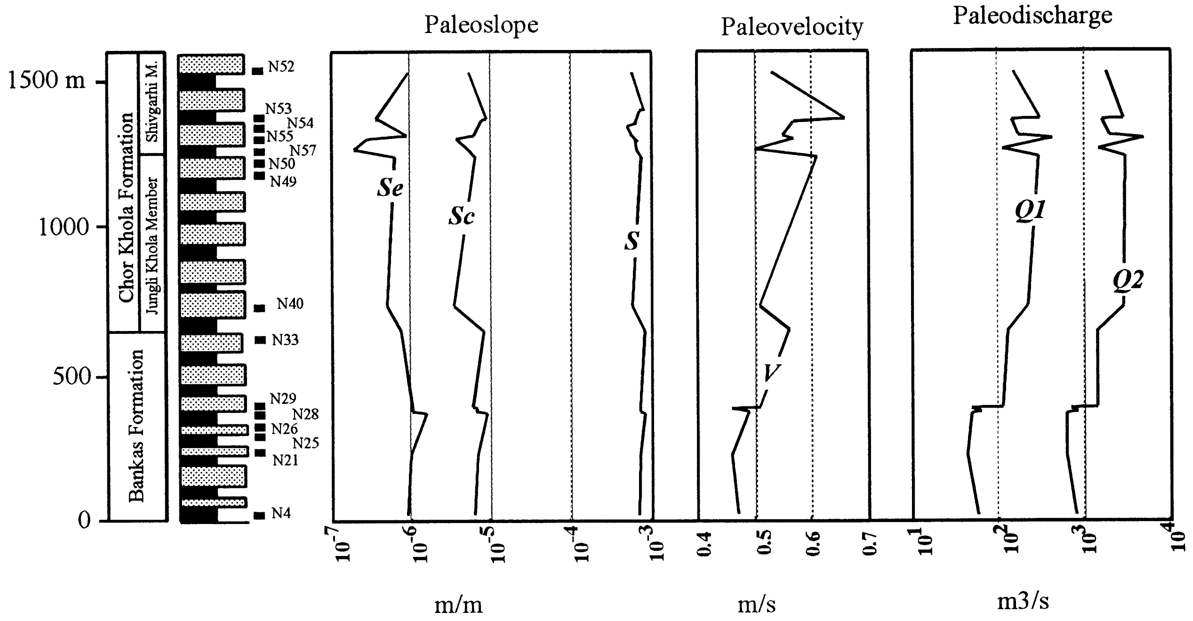

Fig. 3: Paleohydrological estimation of the Siwalik Group along the Kalakati–Bhalubang section, Surai Khola area, west Nepal.

Our results also show a change in paleohydrological values after deposition of the Shivgarhi Member, with increasing values after 9.5 Ma (Fig. 4). The change in fluvial style, increasing sedimentation rates and paleohydrological values, and changes in sediment provenance are likely to be caused by the intensification of the Asian monsoon. However, progressive incrementation of paleohydrological values in the study area may also reflect regional tectonism as well as monsoon precipitation.

Acknowledgements

We thank Dr. B. P. Roser (Shimane University, Japan) for critically going through the first draft of the manuscript,

Table 4. Summary of paleohydrological estimates from the Kalakati– Bhalubang section, Surai Khola, west Nepal.

	Bankas Formation	Chor Khola F. Jungli Khola M.	Chor Khola F. Shivgarhi M.
Grain size *(D_m)* (m)	**$3.98\text{x}10^{-4}$** to **$1.91\text{x}10^{-4}$**	**$4.39\text{x}10^{-4}$** to **$1.88\text{x}10^{-4}$**	**$2.72\text{x}10^{-4}$** to **$6.18\text{x}10^{-4}$**
Gradient *(S)* (m/m)	**$7.06\text{x}10^{-4}$** to **$8.28\text{x}10^{-4}$**	**$5.84\text{x}10^{-4}$** to **$7.71\text{x}10^{-4}$**	**$6.32\text{x}10^{-4}$** to **$8.71\text{x}10^{-4}$**
Velocity *(V) m/s*	**0.46 to 0.56**	**0.50 to 0.61**	**0.53 to 0.66**
V_{cr}	**0.25 to 0.31**	**0.27 to 0.33**	**0.28 to 0.37**
V_{rd}	**0.48 to 0.66**	**0.50 to 0.74**	**0.43 to 0.57**
V_{dpb}	**0.48 to 0.75**	**0.55 to 0.84**	**0.63 to 0.81**
Discharge *(Q)* (m^3/s)	**$0.44\text{x}10^{0}$** to **$1.43\text{x}10^{3}$**	**$1.61\text{x}10^{1}$** to **$3.06\text{x}10^{3}$**	**$0.44\text{x}10^{1}$** to **$4.89\text{x}10^{3}$**

