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Facies analysis and basin architecture of the Thakkhola-Mustang Graben (Neogene-Quaternary), central Nepal Himalaya

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Abstract

The Thakkhola-Mustang Graben of central Nepal Himalaya represents the Cenozoic extensional tectonic phase of the Tibetan Plateau and the whole Himalaya. The graben is an asymmetrical basin containing a more than 850 m thick pile of Neogene to Quaternary sediments. These sediments have been divided into five formations: the Tetang Formation, the Thakkhola Formation, the Sammargaon Formation, the Marpha Formation and the Kaligandaki Formation. Younger Sammargaon and Marpha formations (Plio-Pleistocene) are lying disconformably above the older Tetang and Thakkhola formations (Miocene/Pliocene). The Thakkhola and Tetang formations are separated by an angular unconformity. The Kaligandaki Formation of Holocene age is in cut and fills relation with Marpha Formation.

Six architectural elements and twelve lithofacies from 18 outcrop locations representing Neogene sediments of the Thakkhola-Mustang Graben have been defined and described. The associations are: (I) matrix-rich conglomerate-gravelly sandstone association, (II) matrix-rich conglomerate with sandstone and mudstone and (III) massive siltstone with mudstone, alternating with carbonate layers. Lithofacies I includes matrix- supported, moderately sorted massive gravel (Gmm), poorly sorted clast-supported gravel (Gci), imbricated to massive conglomerate (Gmg) and poorly sorted pebble and cobble sized conglomerate with laminated sandstone (Gh). Moderately thick matrix-rich conglomerate with sandy matrix (Gt), coarse to very coarse stratified sandstone (Sp), massive grey to black mudstone (Fr) and well sorted pebbly conglomerate with laminar grey siltstone (Fl) characterized the lithofacies assemblages II. Fine sandstone with carbonate deposits of lithofacies assemblages III consists of poorly consolidated laminated to massive calcareous mud (C), silt and mud with organic layers (Fsm), structureless conglomerate streaks within mudstone and sandstone beds (Gcm) and laminated yellow colored carbonate (P) lithofacies.

Sediments were deposited in alluvial fan, braided river, fluvio-lacustrine and lacustrine environments. The materials are derived mainly from the Paleozoic and Mesozoic basement highlands. Periodic appearance of carbonate layers indicate the damming of paleo Kali Gandaki River in different time intervals. The graben is interpreted as a half-graben along a western main boundary fault (Dangardzong Fault). Palynology data indicate an evolution from warm and relatively humid to more arid during the Miocene/Pliocene.

Der Thakkhola-Mustang Graben im zentralen Nepalesischen Himalaya representiert Sedimentation während der Känozoischen Extensionsphase des Tibetischen Plateaus und des gesamten Himalaya. Der Graben besteht aus einem asymmetrischen Becken mit einem mehr als 850 m mächtigen Stapel neogener bis quartärer Sedimente. Die Abfolge wurde in fünf Formationen unterteilt: Tetang-Formation, Thakkhola-Formation, Sammargaon-Formation, Marpha-Formation und Kaligandaki-Formation. Die jüngeren Sammargaon- and Marpha-Formationen (Plio-Pleistozän) liegen diskordant über den älteren Tetang- und Thakkhola-Formationen (Miozän/Pliozän). Die Thakkola-Formation ist durch eine Winkeldiskordanz von der Tetang-Formation getrennt. Die jüngste Kaligandaki-Formation des Holozäns schneidet erosiv in die Marpha-Formation ein.

Sechs sedimentäre Architekturelemente und zwölf Lithofaziestypen konnten von 18 untersuchten Aufschlussgebieten der neogenen Sedimente des Thakkhola-Mustang-Graben definiert und beschrieben werden: Folgende Lithofaziesassoziation wurden unterschieden: (I) matrix-reiche Konglomerate-konglomeratische Sandsteine, (II) matrix-reiche Konglomerate mit Sandsteinen und Tonsteinen, (III) massive Siltsteine und Tonsteine mit Karbonatlagen. Lithofazies-Assoziation I beinhaltet matrix-gestützte, mäßig sortierte massive Kiese (Gmm), schlecht sortierte, klastengestützte Kiese (Gci), imbrikierte bis massive Konglomerate (Gmg) und schlecht sortierte grobe Konglomerate mit laminierten Sandsteinlagen (Gh). Mäßig mächtige matrixreiche Konglomerate mit Sandmatrix (Gt), sehr grobe bis grobe, geschichtete Sandsteine (Sp), massive graue bis schwarze Tonsteine (Fr) und gut sortierte geröllführende Konglomerate mit laminierten grauen Siltsteinen charakterisieren Lithofaziesassoziation II. Feinsandsteine und Karbonate der Lithofaziesassoziation III bestehen aus schlecht verfestigten laminierten bis massiven karbonatischen Ton (C), Silt und Ton mit organischen Lagen (Fsm), strukturlosen Konglomeratlagen in Tonsteinen und Sandsteinlagen (Gcm) und laminierten ockerfarbenen Karbonaten (P).

Die Beckenfüllung wurde vor allem durch alluviale Schwemmfächer, aufgenetzten Flüssen, und in fluviatil-lakustrinen und lakustrinen Environments abgelagert. Das Material stammt überwiegend vom paläozoischen bis mesozoischen Hochzonen. Das periodische Auftreten von Karbonatlagen weist auf Stauphasen des Paläo-Kali Gandaki Flusses hin. Der Graben kann als Halbgraben mit

Absenkung entlang einer westlichen Hauptabschiebung (Dangardzong Fault) interpretiert werden. Palynologische Daten zeigen eine Entwicklung von warm und relativ humid zu arideren Bedingungen während des Miozän/Pliozäns.

1. Introduction

North-south trending grabens developed in southern Tibet and the Himalayan mountain belt during Cenozoic east-west extension. Most of these grabens are filled with thick sedimentary successions (Fort et al., 1982; Garzione et al., 2003; Wang et al., 2006; Mahéo et al., 2007). The Thakkhola-Mustang Graben, located in the Tibetan-Tethys zone, is a geomorphologically distinct area of about ca. 90 km north-south and ca. 30 km east-west extent. Both eastern and western margins of the graben are bounded by faults, i.e. the Muktinath fault and the Dangardzong fault, respectively (Fig. 1). This graben is filled with more than 850 m of Neogene sediments including a wide range of lithologies such as conglomerates, sandstones, siltstones, limestones, and mudstones (Garzione et al., 2003).

