島根大学地球資源環境学研究報告　36, 1～13 ページ（2018 年 3 月）
Geoscience Rept. Shimane Univ., 36, p.1～13（2018）

Article

Petrographic and whole-rock geochemical analyses of Neogene sedimentary rocks of the Siwalik Group, Khutia Khola section, far-western Nepal Himalaya

Swostik Kumar Adhikari, Tetsuya Sakai and Barry P. Roser*

Abstract

This report presents petrographic analyses of 67 sandstones and whole-rock major and trace element X-ray fluorescence analyses (55 mudstones and 67 sandstones), of Neogene Siwalik Group samples from the Khutia Khola section of far-western Nepal. Analyses are reported for the Jagati and Kala Formations, in which four facies associations have been reconstructed. These are a fine-grained meandering river system (FA1), a flood-flow dominated meandering river system (FA2), a deep sandy braided river system (FA3), and a shallow sandy braided river system (FA4), in ascending order. The average composition of all sandstones is Q 70%, F 8%, L 22%. The Pettijohn QFL ternary diagram shows these sandstones are classified as sublitharenites and litharenites. SiO_2 is the most abundant major element, but contents show considerable variation (38.25 to 91.09 wt%). CaO content is more abundant in sandstones than mudstones. The average CaO values in all facies associations are higher than in average Upper Continental Crust (UCC) and Post-Archean Australian Shale (PAAS) values, except in FA4 mudstone. The remaining elements analyzed are generally enriched in the mudstones relative to the sandstones. A Herron geochemical classification diagram shows that most of the mudstones are classified as wackes and shales, and the sandstones as sublitharenites and litharenites.

Key words: Petrography, geochemistry, Siwalik Group, Khutia Khola, Nepal

Introduction

The Siwalik Group, which comprises molassic sediments exposed in association with Himalayan uplift, was deposited during the middle Miocene to the early Pleistocene as a 4 – 6 km thick fluvial sediment sequence at the southern front of the entire Himalayan belt (Gansser, 1964; Prakash *et al*., 1980; Tokuoka *et al*., 1986; Harrison *et al*., 1993; Appel and Rosler, 1994; Gautam and Appel, 1994; Dhital *et al*., 1995; Burbank *et al*., 1996; DeCelles *et al*., 1998; Gautam and Fujiwara, 2000). The Siwalik Group has been studied as an important archive of both Himalayan uplift and climatic change (Quade *et al*., 1995; Dettman *et al*., 2001 and others), due to features such as difference in progradation style of the fluvial system to the south (Brozovic and Burbank, 2000).

The petrography of sandstones provides a means of deciphering the nature of the source rocks, tectonic setting of the source area, and climatic conditions during sedimentation (Dickinson, 1970, 1985; Pettijohn, 1975; Dickinson and Suczek, 1979; Ingersoll and Suczek, 1979; Folk, 1980; Blatt *et al*., 1980; Suttner *et al*., 1981; Dickinson *et al*., 1983; Suttner and Dutta, 1986; Weltje *et al*., 1998, and others). Geochemical studies of sedimentary rocks have also been widely used for evaluation of the influence of provenance, source weathering, and tectonic setting (Nesbitt and Young, 1982; Bhatia and Crook, 1986; Roser and Korsch, 1986, 1988; Condie, 1993, Johnsson, 1993; McLennan *et al*., 1993; and others). This report presents the datasets arising from petrographic analysis of 67 sandstones and whole-rock major and trace element analysis of 122 sandstones and mudstones from the Neogene Siwalik Group along the Khutia Khola section, far-western Nepal.

Geological Setting

The Siwalik Group formed along the southern front of the entire Himalayan belt in association with Himalayan uplift (Gansser, 1964; Prakash *et al*., 1980; Burbank *et al*., 1996; DeCelles *et al*., 1998; Upreti, 1999). The Siwalik Group is demarcated from the Lesser Himalaya to the north by the Main Boundary Thrust, and from the Indo-Gangatic Plain to the south by the Main Himalayan Thrust (Nakata, 1989; Mugnier *et al*., 1999). In general, the Main Dun Thrust (MDT) separates the Siwalik Group into southern and northern belts (Tokuoka *et al*., 1986; DeCelles *et al*., 1998; Ulak and Nakayama, 1998; Robinson *et al*., 2006). In the study area, the Jogbudha Thrust (equivalent to the MDT) and the Rangun Khola Thrust divide the Siwalik Group into southern, central and northern belts (Sharma *et al*., 2007).

The Siwalik Group has traditionally been divided into three units known as the Lower, Middle and Upper Siwaliks (Auden, 1935; Hagen, 1969; Yoshida and Arita, 1982; Quade *et al*., 1995; DeCelles *et al*., 1998; Gautam and Fujiwara, 2000; Ojha *et al*., 2000; Robinson *et al*., 2006; Sharma *et al*., 2007). Locally, two-, four- or five- fold divisions are also acceptable (Glennie and Ziegler, 1964; Sharma, 1973; Tokuoka *et al*., 1986, 1988; Corvinus and Nanda, 1994; Sah *et al*., 1994; Dhital *et al*., 1995; Ulak and Nakayama, 1998; Sigdel *et al*., 2011). The common three-fold classification generally begins with the mudstone-dominated Lower Siwalik, grading upward into the sandstone-dominated

* Department of Geoscience, Shimane University, Matsue 690-8504, Shimane, Japan

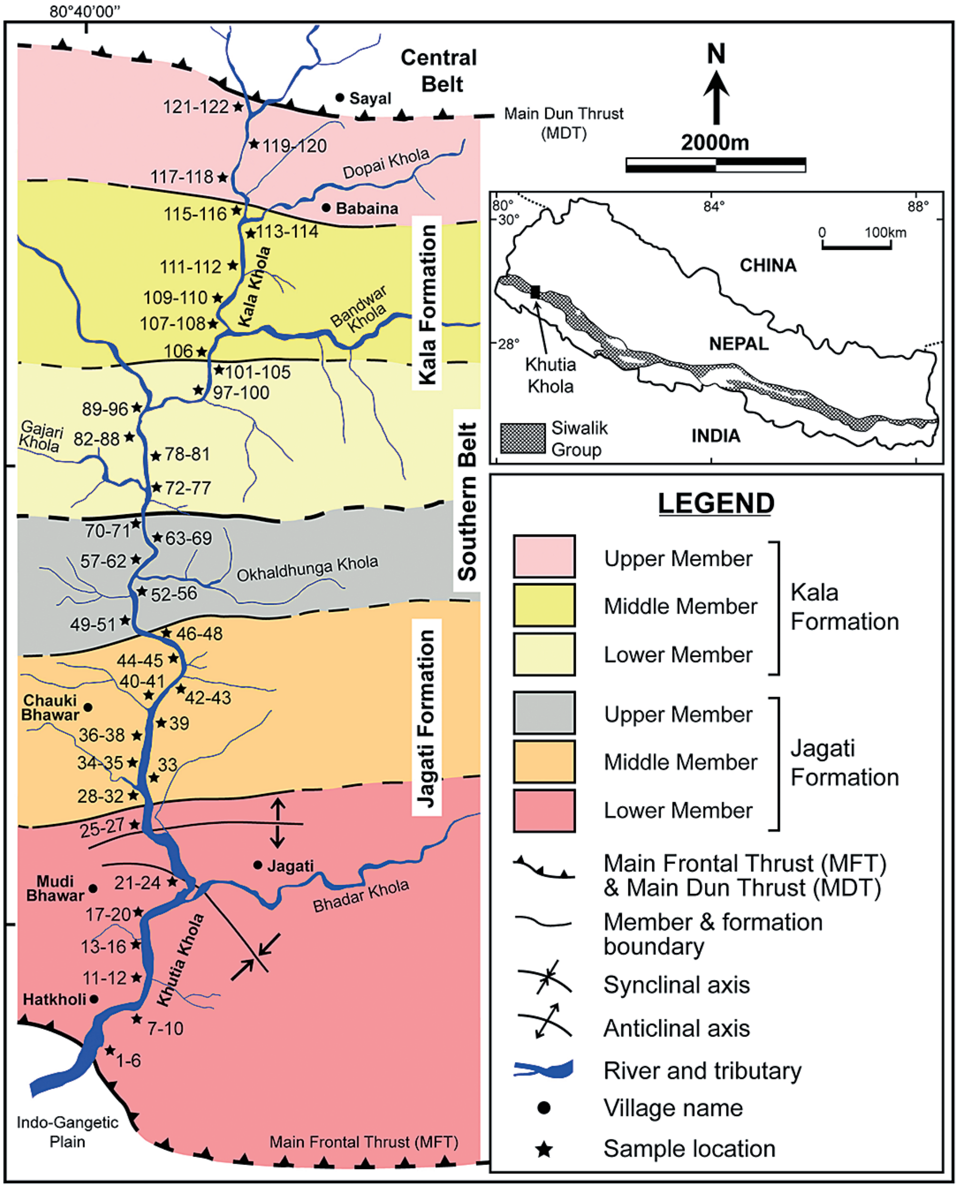

Fig. 1. Generalized geological map of the Siwalik Group along the Khutia Khola section, far-western Nepal (modified after Adhikari and Sakai, 2015), showing sample locations (grouped by sample number).

Middle Siwalik, followed by conglomerate-dominated sediments of the Upper Siwalik (Medlicott, 1875; Pilgrim, 1913; Auden, 1935; Wadia, 1957; Hagen, 1969; Yoshida and Arita, 1982; Quade *et al*., 1995; DeCelles *et al*., 1998; Upreti, 1999; Gautam and Fujiwara, 2000; Ojha *et al*., 2000; Robinson *et al*., 2006). Previous studies of the Siwalik Group along the Khutia Khola section also followed the classical tripartite classification (DeCelles *et al*., 1998; Ojha *et al*., 2000; Sharma *et al*., 2007). Adhikari and Sakai (2015) recently established the lithostratigraphy of the southern belt in the area. This consists of the Jagati Formation (2,110 m thickness, equivalent to the Lower Siwalik) and the Kala Formation (2,050 m, equivalent to the Middle Siwalik), in ascending order (Fig. 1). The Upper Siwalik is not exposed in the area, and may be masked by the Jogbudha Thrust, thrusting the central block onto the southern belt rocks from the north. Both the Jagati and Kala Formations are further subdivided into lower, middle and upper members.

The Jagati Formation is composed of variegated, reddish-brown, yellowish-brown, brown, yellowish-grey, grey to greenish-grey mudstones and very fine- to coarse-grained, brown, reddish-grey, light grey, grey to greenish-grey sandstones. Most of the mudstones show characteristics typical of paleosols, containing burrows, rhizoliths, desiccation cracks, and nodules. However, some mudstones are thinly laminated or massive. The Kala Formation consists of thin- to thick-bedded, medium- to very coarse-grained, light grey, grey to greenish-grey sandstones and pebbly sandstones, interbedded with reddish-brown, brown, grey, greenish-grey to dark grey mudstones. Finely laminated or massive mudstones are common, whereas paleosols are infrequent. Biotite, quartz and feldspar are abundant in the sandstones, leading to characteristic "salt and pepper" appearance. Sub-rounded to rounded pebbles 1-2 cm diameter are present in the sandstones in the lower part of the upper member, whereas gravel size tends to be larger and some cobble-sized gravels appear in the upper part of this member.

