Textural and mineralogical maturities and provenance of sands from the Budhi Gandaki-Narayani Nadi, central Nepal

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ABSTRACT

The Budhi Gandaki-Narayani Nadi in the Central Nepal flows across fold-thrust belts of the Tethys Himalaya, Higher Himalaya, Lesser Himalaya, and the Sub-Himalaya, and is located in sub-tropical to humid sub-tropical climatic zone. Within the Higher Himalayas and the Lesser Himalayas, a high mountain and hilly region give way to the long high-gradient, the Budhi Gandaki Nadi in the northern region. At the southern region within the Sub-Himalayas, having a wide Dun Valley, gives way to the long low-gradient Narayani Nadi. Sands from Budhi Gandaki-Narayani Nadi were obtained and analysed for textural maturity and compositional maturity. The textural analyses consisted of determining roundness and sphericity of quartz grains for shape, and determining size of sand for matrix percent and various statistical measures including sorting. The analysis indicates that the textural maturity of the majority of sands lies in submature category though few textural inversions are also remarkable. Sands from upstream to downstream stretches of the main stem river show depositional processes by graded suspension in highly turbulent (saltation) current to fluvial tractive current, as confirmed from the C-M patterns.

The compositional variation includes quartz, feldspar, rock fragments, mica, etc. The quartz grain percent slightly increases from the mountains to the lower relief areas. The percent feldspar decreases rapidly whereas the percent rock fragment decreases gradually along the downstream transport of sediment. The Budhi Gandaki-Narayani Nadi sands range from sublitharenite to lithic arenite composition in QFL diagram, and are remarkably poorer in feldspar compared to rock fragment. Among the rock fragments, the high-grade metamorphic rock fragments are dominant in the upstream stretch of the main stem Narayani Nadi stretch while the sedimentary lithics are remarkable in the downstream stretch. The QFL plots also show that the studied sands belong to recycled orogeny provenance and agree with the current tectonic setting of the Himalayas. Mineralogically, the sands (MMI=100%-203%) are not as matured as the normal sands. MMI fluctuates along downstream distance due to mixing of sediments from the major tributaries at various places along the main stem river.

Key words: Fluvial sand, Sedimentary process, Graphic measures, Textural maturity, Mineralogical maturity

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INTRODUCTION

The Gandaki Nadi is one of the main rivers of Nepal. The Budhi Gandaki-Narayani Nadi are the major tributaries of the Gandaki River. The Gandaki Nadi has a total catchment area of 46,300 sq. km, and the Gandaki basin contains three of the world’s 14 mountains over 8,000 meters, i.e. Dhaulagiri, Manaslu and Annapurna I. Among them the Manaslu is the source of the Budhi Gandaki Nadi. The other main tributaries of the Gandaki River are Trishuli, Marshyangdi, Madi, Seti Gandaki, Kali Gandaki and the Rapati Nadis (Fig. 1). Nepal covers about 700 km long segment stretching NW-SE of the Central Himalaya which is tectonically active consisting of fragile geology. Hence from the North to the South across the Himalayas different morphotectonic zones can be recognized.

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Fig. 1: Geological map of study area. Source complied from map of Central Nepal, Stöcklin and Bhattarai (1977), Geological Map of Central Nepal, DMG (1980), and Annapurna- Manaslu-Ganesh Himal, Colchen et al. (1986)
Riverbank erosion and bank failure may produce a significant amount of sediment (Rosgen, 1976) in the Himalayan rivers. These sediments are deposited and transferred through the river systems and are finally carried to the Bay of Bengal through the grand river like the Ganges. The fluvial sediments are probably characterized by their composition and textural properties, which are believed to be not constant over the distance of transport along the river course, though they tended to be affected by frequent local contribution by contributories. The initial composition and texture of the sediment mainly depends on the source rock and tectonics (Ingersoll and Suczek, 1979; Dickinson et al., 1985). Depending upon the climate, topography and weathering conditions (Beryer and Bart, 1976), extent of abrasion and sorting and scale of recycling (Cavazza et al., 1993; Cox and Lowe, 1995), the sand composition and texture are affected.