Some attempts have already been made in order to infer the depositional environment and facies of the fill of the Thakkhola-Mustang Graben. According to Fort et al. (1982), Garzione et al. (2003) and Hurtado et al. (2001) the lower part of the graben fill were deposited in alluvial fan, braided river and lacustrine environments. The deposition of alternating fluvial, lacustrine and palustrine layers in the sediments indicates that the graben was occupied by a flat piedmont plain with torrential fans and small lakes (Fort et al., 1982). Yoshida et al. (1984) reported that the climate during the depositional interval was quite warmer than that of present time based on palynormorphs (i.e. *Lonicera*, *Caragana*, *Ephedra*, *Artemisia* and others). Based on pollen data, Adhikari et al. (2010) inferred that during this period, the southern part of Tibet was covered mainly by steppe vegetation, indicating dry climate. Yoshida et al. (1984) also reported that their Takmar Series (Thakkhola and Tetang formations in this paper) could be correlated with the Tatrot and Pinjor formations of the Siwalik Group (Johnson et al., 1982). Adhikari and Wagreich (2011) evaluated the provenance evolution of the clastic fill and inferred phases in the tectonic evolution

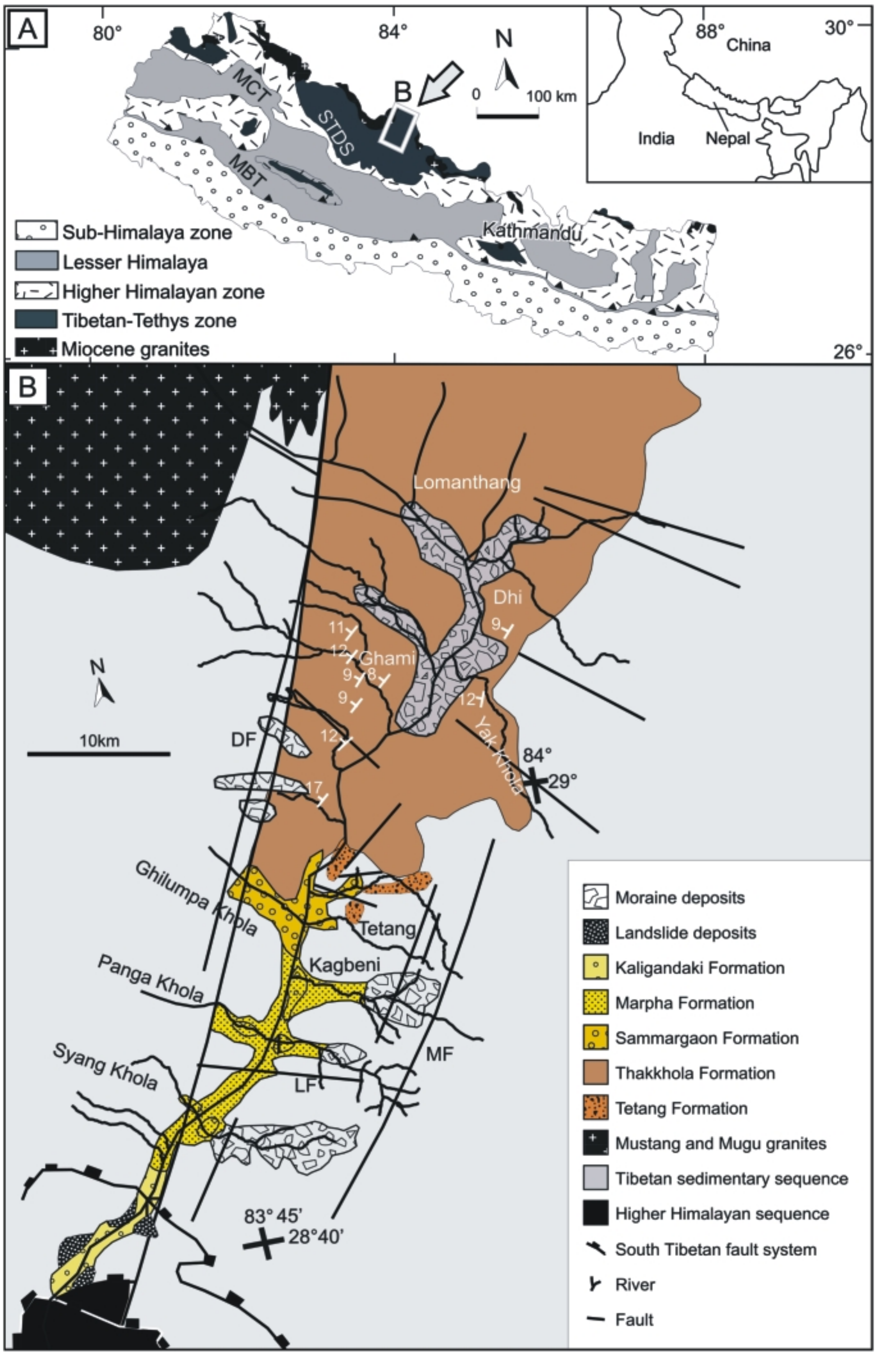

Figure 1: Location map of the Thakkhola-Mustang Graben. A) Regional geological map of the Nepal Himalaya (modified from Robinson et al, 2001). Principle faults include the South Tibetan detachment system (STDS), the Main Central thrust (MCT), the Main Boundary thrust (MBT) and the Main frontal thrust (MFT). B) Geological map of the Thakkhola-Mustang Graben showing the graben fill units (modified from Fort et al, 1982, Hurtado et al, 2001 and present work). The faults which are in southern part extending east-west represent the South Tibetan detachment fault system (STDS), Dangardzong fault (DF), Muktinath fault (MF) and Lupra fault (LF). A= Chaile village, B= Tetang Village. The location B is shown in Fig. A.

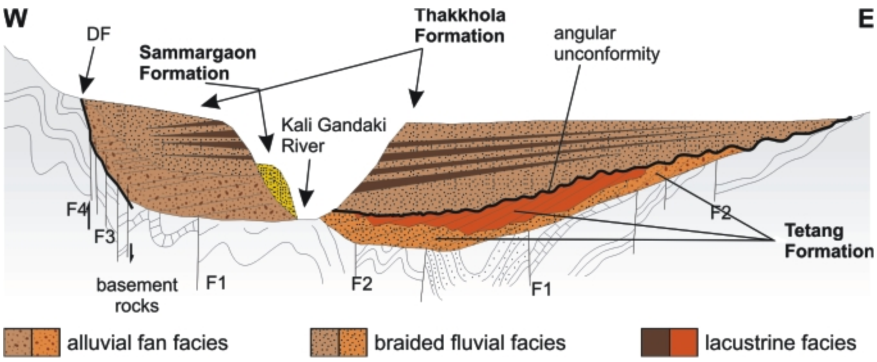

Figure 2: Schematic cross section of the Thakkhola-Mustang Graben showing important stratigraphic and tectonic features of the basin. F1, F2, F3, F4 denote faults of different deformation phases in the basement rocks (modified from Fort et al., 1982, and Garzione et al., 2003). DF = Dangardzong Fault.

of the graben.

This paper focuses on facies assemblages and basin architecture of the sedimentary fill of the Thakkhola-Mustang Graben. We describe the internal structures and sedimentary facies of primarily the Neogene (Miocene-Pliocene) graben deposits for the decipherment of the sedimentary history of the Thakkhola-Mustang Graben during the deposition of alluvial-fluvial and lacustrine systems. Additional palynology data and stable isotope data are used to infer general environmental conditions during sedimentation.

