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Palaeohydrological Characteristics of the Amlekhganj Formation in Central Nepal Sub Himalaya

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ABSTRACT

The palaeohydrological studies of the Middle Member of the Amlekhganj Formation, Nepal Sub Himalaya, are based on the grain size and flow depth for values of the palaeoslope gradient, palaeovelocity, and palaeodischarge. The grain size distribution was measured by using the laser diffraction particle size analyser (SALD 3000S; Shimazu), and the flow depth was estimated from the autogenic fining upward succession. The measured values of the palaeoslope gradient, palaeovelocity, and palaeodischarge were 1.21-1.88x10^{-6} m/m, 0.67-0.78 m/s, and 10^3-10^5m^3/s, respectively. The palaeoslope is comparable to the slopes of such modern Himalayan frontal fans as the Kosi Fan.

INTRODUCTION

Palaeohydrological reconstruction of ancient fluvial deposits is important for quantifying the past hydraulic environments and comparing them with modern ones. For this purpose, the results of flume experiments were used together with the study of physical parameters of modern depositional systems. The bed slope, flow velocity, and bankfull discharge were estimated on the basis of grain size and bedload thickness. In this study, the bedload thickness measured in the outcrop was regarded as the channel palaeodepth (and flow depth), as the sediments were unconsolidated and not much compacted. Therefore, the decompacted thickness was not calculated.

The study area (Fig. 1) lies in the Siwalik Group of Central Nepal. The Group is a 6 km thick succession of middle Miocene to lower Pleistocene fluvial sediments. The Group is widely distributed in the foreland basin on the southern part of the Himalaya. The sediments were strongly influenced by Himalayan uplift tectonics and climatic change through the development of a monsoon climate.

The palaeohydrological estimation and detailed sedimentological studies of the Siwalik Group in the Potwar basin was carried out by Willis (1993a, 1993b), Khan et al. (1997), and Zaleha (1997a, 1997b). However, there are no palaeohydrological studies in the Siwalik Group of Nepal. The stratigraphy of the Siwaliks in Nepal was worked out by Auden (1935), Sharma (1977), Tokuoka et al. (1986), Sah et al. (1994), Dhital et al. (1995), Ulak and Nakayama (1998), and others. The magnetostratigraphic work by Harrison et al. (1993) in the Bakiya Khola section, which is about 10 km east of the study area, implies that the succession in this area ranges from 11 Ma to about 1.0 Ma in age. The stratigraphy of the Siwalik Group was established in the Potwar basin of Pakistan on the basis of lithology and palaeomagnetism (Johnson et al. 1982, Opdyke et al. 1982). Hisatomi and Tanaka (1994), Tanaka (1997), and Nakayama and Ulak (1999) studied the group in Nepal from the viewpoint of the evolution of fluvial styles.

This paper focuses on the estimation of palaeohydrology of the Siwalik Group in Nepal. The methods used in estimating the Pakistan Siwaliks by Willis (1993a, 1993b), Khan et al. (1997), and Zaleha (1997a, 1997b) are not applicable to the Nepal Siwaliks because of the outcrop limitations. Consequently, several methods applicable to the small-scale (less than 100 m in lateral length) outcrops are used.