Depositional Setting

Adhikari (2017) studied fluvial facies and depositional environment in the Khutia Khola section, and reconstructed meandering and braided river systems, as had been recognized in other Siwalik sections in Nepal Himalaya (cf. Nakayama and Ulak, 1999; Ulak and Nakayama, 2001; Ulak, 2004, 2009; Huyghe *et al*., 2005; Sigdel and Sakai, 2016). Both of these fluvial systems are made up of two facies associations. The lowermost meandering river system comprises a fine-grained meandering river system (FA1) and a flood-flow dominated meandering river system (FA2). The braided river system is divided into a deep sandy braided river system (FA3) and a shallow sandy braided river system (FA4). The facies associations also more or less correspond to stratigraphic divisions, with FA1 being the lower member and up to the middle part of the middle member of the Jagati Formation, and FA2 comprising the remainder of the middle member and the upper member. Similarly, FA3 corresponds to the lower and middle members of the Kala Formation, and FA4 to its upper member. Ojha *et al*. (2000) analyzed the magnetostratigraphy in the study area, and the rock units were dated from 13.30 to 7.65 Ma. The change in the river systems from fine-grained meandering river system (FA1) to flood-flow dominated meandering river system (FA2) is inferred to have occurred a little before 13.3 Ma, probably around 13.5 Ma. Similarly, the change from the meandering river system (FA1-FA2) to the braided river system (FA3-FA4) took place at around 11.0 Ma.

Analytical Methods

Petrographic Analyses

Sixty-seven sandstone samples from the southern belt of the Siwalik Group along the Khutia Khola section were examined using standard thin-section petrography. Framework modal compositions were quantified using the Gazzi-Dickinson method (Ingersoll and Suczek, 1979; Dickinson, 1985). A total of 500 grains were counted per thin section, using a Swift point counter with horizontal grid spacing of 0.3 mm, to avoid individual grains being counted more than once. The main categories of grains identified included monocrystalline quartz (Qm), polycrystalline quartz (Qp), plagioclase (P), K-feldspar (K), sedimentary lithics (Ls), carbonate lithics (Lc), metamorphic lithics (Lm), volcanic lithics (Lv) and chert. In addition, biotite, muscovite, chlorite, calcite cement, other cements, heavy minerals, altered minerals, accessory minerals, matrix and opaques were also included in the point counts.

Geochemical Analyses

A suite of 122 samples (55 mudstones, and all 67 sandstones from the petrographic analysis) was assembled for geochemical analysis. The samples were prepared for analysis using the standard methods applied in the Department of Geoscience of Shimane University (Roser *et al*., 1998; 2000). Each sample was reduced to chips about 1 – 2 cm in diameter using a hammer and a manual hydraulic rock trimmer. Any chips containing deleterious material such as veins or surface coatings were discarded. The remaining chip was then washed repeatedly in water to remove any surface dust. The washed samples were oven-dried at 110˚C for 24 hours. Roughly 100 grams of each dried sample were subsequently crushed in a Rocklabs® tungsten carbide ring mill, with crushing times of about 20 – 30 seconds for the mudstones, and up to 60 seconds for the sandstones. The mill was cleaned with ethanol between samples, or (if necessary) by crushing of a load of quartzose sand, followed by cleaning with ethanol.

Loss on ignition (LOI) values were determined by ignition of 8 – 10 grams of crushed sample in ceramic crucibles in a muffle furnace at 1010˚C for at least 3 hours, compared to the normal ignition time of 2 hours. The longer time was adopted to ensure complete sublimation of carbonate cement and carbonate lithic fragments. The ignited samples were manually disaggregated in an agate pestle and mortar, and stored in glass vials in a 110˚C oven for at least 24 hours before preparation of glass fusion beads (anhydrous basis). The glass fusion beads were prepared using an alkali flux consisting of 80% lithium tetraborate (Merck Spectromelt® A10) and 20% lithium metaborate (Merck Spectromelt® A20). The beads contained 1.8000 ± 0.0004 g of ignited sample and 3.6000 ± 0.0004 of flux (sample to flux ratio of 1:2). The beads were made in platinum crucibles using an automatic bead sampler, with two static 120 second fusions, followed by fusion and rotation mixing for 360 seconds. The glass beads were then analyzed using a RIX 2000 XRF spectrometer (Rigaku Denki Co. Ltd.). Abundances of the major elements and fourteen trace elements (Ba, Ce, Cr, Ga, Nb, Ni, Pb, Rb, Sc, Sr, Th, V, Y and Zr) were determined in all samples. Analytical methods, instrument conditions and calibration followed those described by Kimura and Yamada (1996). Calibrations for individual elements were confirmed by analysis at run time of nine standard rocks produced by the Geological Survey of Japan, spanning the compositional range between gabbro/basalt and granite/rhyolite. These standards also included two shales (JSl-1 and JSl-2).

Results

Petrographic Analyses

The recalculated modal analyses of individual samples

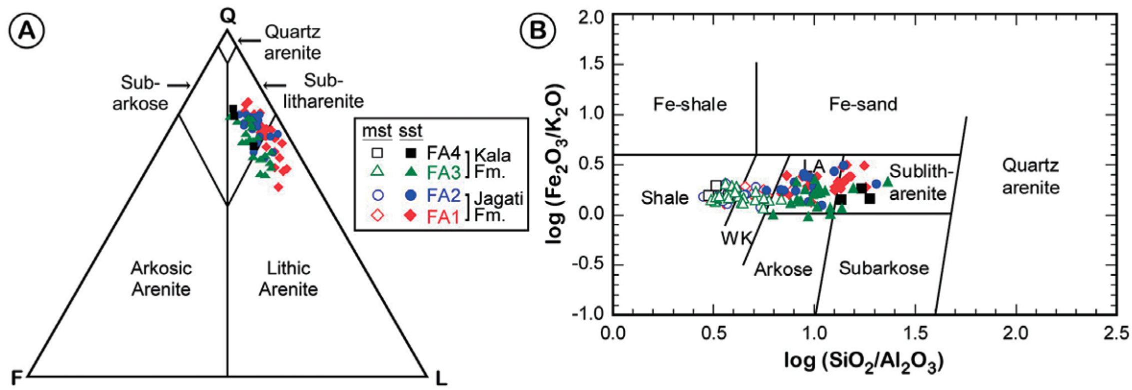

Fig. 2. (A) Q – F – L (Quartz, feldspar, lithic fragments) ternary diagram for sandstone classification (after Pettijohn, 1975). (B) Log (SiO_2/Al_2O_3) – Log (Fe_2O_3/K_2O) geochemical classification (after Herron, 1988). Abbreviations: WK – wacke; LA – litharenite; mst – mudstone; sst – sandstone; FA – facies association; Fm – formation.

by formation are listed in Table 1, and average recalculated modal analyses by facies association are listed in Table 2. The average compositions of FA1-FA2 and FA3-FA4 are $Q_{70}F_7$, L_{23} and $Q_{68}F_{10}L_{22}$ respectively. The average composition of all sandstones overall is $Q_{70}F_8L_{22}$.

These sandstones are rich in quartz, and monocrystalline quartz is more abundant (65%) than polycrystalline quartz (35%). Lithic fragments are the second most abundant detrital constituent, among which sedimentary (Ls = 55%) and metamorphic (Lm = 43%) lithic fragments are much more abundant than volcanic (Lv = 2%) lithic fragments. Feldspar is the least abundant among the framework QFL constituents. In most samples K-feldspar (K) is dominant over plagioclase (P), but overall their distribution is almost equal at P = 49% and K = 51%. The QFL diagram for classification (Pettijohn, 1975) shows that these sandstones are classified as sublitharenites and litharenites (Fig. 2A).

Geochemical Analyses

Major and trace element analyses of individual samples are listed in Table 3. The data are listed on anhydrous basis, with the major elements normalized to sum to 100%. The same normalization factors were also applies to the individual trace element data, so that the original ratios between major and trace elements were maintained. Original LOI values (hydrous basis) are also listed, along with the anhydrous total of the major elements in the original XRF analysis. These data allow recalculation of the analyses on a hydrous "as-analyzed" basis if desired.

In a geochemical study of the Bakiya Khola Siwalik section, Roser *et al*. (2002) suggested that the fluvial style apparently influenced the compositions of the sediments and hence geochemical trends in the sequence. Consequently, we also calculated averages by facies association in the Khutia Khola section. Average chemical compositions by facies association and lithotype (sandstone and mudstone) are listed by formation in Table 4, also on an anhydrous normalized basis, as in Table 3. Average LOI values in the mudstones are higher than those in the sandstones of equivalent facies associations, except in FA4, where the average sandstone LOI value (8.43 wt%) is greater than of the average mudstone (6.15 wt%, Table 4).

The most abundant major element is SiO_2, which reaches a maximum value of 91.09 wt% and a low of 38.24 wt% in individual sandstones and mudstones, respectively (Table 3). The average SiO_2 content of the sandstones (average 77.19 wt%) in all facies associations (FA) are higher than those in the average Upper Continental Crust (UCC) (66.00 wt%) and Post-Archean Australian Shale (PAAS) (62.80 wt%) of Taylor and McLennan (1985), whereas UCC and PAAS values are higher than the average SiO_2 content in the mudstones, except in FA1 and FA4, where average SiO_2 contents are slightly greater than in PAAS (Table 4). The next most abundant major element, Al_2O_3, ranges in abundance from 3.57 to 11.53 wt% (average 6.76 wt%) in the sandstones, and from 8.58 to 20.40 wt% (average 15.20 wt%) in the mudstones. The average Al_2O_3 contents are lower than the UCC (15.20 wt%) and PAAS (18.90 wt%) values except in FA4 mudstones (19.47 wt%). Abundances of CaO are very high in both lithotypes, ranging from 0.11 to 44.93 wt% (average 10.67 wt%) in the sandstones and from 0.18 to 34.66 wt% (10.13 wt%) in the mudstones. The average values of CaO in all facies associations are higher than in UCC (4.20 wt%) and PAAS (1.30 wt%) values except in FA4 mudstone (1.18 wt%). Fe_2O_3, MgO, CaO and K_2O are the three next most abundant major elements. Average concentrations of the four remaining major elements (TiO_2, MnO, Na_2O, and P_2O_5) by FA and lithotype, are all less than 1 wt%.

Seven trace elements (Ba, Ce, Cr, Rb, Sr, V and Zr) are present in concentrations near to or exceeding 100 ppm. The seven remaining trace elements (Ga, Nb, Ni, Pb, Sc, Th and Y) are present in concentrations of less than 50 ppm. Most of these elements have higher values in the mudstones than in the sandstones.

The geochemical classification of Herron (1988) provides

Table 1. Recalculated framework compositions (%) of the Siwalik sandstones from the Kala and Jagati Formations, Khutia Khola section, Nepal.