2. Geological setting

The Thakkhola-Mustang Graben is located in central Nepal Himalaya between 83°50”-84° east longitudes and 29°-28°50” north lati-tudes (Fig. 1). The Thakkhola-Mustang Graben lies unconformably above the Paleozoic to Cretaceous rocks of the Tibetan-Tethys Zone between the South Tibetan Detachment Fault System (STDS) (Burchfiel et al., 1992) to the south and the Indus-Tsangpo Suture Zone (ITSZ) to the north. The Mustang-Mugu leucogranites massif (Le Fort and France-Lanord, 1994), which has been dated by Th-Pb monazite at 17.6 ± 0.3 Ma (Harrison et al., 1997), lies to the northwest of the graben.

The graben is a part of the normal faulting system affecting the whole Tibetan Plateau (Molnar and Tapponnier, 1978). The rocks of the Tibetan-Tethys Zone consist of a thick and nearly continuous lower Paleozoic to Mid-Cretaceous marine sedimentary succession. These sedimentary rocks were deposited originally on the northern continental margin of the Indian Plate and were stacked and deformed as a consequence of collision between India and Eurasia from the early Eocene onwards (Garzanti et al., 1987; Searle et al., 1987).

The graben basement rocks of Paleozoic to Mesozoic ages are unconformably overlain by Neogene to Quaternary sediments of the graben fill (Fort et al., 1982; Yoshida et al., 1984). These deposits have been divided into five formations. The Tetang and Thakkhola formations are the oldest sedimentary units of middle Miocene to Pliocene/Pleistocene age and they are disconformbly overlain by upper Pliocene to upper Pleistocene Sammargaon and Marpha formations, respectively (Fig. 1B). The best-estimated age for the Tetang Formation is between ca. 11 and 9.6 Ma and the maximum age of the Thakkhola Formation is 8 Ma based on magnetostratigraphy (Garzione et al., 2000). The deposition of Thakkhola Formation continued up to at least 2 Ma (Yoshida et al., 1984). The two older Thakkhola and Tetang formations lie unconformably on a substratum of the high strain rocks of the deformed Tibetan-Tethys sedimentary sequences and they are separated by an internal low angle (~5°) unconformity (Fort et al., 1982) (Fig. 2 and 3). The overlying Sammargaon Formation is associated with glacial moraines and was interpreted to be a glacio-fluvial package deposited during Middle Pleistocene glaciations (Fort et al., 1982). The Marpha Formation is composed of lacustrine sediments whereas the youngest Kaligandaki Formation consists mainly of Holocene fluvial conglomerates (Fig. 4).

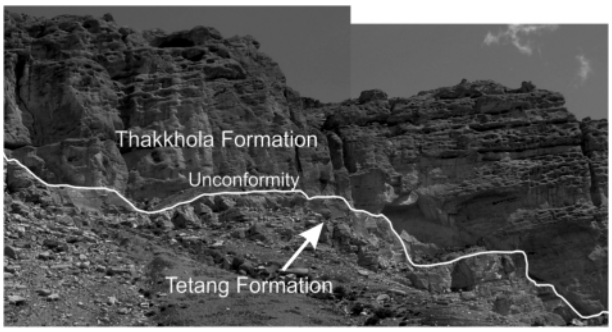

Figure 3: Photo mosaics of the angular unconformity (~5°) at the stratigraphic contact between the Thakkhola Formation and the Tetang Formation near Tetang village along the Narsing Khola.

3. Methods

This study is based on the integration of lithologic and sedimentologic data collected during two field seasons in the Thakkhola-Mustang Graben. We logged and sampled 18 stratigraphic sections on the both sides of the Kali Gandaki River and its tributaries. To characterize the sediments we mainly used a modified lithofacies and architectural classification scheme from Miall (1996). Detailed columnar sections were constructed based on textures, sedimentary structures and their association. Twelve distinct sedimentary facies have been identified and classified into three facies associations based on lithology, bed-geometry and internal structure within the sedimentary succession of the Tetang, Thakkhola, Sammargaon, Marpha and Kaligandaki formations. Pebble orientation as measured to constrain dispersal patterns, pebble compositions and heavy minerals were studied for provenance analysis (see Adhikari and Wagreich, 2011). Each pie diagram of clast compositions are plotted in the columnar sections (Fig. 5). Carbonates were studied by thin section analysis. Additional pollen analysis and stable isotope analysis was done for paleoclimate analysis (see Adhikari, 2009; Adhikari et al., 2010).

4. Basin fill stratigraphy

4.1 Tetang Formation

The basal Tetang Formation is well exposed around the Tetang village (Fig. 1). The Tetang Formation rests uncomformably upon the Cretaceous Chuck Formation (Colchen et al., 1986). The thickness varies from a few meters to more than 200 m. Four main units within the Tetang Formation have been distinguished based on their lithostratigraphic characteristics (Fig. 5A). In the southeastern part of the basin, Cretaceous rocks were slightly eroded before the Neogene deposition. The predominance of the western fault system during the Tetang and Thakkhola periods influenced the polarity of the aggradation in that its vertical displacement fixed the volume and the sedimentary facies, suggesting quite regular and sustained deformational movement (Colchen, 1999).

The following lithofacies could be distinguished:

1) Basal pebble and gravel (0-68 m): Massive conglomerate beds (few cm to 1 m thick) containing quartzite, shale, sandstone and carbonate clasts derived directly from the Mesozoic bedrocks, which is best exposed on the Tetang village section. Some massive conglomerate beds with sand lenses are interbedded with imbricated conglomerate beds (Fig 7A). Some massive conglomerate beds are up to 22 m thick with minor sand lenses alternating with imbricated conglomerate beds. Clast sizes range from few cm to 1m.
2) Interbedding of conglomerates with sand and silt layers (68-115 m): Mainly imbricated conglomerate beds are dominating but they are interbedded with sand and silt layers. Carbonate and iron concretions are present in the sandstone beds. Conglomerate beds range from few cm to 2 m while sandstone and siltstone beds are between 0.02 m to 0.3 m thick.
3) Sand dominated sequences (115-172 m): Sand layers are alternating with imbricated conglomerate layers and siltstone. Sand layers have mainly parallel lamination with cross bedding in some layers. Some grey fine-grained sandstone layers contain plant fossils. Mainly fining upward cycles represent this unit (Fig. 5A).
4) Fine siltstone with limestone intervals (172-215 m): This unit is mainly dominated by fine sand and silt layers and limestone beds. Thick siltstone beds contain plant fossils (Fig. 5A). Limestones are very fine grained and contain some ostracodes.