The four major provenance terranes; stable craton, basement uplift, magmatic arc and recycled orogeny were distinguished in earlier studies (Ingersoll and Suczek, 1979; Dickinson et al., 1985). The detrital framework constituents of sand tend to vary depending on these provenance settings.

Buynevich and FitzGerald (2001) studied the textural and compositional characterization of recent sediments along a paraglacial estuarine coastline, Maine, USA. They analysed bottom sediments at the mouth of the Kennebec River and concluded that the mineralogical maturity increased from channel and outer bar to offshore sands.

Tamrakar and Gurmaita (2001) studied textural and compositional variation of sand along the Manahara-Bagmati River. They found that the grain size decreased downstream, sorting improved, quartz content increased whereas feldspar and rock fragments decreased downstream quite remarkably. The modified maturity index reported ranged from 19.8 to 214, which increased from the Manahara to Bagmati River sands.

Tamrakar and Shrestha (2008) suggested that rivers originating from the Lesser Himalaya with unstable slope are even more capable to flush out sediment compared to the rivers of the Siwaliks. Tamrakar et al. (2008) studied petrology of Rapati River sand, Hetauda-Chitwan Dun Basin, central Nepal and concluded that the Rapati River sand was quarto-lithic in composition and plotted on recycled orogeny provenance. The Rapati River sand was poorer in feldspar but richer in lithic fragments and quartz compared to the other sands/sandstones and also concluded that due to the dilution of feldspar by weathering and rapid breakdown in head waters the maturity of sand improved downstream.

Hulka and Heubeck (2010) studied composition and provenance history of late Cenozoic sediments in southeastern Bolivia and concluded that the textural maturity of sandstone decreased stratigraphically upward throughout the section and mineralogical maturity decreased upsection of the Chaco Basin, probably due to the high degree of reworking in shoreline systems.

The aims of the present study were to assess the maturity status and their downstream variation for the fluvial sands from one of the major river systems of the Himalayan region, i.e., the Budhigandaki-Narayani Nadi stretch, and to verify the provenance mode for the studied sands.

**METHODOLOGY**

The sediment sample from the river was collected from intended location and exact location was marked and verified by looking topographic map and using GPS. The head water distance was taken from Samdo about 500 m south from the Larke Bazar from where the Budhi Gandaki Nadi begins to flow by melting of glaciers, e.g., Sonam Glacier. The Budhi Gandaki Nadi is the continuation of the Larke Khola.

For the purpose of compositional and textural studies, 25 sediment samples of about 500g each were collected at interval of 10-15 km (Fig. 2), of which 20 sediment samples were from the Budhi Gandaki-Narayani Nadi and 5 samples were from the confluence rivers. They were obtained from bars, essentially above the flow level. Each sample was sieved at an interval of 1φ. The sieve size was selected according to modified Udden-Wentworth grain-size scale proposed by Blair and McPherson (1990). The fraction retained in pan was further analysed using pipette analysis to obtain proportion of silt and clay in each sample.

![Fig. 2: Longitudinal profile of the Budhi Gandaki-Narayani Nadi](image)

The potash feldspar stained to yellow and plagioclase stained to pink (Haye’s and Klugman’s method). In case of carbonate, the sand grain sample was stained in silver nitrate solution and potassium chromate.  Carbonate grains stained a deep red brown. Then two-hundred grains per slide were point counted using modal analysis following Gazzi-Dickinson’s method of counting. The constituents like quartz, feldspar, rock fragment, heavy mineral, mica and other grains were distinguished and counted and percentage was calculated.

