

Erosional unroofing of Himalaya in far western Nepal: a detrital zircon U-Pb geochronology and petrography study

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ABSTRACT

Since the collision between the Indian and Asian plates, several peripheral foreland basin were formed, and started to accumulate the sediments from the hinterland Himalayan orogeny. The sediments deposited at the northern tip of the Greater India have been uplifted, exhumed after the activation of several south propagating thrusts and finally transported to the foreland basin by southward flowing fluvial system. We present petrography and detrital zircon dating for the interpretation of possible provenance of the Neogene Siwalik foreland basin sediments in far western Nepal. The QFL ternary plot for provenance analysis show a 'recycled orogeny' field for the studied sandstone samples, indicating Tethys Himalaya, Higher Himalaya and Lesser Himalaya as the source of the foreland basin sediments. The detrital zircon U-Pb ages of the studied samples have shown that during the time of deposition there was dominant numbers of detritus supplied from the Tethys and upper Lesser Himalaya. Subsequently the amount of the Higher and Lower Lesser Himalaya increased during the time of deposition of the Middle Siwalik.

Keywords: U-Pb geochronology, Provenance, Siwalik Group, Nepal Himalaya

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INTRODUCTION

Petrographic study is precise and well-known tool for the provenance analysis of the detritus sediments (Dickinson 1970). Since last decade, detrital zircon U-Pb geochronology is well-established methodology in the aspect of associating the source and the sink, due to its uniqueness, i.e. chemically stable and mechanically durable, within the different depositional environments and weathering condition (DeCelles et al. 1998; DeCelles 2011; DeCelles and Giles 1996). The detritus sediments deposited in the foreland basin hold crucial information of the paleo tectonic activities during the time of the Himalaya exhumation. About 2400 km long world famous Himalayan mountain chain, extending from the Nanga Parbat in the west to the Namche Barwa in the east, is a typical continent-continent collision zone between Indian and Eurasian plates (Gansser 1964; Patriat and Achache 1984). Since the collision, several peripheral foreland basins were formed and started to accumulate the sediments from the hinterland Himalayan orogeny. The sediments deposited at the northern tip of the Greater India have been uplifted and exhumed, after the activation of several south propagating thrusts and finally transported to the foreland basin by southward flowing fluvial system. The coarsening-upward fluvial deposit of the Siwalik Group was deposited during middle Miocene to early Pleistocene tectonic activity (Tokuoka et al. 1986; Tokuoka et al. 1988a). The basal part is dominated by the mudstone, which gradually changed to coarse-grained sandstone at the middle and finally boulder conglomerate at the upper unit. These

detritus are well exposed and well-studied at various locations by numerous scientists with different perspective, like rate of sediment deposition, rate and exhumation history of the source region, climatic changes, paleogeography, and provenance analysis (Chirouze et al. 2012; DeCelles et al. 1998; Dhital et al. 1995; Huyghe et al. 2005; Mugnier et al. 1999a; Mugnier et al. 1999b; Nakayama and Ulak 1999; Ojha et al. 2000; Ojha et al. 2009; Robinson et al. 2001; Szulc et al. 2006; Tokuoka et al. 1990; Ulak and Nakayama 1998, 2001; Ulak 2005, 2009). The detritus in the Neogene Subathu basin were transported from the Lhasa terrace, Gangdese batholiths, Indus-Tsangpo suture zone, ultra-high pressure gneiss terrace and Tethys Himalaya (Ravikant et al. 2011 and reference therein). However, a study in Nepal Himalaya has shown that Neogene foreland basin sediments were mainly derived from the Dadeldhura Thrust sheet and possibly, from the Higher Himalaya, instead there was missing of detritus from Higher Himalayan Series (HHS) Leucogranite (DeCelles et al. 1998). Nevertheless, the present study recorded some younger grains resembling the age of the HHS leucogranite. The result inferred a straightforward sediment mixture from the Tethys Himalayan Series (THS), Lesser Himalayan Series (LHS) and partly from the HHS. Our purpose of this study is to accentuate the possible provenance of the Siwalik Group sediments in far western Nepal by means of combined optical petrography and U-Pb dating of detrital zircon grains of the representative samples of sandstones and siltstones along the Macheli Khola (MK) and Khutia Khola (KK).