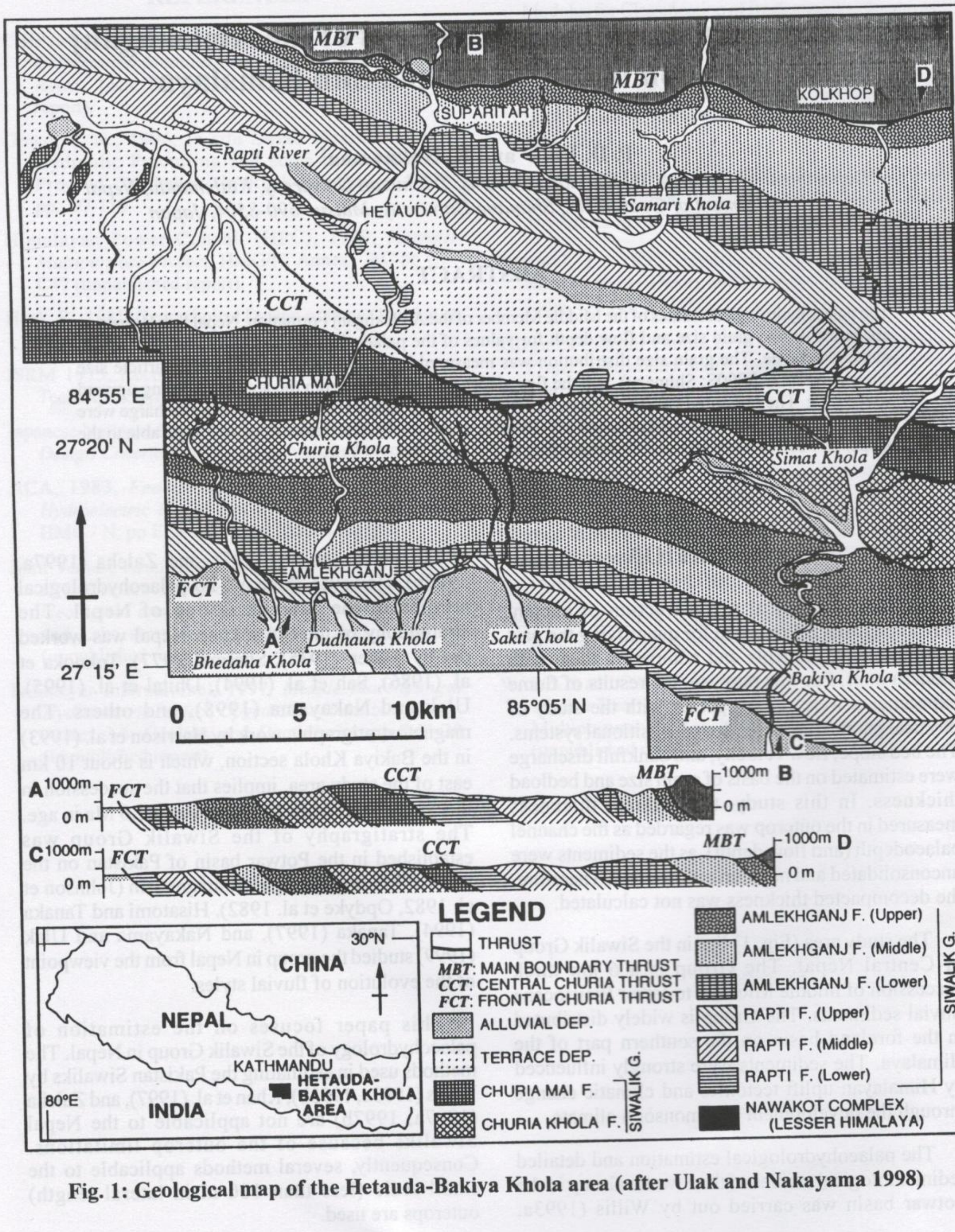

Fig. 1: Geological map of the Hetauda-Bakiya Khola area (after Ulak and Nakayama 1998)

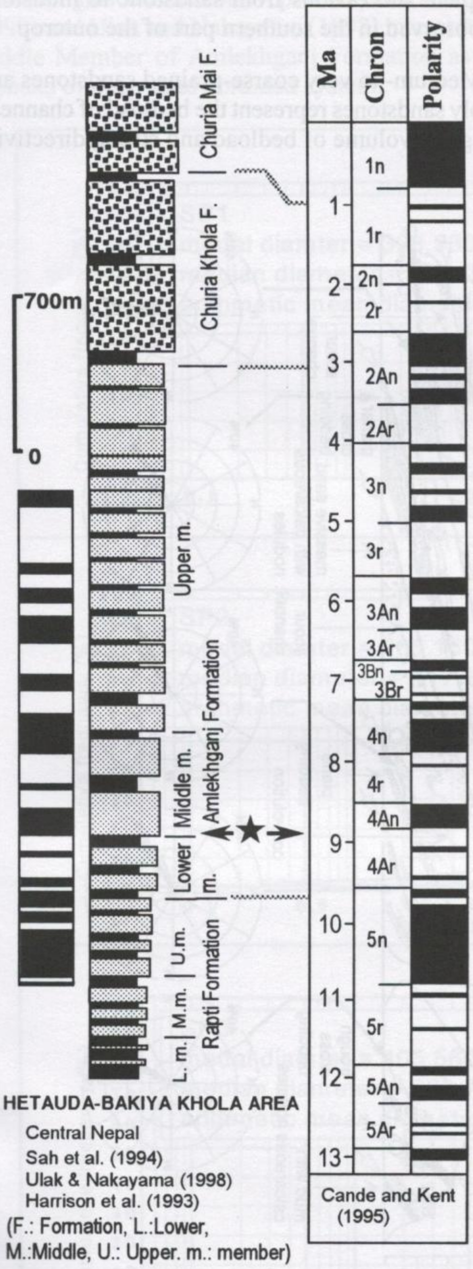

Fig. 2: Lithology and magnetostratigraphy of the Siwalik Group in the Hetauda-Bakiya Khola section, Central Nepal. Star mark denotes the stratigraphic position of the outcrop studied.