SmN	Metre	Lith	FA	Modal composition (%)																Recal QFL (%)		
				Qm	Qp	Chert	P	K	Ls	Lm	Lv	Mus	Biot	Chl	Cem	Alt	Mat	Opq	Oth	Q	F	L
KALA FORMATION																						
Upper Member																						
KS-121	4108	CS	FA4	37.2	15.0	1.4	3.8	4.2	8.6	8.6	0.4	1.8	1.2	0.0	6.4	2.0	6.8	0.6	2.0	67.1	10.3	22.6
KS-120	3983	VCS	FA4	38.6	18.4	1.0	4.6	3.4	3.8	6.8	0.6	3.2	3.6	0.0	5.2	1.8	5.8	0.8	2.4	74.8	10.5	14.7
KS-118	3898	CS	FA4	39.6	21.8	0.4	3.6	4.4	4.6	5.4	0.8	3.8	2.8	0.0	3.4	2.0	4.6	0.4	2.4	76.6	10.0	13.5
Middle Member																						
KS-116	3756	CS	FA3	40.6	16.2	0.2	3.4	2.8	7.0	6.2	0.4	3.0	3.4	0.0	5.6	1.4	5.6	1.0	3.2	74.2	8.1	17.8
KS-114	3623	CS	FA3	35.8	20.2	0.6	3.0	3.6	8.6	6.8	0.2	1.2	0.8	0.0	6.6	1.6	8.2	0.8	2.0	71.6	8.4	19.9
KS-112	3510	CS	FA3	34.6	17.2	1.2	3.6	4.0	6.4	9.4	0.8	3.4	3.6	0.0	4.6	1.6	7.8	0.2	1.6	68.2	10.0	21.8
KS-110	3217	CS	FA3	36.4	18.2	0.6	3.0	3.6	8.4	8.8	0.6	3.8	2.8	0.0	5.2	2.0	4.2	0.6	1.8	69.1	8.4	22.5
KS-107	3125	CS	FA3	34.4	22.6	0.8	4.2	4.4	4.0	7.2	1.2	4.4	3.6	0.0	4.8	1.4	4.4	0.6	2.0	73.1	11.0	15.9
KS-106	2960	VCS	FA3	28.0	24.8	1.6	3.8	4.2	5.2	9.8	1.4	6.2	4.6	0.0	4.2	1.6	3.2	0.2	1.2	68.4	10.4	21.2
Lower Member																						
KS-104	2895	CS	FA3	35.2	13.6	1.4	4.6	3.6	8.0	6.0	0.6	3.4	3.0	0.0	9.2	1.8	7.4	0.6	1.6	68.2	11.5	20.4
KS-103	2880	CS	FA3	33.2	19.4	1.2	4.0	5.2	9.8	8.6	0.0	3.0	2.2	0.0	7.2	1.8	2.6	0.4	1.4	65.6	11.5	22.9
KS-99	2765	VCS	FA3	40.6	17.2	1.6	4.2	4.8	4.8	5.4	0.4	3.0	2.8	0.0	5.2	1.6	6.0	0.6	1.8	74.7	11.6	13.7
KS-98	2720	CS	FA3	31.8	21.4	0.4	2.8	3.2	7.0	6.2	1.0	4.2	3.4	0.0	7.6	1.8	6.6	1.0	1.6	72.5	8.2	19.3
KS-97	2714	FS	FA3	34.6	17.2	0.2	4.6	3.2	8.2	5.8	0.4	3.2	3.8	0.0	8.4	0.8	7.8	0.4	1.4	70.0	10.5	19.5
KS-94	2666	VCS	FA3	32.4	24.6	1.8	4.4	4.2	7.6	8.6	0.0	2.6	3.2	0.0	5.4	0.4	3.4	0.8	0.6	69.7	10.5	19.8
KS-93	2635	CS	FA3	35.2	14.8	1.8	3.4	3.6	14.0	5.6	0.6	2.8	2.6	0.0	5.8	1.0	6.8	0.6	1.4	64.8	9.1	26.2
KS-91	2585	VCS	FA3	33.0	21.8	1.2	3.8	4.6	11.8	5.0	0.0	2.2	3.2	0.0	6.6	1.4	4.4	0.4	0.6	68.5	10.5	21.0
KS-89	2560	MS	FA3	36.2	15.8	0.2	5.2	4.2	8.4	6.4	0.2	3.0	2.4	0.4	9.2	1.8	5.6	0.4	0.6	68.1	12.3	19.6
KS-86	2432	CS	FA3	33.4	16.8	1.0	4.2	3.8	8.8	10.2	1.4	3.2	1.2	0.0	7.0	1.0	6.2	0.4	1.4	63.9	10.2	26.0
KS-84	2368	CS	FA3	28.4	20.6	0.4	4.6	5.4	13.2	8.2	1.0	2.8	1.4	0.0	7.8	1.4	3.2	0.0	1.6	60.2	12.3	27.5
KS-82	2330	MS	FA3	30.8	18.2	0.4	3.8	4.4	10.4	8.4	1.0	2.8	2.2	0.0	8.6	1.4	6.6	0.4	0.6	63.6	10.6	25.7
KS-80	2272	FS	FA3	29.8	17.2	0.2	3.2	3.8	11.6	9.8	0.8	2.6	1.6	0.0	9.8	2.0	6.4	0.6	0.6	61.7	9.2	29.1
KS-78	2240	CS	FA3	31.6	22.2	0.0	2.8	3.2	18.6	3.8	0.0	1.8	1.4	0.0	8.6	0.4	5.2	0.2	0.2	65.5	7.3	27.3
KS-76	2210	FS	FA3	32.6	20.2	0.0	2.2	3.0	12.8	0.8	0.0	2.2	1.6	0.0	18.0	1.4	3.8	0.4	1.0	73.7	7.3	19.0
KS-74	2157	MS	FA3	32.2	11.8	1.2	3.8	4.6	12.4	7.8	1.0	5.0	4.0	0.2	8.4	1.8	5.2	0.2	0.4	59.8	11.4	28.8
KS-72	2120	CS	FA3	28.4	23.2	1.2	3.2	4.2	11.2	11.4	0.6	3.4	1.6	0.0	3.8	1.6	4.4	0.8	1.0	62.8	9.0	28.2
JAGATI FORMATION																						
Upper Member																						
KS-70	2075	MS	FA2	34.6	16.0	0.0	4.4	4.0	11.8	6.2	0.0	1.6	1.8	0.2	11.4	1.4	3.8	1.4	1.4	65.7	10.9	23.4
KS-68	2028	FS	FA2	33.6	19.4	0.0	3.6	2.2	9.6	7.4	0.6	2.6	3.2	0.0	9.0	2.8	4.0	0.6	1.4	69.4	7.6	23.0
KS-66	1988	CS	FA2	35.8	18.4	0.6	3.2	4.0	16.2	2.0	0.0	2.4	1.6	0.2	8.6	0.8	4.4	0.6	1.2	68.1	9.0	22.9
KS-64	1938	MS	FA2	36.2	16.8	0.8	3.8	4.0	15.0	6.8	0.2	2.2	1.6	0.0	6.2	1.4	3.0	0.6	1.4	64.0	9.4	26.6
KS-62	1893	MS	FA2	39.2	18.6	0.0	3.2	3.4	8.6	7.8	0.0	3.6	2.8	0.0	4.4	1.6	5.4	0.6	0.8	71.5	8.2	20.3
KS-60	1872	MS	FA2	41.2	19.6	0.0	2.8	3.0	8.6	9.2	0.0	2.2	1.8	0.0	5.0	0.8	4.4	0.4	1.0	72.0	6.9	21.1
KS-58	1830	FS	FA2	33.8	20.4	0.0	2.6	4.4	7.4	5.6	0.2	2.8	0.8	0.2	13.6	1.4	4.6	0.4	1.8	72.8	9.4	17.7
KS-56	1788	FS	FA2	35.2	23.8	0.0	1.8	3.4	7.2	7.2	0.8	4.4	5.0	0.0	5.6	1.2	3.2	0.2	1.0	74.3	6.5	19.1
KS-54	1743	MS	FA2	25.2	9.8	0.0	1.0	2.6	12.2	2.6	0.0	5.8	4.0	0.2	24.4	1.6	8.2	0.8	1.6	65.5	6.7	27.7
KS-53	1738	MS	FA2	42.2	17.4	1.2	3.4	4.6	7.8	6.8	0.4	2.4	1.8	0.0	5.4	1.4	4.2	0.4	0.6	72.2	9.7	18.2
KS-51	1672	CS	FA2	39.4	23.6	0.4	3.6	3.0	6.8	7.4	0.6	3.4	2.6	0.0	4.8	0.6	3.6	0.0	0.2	74.6	7.8	17.5
KS-49	1628	FS	FA2	33.6	20.8	0.4	2.4	2.8	5.8	9.0	0.0	3.4	2.4	0.2	9.6	1.6	6.2	0.8	1.0	73.1	7.0	19.9
Middle Member																						
KS-47	1620	FS	FA2	41.4	20.4	0.0	3.0	3.4	6.0	8.2	0.0	3.2	2.4	0.0	5.4	0.8	4.4	0.6	0.8	75.0	7.8	17.2
KS-45	1574	FS	FA2	34.6	18.6	0.2	1.4	1.2	16.8	3.2	0.0	1.6	1.4	0.0	11.2	0.8	7.2	0.8	1.0	70.2	3.4	26.4
KS-44	1545	CS	FA2	39.6	25.8	0.6	1.8	2.4	9.8	7.6	0.2	1.8	1.0	0.0	4.2	0.6	2.8	1.4	0.4	75.0	4.8	20.2
KS-42	1490	MS	FA2	37.8	25.2	0.0	2.0	3.2	8.4	9.2	0.0	1.6	0.2	0.0	9.0	1.0	2.2	0.2	0.0	73.4	6.1	20.5
KS-41	1450	FS	FA2	38.2	19.8	0.0	3.2	4.2	6.6	5.4	0.0	3.8	2.2	0.0	10.8	1.2	3.4	0.6	0.6	74.9	9.6	15.5
KS-40	1419	FS	FA2	37.2	19.2	0.0	1.6	2.8	11.2	9.2	0.0	1.8	2.6	0.0	9.2	0.8	3.2	0.8	0.4	69.5	5.4	25.1
KS-37	1250	FS	FA1	36.6	28.0	0.0	4.2	2.6	6.4	7.4	0.0	2.2	2.4	0.0	3.8	1.0	4.4	0.2	0.8	75.8	8.0	16.2
KS-36	1230	CS	FA1	38.2	27.4	0.2	1.8	2.2	8.6	8.6	0.0	1.6	0.6	0.0	5.6	0.4	3.8	0.4	0.6	75.6	4.6	19.8
KS-34	1155	CS	FA1	32.8	29.2	0.0	2.2	1.2	13.6	11.8	0.4	0.8	1.0	0.0	3.4	0.0	3.4	0.0	0.2	68.0	3.7	28.3
KS-31	960	MS	FA1	35.2	23.6	1.4	2.0	3.4	8.8	11.2	0.0	2.2	1.0	0.0	3.6	1.8	5.0	0.4	0.4	69.8	6.4	23.8
KS-30	955	CS	FA1	30.2	20.4	0.0	2.2	2.6	12.4	14.0	0.2	1.2	0.8	0.0	11.8	0.4	3.2	0.2	0.4	61.7	5.9	32.4
KS-28	920	MS	FA1	34.2	19.4	0.6	2.8	2.2	12.6	12.2	0.0	2.4	1.8	0.4	7.8	0.0	2.4	0.4	0.8	64.3	6.0	29.7

Abbreviations: SmN - sample number; Metre - stratigraphic height in metres; Lith - lithology: FS, M, CS, VCS - fine, medium, coarse, very coarse grained sandstone, respectively; FA - Facies association; FA1 - fine-grained meandering; FA2 - flood-flow dominated meandering; FA3 - deep sandy braided; FA4 - shallow sandy braided; Qm - monocrystalline quartz; Qp- polycrystalline quartz; P - Plagioclase; K - K-feldspar; Ls - sedimentary lithic fragment; Lm - metamorphic lithic fragment; Lv - volcanic lithic fragment; Mus - muscovite; Biot - biotite; Chl - chlorite; Cem - cement; Alt - altered; Mat - matrix; Opq - Opaque; Oth - others; Q - total quartz (Qm + Qp); F - total feldspar (P + K); L - total lithic fragments (Ls + Lm + Lv); Recal - recalculated.