REGIONAL GEOLOGY

Brief geology of the Nepal Himalaya

Nepal Himalaya is classified into four broad geotectonic belts which are separated by continental scale thrusts that developed parallel to the orogeny due to ongoing north-south compression thrust/faults system; the Tethys Himalayan Series (THS), Higher Himalayan Series (HHS), and Lesser Himalayan Series (LHS), and southernmost unit marked by the Neogene fluvial deposit; Siwalik Group (Gansser 1964) (Fig. 1). The THS is the northern unit, bounded between Indus Tsangpo Suture Zone (ITSZ) and a system of normal faults; South Detachment Fault System (STDS) (Godin et al. 1999a; Godin et al. 1999b; Hodges et al. 1996). It comprises folded and thrust/faulted highly deformed low-grade metamorphic and fossiliferous sedimentary rocks of Paleozoic through Eocene age. The sedimentary rocks were deposited before, during and immediate after the collision of Indian and Asian Plates (Gaetani and Garzanti 1991). This sedimentary rocks overlain the Miocene aged amphibolite grade, meta-sedimentary and meta-igneous rocks of the HHS and extends to the Main Central Thrust (MCT) in the south. The gneiss body of the HHS was further divided into three members. First member named as Formation I consists of paragneiss and pelitic schist. Formation III consists of orthogneiss body that intrudes the calcisilicate gneiss and paragneiss of Formation II. In the upper part of the HHS large body of leucogranite of age 24 and 12 Ma (Carosi et al. 1999; Hodges et al. 1996) present whereas in the southern

most part large bodies of Cambrian-Ordovician granitic mylonites and undeformed granitic body present (DeCelles et al. 2000; DeCelles et al. 1998; DeCelles et al. 2014; Gehrels et al. 2011; Hodges et al. 1996). The HHS detrital zircon ages broadly cluster around 1000 Ma with lesser peaks at 500 Ma, 1700–1500 Ma and 2500 Ma (DeCelles et al. 2000; Gehrels et al. 2003; Gehrels et al. 2006; Martin et al. 2005; Parrish and Hodges 1996; Richards et al. 2005). Before middle Miocene, the HHS was underneath the surface and that was exposed to the surface after 15–13 Ma (Godin et al. 2001b; Hodges et al. 1994). The huge proportion of the Himalaya was occupied by the Lesser Himalayan rock that exposed between south of MCT and north of Main Boundary Thrust (MBT). The whole zone of the LHS in Nepal was classified into lower and upper by Pan African diastrophism (Valdiya 1995; Valdiya 1998). The Lower Lesser Himalayan Series (LLHS) comprises Paleoproterozoic to upper most Precambrian age (Parrish and Hodges 1996; Sakai 1983; Valdiya 1995; Valdiya 1998). The Ulleri augen gneiss peaks at late Paleoproterozoic age resemble the age of the Lower Lesser Himalaya (Kohn et al. 2010; Richards et al. 2005). The Upper Lesser Himalayan Series (ULHS) consists of Permo- Carboniferous Gondwana rocks that were overlain by early Cretaceous to Eocene marine sedimentary rocks. The upper most part of this litho unit is the fluvial deposit of Miocene Dumri Formation that unconformably overlain the marine deposit (DeCelles et al. 1998; DeCelles et al. 2004). The Neogene Siwalik Group overlain the Quaternary fluvial deposit named as Indo Gangetic Plain.