For each of coarse, medium, fine and bulk sands, about 100 quartz grains were separated and studied for roundness and sphericity. Powers (1953) roundness chart was used to...
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RESULTS

Classification of sand size grade

The majority of the samples were fresh and are light grey to dark grey in colour (Table 1). Sediments from the Budhi Gandaki Nadi ranged from slightly muddy sand to sand (Table 2; Fig. 3). Those of the Trishuli Nadi and Narayani Nadi ranged from gravelly sand to sand. The samples from the confluence rivers were mainly sand.

Table 2: Sediment texture of samples

| Section | Sample | Clay | Silt | Sand | Muddy Sand | Gravelly Sand | Sedimentary Texture |
|---------|--------|------|------|------|------------|---------------|---------------------|
| Budhi Gandaki | S1 | 2 | 3 | 55 | 10 | 10 | slightly gravelly sand |
| | S2 | 1 | 3 | 43 | 20 | 16 | gravelly sand |
| | S3 | 1 | 2 | 50 | 17 | 13 | slightly gravelly sand |
| | S4 | 1 | 3 | 50 | 18 | 15 | gravelly sand |
| | S5 | 1 | 3 | 50 | 18 | 15 | slightly gravelly sand |
| | S6 | 1 | 3 | 50 | 18 | 15 | gravelly sand |
| | S7 | 1 | 3 | 50 | 18 | 15 | slightly gravelly sand |
| | S8 | 1 | 3 | 50 | 18 | 15 | gravelly sand |
| | S9 | 1 | 3 | 50 | 18 | 15 | slightly gravelly sand |
| | S10 | 1 | 3 | 50 | 18 | 15 | gravelly sand |
| | S11 | 1 | 3 | 50 | 18 | 15 | slightly gravelly sand |
| | S12 | 1 | 3 | 50 | 18 | 15 | gravelly sand |
| | S13 | 1 | 3 | 50 | 18 | 15 | slightly gravelly sand |
| | S14 | 1 | 3 | 50 | 18 | 15 | gravelly sand |
| | S15 | 1 | 3 | 50 | 18 | 15 | slightly gravelly sand |
| | S16 | 1 | 3 | 50 | 18 | 15 | gravelly sand |
| | S17 | 1 | 3 | 50 | 18 | 15 | slightly gravelly sand |
| | S18 | 1 | 3 | 50 | 18 | 15 | gravelly sand |
| | S19 | 1 | 3 | 50 | 18 | 15 | slightly gravelly sand |
| | S20 | 1 | 3 | 50 | 18 | 15 | gravelly sand |
| | S21 | 1 | 3 | 50 | 18 | 15 | slightly gravelly sand |
| | S22 | 1 | 3 | 50 | 18 | 15 | gravelly sand |
| | S23 | 1 | 3 | 50 | 18 | 15 | slightly gravelly sand |
| | S24 | 1 | 3 | 50 | 18 | 15 | gravelly sand |
| | S25 | 1 | 3 | 50 | 18 | 15 | slightly gravelly sand |
| | S26 | 1 | 3 | 50 | 18 | 15 | gravelly sand |

Where, Sam. = sample number, dist. = distance from head water, d. = dark, gr.= grey; sG = sandy gravel, pS = pebbly sand, cpS = cobble pebble sand, gS = gravelly sand, mS = muddy sand; SB = side bar; sW = slightly weathered, mW = moderately weathered, F = fresh;

compare the outlines of quartz to determine roundness value of Folk (1955). For determining the projection sphericity, Rittenhouse’s (1943) chart was used.

Sands were classified texturally ad compositionally. Textural maturity of sands was determined using criteria of Folk (1951). Folk (1951) studied stages of textural maturity in sedimentary rocks and concluded that there are mainly four stages of textural maturity in sediments, (i) immature, (ii) sub mature (iii) mature and (iv) super mature. Besides, Folk (1980) also suggested for textural inversion occurring in sediment.