Table 1. Continued.

SmN	Metre	Lith	FA	Modal composition (%)																Recal QFL (%)		
				Qm	Qp	Chert	P	K	Ls	Lm	Lv	Mus	Biot	Chl	Cem	Alt	Mat	Opq	Oth	Q	F	L
JAGATI FORMATION (ctd.)																						
Lower Member																						
KS-26	845	FS	FA1	41.0	18.4	0.2	2.4	2.8	9.6	7.8	0.0	5.2	2.4	0.0	2.6	0.4	6.8	0.4	0.0	72.4	6.3	21.2
KS-25	820	FS	FA1	40.2	20.6	0.2	3.6	2.2	7.6	7.4	0.0	4.8	3.6	0.0	3.2	0.6	4.8	0.6	0.6	74.5	7.1	18.4
KS-24	750	MS	FA1	39.6	22.6	0.4	3.0	3.4	7.6	7.8	0.2	3.0	2.6	0.0	3.6	1.2	3.4	0.6	1.0	73.9	7.6	18.5
KS-22	700	FS	FA1	42.8	19.6	0.4	3.4	3.2	10.8	5.8	0.0	3.2	1.2	0.0	3.2	1.8	3.2	0.6	0.8	72.9	7.7	19.4
KS-19	595	CS	FA1	41.0	25.4	0.0	3.2	2.4	6.4	6.8	0.0	2.4	2.8	0.0	3.2	1.2	3.6	0.8	0.8	77.9	6.6	15.5
KS-18	585	CS	FA1	43.4	18.4	1.0	3.0	2.6	11.0	10.2	0.0	1.6	1.4	0.0	3.4	0.4	2.6	0.4	0.6	69.8	6.3	23.9
KS-17	570	CS	FA1	36.8	19.8	0.2	3.0	2.4	14.0	9.8	0.0	2.0	1.8	0.0	3.6	1.2	4.0	0.6	0.8	66.0	6.3	27.7
KS-15	510	FS	FA1	32.2	10.0	0.0	3.8	3.6	17.2	7.0	0.2	6.8	5.2	0.2	7.8	0.4	4.2	0.2	1.2	57.0	10.0	33.0
KS-14	460	FS	FA1	31.8	16.6	0.4	4.2	2.4	15.6	7.8	0.0	4.0	2.6	0.4	7.6	1.2	3.4	0.8	1.2	61.7	8.4	29.8
KS-13	430	FS	FA1	40.6	19.6	0.2	2.2	1.4	10.8	9.4	0.2	5.4	4.2	0.0	2.4	0.4	2.0	0.4	0.8	71.5	4.3	24.2
KS-11	345	FS	FA1	29.6	15.8	0.0	2.6	2.6	14.6	9.2	0.2	3.2	3.6	0.0	9.2	0.6	6.8	0.6	1.4	60.9	7.0	32.2
KS-10	240	FS	FA1	36.6	22.0	0.2	3.2	2.8	11.2	7.2	0.0	3.6	2.6	0.0	6.4	0.6	2.0	0.6	1.0	70.6	7.2	22.2
KS-7	180	MS	FA1	43.8	21.6	0.2	1.6	3.6	8.6	7.6	0.0	1.6	2.8	0.0	5.0	0.6	2.2	0.2	0.6	75.3	6.0	18.7
KS-5	75	MS	FA1	38.2	21.2	1.2	2.6	1.8	10.4	8.4	0.4	1.6	1.0	0.0	6.2	1.6	4.4	0.4	0.6	71.6	5.3	23.1
KS-4	65	MS	FA1	38.8	20.8	0.8	2.2	1.8	14.0	8.2	0.4	3.0	1.8	0.0	4.8	0.2	2.0	0.4	0.8	69.1	4.6	26.2
KS-3	60	MS	FA1	35.2	19.4	0.6	3.4	2.6	11.4	9.0	0.2	3.0	2.6	0.0	3.2	2.8	5.0	0.4	1.2	67.2	7.4	25.4
KS-1	35	MS	FA1	40.4	23.2	0.4	2.6	2.2	7.2	5.2	0.4	4.2	3.8	0.0	3.8	0.8	4.2	0.6	1.0	78.3	5.9	15.8

Table 2. Average recalculated framework compositions (%) of the Siwalik sandstones from the Khutia Khola section, by facies association.

FA	Fm.	N	Modal composition (%)																Recal QFL (%)		
			Qm	Qp	Chert	P	K	Ls	Lm	Lv	Mus	Biot	Chl	Cem	Alt	Mat	Opq	Oth	Q	F	L
FA4	K. Fm.	3	38.5	18.4	0.9	4.0	4.0	5.7	6.9	0.6	2.9	2.5	0.0	5.0	1.9	5.7	0.6	2.3	72.8	10.3	16.9
FA3	K. Fm.	23	33.4	18.9	0.8	3.7	4.0	9.5	7.2	0.6	3.2	2.6	0.0	7.3	1.4	5.4	0.5	1.3	67.7	10.0	22.3
FA2	J. Fm.	18	36.6	19.6	0.2	2.7	3.3	9.8	6.7	0.2	2.8	2.2	0.1	8.8	1.2	4.3	0.6	0.9	71.2	7.6	21.2
FA1	J. Fm.	23	37.4	21.0	0.4	2.8	2.5	10.9	8.7	0.1	3.0	2.3	0.0	5.0	0.9	3.8	0.4	0.8	69.8	6.5	23.7

Abbreviations: K. Fm. - Kala Formation; J. Fm. - Jagati Formation; N - number of samples; for other parameters refer to Table 1.

an important clue for estimating the character and origin of sediments. The Herron diagram shows that samples spread across the sublitharenite, litharenite (LA), wacke (WK) and shale fields (Fig. 2B). The sandstones are mainly classified as sublitharenites and litharenites, whereas the mudstones are mostly classified as wackes and shales.

A number of key provenance and paleoweathering indicators (e.g. SiO_2/Al_2O_3, K_2O/Na_2O, Th/Sc, Zr/Sc, Al_2O_3/Na_2O, Al_2O_3/K_2O) (not illustrated here) show systematic shifts within lithotypes and facies associations, which indicate that stratigraphic shifts in geochemical composition occur within the Siwalik Group in the Khutia Khola section. These features will be discussed in detail elsewhere in the future studies.

Acknowledgements

We thank the Department of Mines and Geology, Government of Nepal, for granting permission to export the samples from Nepal to Japan. We are indebted to Dr. P. D. Ulak, Dr A. P. Gajurel, and Dr. A. Sigdel for their valuable suggestions for the fieldwork and sample collection. This work was supported by a MEXT scholarship to S. K. Adhikari.

References

Adhikari, S. K. 2017. Geological and geochemical studies of the Neogene Siwalik Group, Khutia Khola section, Nepal Himalaya and comparison with the Middle Bengal Fan sediments: implications for provenance, paleoclimate and Himalayan tectonics. *Unpublished doctoral thesis, Shimane University,* 232p.

Adhikari, S. K. and Sakai, T. 2015. Lithostratigraphy of the Siwalik Group, Khutia Khola section, Far Western Nepal Himalaya. *Journal of Nepal Geological Society,* **49**, 29–39.

Appel, E. and Rosler, W. 1994. Magnetic polarity stratigraphy of the Neogene Surai Khola section (Siwalik, SW Nepal). *Himalayan Geology,* **15**, 63–68.

Auden, J. B. 1935. Traverses in the Himalaya. *Records of the Geological Survey of India,* **69**, 123–167.

Bhatia, M. R. and Crook, K. A. W. 1986. Trace element characteristics of greywackes and tectonic setting discrimination of sedimentary basins. *Contributions to Mineralogy and Petrology,* **92**, 181–193.

Blatt, H., Middleton, G. V. and Murray, R. C. 1980. *Origin of sedimentary rocks.* Prentice Hall Inc., 782p.

Brozovic, N. and Burbank, D. W. 2000. Dynamic fluvial systems and gravel progradation in the Himalayan foreland. *Geological Society of America Bulletin,* **112**, 394–412.

Burbank, D. W., Beck, R. A. and Mulder, T. 1996. *The Himalayan Foreland.* In Y. An & M. Harrison (Eds.), *Asian Tectonics* (pp.149–188). Cambridge University Press, Cambridge.

Condie, K. C. 1993. Chemical composition and evolution of the upper continental crust: Contrasting results from surface samples and shales. *Chemical Geology,* **104**, 1–37.

Corvinus, G. and Nanda, A. C. 1994. Stratigraphy and paleontology of the Siwalik group of Surai khola and Rato khola in Nepal. *Neues Jahrbuch für Geologie und Paläontologie, Stuttgart,* **191(1)**, 25–68.

DeCelles, P. G., Gehrels, G. E., Quade, J., Ojha, T. P., Kapp, P. A. and Upreti, B. N. 1998. Neogene foreland basin deposits, erosional unroofing, and the kinematic history of the Himalayan fold-thrust belt, western Nepal. *Geological Society of America Bulletin,* **110**, 2–21.

Dettman, D. L., Kohn, M. J., Quade, J., Ryerson, F. J., Ojha, T. P. and Hamidullah, S. 2001. Seasonal stable isotope evidence for a strong Asian

Table 3. XRF analyses of the Siwalik sandstones and mudstones from the Kala and Jagati Formations, Khutia Khola section, Nepal.