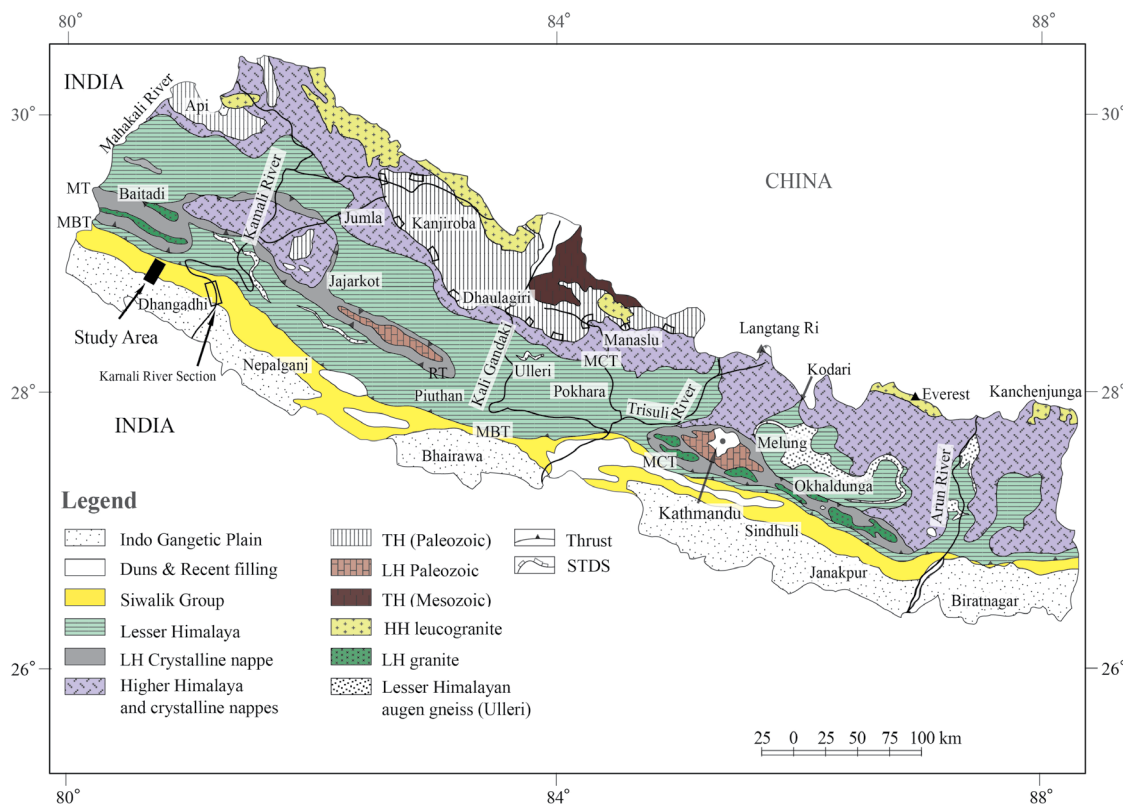


Fig. 1: Geological map of Nepal modified after Upreti and Le Fort (1999). LH: Lesser Himalaya, HH: Higher Himalaya, TH: Tethys Himalaya, MBT: Main Boundary Thrust, MCT: Main Central Thrust, HFT: Himalayan Frontal Thrust, STDS: South Tibetan Detachment System. Thick solid black rectangle shows the study area.

Tertiary Foreland basin

Dumri Formation is the youngest unit of the Neogene foreland sediments found along the hanging wall of MBT that was deposited during early to mid-Miocene age. The unit is about 1300 m thick and composed mainly sandstone and mudstone those deposited as fluvial channel, crevasse splay, and over bank deposit (Sakai 1983; Sakai 1989) in foredeep foreland basin system. Although this formation is beyond the scope of this paper, it is mentioned here because this formation is the first fluvial deposit in Neogene Foreland basin (DeCelles et al. 1998).