which helped to improve this paper significantly. This study was partly supported by a Japanese Ministry of Education (JME) grant–in aid (10045027, 11691112; KN) and by a JME graduate course scholarship to PDU. Prof. K. Takayasu (Shimane University), Prof. M. P. Sharma, Prof. B. N. Upreti, Drs. M. R. Dhital and V. Dangol (Tribhuvan University) are thanked for their valuable suggestions during the preparation of this manuscript.

References

Allen, P. A. and Allen, J. R. 1990. *Basin Analysis: Principles and Applications*. Blackwell, London, 451 p.

Allen, P. A. and Homewood, P. 1984. Evolution and mechanics of a Miocene tidal sandwave. *Sedimentology*, **31**, 63-81.

Appel, E., Rosler, W. and Corvinus, G. 1991. Magnetostratigraphy of the Miocene–Pleistocene Surai Khola Siwaliks in west Nepal. Geophys. *Jour. International*, **105**, 191-198.

Auden, J. B. 1935. Traverses in the Himalaya. *Rec. Geol. Surv. India*, **69 (2)**, 123-167.

Bagnold, R. A. 1966. An approach to the sediment transport problem from general physics. *US Geol. Surv. Prof. Paper* 422-I.

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. *Jour. Sed. Res.*, **A 64 (3)**, 450-489.

Bray, D. I. 1979. Estimating average velocity in gravel bed rivers. *Jour. Hydraul. Div., Amer. Soc. Civ. Eng.*, **106**, 1443-1456.

Cande, S. C. and Kent, D. V. 1995. Revised calibration of the geomagnetic polarity time scale for the Late Cretaceous and Cenozoic. *Jour. Geophys. Res.*, **100**, 6093-6095.

Clastic Sediment Research Group, 1983. *Techniques on sediments*. Association for Geological Collaboration. Japan, Tokyo, 377 p.

Corvinus, G. and Nanda, A. C. 1994. Stratigraphy and paleontology of the Siwalik Group of the Surai Khola and Rato Khola in Nepal. *N. Jb. Geol. Palaönt. Abh.*, **191**, Stuttgart, Marz, 25-68.

Costa, J. E. 1983. Paleohydraulic reconstruction of flash–flood peaks from boulder deposits in the Colorado front range. *Geol. Soc. Amer. Bull.*, **94**, 986-1004.