4.2 Thakkhola Formation

The Thakkhola Formation spreads mostly the northern part of the Thakkhola-Mustang Graben, extending from Tetang village to Lomanthang village (Fig. 1). Its western extent is strictly controlled by the north-south running Dangardzong Fault. An angular unconformity (~5°) separates the basal conglomerate layer of the Thakkhola Formation with the topmost carbonate layer of the Tetang Formation in the Tetang village and Dhinkyo Khola sections (Fig. 3). The sediment thickness of this formation varies from place to place with a maximum thickness of more than 620 m in the Chaile gaon area. However, the sediment thickness decreases progressively eastwards above the Tetang Formation and Mesozoic basement rocks. Facies changes laterally from south to north with decreasing sediment thickness which reaches ~ 210 m in Dhi gaon (northeastern part). Size of clasts in the conglomerate beds and the thickness of the conglomerate beds decrease towards the north while the frequency of silt layers increase. The Thakkhola Formation is divided into 4 units based on lithological character, composition of clasts and lithofacies association based on the Chaile gaon area (Fig. 5B).

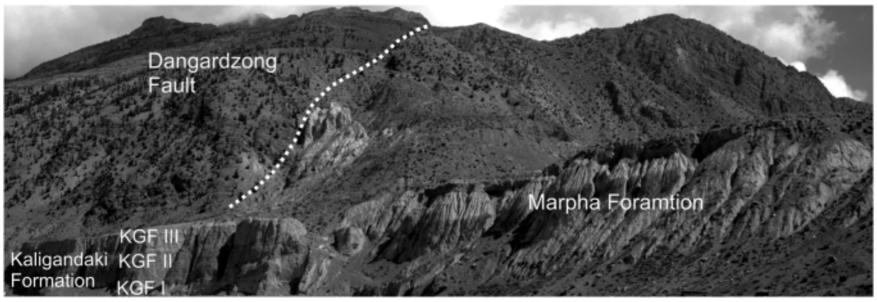

Figure 4: Marpha and Kaligandaki formations (KGFI-KGFIII) with the Dangardzong Fault on the eastern side of the Syang Khola.

1) Basal conglomerates (0-182 m): This unit lies just above the Tetang Formation and is mainly composed of massive conglomerate and imbricated conglomerate beds alternating with coarse sand layers. Pebbles are mainly composed of Paleozoic rocks like shale, sandstone and some granite pebbles from the Mustang-Mugu granites. The thicknesses of the beds range from 1 m to 20 m and the average grain size is ~18 cm (Fig.5B).
2) Alternation of imbricated conglomerate beds with sandstone and siltstone (182-320 m): Mainly coarse to fine-grained, fossiliferous bioturbated sandstone and siltstone dominate all the sequences but some conglomerate beds (average clast size ~3 cm) having red matrix are also present in this unit. Mainly Paleozoic clasts are present in the conglomerated beds with some Mesozoic carbonate clasts. Carbonate and iron concretions occur in the sandstone and siltstone beds whereas siltstone beds contain some plant fossils and display bioturbation structures (Fig. 5B).
3) Fine grained facies (320-500 m): This unit consists of various kinds of facies like lenses or beds of sandstone, poly-

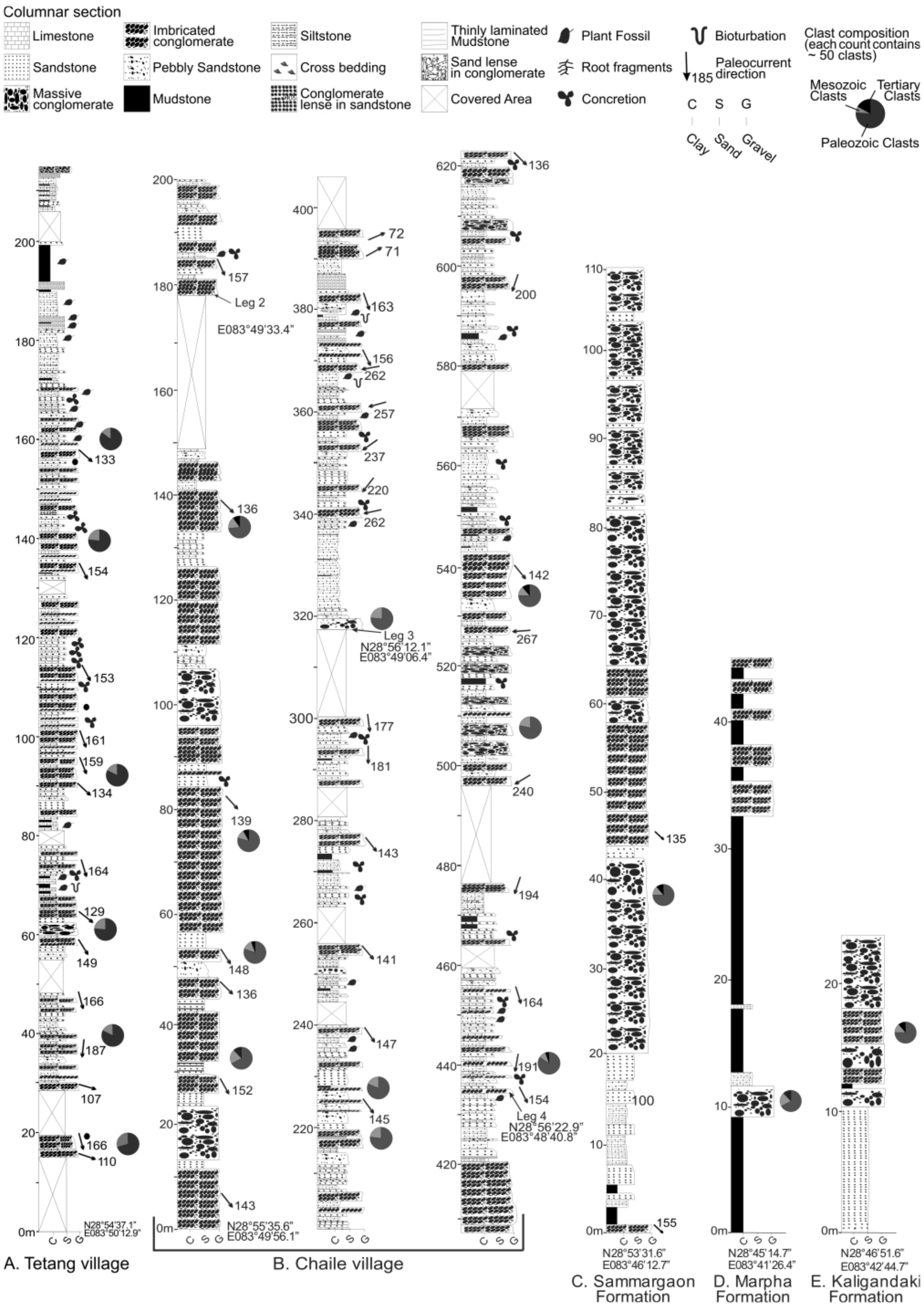

FIGURE 5: Detailed columnar sections of the Thakkhola-Mustang Graben, A) Tetang Formation at Tetang village, B) Thakkhola Formation at Chaile village, C) Sammargaon Formation, D) Marpha Formation, E) Kaligandaki Formation.

genic pebbly conglomerate, lacustrine limestone and silt beds (Fig. 5B). Grey to black siltstone beds are alternating with imbricated conglomerate and fine to coarse-grained sandstone. Thick (12 to 25 m) siltstone intervals are present at level 320 m of the succession (Fig. 5B). Clasts in imbricated conglomerates are composed of mainly Paleozoic followed by Mesozoic and Cenozoic rocks. Oncolitic, micritic-microsparitic, detrital and micritic organic carbonate facies with several algal mats are dominating in the limestone intervals whereas bioturbation, root fragments and iron-rich concretions are widespread in the siltstone beds.