LOCALITY AND STRATIGRAPHIC POSITION

In Nepal, the Siwalik Group is well exposed in several river (Khola in Nepali language) sections. Generally, the grain size of the group gradually increases stratigraphycally upward (Fig. 1 and 2).

The lithostratigraphy in the Hetauda-Bakiya Khola area was established by Sah et al. (1994), and Ulak and Nakayama (1998). The Group is 5650 m thick, and comprises the Rapti, Amlekhganj, Churia Khola, and Churia Mai Formations, respectively in an ascending order. The Rapti Formation is more than 1,100 m thick in the type section. It is composed of very fine- to medium-grained, greenish grey sandstones and bioturbated, variegated mudstones. Sandstones and mudstones are present in roughly equal or mudstone-dominated proportions. The Amlekhganj Formation is 3,050 m thick and is characterised by thick-bedded, medium- to very coarse-grained, "salt and pepper" sandstones, the appearance of which is due to significant contents of quartz and biotite grains. The Churia Khola Formation is 1,100 m thick. It comprises well sorted, clast-supported cobble- to pebble-sized conglomerates. The Churia Mai Formation is more than 500 m in thickness and consists of poorly sorted boulder-sized conglomerates with subordinate dark mudstones. Most of the sandstone boulders are from the lower part of the Siwalik Group.

The focus horizon discussed here lies in the Chure Khola section, which is located between Hetauda and the Bakiya Khola in Central Nepal (Fig. 1 and 2). It is a riverside cliff along the Chure Khola lying at 27°18'45"N and 84°59'58"E. Stratigraphycally, it is at the horizon of the lowermost of the Middle Member of the Amlekhganj Formation (ca. 9 Ma).

OUTCROP DESCRIPTION AND SEDIMENTOLOGY

The rocks in this outcrop (the Middle Member of Amlekhganj Formation) strike N65°E and dip due north. They are represented mainly by medium- to very coarse-grained, trough cross-stratified sandstone beds, with associated plane-stratified and planar cross-stratified sandstone beds. Interbedded pebbly sandstones and grey mudstones also occur. The outcrop is of exceptionally large size in the Hetauda-

Bakiya Khola area, however, accretional architectures are not observed within the outcrop. The outcrop is composed of more than 10 storeys of autogenetic fluvial succession, which displays the upward fining in grain size and/or upward decreasing in bedform size. The bases of these successions are delineated by an erosion surface (Fig. 3). These successions range from 10 to 23 m in thickness. Two complete successions from sandstone to mudstone are observed in the southern part of the outcrop.

Medium- to very coarse-grained sandstones and pebbly sandstones represent the bedload of channels. The great volume of bedload and strong directivity