Siwalik Group

The youngest Himalayan unit is a fluvial deposit of middle Miocene to early Pleistocene age making the southern hills of the Himalaya. The unit is about 5 km thick, and based on the lithological distribution the unit was further classified into three sub groups; lower, middle, and upper Siwaliks (Quade et al. 1995; 1990; Tokuoka et al. 1986; 1988b). The basal part is dominated by the variegated mudstone intercalated with fine-grained sandstone and siltstone with dominancy of mudstone. The sediments were deposited in the foredeep of the foreland basin by meandering fluvial system. The Middle Siwalik is dominated by coarse-grained sandstone having a typical “salt and pepper” texture, interbedded with grey mudstone. The sediments in this subgroup were deposited in foredeep fluvial system by different flow regime. The basal part and the middle part of this subgroup was deposited by flood flow dominated meandering system while the upper most part containing the very-coarse grained to pebbly sandstone were deposited by braided river (Dhital et al. 1995; Ulak 2005). The lowermost boundary of this subgroup was marked as ~10 Ma while the upper boundary was marked as ~3-4 Ma (Appel et al. 1991; Nakayama and Ulak 1999). The upper most sub group; Upper Siwalik, is dominated by pebble to boulder conglomerate with some sand and mud lenses. This unit was deposited in wedge top system by anastomosed river channels at the basal part that changes to gravelly braided at the middle part and the upper part the boulder conglomerate was deposited by debris flow dominated fluvial system (Dhital et al. 1995; Ulak 2005). The biostratigraphy study constrain the age of the Siwalik Group between ~14 Ma and ~1 Ma (Corvinus and Nanda 1994) which is identical with the paleomagnetic age (Appel et al. 1991; Gautam and Rösler 1999; Harrison et al. 1993; Ojha et al. 2000; Ojha et al. 2009; Rösler et al. 1997). However, a recent paleomagnetic study of Siwalik Group along the Karnali River Section (east from the current study area) suggested the oldest age of the Siwalik Group as ~16 Ma (Gautam and Fujiwara 2000) and postulate the Siwalik was deposited since earliest mid Miocene. A lithostratigraphic study in Karnali River section has shown that the paleo-Karnali River had a large drainage basin system, which accommodate the sediments from Higher Himalaya, earlier than rest of the sections in Central Himalaya (Sigdel et al. 2011). However, in Khutia Khola section (~50 Km west of the Karnali River) the fluvial facies during the Neogene was interfluvial setting of major streams (Adhikari and Sakai 2015).

METHODOLOGY

All the laboratory analysis has been done at Key Laboratory of Continental Collision and Plateau Uplift, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing China.

Petrography

Sandstone petrographic study is well suited for the provenance analysis of the detritus sediments (Dickinson 1970; Ingersoll et al. 1984). Total five samples were analyzed for the petrographic study following the Gazzi-Dickinson point counting method (Dickinson 1970; Gazzi 1966) by means of Olympus BX 41 polarizing microscope. We collected and analyzed three samples from Machheli Khola section (Lower Siwalik 2, Middle Siwalik 1) and two Middle Siwalik samples from Khutia Khola. More than 300 grains per sample were counted differentiating Feldspar (K-feldspar and plagioclase), Quartz (mono crystalline and polycrystalline quartz) and lithic grains (rock fragments) under different magnification levels and the results were plotted in ternary diagram.