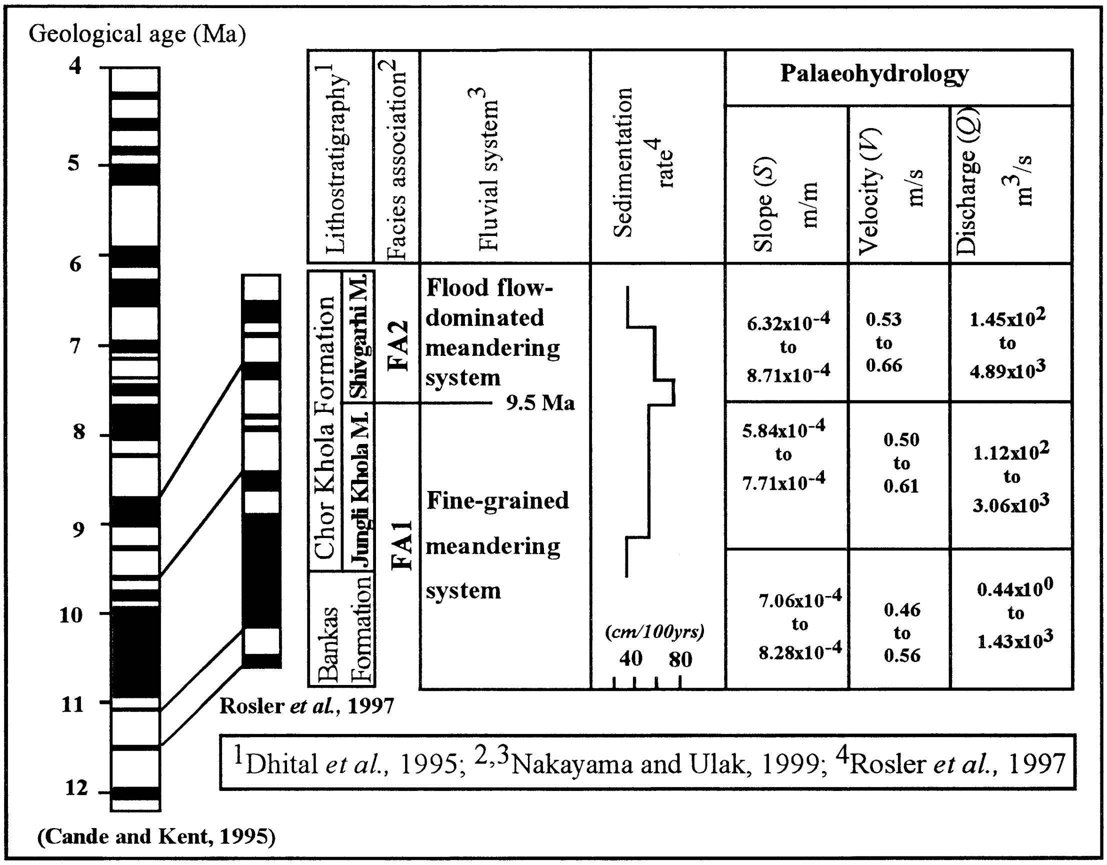

Fig. 4: Comparison of paleohydrological estimates with the change in fluvial style and sedimentation rate.

DeCelles, P. G., Gehrels, G. E., Quade, J., Kapp, P. A. and Upreti B. N. 1998. Provenance and sedimentology of Miocene foreland basin deposits, western Nepal: Implication for Himalayan Geodynamics and erosional unroofing. *Geol. Soc. Amer. Bull*., **110 (1)**, 2-21.

Dhital, M. R., Gajurel, A. P., Pathak, D., Paudel, L. P. and Kizaki, K. 1995. Geology and structure of the Siwaliks and Lesser Himalaya in the Surai Khola–Bardanda area, mid–western Nepal. *Bull. Dept. Geol., Tribhuvan Univ*., **4**, Special issue, 1-70.

DuBoys, M. P. 1879. Etudes du regime et l'action exercee par les eaux sur un lit a fond de graviers indefiniment affoiable. *Annals de ponts et chaussees*, **18**, 141-195.

Els, B. G. 1990. Determination of some paleohydralic parameters for a fluvial Witwatersrand succession. *South. Afr. Jour. Geol*., **93**, 531-537.

Friedman, G. M. and Johnson, K. G. 1982. *Exercises in sedimentology*. John Wiley & Sons, New York, 208 p.

Gibbs, R. J., Matthews, M. D. and Link, D. A. 1971. The relationship between sphere size and settling velocity. *Jour. Sed. Pet*., **41**, 7-18.

Hisatomi, K. and Tanaka, S. 1994. Climatic and environmental changes at 9 and 7.5 Ma in the Churia (Siwalik) Group, West Central Nepal. *Him. Geol*., **15**, 161-180.

Kellerhals, R. 1967. Stable channels with gravel–paved beds. *Jour. Waterways Harbors Div., Amer. Soc. Civ. Eng*., **93**, 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*, **44 (2)**, 349-368.

Miall, A. D. 1978. Lithofacies types and vertical profile models in braided river: A summary. In: Fluvial Sedimentology (ed.) A. D. Miall, *Mem. Can. Soc. Petrol. Geol., Calgary*, **5**, 597-904.

Miall, A. D. 1985. Architectural–element analysis: a new method of facies analysis applied to fluvial deposits. *Earth Sci. Rev*., **22**, 261-308.

Miall, A. D. 1996. *The Geology of Fluvial Deposits, Sedimentary Facies, Basin Analysis and Petroleum Geology*. Springer–Verlag., 1-582.

Miller, W. J., McCave, I. N. and Komar, P. D. 1977. Threshold of sediment motion under unidirectional currents. *Sedimentology*, **34**, 507-527.

Nakayama, K. 1997. Unidirectional to bidirectional subtidal sandwaves influenced by gradually decreasing steady flow velocity. *Geol. Mag*., **134**, 557-561.