4) Upper imbricated conglomerate and sandy layers (500-623 m): Some bioturbated siltstones consist of iron-rich carbonate concretions. Massive to imbricated matrix supported conglomerate beds containing Paleozoic and Mesozoic clasts (average size ~5 cm) represent this unit.

4.3 Sammargaon Formation

This formation unconformably overlies the Thakkhola Formation in the northern part of the Thakkhola-Mustang Graben (Fort et al., 1982). It is well exposed nearby the Tangbe village and Ghilumpa Khola, and comprises a more than 110 m thick package of breccias and conglomerate (Fig. 5C). These conglomerates poorly sorted and contain angular clasts. The basal unit consists of fine-grained sandstones with parallel laminated siltstones with dominant quartz and calcite. Massive conglomerate beds of an average clast size of 23 cm are present above the sandy layers and the imbricated clasts of conglomerate suggest southeastern paleoflow. Some coarse sand layers are present in between the diamictic conglomerate layer

Facies association	Lithofacies type	Facies code	Stratigraphic units	Description	Architectural element	Interpretation
I	Matrix-supported, massive gravel (Facies A)	Gmm	Tetang, Thakkhola, Sammargoan	Moderately sorted, gravel, massive conglomerate, with sandy matrix, gravels up to 21 cm, erosive base, units up to 6 m thick.	GB, CH, LA	Longitudinal bars, sheet flood to channel deposits (high-strength, viscous)
I	Clast-supported gravel (Facies B)	Gci	Tetang, Thakkhola, Sammargoan	Poorly sorted, clast supported , cobble to boulder conglomerate, units up to 0.5 to 3 m.	GB, CH, LA	Linguoid bars or Pseudoplastic debris flow (low strength, viscous)
I	Matrix-supported gravel (Facies C)	Gmg	Tetang, Thakkhola	Imbricated to massive, moderately sorted pebble to gravel conglomerate and laterally extensive beds.	GB, CH, LA	Clast-rich debris flow (high strength), or fluvial deposits
I	Clast-supported, curdly bedded gravel (Facies D)	Gh	Tetang, Thakkhola	Poorly sorted pebble and cobble sized conglomerate with associated lenses of reddish-wedged shaped horizontally laminated sandstone.	GB, CH, LA	Longitudinal bedforms, lag deposits, sieve deposits, Sheet flows.
II	Gravel, stratified (Facies E)	Gt	Tetang, Thakkhola	Moderately thick matrix-rich conglomerate of limited extend with sandy matrix.	GB, LA, CH	Minor channel fills and transverse bars.
II	Sand, fine to v. coarse may be pebbly (Facies F)	Sp	Thakkhola Formation	Coarse to very coarse grained cross-stratified sandstone. Pebbles of different composition are aligned in the cross-stratification.	CH, SB	Sinuously crested and linguoid (3-D) dunes, sheet flow to channel deposits
II	Mud, silt (Facies G)	Fr	Tetang, Thakkhola	Massive gray, red and sometimes black compact mudstone with root fragments, biotubation and plant fossils.	OF	flood plain deposits or
II	Sand, silt, Mud (Facies H)	Fl	Thakkhola, Marpha	Well sorted pebbly conglomerate with laminar grey sandstone.	LS, OF, SB	Overbank, abandoned channel, or waning flow deposits or sheet flow deposits
III	calcareous mud (Facies I)	C	Thakkhola	Poorly consolidated laminated to massive calcareous mud	OF	Vegetated swamp deposits, open lacustrine
III	Silt, Mud (Facies J)	Fsm	Tetang, Thakkhola Marpha	Comprises of organic layers with plant fossils	OF, SB	Back swamp or abandoned channel deposits
III	Clast supported. Massive gravel (Facies K)	Gcm	Tetang, Thakkhola	Structureless conglomerate within the mudstone and siltstone beds with lenses of conglomerate.	GB, CH, LA	Pseudoplastic debris flow (intertial bedload, turbulent flow)
III	carbonate (Facies L)	P	Tetang, Thakkhola	Laminated, yellow color, micritic matrix, with ostracods, overlained by claystone and organic layers.	LS, CH	Soil with chemical properties. Palustrine

Table 1: Facies association and their occurrences in the Thakkhola-Mustang Graben (facies are adapted from Miall 1996).

Architectural element	Grain size	Description	Interpretation
Channel-fill complex (CH)	Pebble to cobble conglomerate, fine-to coarse-grained sandstone with mudclasts	Lenticular, multi-and single-storeys, sharp concave-up erosive base. Gmm, Gci, Gmg, Gh, Gt, Sp, Gcm, P.	Growth of gravelly and sandy channel fills
Gravel bars (GB)	Clast-supported granules to cobble conglomerate interbedded with sandstone	Sheet-like and lens, more than 50 m lateral extend. Gmm, Gci, Gmg, Gh, Gt, Gcm	Gravel sheets and lens, relative low-relief longitudinal bars
Sandy bedforms (SB)	Fine- to coarse-grained sandstone	Lens, sheet, blanket, wedge with erosional surface, lateral extent more than 100 m. Sp, Fl, Fsm	Channel fills, crevasses splays and minor bars
Lateral accretion (LA)	Granule to pebble conglomerate, fine-to coarse-grained sandstone	Wedge, sheet with lateral extent more than 5m. Gmm, Gci, Gmg, Gh, Gt, Gcm.	Internal lateral accretion of gravel and sand bars
Laminated sand sheet (LS)	Very fine-to medium grained sandstone	Sheet, blanket, erosive base. Fl, P.	Crevasse splay, flash flood deposits
Overbank fines (OF)	Mudstone and very-to fine-grained sandstone	Sheet-like, lateral extent for more than 1 km. Fr, C, Fsm.	Overbank and flood plain

Table 2: Description and interpretation of fluvial architectural elements in the Thakkhola-Mustang Graben.

(Hurtado et al., 2001). The Sammargaon Formation was interpreted to be a glacio-fluvial package of Middle Pleistocene age (Fort et al., 1982).

4.4 Marpha Formation

The Marpha Formation, which is exposed in the Syang Khola and Marpha village, consists of fine to medium sand and mud layers in the basal section with gravitational slump structures (Fig. 4). The basal section is composed of fine to medium lacustrine sand with mud layers (Fig. 5D) Conglomerate beds contain mainly quartzite, sandstone, slate, granite and carbonate clasts of an average size of ~28 cm are interbedded with the mudstone on the upper part of the sequence. Most of the beds in this formation dip at low angle ranging from 5-7 degrees. At Syang Khola, the Marpha Formation is more coarse grained and consists of massive coarse-grained sandstone with a conglomerate of mean particle size of 37 cm (mean of 50 largest clasts), which is interpreted as a glacio-lacustrine sedimentary deposits (Fig. 4). Fort et al. (1982) correlate the lowermost part of the following Marpha Formation with the uppermost Sammargaon Formation based on the association of the Marpha Formation with glacial till. The age of the Marpha Formation is assigned to the Middle Pleistocene (150 ka; Iwata, 1984; Yoshida et al., 1984; 33-37 ka, Hurtado et al., 2001).The Holocene Kaligandaki Formation is in a cut-and-fill relation with these older formations (Fig. 4).