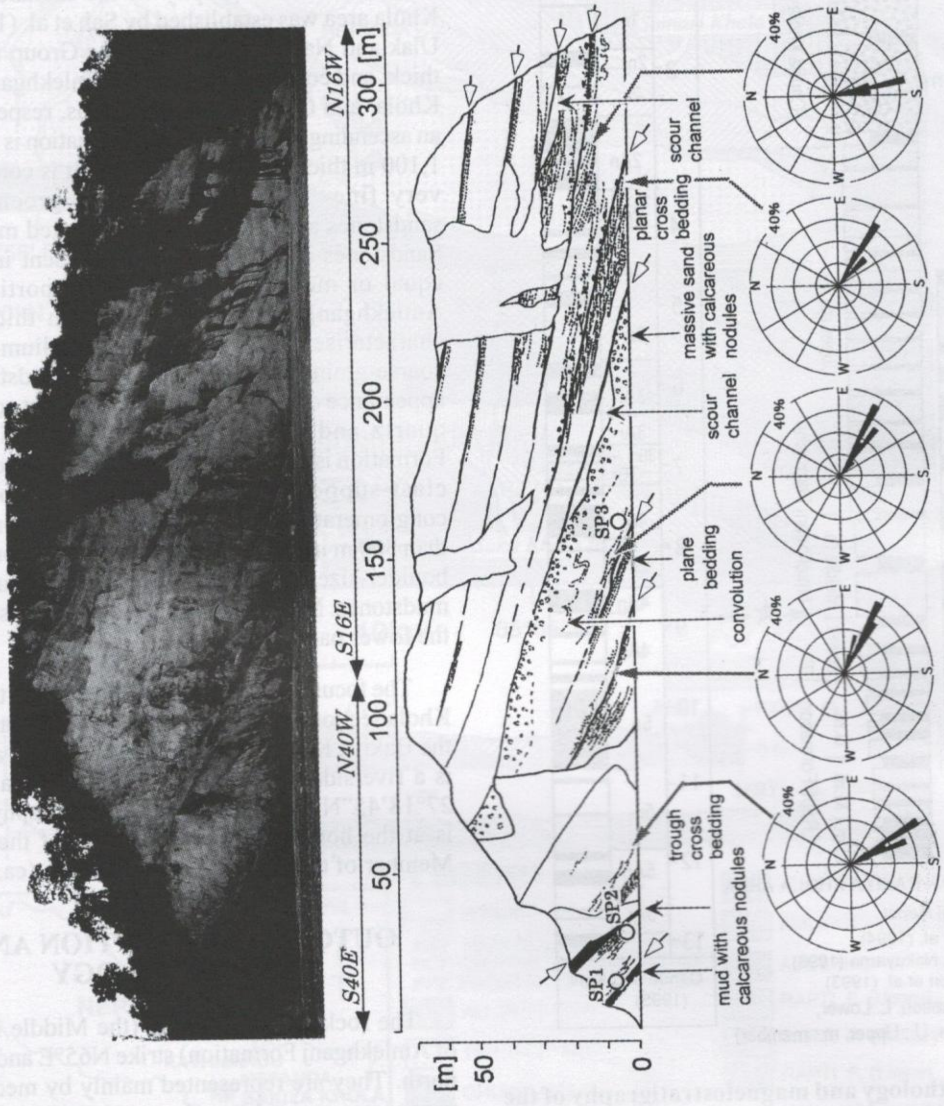

Fig. 3: Photograph and sketch of the studied outcrop. SP1 to SP3 are the sampling positions for grain analysis. Open arrows indicate the boundaries of autogenetic fluvial succession, which displays the upward fining grain size, and/or upward decreasing bedform size. Rose diagrams suggest the palaeocurrent directions based on cross bedding.

of flow are indicative braided systems. Channel shape is not recognised in this outcrop. Nakayama and Ulak (1999) and Ulak and Nakayama (1998) interpret the Middle Member of Amlekhganj Formation as the deposits of deep sandy braided system.

PALAEOHYDROLOGICAL BACKGROUND

Samples for grain analysis were obtained from two autogenetic fluvial successions (Figs. 2 and 4).