Nakayama, K. and Ulak, P. D. 1999. Evolution of the fluvial styles in the foothills of Siwalik in Nepal Himalaya. *Sed. Geol*., **125**, 205-224.

Parker, G. 1979. Hydraulic geometry of active gravel rivers. *Jour. Hydraul. Div., Amer. Soc. Civ. Eng*., **105**, 1185-1201.

Rosler, W., Metzer, W. and Appel, E. 1997. Neogene magnetic polarity stratigraphy of some fluviatile Siwalik sections, Nepal. *Geophys. Jour. Int*., **130**, 211-216.

Sah, R. B., Ulak, P. D., Gajurel, A. P. and Rimal, L. N. 1994. Lithostratigraphy of Siwalik sediments of Amlekhganj–Hetauda area, Sub–Himalaya, central Nepal. *Him. Geol*., **15**, 37-48.

Tamura, Y. and Nakayama, K. 1993. Guide for a grain size analyzer with a settling tube system, and characteristics of its analysis. *Geol. Rep. Shimane Univ*., **12**, 17-22 (in Japanese with English abstract)

Tokuoka, T., Takayasu, K., Yoshida, M. and Hisatomi, K. 1986. The Churia (Siwalik)Group of the Arung Khola area, west central Nepal. *Mem. Fac. Sci. Shimane Univ*., **22**,. 135-210

Ulak, P. D. and Nakayama, K. 1998. Lithostratigraphy and the evolution of the fluvial style of the Siwalik Group in the Hetauda–Bakiya Khola area, Central Nepal. *Bull. Dept. Geology, Tribhuvan Univ., Nepal*,. **6**, 1-14.

Ulak, P. D. and Nakayama, K. 1999. Paleohydrological characteristics of the Amlekhganj Formation in central Nepal, Sub Himalaya. *Jour. Geol. Soc. Nepal*, **19**, 9-18

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

Willis, B. 1993 a. Ancient river systems in the Himalayan foredeep, Chinji village area, northern Pakistan. *Sed. Geol*., **88**, 1-76.

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

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

Zaleha, M. J. 1997 a. Fluvial and lacustrine paleoenvironments of the Miocene Siwalik Group Khur area, northern Pakistan. *Sedimentology*, **44**, 349-390.

Zaleha, M. J. 1997 b. Intra– and extrabasinal controls on fluvial deposition in the Miocene Indo–Gangetic foreland basin, northern Pakistan. *Sedimentology*, **44 (2)**, 369-390.

(Recieved: 10 Dec. 2001, Accepted: 17 Dec. 2001)

（要旨）

P. D. Ulak・中山勝博，2001，ネパール西部カラカチ・バルバンセクション沿いスライコラ地域に分布するシワリク層群の古水理の復元，島根大学地球資源環境学研究報告，20，41-48

ネパール西部のシワリク層群バンカス層・ジュンリコラ層・シブガリ部層について，チャネルベット傾斜・流速・堆積物充填量などを基に古水理に関する復元を行った。検討したサクセッションはカラカチ，バルバンセクション間で，層厚約1500 mに達する。堆積物の粒径と厚さから，チャネルベット傾斜，流速および堆積物充填量を推定した。粒径は，従来法の岩石薄片ポイントカウンター法と沈降管法によって測定した。ベッドロードの厚さは，河川堆積物遷移層の上方細粒化相を用いて測定された。中期中新世から後期鮮新世における古斜面の傾斜は，バンカス層中で7.06×10^{-4} m/mから8.28×10^{-4}m/m，ジュンリコラ部層（チョーコラ層中）で5.84×10^{-4}m/mから7.71×10^{-4}m/mおよびシブガリ部層（チョーコラ層中）で6.32×10^{-4}m/mから8.71×10^{-4}m/mまで変化した。これら3層準中の古流速は，それぞれ0.46-0.56 m/s，0.50-0.61 m/sおよび0.53-0.66 m/sと推定され，堆積物供給量は，それぞれ0.44×10^{0}-1.43×10^{3}，1.12×10^{2}-3.06×10^{3}および1.45×10^{2}-$4.89\times10^{3}$$m^{3}$/sと推定された。これらの古水理的パラメーターが累進的に増加していることは，新第三紀のヒマラヤ上昇を示している。