Soft sediment deformational structures in the Marpha Formation imply that sedimentation took place within a seismically active basin with deposition close to the Dangardzong fault (Adhikari, 2009).

4.5 Kaligandaki Formation

The Kaligandaki Formation overlies the Marpha Formation in a cut and fill relationship in the Syang Khola section, a tributary of Kali Gandaki River. The type section is more than 30 m in thickness on the western side of the Syang Khola (Fig. 5E). This formation is divided into three main units. The basal section is composed of sandstone (KGF I), fluvial crudely imbricated conglomerate with sub-rounded to rounded clasts (KGF II) and an upper debris flow breccias (KGF III) (Fig. 4). Hurtado et al. (2001) correlated the fluvial conglomerate of this formation with the coarse-grained fluvial conglomerates at the mouth of the Jhong Khola at Kagbeni of age 17-5.5 ka.

5. Facies description

We used the modified lithofacies and architectural elements classification of Miall (1996) for facies analysis. Twelve distinct sedimentary facies types were identified based on lithology, bedgeometry and internal structures in the Tetang, Thakkhola, Sammargaon, Marpha and Kaligandaki formations, forming three facies associations (Fig. 5). These various lithofacies and architectural elements are described and interpreted (Table 1 and 2).

5.1 Facies association I: Matrix-rich conglomerate-gravelly sandstone association

5.1.1 Description

This facies association is exposed mainly along the eastern and western sides of the basin containing four different lithofacies A-D.

Facies A is composed of a moderately sorted, gravel-boulder (recorded longest clast diameter is 21 cm) massive conglomerate with sandy matrix. Carbonate, quartzite and slates represent the coarseclast population (Gmm) (Fig. 6A). This matrix-rich conglomerate beds are 0.5 to 6 m in thickness.

Lithofacies B consists of subangular to subrounded poorly sorted, clast-supported conglomerate with coarse-grained sand (Gci). Thicknesses of individual beds are 0.5 to 3 m (Fig. 5 A, B and C).

Imbricated to massive, moderately sorted pebbly conglomerate and laterally extensive beds characterize lithofacies C (Gmg) (Fig. 6B). The thickness of the conglomerate beds ranges from 0.3 to 12 m; clasts are predominantly granite, quartzite, sandstone and slate.

Lithofacies D comprises poorly sorted pebble to cobble-sized conglomerates with associated lenses of red, wedged shaped horizontally laminated sandstone (Gh). The coarse-grained sandstones are continuous to more than 20 m, and then pinch out laterally. Some beds display a massive character with crude horizontal stratification of alternating pebble free sandstone and pebbly sandstone (Fig. 5 A and B).

5.1.2 Interpretation

The wide lateral extent, moderately sorted, randomly oriented clasts of massive conglomerate of lithofacies A having erosive base and sandy matrix within the conglomerate beds suggest sheet flood to channel deposits where the water had