(A) SANDSTONES

SmN	Metre	Lith	FA	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Ba	Ce	Cr	Ga	Nb	Ni	Pb	Rb	Sc	Sr	Th	V	Y	Zr	Total*	LOI
KALA FORMATION																													
Upper Member																													
KS-121	4108	CS	FA4	72.84	0.20	4.27	1.59	0.19	0.47	19.50	0.03	0.86	0.05	146	32	3	0	6	3	11	49	12.9	74	7.9	10	15	116	98.98	13.59
KS-120	3983	VCS	FA4	84.21	0.32	6.23	1.80	0.04	0.75	5.04	0.27	1.28	0.05	261	58	7	0	9	6	16	75	12.1	65	18.9	26	18	275	99.46	5.02
KS-118	3898	CS	FA4	84.19	0.23	4.48	1.25	0.31	0.43	8.10	0.10	0.86	0.03	176	31	3	1	7	2	12	52	12.6	43	8.2	15	11	149	99.56	6.69
Middle Member																													
KS-116	3756	CS	FA3	80.72	0.31	5.23	1.79	0.07	1.54	8.99	0.34	0.97	0.05	192	54	14	3	8	5	11	51	14.3	111	11.1	27	19	248	99.22	7.59
KS-114	3623	CS	FA3	82.39	0.15	3.57	1.15	0.20	0.39	11.55	0.04	0.53	0.03	139	31	0	0	5	2	9	34	12.4	97	5.5	4	15	98	99.77	8.95
KS-112	3510	CS	FA3	76.82	0.27	6.46	1.74	0.06	1.06	11.68	0.38	1.47	0.05	222	41	10	4	7	7	14	82	12.7	166	10.3	19	17	146	99.44	9.38
KS-110	3217	CS	FA3	77.37	0.29	7.57	1.91	0.06	1.19	9.10	0.89	1.58	0.06	248	51	7	6	8	5	16	89	13.8	136	11.8	26	18	123	99.61	8.21
KS-107	3125	CS	FA3	77.33	0.39	10.21	2.91	0.06	1.14	4.31	1.35	2.19	0.10	402	65	15	5	11	8	21	118	12.5	88	18.3	38	25	164	99.93	4.26
KS-106	2960	VCS	FA3	80.46	0.36	9.85	3.19	0.02	1.38	1.89	0.60	2.21	0.04	401	41	34	11	10	18	21	131	13.1	57	9.3	50	13	128	100.51	3.16
Lower Member																													
KS-104	2895	CS	FA3	70.67	0.26	7.65	1.66	0.07	1.31	16.17	0.44	1.72	0.05	294	43	14	6	7	9	16	84	13.6	191	8.6	18	16	136	99.61	12.37
KS-103	2880	CS	FA3	74.49	0.36	7.17	3.11	0.05	1.90	10.87	0.38	1.60	0.07	252	42	15	9	9	11	16	86	10.4	137	10.0	31	22	140	98.98	9.74
KS-99	2765	VCS	FA3	89.08	0.24	6.58	1.59	0.01	0.65	0.12	0.35	1.35	0.02	245	41	8	7	7	7	13	81	5.8	24	9.2	18	14	123	99.49	1.22
KS-98	2720	CS	FA3	71.89	0.29	4.62	1.72	0.06	2.09	18.29	0.06	0.93	0.06	164	64	3	4	7	4	10	48	12.1	274	10.5	15	25	298	97.79	14.03
KS-97	2714	FS	FA3	54.53	0.47	8.81	3.26	0.21	7.31	21.98	0.06	3.20	0.18	314	54	36	12	10	17	34	124	9.8	290	12.5	44	21	137	99.15	19.95
KS-94	2666	VCS	FA3	83.09	0.35	8.73	2.71	0.03	1.25	1.00	0.79	1.99	0.06	361	51	14	11	9	12	19	107	10.1	42	12.1	35	16	143	99.82	2.33
KS-93	2635	CS	FA3	62.56	0.30	6.09	2.37	0.09	1.35	25.58	0.18	1.43	0.05	235	49	16	7	8	8	15	73	11.9	275	8.2	23	26	159	97.88	16.99
KS-91	2585	VCS	FA3	80.46	0.21	6.78	1.62	0.05	1.09	7.92	0.26	1.56	0.04	281	27	9	8	7	8	17	89	9.3	145	6.5	17	11	104	98.53	7.20
KS-89	2560	MS	FA3	67.65	0.36	7.96	2.49	0.10	1.48	17.65	0.45	1.80	0.06	304	49	15	8	9	10	16	93	14.1	258	10.4	25	23	178	97.98	13.25
KS-86	2432	CS	FA3	77.25	0.41	6.90	2.28	0.07	1.23	10.26	0.23	1.30	0.07	217	65	13	7	10	7	16	69	13.2	185	12.1	29	27	247	98.55	8.86
KS-84	2368	CS	FA3	77.66	0.31	7.93	2.28	0.07	1.27	8.71	0.29	1.40	0.06	238	47	12	8	8	9	19	79	11.2	173	10.1	24	21	155	98.57	8.08
KS-82	2330	MS	FA3	75.52	0.37	7.10	2.57	0.05	1.68	10.95	0.16	1.53	0.06	256	62	25	9	9	11	16	74	13.6	182	10.8	31	17	182	99.07	9.89
KS-80	2272	FS	FA3	70.44	0.44	7.08	3.24	0.05	1.63	15.59	0.03	1.42	0.08	221	79	31	8	10	13	15	68	14.4	226	14.5	39	20	264	98.38	12.67
KS-78	2240	CS	FA3	47.25	0.41	5.85	2.71	0.07	1.30	40.78	0.24	1.25	0.13	199	111	14	5	9	14	17	56	3.0	357	17.9	23	28	668	98.45	9.41
KS-76	2210	FS	FA3	76.15	0.38	7.40	2.37	0.07	1.66	10.23	0.36	1.30	0.08	254	67	12	8	10	8	20	71	11.8	174	13.7	25	27	236	98.81	23.38
KS-74	2157	MS	FA3	61.34	0.37	6.89	2.87	0.15	1.58	24.64	0.14	1.59	0.42	249	52	24	9	9	11	21	81	12.5	251	7.7	30	28	157	98.01	16.61
KS-72	2120	CS	FA3	80.13	0.39	9.57	2.75	0.03	1.40	3.02	0.62	2.03	0.06	312	49	18	13	11	13	17	125	10.0	74	10.6	38	16	136	99.67	4.25
JAGATI FORMATION																													
Upper member																													
KS-70	2075	MS	FA2	66.49	0.39	7.34	3.26	0.08	0.97	19.70	0.36	1.33	0.08	204	70	16	9	10	13	20	76	15.3	162	12.5	30	25	238	98.38	13.92
KS-68	2028	FS	FA2	65.86	0.47	8.21	3.24	0.07	2.12	18.27	0.15	1.52	0.09	228	65	29	10	11	14	19	80	14.2	172	12.8	40	26	254	98.52	14.23

Major elements wt%, trace elements ppm, total iron as Fe_2O_3. Data are tabulated anhydrous normalized (major elements summing to 100.0 wt%). Original anhydrous analytical total (Total*) and hydrous loss on ignition (LOI) are listed at right. Abbreviations: SmN - sample number; Metre - stratigraphic height in metres; Lith - lithology: FS, M, CS, VCS - fine, medium, coarse, very coarse grained sandstone, respectively; Mst - mudstone; FA - Facies association; FA1 - fine-grained meandering; FA2 - flood-flow dominated meandering; FA3 - deep sandy braided; FA4 - shallow sandy braided.

Table 3. Continued.

SANDSTONES (ctd.)

SmN	Metre	Lith	FA	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Ba	Ce	Cr	Ga	Nb	Ni	Pb	Rb	Sc	Sr	Th	V	Y	Zr	Total*	LOI
JAGATI FORMATION(ctd.)																													
Upper member (ctd.)																													
KS-66	1988	CS	FA2	61.45	0.24	5.60	1.69	0.12	1.10	28.35	0.06	1.34	0.05	206	39	9	6	6	6	28	70	12.0	223	6.4	13	24	130	97.87	18.10
KS-64	1938	MS	FA2	68.79	0.33	6.72	2.01	0.22	1.04	19.15	0.54	1.13	0.07	163	62	13	7	9	7	36	65	10.8	191	10.6	15	32	204	98.31	13.77
KS-62	1893	MS	FA2	79.49	0.43	7.98	2.37	0.07	0.92	6.71	0.49	1.46	0.08	209	72	12	10	11	10	18	89	9.4	91	13.5	32	25	294	99.20	6.27
KS-60	1872	MS	FA2	80.13	0.39	8.02	2.06	0.11	0.73	6.94	0.49	1.07	0.06	168	73	12	8	10	10	18	76	11.5	135	17.1	28	28	305	98.89	6.75
KS-58	1830	FS	FA2	72.04	0.43	7.62	1.88	0.10	1.18	15.08	0.21	1.38	0.09	198	74	26	8	10	12	16	73	14.8	180	14.8	29	23	325	98.26	11.89
KS-56	1788	FS	FA2	78.84	0.45	9.66	3.37	0.07	1.19	4.19	0.21	1.92	0.09	298	68	30	11	11	16	42	109	12.6	77	13.2	48	21	208	98.93	5.3
KS-54	1743	MS	FA2	54.97	0.54	7.73	3.13	0.17	1.66	29.80	0.11	1.77	0.12	285	87	21	9	12	13	35	83	12.2	266	15.2	39	31	336	98.16	19.3
KS-53	1738	MS	FA2	85.64	0.36	6.05	1.73	0.04	0.61	4.76	0.18	0.55	0.08	146	61	6	7	9	6	11	45	10.1	65	11.8	23	21	256	99.09	4.8
KS-51	1672	CS	FA2	89.91	0.27	4.37	0.96	0.12	0.43	3.24	0.17	0.47	0.05	106	44	3	5	8	5	32	35	8.6	65	7.4	15	19	117	99.51	3.4
KS-49	1628	FS	FA2	77.96	0.44	8.71	3.25	0.06	0.97	6.71	0.57	1.25	0.08	271	61	17	11	11	15	16	76	11.4	107	12.5	39	21	248	99.17	6.76
Middle Member																													
KS-47	1620	FS	FA2	79.47	0.56	11.53	4.03	0.01	1.18	0.23	0.74	2.22	0.04	325	84	39	15	13	18	15	129	8.2	46	17.0	60	28	307	99.96	2.59
KS-45	1574	FS	FA2	34.89	0.35	5.98	2.97	0.09	9.05	44.93	0.01	1.67	0.06	187	37	24	8	8	12	32	61	3.5	161	6.0	27	18	138	101.17	28.87
KS-44	1545	CS	FA2	82.23	0.29	8.00	2.28	0.02	1.68	3.74	0.56	1.14	0.06	167	48	13	9	9	11	12	74	7.2	53	8.6	28	15	142	99.47	5.28
KS-42	1490	MS	FA2	82.67	0.28	6.51	1.62	0.09	0.88	7.12	0.18	0.59	0.06	113	52	14	7	8	6	25	45	11.6	92	8.3	26	17	169	98.83	6.84
KS-41	1450	FS	FA2	73.37	0.42	7.60	2.61	0.12	1.46	12.85	0.40	1.10	0.07	189	64	16	9	10	11	26	67	12.2	138	11.5	32	25	218	98.46	10.62
KS-40	1419	FS	FA2	77.62	0.40	7.31	2.50	0.12	1.12	9.21	0.15	1.46	0.09	243	76	24	8	10	12	42	81	9.6	107	11.1	27	19	251	98.67	8.02
KS-37	1250	FS	FA1	82.42	0.54	9.41	3.43	0.05	1.14	1.05	0.56	1.39	0.03	230	90	34	11	13	21	14	80	10.8	40	17.2	48	27	234	100.08	2.79
KS-36	1230	CS	FA1	88.91	0.32	6.76	2.06	0.01	0.75	0.11	0.10	0.94	0.04	162	47	17	9	9	8	19	56	7.6	21	8.8	31	14	156	99.61	1.39
KS-34	1155	CS	FA1	88.22	0.51	6.34	2.65	0.04	0.84	0.28	0.22	0.86	0.06	133	58	11	8	13	9	8	54	8.6	19	11.8	33	22	199	99.64	1.34
KS-31	960	MS	FA1	89.60	0.29	6.59	1.73	0.02	0.64	0.14	0.04	0.92	0.02	262	49	16	9	9	14	9	69	5.6	24	9.4	33	16	132	99.99	1.55
KS-30	955	CS	FA1	69.82	0.24	4.79	2.01	0.21	0.98	21.26	0.01	0.62	0.05	128	40	6	6	7	6	12	35	13.1	166	6.1	18	20	102	97.99	15.00
KS-28	920	MS	FA1	72.42	0.27	4.84	1.70	0.11	1.28	18.64	0.00	0.68	0.06	115	49	8	5	8	5	29	39	13.5	179	6.8	10	24	122	98.02	13.81
Lower Member																													
KS-26	845	FS	FA1	84.91	0.61	8.77	1.97	0.02	0.86	1.14	0.23	1.43	0.07	522	100	29	11	13	15	14	77	9.5	46	16.9	52	25	499	99.36	2.73
KS-25	820	FS	FA1	83.07	0.57	10.25	3.00	0.01	1.14	0.25	0.27	1.42	0.01	226	106	31	13	13	15	9	83	8.5	27	18.1	51	23	434	100.03	3.50
KS-24	750	MS	FA1	87.87	0.42	6.21	1.45	0.04	0.69	2.31	0.29	0.66	0.05	136	78	20	7	10	7	12	44	8.4	45	12.5	33	20	355	99.66	3.10
KS-22	700	FS	FA1	83.15	0.48	8.41	2.71	0.08	0.86	2.75	0.12	1.38	0.06	229	88	27	11	12	19	28	81	9.2	52	16.4	50	27	337	99.78	4.16
KS-19	595	CS	FA1	91.09	0.34	5.98	1.40	0.01	0.47	0.11	0.01	0.56	0.03	110	70	12	7	9	11	8	42	6.4	19	10.5	19	21	309	99.61	1.50
KS-18	585	CS	FA1	89.18	0.36	7.00	1.58	0.01	0.74	0.14	0.13	0.81	0.05	134	61	15	9	10	10	10	58	8.2	17	11.5	33	19	242	100.01	1.84
KS-17	570	CS	FA1	84.92	0.45	8.19	2.48	0.03	0.97	1.62	0.29	0.99	0.07	161	70	19	10	11	13	8	64	10.1	31	13.8	44	20	263	99.77	3.20
KS-15	510	FS	FA1	67.06	0.61	9.75	2.98	0.12	2.52	14.73	0.34	1.79	0.10	285	79	37	12	14	20	22	87	14.1	157	15.9	52	25	348	98.64	13.13
KS-14	460	FS	FA1	78.04	0.50	8.61	3.04	0.07	1.64	6.36	0.46	1.18	0.10	223	88	16	10	12	13	13	69	9.7	66	14.8	47	24	360	99.46	7.34
KS-13	430	FS	FA1	84.52	0.51	9.08	2.64	0.02	1.13	0.39	0.32	1.33	0.06	202	82	28	11	12	17	14	78	7.3	36	16.0	48	27	364	99.86	2.38
KS-11	345	FS	FA1	44.66	0.63	6.09	3.06	0.37	1.29	42.47	0.13	1.22	0.09	178	129	15	7	12	12	35	54	3.9	139	17.2	32	41	701	99.34	24.73
KS-10	240	FS	FA1	75.60	0.54	10.08	3.55	0.05	2.28	5.55	0.13	2.15	0.07	300	77	32	13	13	18	22	108	13.4	67	17.1	49	25	295	99.51	7.41
KS-7	180	MS	FA1	90.84	0.32	5.02	1.40	0.02	0.68	0.83	0.13	0.72	0.04	113	60	8	6	9	4	9	43	7.6	26	9.1	25	17	255	99.52	1.71