Compositional maturity was determined from modified Maturity Index (MMI) of McBride and Picard (1987). Initially, Pettijohn (1957) introduced the mineralogical maturity index as:

\[
MI = \left(\frac{\%\text{quartz} + \%\text{chert}}{\%\text{feldspar} + \%\text{rock fragments}}\right) * 100
\]

McBride and Picard (1987) and Picard and McBride (1993) have introduced modified maturity index as:

\[
MMI = \left(\frac{\%\text{quartz} + \%\text{chert}}{\%\text{other grains}}\right) * 100
\]

They suggested that for mineralogical maturity the heavy minerals, mica and skeletal grains play important role.
Fig. 3: Gravel, sand and mud triangular diagram (after Folk 1974) for classifications and nomenclature of the Budhi Gandaki–Narayani Nadi sediments.

Statistical parameters of grain size

In the Budhi Gandaki Nadi Segment, Mean (Mz) and median (ɸ50) grain sizes range, respectively from 1.45ɸ (S2) to 2.55ɸ (S3) and from 1.6ɸ (S2) to 2.6ɸ (S3) (Table 3). Inclusive graphic standard deviation of samples from the Budhi Gandaki Nadi Segment ranges from 0.47 ɸ (S5) to 1.36 ɸ (S2), and are poorly to moderately sorted. Inclusive Graphic Skewness (SKI) ranges from -0.09 (S1) to 0 (S5) as from coarse-skewed to near symmetrical skewness. Kurtosis (KG) ranges from 1.06 (S1) to 1.97 (S3), and are mesokurtic to very leptokurtic, respectively.

Mean (Mz) and median (ɸ50) grain sizes of samples from the Trishuli Nadi range from 1.36 ɸ (S11) to 2.45 ɸ (S14) and from 1.75 ɸ (S8) to 2.5 ɸ (S14), respectively.  The samples are poorly 1.28ɸ (S12) to moderately 0.54ɸ (S9) sorted. Skewness (SKI) ranges from -0.36 (S12) to 0.04 (S13) as from strongly coarse-skewed to near symmetrical skewness. Kurtosis (KG) ranges from 0.45 (very platykurtic, S12) to 1.20 (leptokurtic, S8).

In the Narayani River Segment, Mean (Mz) and median (ɸ50) grain sizes range respectively from 1.8ɸ (S19) to 3.33ɸ (S15) and from 1.35ɸ (S20) to 3.25ɸ (S15 and S17). Inclusive graphic standard deviation of samples shows moderately sorted 0.44ɸ (S16) to poorly sorted 1.15ɸ (S20). Skewness (SKI) ranges from -0.25 (S21) to 0.19 (S15) as from coarse-skewed to fine skewness. Kurtosis (KG) ranges from 0.60 (very platykurtic, S20) to 1.33 (leptokurtic, S21) (Fig. 4; Table 3).

The confluence river sample (C1) from the Trishuli Nadi is moderately sorted, near symmetrical skewed and mesokurtic. The sample C2 from the Marsyangdi Nadi is moderately well sorted near symmetrical skewed and platykurtic (Table 6). The confluence river sample C3 from the Seti Nadi is moderately well sorted, near symmetrical skewed and platykurtic, whereas the confluence river sample C4 from the Kali Gandaki Nadi is moderately well sorted, finely skewed and mesokurtic. The sample C5 from the Rapati Nadi shows well sorting, fine skeweness and is mesokurtic. The overall sorting decreases form the Budhi Gandaki to the Narayani Nadi, which means the sorting improves from poor sorting to well sorting indicating that the sand sized sediments tend to be well sorted towards downstream (Fig. 4; Table 3). The improvement of sorting against the distance of transport is attributed to hydraulic sorting and contribution of fines from the confluence rivers and streams. The overall skewness fluctuates but a trend line...
slightly increases indicating the apparent increase of fines in the downstream stretches. Relatively coarse skewed sediments in the Budhi Gandaki Nadi compared to those from the Narayani Nadi Segment reflects higher gradient and stream power of the former river.