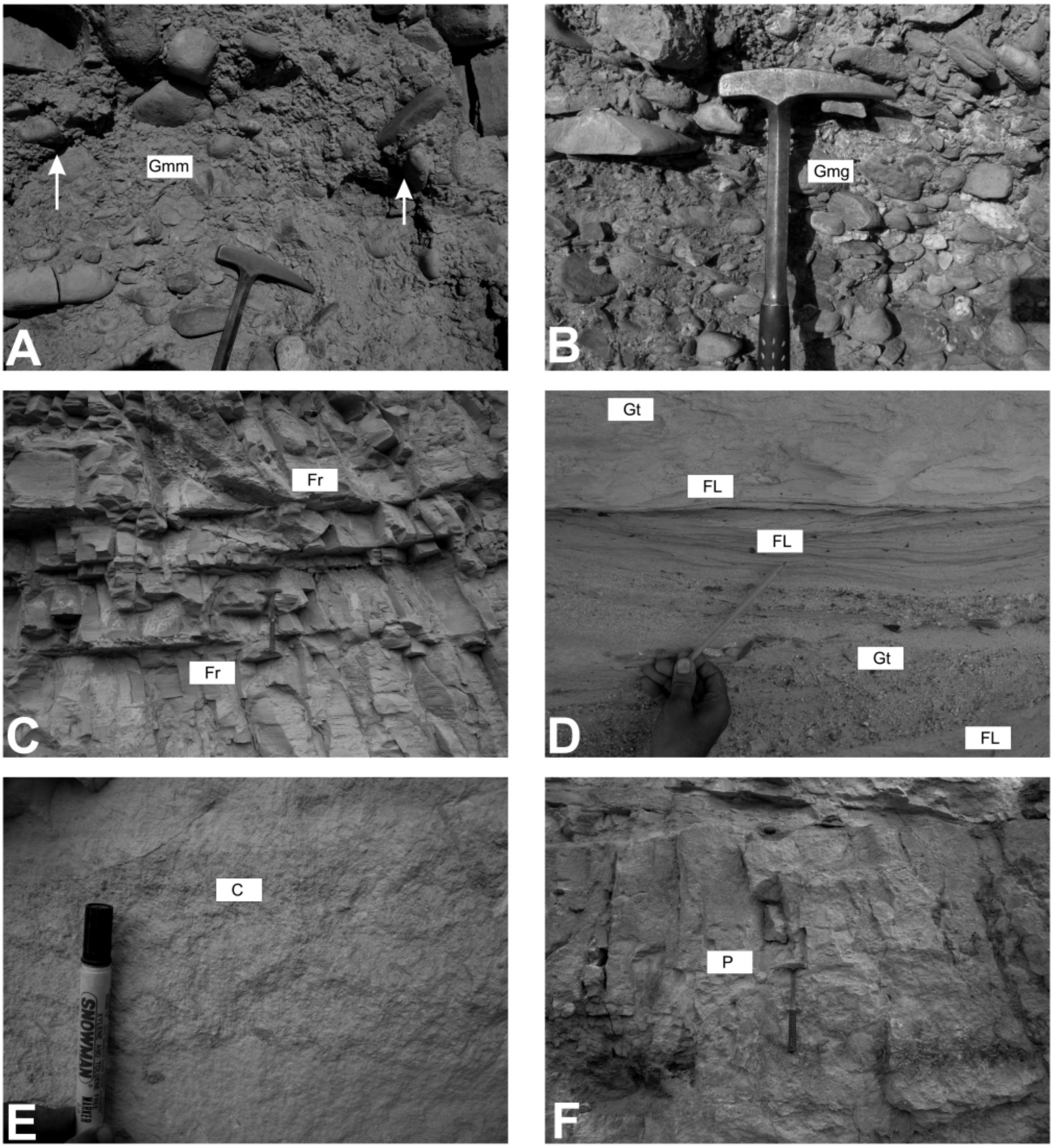

Figure 6: A) Sheet flood to channel deposits characterized by massive conglomerate (Gmm) of the Tetang Formation in Dhinkyo Khola section, white arrows show scour surface; B) imbricated conglomerate (Gmg) of the Thakkhola Formation in the Tange section; C) thick mud and silt layers with root and bioturbation (Fr) and plant fossil of the Thakkhola Formation in the Chaile section; D) sheet flood deposits of braided streams are characterized by matrix-rich massive conglomerate (Gt) and grey laminar sandstone (Fl) of the Thakkhola Formation in the Ghiling section; E) lacustrine facies characterized by thick calcareous mud (C) of the Thakkhola Formation in the Dhi section, F) palustrine limestone facies characterized by thick laminated limestone bed (P) of the Thakkhola Formation in the Chaile section.

a high strength and viscosity. The clasts of carbonate, quartzite and slate appear to be derived from the surrounding rocks (Adhikari and Wagreich, 2011). This organized clast-supported massive conglomerate with moderately developed clast imbrications may be a result of incised-channel gravel bed sedimentation under accreting low- to waning-energy flows (Jo et al., 1997; Blair, 1999). The bed geometry represents gravel sheets or low relief longitudinal fluvial bars.

Poorly sorted, clast-supported and cobble to boulder conglomerate without stratification of lithofacies B is interpreted as debris flows deposits (Johnson, 1970, 1984; Garzione et al., brications may be a result of incised-channel gravel bed sedimentation under accreting low- to waning-energy flows (Jo et al., 1997; Blair, 1999). The bed geometry represents gravel sheets or low relief longitudinal fluvial bars.

Poorly sorted, clast-supported and cobble to boulder conglomerate without stratification of lithofacies B is interpreted as debris flows deposits (Johnson, 1970, 1984; Garzione et al., 2003) of low strength. Sub-angular to sub-rounded clasts with a small proportion of boulders within the coarse-grained sand were deposited in linguoid gravel bars during stream flow.

Lithofacies C is interpreted as the product of low-cohesive clast-rich debris flows transitional to stream flow, that were deposited mainly as channel fills according to their geometry. Pebble imbrications show that the sediments were transported partly in traction flows. Dasgupta (2007) suggested that these types of sediments are a product of rapid sedimentation from flow of transitional character between debris flow and hyperconcentrated fluidal flow on a gravelly alluvial fan system (see also Blair and McPherson, 1994).

Poorly sorted pebbles and cobble-sized conglomerate with reddish wedge-shaped horizontally laminated sandstone of facies D was deposited primarely by sheet flow processes. Sediments are generally deposited in the form of longitudinal banks and lag deposits. Nakayama and Ulak (1999) suggested that such kinds of sediments in the Siwaliks of the Nepal Himalaya are deposits of a gravelly braided river system.

5.2 Facies association II: Matrix-rich conglomerate with sandstone and mudstone

5.2.1 Description

This type of lithofacies is widespread within the Thakkhola-Mustang Graben comprising mainly conglomerates with sandstone and mudstone of lithofacies E - H.

Lithofacies E comprises moderately thick matrix-rich conglomerates containing imbricated clasts of granite, carbonate and calcareous sandstone (Gt) (Fig, 5A and B). Conglomerate beds are 0.8 to 2 m thick, which can be traced more than 500 m laterally.

Lithofacies F is characterized by coarse to very coarse grained planar cross-stratified sandstone of 0.2 to 3 m thick, which can be traced more than 20 m laterally (Sp) (Fig. 5A).

Lithofacies G consists of massive gray, red and sometimes black massive mudstone containing root fragments, bioturbation and plant fossils (Fr) (Fig. 6C). Mudstone beds are 0.1 to 2 m in thickness and have a higher lateral continuity as these beds can be traced more than 1 km laterally.

Lithofacies H is composed of lenses of mainly well-sorted pebble and cobble-sized conglomerate interbedded with laminar grey sandstone containing iron-rich carbonate concretions (Fl) (Fig. 6D). The conglomerate beds with erosive surface are 0.1 to 3 m thick, which consist of mud lenses.

5.2.2 Interpretation

Lithofacies E is interpreted as longitudinal bar deposits of stream-flow in river systems. Erosional features of the imbricated conglomerate imply relatively shallow and/or unstable channel system. Some normal graded beds may have been developed during waning flow stages (Garzione et al., 2003). Rounded to sub-rounded and imbricated conglomerates originated from the bed load of a gravelly braided river.

Coarse to very coarse cross-stratified sandstones of lithofacies F were deposited as sheet flow to channel deposits. The sheet-like geometry of sandstones and pebbly sandstones, the development of planar cross-stratification, and the less clear upward-fining succession are characteristics of the classic 'Platte-type' braided river deposits (Smith 1972; Miall, 1985).

Massive grey, red and black compact mudstones of lithofacies G indicate deposition from standing water, most probably (ephemeral) lakes in a flood plain environment. Root fragments, bioturbation and plant fossils suggest that the riverbanks were stable over a longer period. The red color of the sediments at the Dhakmar area could be related to the chemical weathering developed under warm and humid condition, having affected the whole area before the formation of the graben (Fort et al., 1982).

Lithofacies H is interpreted as an overbank deposit, abandoned channel and waning flow deposit or sheet flow. The presences of granular interlayers indicate that the pebbly conglomerates are the product of a heavily sediment-laden turbulent flow. The stratified character of the fine-grained conglomerate and granular sandstone without distinct bedding surface can be attributed to continuous traction carpet deposition (Sohn et al., 1999).

5.3 Facies association III. Massive siltstone with mudstone- carbonate

5.3.1 Description

Thick mudstone, marls, carbonate beds and some structureless pebbly conglomerate characterized this type of facies association, including lithofacies I - L.

Facies I is characterized by poorly consolidated, laminated to massive carbonate mud containing algal mats, carbonate nodules and bioturbation (C) (Fig. 6E). This type of facies is distributed mainly in the Dhi gaon area of the Thakkhola Formation.

Facies J comprises carbonaceous layers with abundant plant remnants and root horizons at the base of massive conglomerate layers (Fsm). This lithofacies is distributed around the Dhi gaon, Tange gaon, Chaile and Tetang villages (Fig. 5 A and B).

Facies K is composed of structureless conglomerates within mudstone and siltstone beds (Gcm) distributed in the Thakkhola Formation. Laminated to massive siltstone beds are interbedded with erosive conglomerate lenses (Fig. 5A).

Facies L consists of carbonate, mainly limestone beds, extending continuously over more than 100 m laterally (C). This type of facies is present in the Chaile and Tetang area of both Tetang and Thakkhola formations (Fig. 6F).