Table 3. Continued.

SANDSTONES (ctd.)

SmN	Metre	Lith	FA	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Ba	Ce	Cr	Ga	Nb	Ni	Pb	Rb	Sc	Sr	Th	V	Y	Zr	Total*	LOI
JAGATI FORMATION(ctd.)																													
Lower Member (ctd.)																													
KS-5	75	MS	FA1	90.61	0.20	5.09	1.87	0.03	0.52	0.80	0.25	0.59	0.03	112	39	1	7	7	6	9	40	6.5	32	7.6	10	14	113	100.18	1.75
KS-4	65	MS	FA1	89.06	0.33	6.23	1.89	0.03	0.71	0.50	0.37	0.83	0.04	133	55	10	8	9	7	10	51	7.5	28	9.3	25	17	203	99.75	1.72
KS-3	60	MS	FA1	76.42	0.52	8.06	2.50	0.06	0.74	10.30	0.10	1.23	0.08	166	93	38	10	12	14	17	61	13.7	119	15.4	51	24	430	98.73	9.26
KS-1	35	MS	FA1	88.19	0.39	6.92	2.12	0.01	0.68	0.09	0.38	1.17	0.04	236	66	14	9	10	10	12	64	6.6	24	10.1	36	19	284	99.36	1.58

(B) MUDSTONES

SmN	Metre	Lith	FA	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Ba	Ce	Cr	Ga	Nb	Ni	Pb	Rb	Sc	Sr	Th	V	Y	Zr	Total*	LOI
KALA FORMATION																													
Upper Member																													
KS-122	4119	Mst	FA4	67.57	0.82	18.23	6.61	0.04	1.90	0.24	0.28	4.26	0.06	736	98	76	15	18	36	30	230	17.3	77	31.8	115	37	249	99.41	4.75
KS-119	3981	Mst	FA4	60.39	0.84	20.40	7.53	0.05	3.11	2.68	0.06	4.83	0.11	672	80	107	16	17	52	40	240	18.0	76	32.7	131	32	155	99.22	7.78
KS-117	3890	Mst	FA4	63.71	0.80	19.77	8.46	0.06	2.11	0.62	0.03	4.32	0.12	685	82	90	17	17	45	34	239	17.0	70	33.3	124	41	169	99.28	5.93
Middle Member																													
KS-115	3742	Mst	FA3	77.45	0.66	13.09	4.03	0.03	1.43	0.22	0.20	2.88	0.01	506	79	48	8	15	25	27	150	13.8	33	27.2	77	28	263	99.84	3.23
KS-113	3617	Mst	FA3	45.35	0.69	12.63	6.13	0.09	2.33	29.66	0.02	2.98	0.11	394	71	62	0	13	33	22	115	14.0	332	27.9	79	23	178	99.67	20.50
KS-111	3497	Mst	FA3	56.07	0.59	12.65	5.28	0.21	4.13	17.18	0.10	3.56	0.23	468	68	59	6	13	27	24	151	20.7	151	24.7	69	34	170	98.83	15.18
KS-109	3215	Mst	FA3	72.02	0.54	10.57	3.58	0.05	2.13	7.92	0.61	2.48	0.09	375	71	34	5	12	19	21	127	15.1	105	24.6	60	26	282	99.18	8.22
KS-108	3135	Mst	FA3	60.21	0.75	18.03	7.36	0.06	3.95	3.97	0.85	4.69	0.12	680	80	77	26	17	33	17	229	18.6	96	23.6	113	32	220	100.26	6.63
Lower Member																													
KS-105	2903	Mst	FA3	50.26	0.63	13.04	7.80	0.15	5.27	18.68	0.06	3.98	0.13	472	65	65	13	13	27	36	174	14.8	168	19.0	80	33	122	100.06	17.09
KS-102	2878	Mst	FA3	61.44	0.71	14.70	5.36	0.07	3.64	10.19	0.31	3.48	0.10	595	88	73	18	16	31	27	159	15.5	158	20.6	81	33	242	98.97	11.46
KS-101	2865	Mst	FA3	44.67	0.59	12.31	5.82	0.51	3.04	29.09	0.04	3.70	0.25	393	58	56	14	13	24	35	156	11.6	117	16.5	64	31	122	99.79	20.04
KS-100	2778	Mst	FA3	54.31	0.74	14.63	5.58	0.11	3.60	17.04	0.09	3.78	0.13	488	83	70	19	15	34	31	171	14.4	182	18.2	96	35	173	99.18	15.20
KS-96	2698	Mst	FA3	67.67	0.68	13.46	4.82	0.05	2.75	6.76	0.33	3.40	0.08	541	91	54	16	15	26	28	175	13.6	114	19.9	80	32	274	99.08	8.09
KS-95	2668	Mst	FA3	58.63	0.75	18.42	7.11	0.16	3.95	5.05	0.60	5.24	0.12	675	73	80	24	16	37	32	229	16.7	90	22.3	114	31	157	99.47	7.85
KS-92	2600	Mst	FA3	72.93	0.65	14.43	5.14	0.04	2.98	0.28	0.49	3.02	0.05	594	87	59	19	14	29	23	181	14.9	78	20.2	80	30	231	99.54	3.78
KS-90	2575	Mst	FA3	76.23	0.71	13.80	3.92	0.01	1.49	0.18	0.30	3.35	0.02	503	123	61	16	15	30	29	182	10.6	69	24.6	76	31	431	99.43	2.94
KS-88	2495	Mst	FA3	53.09	0.77	16.43	6.66	0.07	3.08	15.15	0.13	4.53	0.09	585	69	82	23	15	38	34	193	19.9	118	19.0	103	34	138	99.70	13.36
KS-87	2440	Mst	FA3	58.92	0.67	19.41	7.97	0.05	5.44	1.68	0.11	5.65	0.11	761	79	91	24	14	54	34	265	16.9	73	25.0	131	25	138	100.01	6.79
KS-85	2390	Mst	FA3	46.27	0.60	11.36	5.69	0.37	5.49	26.42	0.15	2.94	0.71	442	70	48	15	13	26	32	128	15.2	228	13.2	62	36	146	99.92	20.57
KS-83	2341	Mst	FA3	51.80	0.81	16.14	6.89	0.11	3.00	16.51	0.03	4.56	0.14	544	96	88	20	17	37	38	173	17.1	217	25.0	103	33	148	99.34	14.84
KS-81	2302	Mst	FA3	54.51	0.79	12.68	4.66	0.10	2.91	20.57	0.19	3.49	0.11	439	87	66	16	16	30	29	147	16.5	243	18.8	84	31	246	98.75	16.18
KS-79	2260	Mst	FA3	45.72	0.73	13.67	5.92	0.14	3.70	26.13	0.02	3.81	0.16	402	86	73	19	15	30	39	147	16.1	272	19.5	82	27	162	99.79	19.75
KS-77	2219	Mst	FA3	57.60	0.74	14.34	6.06	0.09	2.62	14.66	0.21	3.58	0.09	504	83	68	18	16	36	36	167	16.9	163	18.4	91	32	218	98.69	12.84
KS-75	2176	Mst	FA3	74.43	0.69	13.40	4.46	0.01	1.32	2.53	0.09	3.06	0.02	535	90	61	17	15	28	29	186	13.0	73	19.8	84	26	323	99.39	4.74
KS-73	2132	Mst	FA3	54.05	0.65	12.34	4.77	0.16	2.24	21.92	0.14	3.60	0.13	465	74	51	16	14	26	33	158	16.5	184	14.9	67	30	179	98.93	16.18

Table 3. Continued.

MUDSTONES (ctd.)