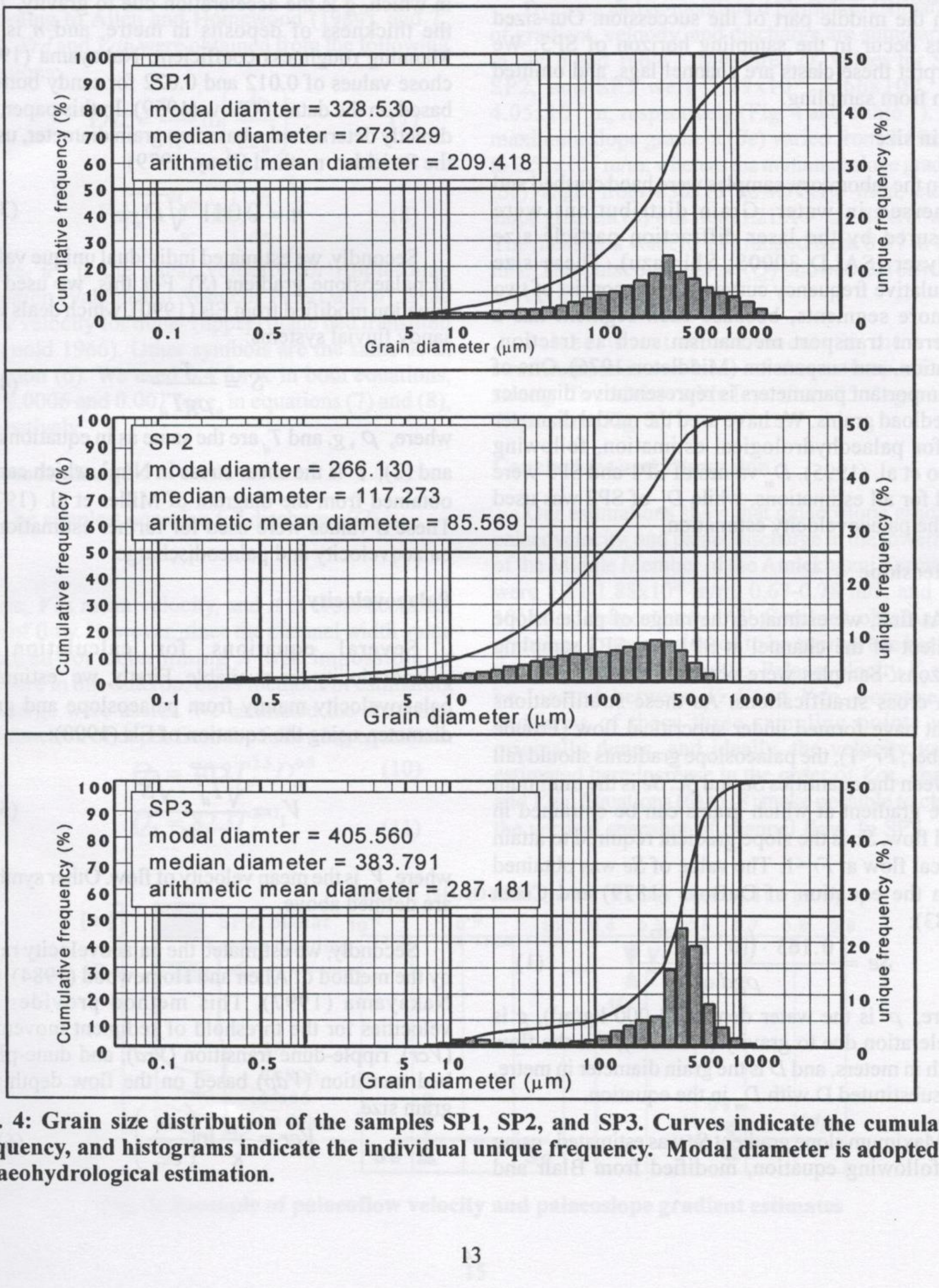

Fig. 4: Grain size distribution of the samples SP1, SP2, and SP3. Curves indicate the cumulative frequency, and histograms indicate the individual unique frequency. Modal diameter is adopted for palaeohydrological estimation.

The samples SP1 and SP2 were collected from one complete succession, which consists of sandstone and mudstone while SP3 was collected from the thickest succession with 23 m thick (Fig. 3). The samples SP1 and SP3 were collected from the bases of fluvial autogenetic fining upward successions, and SP2 was from the middle part of the succession. Out-sized clasts occur in the sampling horizon of SP3. We interpret these clasts are channel lags, and omitted them from sampling.

Grain size

In the laboratory, samples were hand crushed and immersed in water. Grain distributions were measured by the laser diffraction particle size analyser (SALD 3000S; Shimazu). These size cumulative frequency curves (Fig. 4) consist of two or more segments, because each segment has a different transport mechanism such as traction, saltation, and suspension (Middleton 1976). One of the important parameters is representative diameter of bedload grains. We have used the modal diameter D_m for palaeohydrological estimation, following Kubo et al. (1995). D_m values of SP1 and SP3 were used for all estimations, while D_m of SP2 was used for the palaeovelocity estimation.

Palaeoslope

At first, we estimated the range of palaeoslope gradient of the channel at SP1 and SP3 sampling horizons. Samples were obtained from sandstones with cross stratifications. As these stratifications might have formed under subcritical flow (Froude number; $Fr<1$), the palaeoslope gradients should fall between the quantities *Se* and *Sc*. *Se* is the minimum slope gradient at which grains can be entrained in fluid flow. *Sc* is the slope gradient required to attain critical flow at $Fr=1$. The value of *Se* was obtained from the equation of DuBoys (1879) and Costa (1983):

$$Se = \frac{0.163 \cdot \left(10^{3} D\right)^{1.213}}{\rho g d} \qquad (1)$$

where, ρ 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 metre. We substituted D with D_m in the equation.