U-Pb Dating

From each samples, following the heavy liquid separation technique, we separated the zircon. About 300 numbers of zircons were mounted and polished until 1/3 of the surface is removed. The dating procedure was run through an Agilent 7500a Inductively Coupled Plasma-Mass Spectrometer (ICP-MS) coupled with a New Wave Research UP193FX Excimer laser (New Wave Instruments, USA) and a homogenizing imaging optical system. Ablated ions were carried from Laser to the ICP-MS torch through a 3 mm i.d. PVC tube mixing with Helium gas and high-purity argon gas. This procedure will reduce elemental fractionation of the sample. The mounted and polished samples (different size and shape) were ablated by laser with a 35 μm spot size, at a repetition rate of 8 Hz with spot energy density of 8 - 10 J/cm². To avoid the atmospheric Pb contamination, after every analytical session the gas line was purged for more than an hour. Duration of each spot analysis was completed in 100 s (15s standby position of laser, laser ablated time 40 s, and delay time 45 s). Detail procedure is described in Cai et al. (2011). The statistical calculation software GLITTER 4.0, calibrated with the zircon standard Plesovice 337 \pm 0.37 Ma (Sláma et al., 2008) for instrumental mass bias and isotopic fractionation was used for data extraction and after that the data was run through excel macro program (available from <http://www.laserchron.org>) that normalized individual curves based on the number of consistent analyses. Each curve includes the same area and then stacks the probability curves (Gehrels et al. 2011). For age determination, raw count rates for ²⁹Si, ²⁰⁴Pb, ²⁰⁶Pb, ²⁰⁸Pb, ²³²Th, ²³⁸U were collected. Three integration times were used: 30 μs for all four Pb, 6 μs for ²⁹Si and 15 μs for the rest of the isotopes. We dated 100 grains from each sample, even though there is a contradiction about the number of grains should be dated to achieve 95% confidence level in sedimentary rocks. Vermeesch (2004) mentioned in his research finding that at

least 114 grains would be the best however, there are some research those pin point that measurement of at least 60 grains will be enough to get the 95% confidence (Cawood and Nemchin 2001; Dodson et al. 1988). We present $\pm 10\%$ of concordance age data and report the $^{206}\text{Pb}/^{238}\text{U}$ for zircons less than 1000 Ma and the $^{207}\text{Pb}/^{206}\text{Pb}$ for zircons >1000 Ma.

RESULTS AND DISCUSSIONS

Lower Siwalik

We analyzed two samples (MK-01 and MK-03) from Lower Siwalik from Machheli Khola section. Sample MK-01 is from fine- to medium-grained grey colored sandstone interbedded with variegated mudstone. The modal composition of the sandstone samples is Qt 84%, F 1%, and L 15% (Table 1). Dominantly small grains quartz cemented the large grains while calcite also presence as cementing material. Calcite grains are nearly altered position and showing the similar optical feature of feldspar. Among the 100 dated grains from sample MK-01, only 86 numbers of grains have concordia age, and the grains clusters between ~500 Ma to 1200 Ma having a distinctive peak age at ~500 Ma and ~809 Ma. Some other subordinate peaks are at ~988 Ma, 1477 Ma, and 2456 Ma. The youngest age recorded is 184 Ma where the oldest age 2974 Ma (Fig. 3). The samples clearly resemble the age of the Upper Lesser Himalaya and the Tethys Himalaya whereas the minor peak of ~988 Ma point out the Higher Himalaya act as a possible source. The presence of few Proterozoic grains added the possibility of Lower Lesser Himalayan source. The next sample, MK-03 is from thick- bedded, medium-grained, mottled reddish grey colored sandstone interbedded with grey mudstone showing the modal composition as Q 83%, P 2%, and L 15% (Table 1). From this sample, only 87 numbers of grains have concordia age, and the age ranges from 118 Ma to 3280 Ma, while a single grain is 35 Ma. The dominant numbers of ages clustered between 418 and 1000 Ma showing the peak age at 452 Ma and 905 Ma. The Proterozoic and older age grains have shown a minor clusters with peaks at 1822 Ma and 2460 Ma (Fig. 3). This result is identical with the previous sample and point out the mixed sediment source dominantly Tethys and Upper Lesser Himalaya with addition of Lower Lesser Himalaya and Higher Himalaya.

Table 1: Point counting result of sandstone samples from western Nepal, Q-Quartz, F- Feldspar, L-Lithic fragments.