**Grain size plot on C-M diagram**

From C-M diagram plot (IV and V categories), the river dominated by sediments of graded suspension in highly turbulent current and river tractive current deposits (Table 4, Fig. 5). Most of the Budhi Gandaki and the Trishuli Nadi have transported sands in suspension, and the Narayani River has transported sands in bed load transport. It may be due to the gradient of the rivers. Therefore, plotting the sand samples shows that some river sand sized sediments have transported in graded suspension while others in tractive current (Fig. 5).

**Grain shape**

Quartz is the most widely studied grain type among the grains for the shape study due to its relative durability to chemical decomposition and mechanical breakdown (Pettijohn et al. 1987). Therefore, roundness and sphericity were estimated for the quartz grains. Roundness ranged from 1.56 to 2.86 for coarse sand fraction, 1.66 to 3.08 for medium sand fraction, 2.42 to 3.5 for fine sand fraction and 1.88 to 3.01 for bulk sand fraction (Table 5). Roundness indicates that the river is active in abrasion, however, due to the mixing of the sediments from other river, the roundness varies. Sphericity ranges from 0.68 to 0.76 for coarse sand, 0.67 to 0.74 for medium sand, 0.69 to 0.74 for fine sand and 0.69 to 0.72 for bulk sand. Sphericity of all coarse, medium, fine and bulk sands suggests that the sphericity of quartz grains varied less than roundness (Table 5). Roundness of quartz in all the size fractions of sands of the Budhi Gandaki–Narayani Nadi tends to increase as the distance of transport increases. The fine sand shows the better trends compared to other sand fractions (Fig. 6).

**Table 4: Summarized table of C-M diagram**

| Sample | Dist. (km) | C1 (%) | C2 (%) | C3 (%) |
|--------|-----------|--------|--------|--------|
| 1      | 0         | 0.78   | 0.63   | 0.3    |
| 2      | 2         | 0.78   | 0.63   | 0.3    |
| 3      | 4         | 0.78   | 0.63   | 0.3    |
| 4      | 6         | 0.78   | 0.63   | 0.3    |
| 5      | 8         | 0.78   | 0.63   | 0.3    |
| 6      | 10        | 0.78   | 0.63   | 0.3    |

**Table 5: Result of grain shape analysis of sand**

| Sample | BS | MS | FS | BK | Val |
|--------|----|----|----|----|-----|
| 1      | 0.78 | 0.63 | 0.3 |
| 2      | 0.78 | 0.63 | 0.3 |
| 3      | 0.78 | 0.63 | 0.3 |
| 4      | 0.78 | 0.63 | 0.3 |
| 5      | 0.78 | 0.63 | 0.3 |

**Fig. 5: Plot C-M diagram of the Budhi Gandaki–Narayani Nadi sediments**

The textural maturity of the Budhi Gandaki- Narayani Nadi is dominated by sub mature texture. The range of texture maturity varied from immature to mature but the sub mature is dominant, since it depends upon mud %, roundness and sorting. The Budhi Gandaki-Narayani Nadi Segment lacks matured sediment due to presence of notable matrix. But in
case of the Narayani Nadi, the samples S15 and S18 show textural abnormality perhaps due to the mixing of fines from mud flows. Mixing of the Kali Gandaki Nadi into the Trishuli Nadi adds fines causing textural abnormality (Fig. 7, Table 6) in the sediment.

Fig. 6: Roundness vs. distance of sand samples: (a) coarse fraction sand, (b) medium fraction sand, (c) fine fraction sand, and (d) bulk fraction of sand.

Figure 6: Roundness vs. distance of sand samples: (a) coarse fraction sand, (b) medium fraction sand, (c) fine fraction sand, and (d) bulk fraction of sand.

Variation trends of sand composition
Quartz

In the Budhi Gandaki Nadi, quartz varies from 50% (S1) to 67% (S7). The percentage of quartz decreases up to 110 km of the Budhi Gandaki Nadi, and begins to increase at 120 km at the Trishuli Nadi where quartz content varies from 58% (S10) to 64% (S11), and the content increases up to 160 km downstream and then again it decreases up to 210 km in the Narayani Nadi Segment. The quartz percent in the Narayani Nadi varies from 53% (S15) to 64% (S21) (Table 7; Fig. 8a). Although the trend line of quartz percentage fluctuates, the overall trend shows that the quartz percent slightly increases towards downstream (Fig. 9a).