Maximum slope gradient *Sc* was estimated, using the following equation, modified from Blair and McPherson (1994), and Nakayama (1999):

$$Sc = \frac{n^2 g}{\sqrt[3]{T_d}} \qquad (2)$$

in which, g is the acceleration due to gravity, T_d is the thickness of deposits in metre, and n is the Manning roughness coefficient. Nakayama (1999) chose values of 0.012 and 0.022 for sandy bottom, based on the data of Chow (1959). In this paper, we directly determined n based on grain diameter, using the Strickler method (Bray, 1979):

$$n = 0.041 \cdot \sqrt[6]{D_m} \qquad (3)$$

Secondly, we estimated individual unique values of palaeoslope gradient (*S*). For this, we used the equation modified from Els (1990), which deals with sandy fluvial systems:

$$S = \frac{\tau}{\rho g T_d} \qquad (4)$$

where, ρ, g, and T_d are the same as in equations (1) and (2); τ is the shear stress in N/m^2, which can be obtained from the diagram of Miller et al. (1977). These *S* values were used for further estimation of palaeovelocity and palaeodischarge.

Palaeovelocity

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

$$V_1 = \frac{\sqrt[3]{T_d^2} \cdot \sqrt{S}}{n} \qquad (5)$$

where, V_1 is the mean velocity of flow. Other symbols are defined above.

Secondly, we estimated the palaeovelocity range by the method of Allen and Homewood (1984), and Nakayama (1997). This method provides the velocities for the threshold of sediment movement (*Vcr*), ripple-dune transition (*Vrd*), and dune-plane bed transition (*Vdp*) based on the flow depth and grain size.

$$Vcr = \frac{u_{cr}}{\kappa} \ln\left(\frac{h}{e z_0}\right) \qquad (6)$$

where, u_{cr} is the shear velocity for the threshold of sediment movement (Vanoni and Nomicos 1959, Yalin, 1963), κ is von Karman's constant, h is the flow depth in meter, and z_0 is the roughness length in m. We used 0.4 and 0.0004 respectively for κ and z_0, according to Allen and Homewood (1984), and T_d for h. *Vrd* and *Vdp* were obtained from the following equations:

$$Vrd = \frac{u_{rd}}{\kappa} \ln\left(\frac{h}{ez_0}\right) \qquad (7)$$

$$Vdp = \frac{u_{dp}}{\kappa} \ln\left(\frac{h}{ez_0}\right) \qquad (8)$$

where, u_{rd} is the shear velocity for ripple-dune transition (Vanoni and Nomicos 1959), and u_{dp} is the shear velocity for dune- (upper) plane bed transition (Bagnold 1966). Other symbols are the same as in equation (6). We used 0.4 for κ in both equations, and 0.0006 and 0.001 for z_0 in equations (7) and (8), respectively.

Palaeodischarge

The simplest equation for discharge (Q) is:

$$Q=VA \qquad (9)$$

where, V is mean velocity, and A is cross-sectional area of flow. However, since the channel width value required for determining A was impossible to measure in this outcrop, other methods of estimating discharge were useful. We estimated the discharge as a function of depth from the following equations:

$$Q_1 = 70.2T_d^{2.5}D_m^{0.3} \qquad (10)$$

$$Q_2 = 82.3T_d^{2.41} \qquad (11)$$

Equation (10) is modified from Kellerhals (1967), and equation (11) is based on Parker (1979).

Results and Findings

By using above-mentioned formulae, estimations of gradient, velocity, and discharge are summarised in Fig. 5 and Table 1. Measured D_m values for SP1, SP2, and SP3 were 3.29×10^{-4}, 2.66×10^{-4}, and 4.05×10^{-4} m, respectively (Fig. 4 and Table 1). The maximum slope gradient (*Se*) varied from 3.59×10^{-7} to 2.53×10^{-7} m/m, whereas the minimum slope gradient (*Sc*) ranged from 4.35×10^{-4} to 4.97×10^{-4} m/m, and the slope gradient (*S*) was from 1.21×10^{-6} to 1.88×10^{-6} m/m. The measured velocity (V) ranged from 0.47 to 0.78 m/s. The palaeodischarge (Q) showed 3.16×10^{3} to 1.41×10^{5} m³/s.

Palaeocurrent measurements in the cross-stratified sandstone beds of the outcrop showed strong directivity with less than 25 degrees of dispersion (Fig. 3).