SmN	Metre	Lith	FA	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Ba	Ce	Cr	Ga	Nb	Ni	Pb	Rb	Sc	Sr	Th	V	Y	Zr	Total*	LOI
JAGATI FORMATION																													
Upper member																													
KS-71	2092	Mst	FA2	67.93	0.68	11.71	4.28	0.10	1.77	9.87	0.44	3.12	0.12	440	93	56	14	15	27	28	151	13.7	156	20.4	64	30	393	98.71	9.07
KS-69	2047	Mst	FA2	40.10	0.62	11.42	6.35	0.15	3.11	34.66	0.06	3.44	0.10	374	62	49	15	14	29	37	155	11.7	177	14.0	71	33	102	100.62	22.61
KS-67	2003	Mst	FA2	45.47	0.65	12.28	5.93	0.12	2.31	30.04	0.03	3.01	0.16	377	71	48	16	13	26	31	133	12.8	217	15.9	64	33	144	99.60	20.34
KS-65	1964	Mst	FA2	40.03	0.60	10.94	5.90	0.27	4.63	34.41	0.10	2.84	0.29	326	75	54	14	12	26	32	115	9.4	350	15.3	63	39	117	100.52	23.82
KS-63	1920	Mst	FA2	68.44	0.62	12.54	3.71	0.07	2.58	8.36	0.48	3.09	0.09	461	78	51	16	14	21	27	136	12.6	127	16.1	71	31	261	98.85	9.20
KS-61	1878	Mst	FA2	59.27	0.79	20.93	9.30	0.03	2.96	0.55	0.04	6.05	0.09	797	85	109	29	17	50	30	286	16.5	48	24.8	133	41	163	99.63	4.92
KS-59	1857	Mst	FA2	55.88	0.71	14.97	5.75	0.22	2.61	14.75	0.31	4.37	0.43	579	72	61	20	16	30	22	205	17.9	180	17.4	78	50	152	99.03	12.52
KS-57	1820	Mst	FA2	54.00	0.73	15.19	5.92	0.10	3.88	15.73	0.04	4.28	0.13	502	89	71	20	15	31	33	178	16.3	171	21.9	87	29	171	99.59	14.66
KS-55	1765	Mst	FA2	62.25	0.75	13.51	5.25	0.06	2.31	12.24	0.26	3.23	0.14	475	83	53	17	16	27	24	145	15.8	161	19.5	84	28	265	98.99	11.50
KS-52	1710	Mst	FA2	38.82	0.56	9.43	4.72	0.29	1.94	41.48	0.10	2.55	0.12	275	64	45	12	12	20	21	101	6.8	154	12.2	64	25	141	100.17	24.77
KS-50	1658	Mst	FA2	56.86	0.78	15.09	6.46	0.10	4.36	11.60	0.21	4.41	0.13	548	90	70	20	16	33	28	186	15.8	167	21.7	98	32	222	99.12	12.62
Middle Member																													
KS-48	1622	Mst	FA2	61.32	0.77	18.72	6.84	0.08	2.31	4.74	0.17	4.92	0.11	646	91	82	25	18	38	36	220	16.8	105	22.7	126	42	165	99.76	7.65
KS-46	1610	Mst	FA2	55.45	0.67	10.70	5.23	0.24	2.55	22.14	0.19	2.72	0.12	404	88	54	14	15	22	41	112	14.9	183	17.0	65	31	299	98.79	16.83
KS-39	1348	Mst	FA2	67.22	0.71	17.43	6.00	0.07	2.84	1.25	0.29	4.08	0.12	718	88	76	23	16	37	21	194	14.5	75	20.9	101	33	198	99.80	5.28
KS-38	1287	Mst	FA2	41.68	0.56	12.49	6.71	0.25	2.85	31.80	0.02	3.56	0.07	461	72	55	17	13	26	32	147	12.1	102	13.6	69	38	105	100.22	21.55
KS-35	1170	Mst	FA1	54.93	0.62	14.05	6.13	0.13	5.36	14.86	0.07	3.74	0.13	561	81	73	20	14	32	26	163	15.9	128	17.5	77	33	161	99.21	14.98
KS-33	1065	Mst	FA1	76.35	0.63	13.61	4.71	0.02	1.49	0.27	0.30	2.58	0.03	500	84	43	17	14	23	19	149	11.7	50	19.5	69	27	269	99.91	3.18
KS-32	975	Mst	FA1	65.21	0.71	18.79	8.01	0.04	2.19	0.08	0.09	4.84	0.04	778	88	88	25	16	39	28	234	13.8	52	23.0	116	33	176	99.85	4.02
KS-29	935	Mst	FA1	45.34	0.58	10.93	6.11	0.29	2.02	31.32	0.07	3.23	0.10	424	72	41	15	13	21	29	141	10.1	127	12.8	63	30	173	99.79	20.48
Lower Member																													
KS-27	855	Mst	FA1	55.46	0.72	18.17	7.24	0.08	2.95	10.08	0.01	5.15	0.15	827	79	93	24	17	39	32	214	18.3	121	18.3	115	41	175	99.44	10.70
KS-23	740	Mst	FA1	71.08	0.52	9.10	3.08	0.09	1.38	12.93	0.09	1.67	0.07	282	68	25	11	12	14	21	91	11.6	83	13.3	48	24	246	98.43	10.73
KS-21	680	Mst	FA1	73.73	0.72	14.65	5.53	0.03	1.31	0.64	0.16	3.19	0.05	510	112	54	19	18	26	26	164	13.7	44	22.3	86	33	292	100.17	3.74
KS-20	600	Mst	FA1	67.26	0.74	18.66	6.44	0.02	1.68	0.27	0.03	4.85	0.07	682	93	93	22	17	47	36	244	16.3	67	24.7	124	28	206	99.75	4.26
KS-16	525	Mst	FA1	38.24	0.43	10.36	4.91	0.62	15.96	27.06	0.01	2.38	0.03	488	52	51	14	9	22	55	92	11.7	354	11.9	53	31	75	101.55	28.02
KS-12	355	Mst	FA1	66.33	0.71	13.53	5.67	0.06	2.47	7.30	0.09	3.41	0.43	581	101	71	15	16	31	27	153	14.4	132	21.7	86	38	302	98.76	8.52
KS-9	235	Mst	FA1	84.20	0.48	9.16	2.87	0.02	1.08	0.73	0.27	1.17	0.02	204	91	29	12	12	20	11	73	8.4	34	16.2	44	23	318	99.86	2.75
KS-8	190	Mst	FA1	69.47	0.53	11.87	4.67	0.09	4.32	5.92	0.06	2.92	0.14	396	81	52	13	13	24	21	134	14.1	48	20.1	67	29	197	98.97	9.22
KS-6	80	Mst	FA1	82.86	0.68	8.58	3.17	0.03	0.91	2.33	0.06	1.32	0.06	320	112	39	12	15	15	31	85	11.3	81	17.3	65	35	461	99.79	4.28
KS-2	40	Mst	FA1	70.85	0.61	15.60	6.79	0.03	1.85	0.32	0.47	3.42	0.06	672	80	59	18	15	32	20	170	11.0	52	21.7	93	27	180	99.66	3.23

Table 4. Average compositions of the Siwalik sandstones and mudstones from the Khutia Khola section, by facies association (data from Table 3).

	Sandstones					Mudstones							
FA	FA1	FA2	FA3	FA4	Average	FA1	FA2	FA3	FA4	Average	Total Average	UCC	PAAS
Code	FGM	FFDM	DSB	SSB		FGM	FFDM	DSB	SSB				
N	23	18	23	3		14	16	22	3				
Major elements (wt%)													
SiO_2	81.76	72.88	73.71	80.42	77.19	65.81	54.73	58.80	63.89	60.81	69.00	66.00	62.80
TiO_2	0.43	0.39	0.33	0.25	0.35	0.62	0.68	0.69	0.82	0.70	0.53	0.50	1.00
Al_2O_3	7.32	7.50	7.22	4.99	6.76	13.36	13.80	14.16	19.47	15.20	10.98	15.20	18.90
Fe_2O_3	2.31	2.50	2.36	1.55	2.18	5.38	5.84	5.68	7.54	6.11	4.14	4.98	7.22
MnO	0.06	0.09	0.07	0.18	0.10	0.11	0.14	0.12	0.05	0.11	0.10	0.10	0.11
MgO	1.02	1.57	1.60	0.55	1.19	3.21	2.83	3.20	2.37	2.90	2.05	2.20	2.20
CaO	5.73	13.39	12.67	10.88	10.67	8.15	17.94	13.26	1.18	10.13	10.40	4.20	1.30
Na_2O	0.21	0.31	0.38	0.14	0.26	0.13	0.21	0.23	0.12	0.17	0.22	3.90	1.20
K_2O^5	1.08	1.30	1.58	1.00	1.24	3.13	3.68	3.72	4.47	3.75	2.49	3.40	3.70
P_2O	0.05	0.07	0.08	0.05	0.06	0.10	0.14	0.14	0.10	0.12	0.09	0.20	0.16
Trace elements (ppm)													
Ba	195	206	261	194	214	516	497	516	698	557	385	550	650
Ce	73	63	54	40	57	85	80	81	86	83	70	64	80
Cr	19	18	16	4	14	58	62	65	91	69	42	35	110
Ga	9	9	7	1	7	17	18	16	16	17	12	17	20
Nb	11	10	9	7	9	14	15	15	17	15	12	25	2
Ni	12	11	9	4	9	28	29	31	44	33	21	20	55
Pb	15	25	17	13	17	27	30	30	35	30	24	20	20
Rb	62	74	83	59	70	150	164	171	237	180	125	112	160
Sc	9	11	12	13	11	13	14	16	17	15	13	11	16
Sr	60	130	170	60	105	98	156	148	74	119	112	350	200
Th	13	12	11	12	12	19	18	21	33	23	17	11	15
V	36	31	27	17	28	79	82	85	123	92	60	60	150
Y	22	23	20	15	20	31	34	31	37	33	27	22	27
Zr	293	230	190	180	223	231	195	207	191	206	215	190	210
LOI (wt%)	5.52	10.46	10.08	8.43		9.15	14.32	12.03	6.15				
Ratios													
SiO_2/Al_2O_3	11.16	9.72	10.21	16.10		4.93	3.97	4.15	3.28		6.29	4.34	3.32
K_2O/Na_2O	5.12	4.19	4.20	7.40		24.57	17.32	16.18	36.61		11.57	0.87	3.08
Th/Sc	1.39	1.08	0.95	0.93		1.43	1.30	1.35	1.87		1.32	0.97	0.91
Zr/Sc	32.11	21.20	16.45	14.37		17.72	13.96	13.33	10.96		16.51	17.27	13.13
Al_2O_3/Na_2O	34.64	24.18	19.18	36.95		104.81	65.01	61.65	159.45		50.93	3.90	15.75
Al_2O_3/K_2O	6.77	5.78	4.56	4.99		4.27	3.75	3.81	4.36		4.40	4.47	5.11

Abbreviations: UCC - Upper Continental Crust values from Taylor and McLennan (1985); PAAS - Post-Archean Australian shale values from Taylor and McLennan (1985); N - number of samples; for other parameters refer to Table 3.

monsoon throughout the past 10.7 m.y. *Geology,* **29**, 31–34.

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. *Bulletin of the Department of Geology, Tribhuvan University,* **4**, 1–70.

Dickinson, W. R. 1970. Interpreting detrital modes of greywacke and arkose. *Journal of Sedimentary Petrology,* **40**, 695–707.

Dickinson, W. R. 1985. Interpreting provenance relations from detrital modes of sandstones. *In: Zuffa, G. G. (Ed.), Provenance of Arenites: North Atlantic Treaty Organization.* Advanced Study Institute Series 148, Reidel Publishing Company, 333–361.

Dickinson, W. R. and Suczek, C. A. 1979. Plate tectonics and sandstone compositions. *American Association of Petroleum Geologists Bulletin,* **63**, 2164–2182.