Table 6: Summarized table of textural maturity

| Section | Sample no. | Distance (km) | Sand | Mean Roundness | d | Textural Maturity (Folk 1974) |
|---------|------------|---------------|------|----------------|---|-------------------------------|
| BK      |            |               |      |               |   |                               |
| BN      |            |               |      |               |   |                               |
| MN      |            |               |      |               |   |                               |
| SN      |            |               |      |               |   |                               |
| RN      |            |               |      |               |   |                               |
| Spl     |            |               |      |               |   |                               |

Where, BK = Bulk sand, A = angular, SA = Sub angular, SR = Sub rounded, TN = Trishuli Nadi, MN = Marsyandi Nadi, SN= Seti Nadi, RN= Rapati Nadi. Spl = sample number. PS= Poorly sorted, MS= Moderately Sorted, MWS= Moderately Well Sorted, WS= Well sorted.
Table 7: Modal composition of the Budhi Gandaki–Narayani Nadi sand

| Section | Sample | Grain (μm) | Composition (%) | Recalculated (%)* | Sediment type | MMI |
|---------|--------|------------|----------------|-------------------|---------------|-----|
| Budhi Gandaki Nadi | S1 | 68 | 9 | 95 | 15 | 1 | 100 | 0.31 |
| | S2 | 102 | 9 | 92 | 12 | 1 | 100 | 0.31 |
| | S3 | 124 | 9 | 89 | 11 | 1 | 100 | 0.31 |
| | S4 | 146 | 9 | 85 | 15 | 1 | 100 | 0.31 |
| | S5 | 168 | 9 | 81 | 18 | 1 | 100 | 0.31 |
| | S6 | 190 | 9 | 77 | 22 | 1 | 100 | 0.31 |
| | S7 | 212 | 9 | 74 | 26 | 1 | 100 | 0.31 |
| | S8 | 234 | 9 | 71 | 29 | 1 | 100 | 0.31 |
| | S9 | 256 | 9 | 68 | 32 | 1 | 100 | 0.31 |
| | S10 | 278 | 9 | 65 | 35 | 1 | 100 | 0.31 |
| | S11 | 300 | 9 | 62 | 38 | 1 | 100 | 0.31 |
| | S12 | 322 | 9 | 59 | 41 | 1 | 100 | 0.31 |
| | S13 | 344 | 9 | 56 | 44 | 1 | 100 | 0.31 |
| | S14 | 366 | 9 | 53 | 47 | 1 | 100 | 0.31 |
| | S15 | 388 | 9 | 50 | 50 | 1 | 100 | 0.31 |
| | S16 | 410 | 9 | 47 | 53 | 1 | 100 | 0.31 |
| | S17 | 432 | 9 | 44 | 56 | 1 | 100 | 0.31 |
| | S18 | 454 | 9 | 41 | 59 | 1 | 100 | 0.31 |
| | S19 | 476 | 9 | 38 | 62 | 1 | 100 | 0.31 |
| | S20 | 498 | 9 | 35 | 65 | 1 | 100 | 0.31 |
| | S21 | 520 | 9 | 32 | 68 | 1 | 100 | 0.31 |
| Narayani Nadi | S22 | 124 | 9 | 89 | 11 | 1 | 100 | 0.31 |
| | S23 | 146 | 9 | 85 | 15 | 1 | 100 | 0.31 |
| | S24 | 168 | 9 | 81 | 18 | 1 | 100 | 0.31 |
| | S25 | 190 | 9 | 77 | 22 | 1 | 100 | 0.31 |
| | S26 | 212 | 9 | 74 | 26 | 1 | 100 | 0.31 |
| | S27 | 234 | 9 | 71 | 29 | 1 | 100 | 0.31 |
| | S28 | 256 | 9 | 68 | 32 | 1 | 100 | 0.31 |
| | S29 | 278 | 9 | 65 | 35 | 1 | 100 | 0.31 |
| | S30 | 290 | 9 | 62 | 38 | 1 | 100 | 0.31 |
| | S31 | 312 | 9 | 59 | 41 | 1 | 100 | 0.31 |
| | S32 | 334 | 9 | 56 | 44 | 1 | 100 | 0.31 |
| | S33 | 356 | 9 | 53 | 47 | 1 | 100 | 0.31 |
| | S34 | 378 | 9 | 50 | 50 | 1 | 100 | 0.31 |
| | S35 | 399 | 9 | 47 | 53 | 1 | 100 | 0.31 |
| | S36 | 421 | 9 | 44 | 56 | 1 | 100 | 0.31 |
| | S37 | 443 | 9 | 41 | 59 | 1 | 100 | 0.31 |
| | S38 | 465 | 9 | 38 | 62 | 1 | 100 | 0.31 |
| | S39 | 487 | 9 | 35 | 65 | 1 | 100 | 0.31 |
| | S40 | 509 | 9 | 32 | 68 | 1 | 100 | 0.31 |