Conclusions and Discussion

Our estimations show that palaeoslope gradient, palaeovelocity, and palaeodischarge in the lowermost of the Middle Member of the Amlekhganj Formation were $1.21\text{-}1.88\times10^{-6}$ m/m, 0.67-0.78 m/s, and 10^3-10^5 m³/s, respectively. All S values obtained by equation (4) are considered to be appropriate because they fall between *Se* and *Sc*. Palaeovelocity V_1 must be located between *Vrd* and *Vdp*, because the bedforms of these three sampling points were originally dunes, and ideally, the velocity values estimated here increase in the order of *Vcr*, *Vrd*, V_1, and *Vdp*. Equations (6) to (8) make possible to clarify the vertical snapshot of channel flow. In SP2, V_1 is

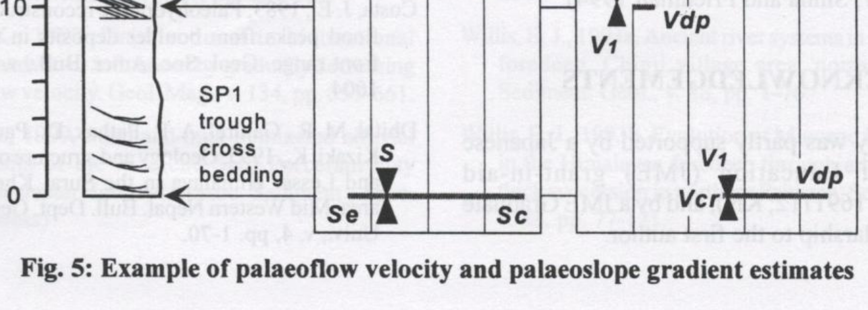

Fig. 5: Example of palaeoflow velocity and palaeoslope gradient estimates

Table 1: Summary of palaeohydrology of the Middle Member of the Amlekhganj Formation

Sample number	Grain modal diameter *Dm* (m)	Thickness of deposits (flow depth) *Td* (m)	Slope			Velocity				Discharge	
			Minimum slope *Se* (m/m)	Maximum slope *Sc* (m/m)	Slope gradient *S* (m/m)	Velocity V_r(m/s)	Sediment movement *Vcr*(m/s)	ripple-dune *Vrd*(m/s)	dune-plane bed *Vdp*(m/s)	Q_1 (m³/s)	Q_2 (m³/s)
SP1	3.29E-04	12.0	3.59E-07	4.97E-04	1.88E-06	0.67	0.34	0.66	0.85	3.16E+03	3.28E+04
SP2	2.66E-04	2.0				0.47	0.26	0.50	0.54		
SP3	4.06E-04	22.0	2.52E-07	4.35E-04	1.21E-06	0.78	0.43	0.64	1.04	1.53E+04	1.41E+05

slightly less than *Vrd.* This invert with 0.03 m/s must be within the permissible range. As the differences between Q_1 and Q_2 values are significant, the magnitude of palaeodischarge must lie within them.

Chronostratigraphically, our focus horizon lies either near the boundary between the Nagri and Dhok Pathan Formations, or at the lowermost part of the Dhok Pathan Formation of the Pakistan Siwaliks. Palaeoslope gradient and palaeovelocity in Pakistan were estimated by Willis (1993a), Zaleha (1997a), and Khan et al. (1997), which range from $5.6x10^{-6}$ to $7.2x10^{-5}$ m/m, and from 0.52 to 0.79 m/s, respectively. Palaeoslope gradients in Pakistan are slightly higher than those in the focus horizon in Nepal, while the values of palaeovelocity in Nepal and Pakistan are similar to each other. Although methodological differences in the estimations must be considered, it is possible that the slightly higher values in the Pakistan Siwaliks reflect the upstream part of the fluvial system, because palaeocurrents data are directed from W or NW to E or SE (Willis 1993a, Zaleha 1997a, Khan et al. 1997).

The palaeoslope values are comparable with the slope of modern Himalayan frontal fans. For example, the Kosi Fan in India has the slope of 0.02 degrees ($3.5x10^{-4}$ m/m) (Wells and Dorr 1987) and the slope of other fans in the Himalayan front ranges from $8x10^{-5}$ to $4x10^{-4}$ m/m (Gole and Chitale 1966, Bristow 1987, Sinha and Friedman 1994).

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