Lithology	Sample Number	Q	F	L
Middle Siwalik	KK-05	81	3	15
Middle Siwalik	KK-06	74	2	23
Middle Siwalik	MK-11	77	8	15
Lower Siwalik	MK-01	84	1	15
Lower Siwalik	MK-03	83	2	15

Middle Siwalik

Three samples (MK-11, KK-05 and KK-06) are collected from Middle Siwalik for further analysis. The samples yielded

the detrital zircon U-Pb ages ranging between 127 Ma and 2976 Ma. Sample MK-11 is from thick-to very-thick bedded “salt and pepper” sandstone with some pebbly sandstone at the upper most units. Some marl beds are observed near by the sample location. The basic composition of sandstone samples observed in thin section is Qt 77%, F 8%, and L 15 % (Table 1). Metamorphic grains are abundant as lithic grains while sedimentary are proportionally less. The detrital zircon U-Pb ages ranging from 438 Ma to 2976 Ma while a single grain have 23 Ma age. The dominant cluster is between 450 Ma and 1170 Ma while some minor clusters at ~1500 Ma and 2500 Ma and the cluster peak ages are at 499 Ma, 998 Ma and 1798 Ma (Fig. 3). Sample KK-05 is from coarse-grained, “salt and pepper” texture sandstone interbedded with brown mudstone. The leading percentage of sandstone increases towards up-section. The petrography study shows that the basic composition of this sample as Qt 81%, F 3%, and L 15% (Table 1) where large number of the space is occupied by the metamorphic lithic grains. Micas are present but proportionally in less numbers. Sample KK-05 yielded the detrital zircon ages from 127 Ma to 2898 Ma. The dominant numbers of grains clusters at ~500 Ma with some minor clusters between ~650 Ma and 1000 Ma marking a distinctive peak at 490 Ma with subordinate peak at 990 Ma (Fig. 3).

Sample KK-06 is from medium-grained, thick- to very-thick bedded sandstone. The basic composition of this sample is Qt 74%, F 2%, and L 23% (Table 1). Abundantly calcite is a cementing material and very few grains of mica are present. Sample KK-06 yielded the detrital zircon age between 142 Ma and 2537 Ma. In this sample the grains clusters at ~400-600 Ma, 700-1200 Ma, 1550-1750 Ma, 1880-2180 Ma and ~2500 Ma, marking a peak age at 490 Ma, 811 Ma and 964 Ma.

The modal QFL composition of sandstone sample from present study is Lower Siwalik Qt 83%, F 2%, L 15%; Middle Siwalik Qt 78%, F 4%, L 18%. In all the samples from both the subgroup, monocrystalline quartz are dominant than polycrystalline quartz. The proportion of feldspar is far less than plagioclase and absent in some samples. The lithic grains are mainly of sedimentary (carbonate, chert, siltstone and mudstone) and metamorphic (schist and gneiss with biotite and muscovite). After plotting the result in ternary diagram for provenance, all the samples fall in “Recycled Orogenic” field (Fig. 2). The distribution of feldspar and lithic grains clearly rules out the major source as is Tethys Himalaya (low-grade rocks) additionally point to the possibility of Higher Himalayan source rock. Even though the characteristic minerals of Higher Himalaya, like garnet, staurolite, sillimanite were not identified in the thin section.

The detrital zircon U-Pb ages of the Lower Siwalik clustering the peak at ~500 Ma clearly resemble the age of the Tethys Himalaya and Upper Lesser Himalayan source and the whereas the minor peak of ~988 Ma point out the Higher Himalaya act as a possible source. The presence of few Proterozoic grains added the possibility of Lower Lesser Himalayan source. A younger grain ~35 Ma possibly source from the Leucogranite of Higher Himalaya and the younger

grains of ~125-130 Ma was sourced from the granitic body of Tethys Himalaya. Similar to the lower Siwalik the detrital zircon U-Pb ages dominantly clusters ~500 Ma and ~1000 Ma while there is presence of some other subordinate peaks at ~1700 Ma and 2500 Ma.