Q = quartz, M = mica, F = feldspar, Ls = total sedimentary rock fragment, Lm = total metamorphic rock fragments, Lt = total rock fragment, H = heavy minerals, MMI = modified maturity index, Sa = Sublitharenite and La = Lithic arenite

Feldspar

The percentage of feldspar decreases along the downstream distance. In the Budhi Gandaki Nadi Segment (from 68 to 124 km stretch), the feldspar ranges from 4% (S7) to 15% (S4). In the Trishuli Nadi Segment (126 to 190 km stretch), the feldspar ranges from 10% (S8) to 15% (S13). Similarly, in the Narayani Nadi Segment (195 to 230 km stretch), the feldspar ranges from 4% (S21) to 13% (S19) (Table 7; Fig. 8b). The trend line shows the diminishing trend of feldspar with the downstream distance of transport (Fig. 9b).

Rock fragments

The percentage of rock fragment varies in overall between 5% and 27%. Along the downstream distance of transport, rock fragments tend to diminish up to the end of the Trishuli Nadi Segment and again increases in the Narayani Nadi Segment, most probably due to tremendous mixing by the Kali Gandaki Nadi (Table 7, Fig. 9c).

Mica

The mica content ranges from 10% (S1) to 16% (S5), 11% (S11) to 17% (S14), and 12% (S19 and S21) to 21% (S15), respectively in the Budhi Gandaki Nadi, the Trishuli Nadi and the Narayani Nadi Segment (Table 7). The percentage of mica tends to increase along the downstream distance (Fig. 9d).

Classification

The bulk sands from the Budhi Gandaki Nadi, the Trishuli Nadi and the Narayani nadi are classified as sublithic and lithic in composition (Fig 10). The mineralogy of sands from the confluence rivers shows sublithic composition that means they are slightly quartzose compared to the main stem river, Budhi Gandaki-Narayani Nadi (Fig. 10).

Modified Maturity Index (MMI)

The MMI ranges from 100 to 205 %, 138 to 177 % and 112

Fig. 8 (a) composition % of the Budhi Gandaki Nadi, (b) composition % of the Trishuli Nadi, (c) composition % of the Narayani Nadi and (d) composition % of confluence Rivers. Where, RF= Rock fragments, Mica= muscovite, Feld = feldspar, Qtz= quartz.