Dickinson, W. R., Beard, L. S., Brakenridge, G. R., Erjavec, J. L., Ferguson, R. C., Inman, K. F., Knepp, R. A., Lindberg, F. A. and Ryberg, P. T. 1983. Provenance of North American Phanerozoic sandstones in relation to tectonic setting. *Geological Society of America Bulletin,* **94**, 222–235.

Folk, R. L. 1980. *Petrology of Sedimentary Rock.* Austin, Texas, Hemphill, 182p.

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

Gautam, P. and Appel, E. 1994. Magnetic polarity stratigraphy of Siwalik Group sediments of Tinau Khola section in west central Nepal, revisited. *Geophysical Journal International,* **117**, 223–234.

Gautam, P. and Fujiwara, Y. 2000. Magnetic polarity stratigraphy of Siwalik Group sediments of the Karnali River section in western Nepal. *Geophysical Journal International,* **142**, 812–824.

Glennie, K. W. and Ziegler, M. A. 1964. The Siwalik Formations of Nepal. *International Geological Congress, 22, Delhi,* **25**, 82–95.

Hagen, T. 1969. Report on the Geological Survey of Nepal, vol. 1. Preliminary Reconnaissance, Druk von Art. *Denkschriften der Schweizerischen Naturforschenden Gesellschaft,* 185p.

Harrison, T. M., Copeland, P., Hall, S. A., Quade, J., Burner, S., Ojha, T. P. and Kidd, W. S. F. 1993. Isotopic preservation of Himalaya/Tibetan uplift, denudation and climate histories in two molasses deposits. *Journal of Geology,* **101**, 157–175.

Herron, M. 1988. Geochemical classification of terrigenous sands and shales from core data. *Journal of Sedimentary Petrology,* **58**, 820–829.

Huyghe, P., Mugnier, J. L., Gajurel, A. P, and Decaillau, B. 2005. Tectonic and climatic control of the changes in the sedimentary record of the Karnali River section (Siwaliks of western Nepal). *The Island Arc,* **14**, 311–327.

Ingersoll, R. V. and Suczek, C. A. 1979. Petrology and Provenance of Neogene sand from Nicobar and Bengal fans, DSDP site 211 and 218. *Journal of Sedimentary Petrology,* **49**, 1217–1228.

Johnsson, M. J. 1993. The system controlling the composition of clastic sediments. *Geological Society of America Special Paper,* **284**, 1–19.

Kimura, J. I. and Yamada, Y. 1996. Evaluation of major and trace element XRF analyses using a flux to sample ratio of two to one glass beads. *Journal of Mineralogy, Petrology and Economic Geology,* **91**, 62–72.

McLennan, S. M., Hemming, S., McDaniel, D. K. and Hanson, G. N. 1993. Geochemical approaches to sedimentation, provenance, and tectonics. *In: M. J. Johnsson and A. Basu (eds). Processes Controlling the Composition of Clastic Sediments, Geological Society of America Special paper,* **284**, 21–40.

Medlicott, H. B. 1875. Note on the geology of Nepal. *Records of Geological Survey of India,* **8**, 93–101.

Mugnier, J. L., Leturmy, P., Mascle, G., Huyghe, P., Chalaron, E., Vidal, G., Husson, L. and Delcaillau, B. 1999. The Siwalik of Western Nepal: I. Geometry and kinematics. *Journal of Asian Earth Sciences,* **17**, 629–642.

Nakata, T. 1989. Active faults of the Himalaya of India and Nepal. *Geological Society of America Special Paper,* **232**, 243–264.

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

Nesbitt, H. W. and Young, G. M. 1982. Early Proterozoic climates and plate motions inferred from major element chemistry of lutites. *Nature,* **299**, 715–715.

Ojha, T. P., Butler R. F., Quade, J., DeCelles, P. G., Richards, D. and Upreti, B. N. 2000. Magnetic polarity stratigraphy of the Neogene Siwalik Group at Khutia Khola, far western Nepal. *Geological Society of America Bulletin,* **112**, 424–434.

Pettijohn, F. J. 1975. *Sedimentary Rocks.* Harper & Row, New York. 628p.

Pilgrim, G. E. 1913. The correlation of the Siwaliks with mammal horizons of Europe. *Records of Geological Survey of India,* **43 (4)**, 264–326.

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

Quade J., Cater, J. M. L, Ojha, T. P., Adam J. and Harrison, T. M. 1995. Late Miocene environmental change in Nepal and the northern Indian subcontinent: Stable isotope evidence from paleosols. *Geological Society of America Bulletin,* **107**, 1381–1297.

Robinson, D. M., DeCelles, P. G. and Copeland, P. 2006. Tectonic evolution of the Himalaya thrust belt in western Nepal: Implication for channel flow models. *Geological Society of America Bulletin,* **118**, 868–885.

Roser, B. P. and Korsch, R. J. 1986. Determination of tectonic setting of sandstone-mudstone suites using SiO_2 content and K_2O/Na_2O ratio. *Journal of Geology,* **94,** 635–650.

Roser, B. P. and Korsch, R. J. 1988. Provenance signatures of sandstone-mudstone suites determined using discriminant function analysis of major-element data. *Chemical Geology,* **67**, 119–139.

Roser, B. P., Sawada, Y. and Kabeto, K. 1998. Crushing performance and contamination trails of a tungsten carbide ring mill compared to agate grinding. *Geoscience Reports of Shimane University,* **17**, 1–11.

Roser, B. P., Kimura, J. I. and Hisatomi, K. 2000. Whole-rock elemental abundances in sandstones and mudrocks from the Tanabe Group, Kii Peninsula, Japan. *Geoscience Reports of Shimane University,* **19,** 101–112.

Roser, B. P., Ulak, P. D., Nakayama, K., Kimura J. I. and Mori, H. 2002. Major element geochemistry of the Upper Cenozoic Siwalik Group along the Bakiya Khola Section, Central Nepal. *In: Charu C. Pant and Arun K. Sharma (eds). Aspects of Geology and Environment of the Himalaya*, Nainital, Gyanodaya Prakashan, 41–62.

Sah, R. B., Ulak, P. D., Gajurel, A. P. and Rimal, L. N. 1994. Lithostratigraphy of the Siwalik sediments of the Amlekhganj-Hetauda area, sub-Himalaya of Nepal. *Himalayan Geology,* **15**, 37–48.

Sharma, C. K., 1973. *Geology of Nepal.* Education Enterprises, Kathmandu, 164p.

Sharma, S. R., Subedi, D. N., KC, S. B., Khanal, R. P. and Tripathi, G. N. 2007. Geological Map of Petroleum Exploration Block-1, Dhangadi, Far Western Nepal (Scale: 1:250,000). *Petroleum Exploration Promotion Project, Department of Mines and Geology, Kathmandu, Nepal.*

Sigdel, A. and Sakai, T. 2016. Sedimentary facies analysis of the fluvial systems in the Siwalik Group, Karnali River section, Nepal Himalaya, and their significance for understanding the paleoclimate and Himalayan tectonics. *Journal of Nepal Geological Society,* **51**, 11–26.

Sigdel, A., Sakai, T., Ulak, P. D., Gajurel, A. P. and Upreti, B. N. 2011. Lithostratigraphy of the Siwalik Group, Karnali River section, far-west Nepal Himalaya. *Journal of Nepal Geological Society,* **43**, 83–101.

Suttner, L. J. and Dutta, P. K. 1986. Alluvial sandstone composition and paleoclimate, I, Framework mineralogy. *Journal of Sedimentary Petrology,* **56**, 329–345.

Suttner, L. J., Basu, A. and Mack, G. H. 1981. Climate and the origin of quartz arenite. *Journal of Sedimentary Petrology,* **51**, 1235–1244.

Taylor, S. R. and McLennan, S. M. 1985. *The continental crust: its composition and evolution,* Blackwell Scientific, Oxford, 312p.

Tokuoka, T., Takayasu, K., Yoshida, M. and Hisatomi, K. 1986. The Churia (Siwalik) Group of the Arung Khola area, west-central Nepal. *Memoirs of the Faculty of Science, Shimane University,* **20**, 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. *Memoirs of the Faculty of Science, Shimane University,* **22**, 131–140.

Ulak, P. D. 2004. Evolution of the fluvial system in Siwalik Group of Chatara-Barahakshetra area, east Nepal Himalaya. *Journal of Nepal Geological Society,* **30**, 67–74.

Ulak, P. D. 2009. Lithostratigraphy and late Cenozoic fluvial styles of the Siwalik Group along the Kankai River section, East Nepal Himalaya. *Bulletin of the Department of Geology, Tribhuvan University,* **12**, 63–74.

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

Ulak, P. D. and Nakayama, K. 2001. Neogene fluvial systems in the Siwalik Group along the Tinau Khola section, west central Nepal Himalaya. *Journal of Nepal Geological Society,* **25**, 111–122.

Upreti, B. N. 1999. An overview of the stratigraphy and tectonics of the Nepal Himalaya. *Journal of Asian Earth Sciences,* **17**, 577–606.

Wadia, D. N. 1957. *Geology of India.* Tata McGraw Hill Publ. Corp., New Delhi, India, 508p.

Weltje, G. J., Meijer, X. D. and De Boer, P. L. 1998. Stratigraphic inversion of siliciclastic basin fills: a note on the distinction between supply signals resulting from tectonic and climatic forcing. In: Hovius, N., Leeder, M. (Eds.), Thematic Set on Sediment Supply to Basins. *Basin Research,* **10**, 129–153.

Yoshida, M. and Arita, K. 1982. On the Siwaliks observed along some routes in Central Nepal. *Journal of Nepal Geological Society, Special Issue,* **2**, 51–58.

(Received: 10. 17, 2017, Accepted: 11. 11, 2017)

（要　旨）

Swostik Kumar Adhikari・酒井哲弥・Barry P. Roser，2018，極西ネパール，クティア川沿いに露出する新第三系シワリク層群の堆積岩の岩石学と全岩化学分析．島根大学地球資源環境学研究報告，36，1-13

ここでは極西ネパール，クティア川沿いに露出する新第三系シワリク層群より採取した砂岩 67 試料の鉱物組成を調べ，泥岩 55 試料と砂岩 67 試料の主要元素と微量元素の分析を，蛍光 X 線分析装置を用いて行った．分析の対象とした地層はジャガティ層とカラ層で，それらの地層からは 4 つの堆積組相が識別された．識別された堆積組相は下位から順に細粒蛇行河川システム（FA1），洪水流卓越蛇行河川システム（FA2），深い網状流河川システム（FA3），そして浅い網状流河川システム（FA4）である．すべての砂岩の平均組成は，石英 70%，長石 8%，岩片 22% であった．Pettijohn の QFL 図へのプロットにより，これらの砂岩は亜石質アレナイト（sublitharenite）から石質アレナイト（litharenite）に区分された．SiO_2 が最も含有量の多い主要元素であるが，その含有量にはばらつきがあった（38.25%～91.09%）．CaO の含有量は泥岩よりも砂岩で多かった．FA4 の泥岩を除くすべての堆積組相で，CaO の平均値は，平均の上部大陸地殻（UCC）と PAAS（Post-Archean Australian Shale）の値よりも大きい値となった．分析した残りの元素について，砂岩に比べて泥岩で含有量の値が高くなる傾向にあった．Herron の地球化学区分図へのプロットにより，泥岩のほとんどがワッケと頁岩に区分され，砂岩は亜石質アレナイトと石質アレナイトに区分された．