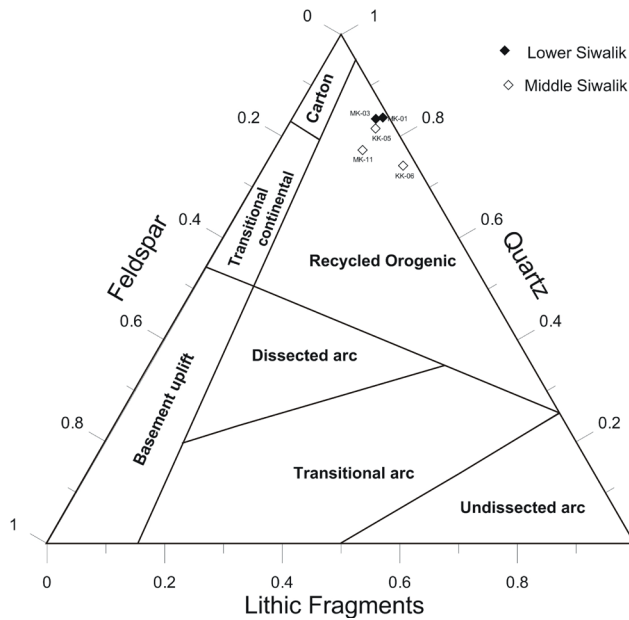


Fig. 2: Quartz Felspar Lithic diagrams of the Siwalik Group along the Machheli Khola (MK) and Khutia Khola (KK) section following Gazzi-Dickinson point counting method.

There are numerous zircon U-Pb studies conducted to constrain the age of the Himalayan unit, which is later compiled by Gehrels et al. (2011). The Lesser Himalaya is divided into lower and upper Lesser Himalaya in which the Upper Lesser Himalaya is Permo-carboniferous to Eocene in age and even Oligocene-Miocene, and the older unit is Lower Lesser Himalaya of Paleoproterozoic to Precambrian age (Parrish and Hodges 1996; Sakai 1983; Valdiya 1995; Valdiya 1998). The intermediate fine-grained volcanic rocks and gneiss found throughout the LHS are ~1850 and ~2500 Ma (DeCelles et al. 2004; McKenzie et al. 2011). The Higher Himalayan rocks yielded the U-Pb peak age at ~1000 Ma with some minor peaks at 500, 1700-2000 and 2500 Ma (DeCelles et al. 2000; Gehrels et al. 2011; Richards et al. 2005) with additional there is presence of Tertiary Leucogranite body (Carosi et al. 1999; Carosi et al. 2013; Godin et al. 2001a). The Tethys Himalayan meta-sedimentary rocks clustered between ~480-570 Ma, 750-1200 Ma and 2430-2560 Ma (Aikman et al. 2008; DeCelles et al. 2000; Gehrels et al. 2011). Regarding the tectonic within the Himalaya, the activation of MBT was at ~10-12 Ma that make rise of the Lesser Himalayan forming the duplex, ultimately higher rate of erosion of the Lower Lesser Himalaya by this time (DeCelles et al. 2001; Mishra et al. 2013). Maybe due to the activation of MCT at 23-20 Ma and was reactivated at 5-3 Ma (Arita et al. 1997; Le Fort 1975) the erosion of the Higher Himalayan rocks were much higher. During the Paleogene time the sediments were sourced from

Lhasa Terrane, Gangdase batholiths, Indus-Tsangpo suture zone, ultra-high pressure gneiss terrane and Tethys Himalaya until the Early Miocene time (Najman et al. 2009; Najman et al. 2004), whereas, during the Miocene the Lesser Himalaya, Higher Himalaya and Tethys Himalayan rocks were much more eroded acting as a major source of sediments for the foreland basin (Baral et al. 2015, 2017; DeCelles et al. 1998a; DeCelles et al. 2004; DeCelles et al. 2014; Neupane et al. 2016; Ravikant et al. 2011).