Fig. 9: Downstream changes of percentage of mineral grains of fluvial sand: (a) quartz, (b) feldspar, (c) rock fragments, and (d) mica

Fig. 10: QFL plot of fluvial sand of the Budhi Gandaki–Narayani Nadi.
to 177%, respectively for sands from the Budhi Gandaki Nadi, the Trishuli Nadi and the Narayani Nadi segments. The maximum MMI (203%) lies at 124 km downstream along the Budhi Gandaki Nadi Segment, whereas the least MMI (100%) lies at 68 km downstream along the Budhi Gandaki Nadi Segment (Fig 11). As MMI for mature sand lies around 300%, the Modified Maturity Index of the studied sands being less than 200% indicating that the studied sands from the Himalayan river have not achieved maturity yet.

**Provenance study of the Budhi Gandaki–Narayani Nadi**

The provenance of the Budhi Gandaki-Narayani Nadi sands lies in recycle orogeny due to enriched quartz content and lithic fragments. The overall QFL composition of the Budhi Gandaki Nadi sands (S1 to S7) is Q67 F11 L22. The overall QFL composition of the Trishuli Nadi sands (S8 to S14) is Q71 F13 L16 and the overall QFL composition of the Narayani Nadi sands (S15 to S21) is Q68 F9 L23. The overall composition is sublithic sand in which the percent of quartz exceeds percent lithic fragments and feldspars. The sand samples plot on recycled orogeny field of the QFL, in agreement with the present-day environmental setting, where collision tectonics and subsequence folding and thrusting provide enormous sediments to the river (Fig. 12).

**CONCLUSIONS**

1. This research focuses on sediment textural and compositional variation along the Budhi Gandaki–Narayani Nadi. At the Budhi Gandaki-Narayani Nadi, sediments ranged from gravelly-sand to fine-grained sands. The sands from the confluence rivers such as C1 (Trishuli Nadi), C2 (Marsyandi Nadi), C3 (Seti Nadi), C4 (Kali Gandaki Nadi), and C5 (Rapati Nadi) show sand sediments.

2. Mean and median grain sizes of sand decreases from the Budhi Gandaki Nadi to the Narayani Nadi. Sorting improves along the river course than other statistical parameters. The skewness changes from coarse skewed to fine skewed from the Budhi Gandaki Nadi to Narayani Nadi showing the enrichment of fines in the lower reach. The kurtosis ranged from very platykurtic to leptokurtic. Fine skewed sands sort out better with the increased downstream distance of transport. The confluence rivers help bringing the fine materials as the fining of sand increase with increase of the downstream distance of transport.

3. Quartz grains, which are angular to sub angular, were derived from crystalline and high-grade metamorphic rocks. Tendency of increase in quartz roundness in the downstream stretches of the Budhi Gandaki–Narayani Nadi suggests abrasion of quartz grains, which were probably derived from the Higher Himalaya. As river emerges from the Tethys Himalaya to the Lesser Himalaya, the amount of feldspar diminishes due to its dilution by weathering and rapid breakdown. The textural and compositional maturities of sand improve downstream significantly.

4. The sands from the Budhi Gandaki-Narayani Nadi plot on recycled orogeny field of QFL diagram, and this result agrees with the current tectonic setup where sands have been originated and deposited in the tectonic set up of collision and recycled orogeny (Fig. 13).
5. The sands have been deposited by the graded suspension in highly turbulent flows in the Budhi Gandaki Nadi, and by the tractive current in the Narayani Nadi Segment indicating that those sands which have been currently transported and deposited by rivers, secures the mechanisms of both tractive transport and turbulent suspension transport in the C-M diagram.

6. The textural maturity of the Budhi Gandaki–Narayani Nadi has been verified as submature indicating that those sands from the rivers have not yet achieved maturity, presumably due to proximity of the source and due to active fluvial transport in high relief area.

7. The composition of the overall samples is sublithic sand in which the percent of quartz exceeds percent lithic fragments and feldspar. No distinct trends of variation could be observed for composition along the downstream distance of transport. The Modified Maturity Index (MMI) ranges from 100 to 203%, which is generally lower compared to the mature sand. Therefore, the compositional maturity of the sand is also poor as the textural maturity. The MMI also fluctuates along the downstream distance of transport, probably due to mixing by major rivers.

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