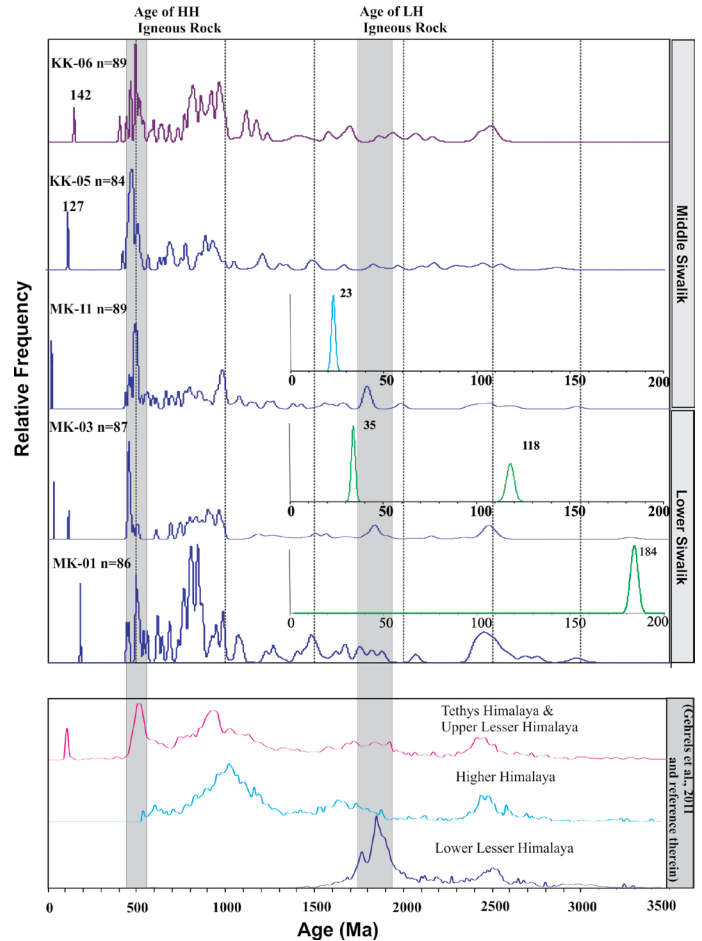


Fig. 3: Normalized probability plot of detrital zircons age for the Machheli Khola and Khutia Khola section (this study): Lower Siwalik (MK-01, MK-03), Middle Siwalik (MK-11, KK-05, KK-06). N = number of grain analyzed. Shade marks indicates the age of Igneous rocks in Himalaya (after DeCelles et. al. 2004), and the lower three curves representing the Himalayan litho units are referenced after Gehrels et al. 2011).

This results from the present study shows that Tethys Himalaya and upper Lesser Himalaya were the dominant source of the sediments while proportionally the Higher Himalaya and Lower Lesser Himalaya also act as a possible source of the sediments during the time of deposition of Middle Siwalik (Fig. 3). Among these, three samples in KK-05 and KK-06, there are presence of Cretaceous grains, which might be eroded from the granitic body in Tethys Himalaya. A single grain of Oligocene age recorded in sample MK-11, possibly eroded from the Higher Himalayan Leucogranite.

CONCLUSION

Since the time of Indo-Asia Collision, the Himalaya was uplifting after the activation of several thrust/faults systems that indicated the exhumation and erosion of Himalaya, which ultimately feed the hinterland foreland basin by southward flowing fluvial system. In different time, different part of the Himalaya was exhumed, in this regards the present study analyzed the detritus of the Neogene foreland basin sediments and put some effort to figure out the change of sediment source and linkup with the Himalayan exhumation. We present petrography and detrital zircon dating for the interpretation of possible provenance of the Neogene Siwalik foreland basin sediments in far western Nepal. The QFL ternary plot for provenance analysis show a “recycled orogeny” field indicating the sediments were reworked and recycled during the Himalayan orogeny. All the three tectonic units, Tethys Himalaya, Higher Himalaya and Lesser Himalaya act as the source of the foreland basin sediments. The detrital zircon U-Pb ages of the studied samples have shown that during the time of deposition there was dominant numbers of detritus supplied from the Tethys and upper Lesser Himalaya. Subsequently the amount of the Higher and Lower Lesser Himalaya increased during the time of deposition of Middle Siwalik.

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