5.3.2 Interpretation

Lithofacies I is interpreted as vegetated swamp or open lacustrine deposits. Massive grey marl is interpreted as deposits of suspended fine-grained mixed sediment under a lacustrine water column (Ramos-Guerrero et al., 2000). Some algal mats are present in the marl, which suggest the existence of a stable oxygenated lacustrine water column. Common bioturbation also indicates oxic bottom water conditions.

Organic layers with plant fossils of lithofacies J are interpreted as back swamp deposits of abandoned channel deposits. Garzione et al. (2003) interpreted similar types of sediments as profundal lacustrine deposits with seasonal accumulation of phytoplankton that remained unoxidized because of stagnant bottom condition.

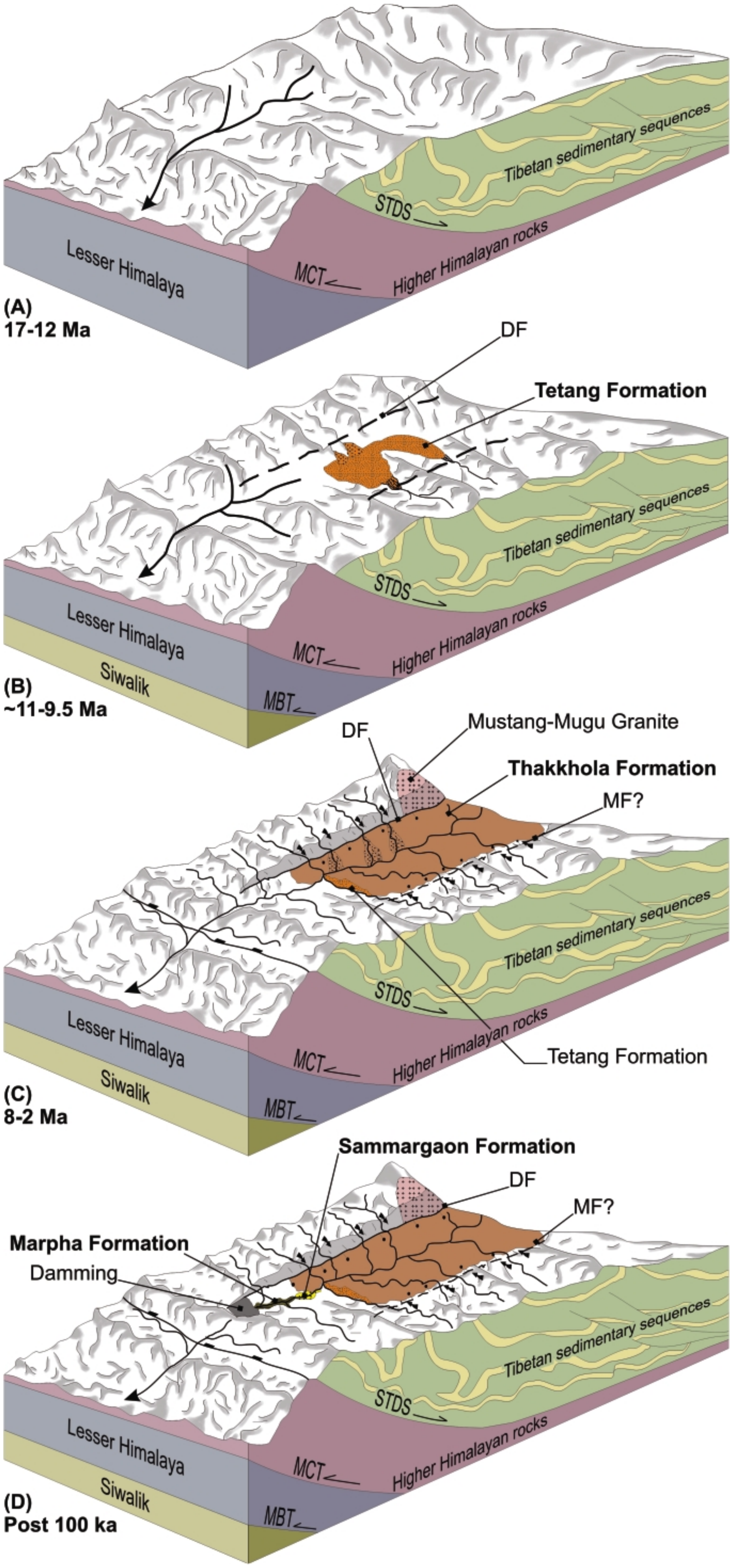

Figure 7: Paleogeographic reconstruction and basin models of the Miocene to Pleistocene evolution of the Thakkhola-Mustang Graben (modified from Garzione et al., 2003) (Age taken from different authors: see in text. DF = Dangardzong Fault, MF = Muktinath Fault). A) Situation before the sedimentation of the Tetang Formation (17-12 Ma); B) During deposition of the Tetang Formation (ca. 11-9.5 Ma) alluvial fans and fluvial environments prevailed, overlain by lacustrine sediments; C) The Thakkhola Formation (8-2 Ma) records exhumation of the Mustang-Mugu granites and activity at the Dangardzong Fault as the main bounding fault of the graben; D) Middle Pleistocene (post 150 ka) to Holocene formations are concentrated along the course of the Kali gandaki valley which was dammed intermittently.

Lithofacies K is interpreted as a pseudoplastic debris flow or suspended sediment carried by rivers into the lakes or as low-sinuosity river deposits. The uneven boundary between the siltstone and conglomerate interbedding with lacustrine sediments indicates that it was deposited mainly by turbidity flows within a lake environment.

Lithofacies L is interpreted as a shallow lacustrine facies of a palustrine system. Limestones are deposited mainly due to biological activity, i.e. algae. Similar limestones are interpreted as a shallow lacustrine marginal to palustrine system on the edge of a possible larger freshwater carbonate lake or part of shallow ponds, situated in a distal environment of the alluvial plain (Gierlowski-Kordesch, 1998).

6. Sediments and Graben Evolution

The Thakkhola-Mustang Graben developed in different successive stages on top of the Tibetan-Tethys sedimentary rocks in the Himalaya (Fig. 7). Different basin fill sedimentary sequences developed in different time intervals with depositional environments controlled mainly by tectonic subsidence and climate, and thus indicate a complex basin evolution. In this work, a half-graben model is attributed to the Thakkhola-Mustang Graben (Fig. 2) because of the presence of only one clearly visible master fault, i.e. the Dangardzong fault along the western boundary (Adhikari, 2009) and the general asymmetric geometry of the sedimentary fill of the basin. Only a minor local fault, the Muktinath Fault, is present at the eastern side, but it is not clearly discernable in the field in the Muktinath area and displays only a minor offset (Adhikari, 2009).

The Miocene Tetang Formation was deposited mostly in the southeastern part of the initial graben near Tetang village and Dhinkyo Khola. Mainly Mesozoic and Paleozoic clasts are found in the conglomerate beds with absence of granite clasts. Thus, neither Mugu and Mustang granites had started to be eroded at this time, or the material derived from them was not transported to the depositional area of the graben (Adhikari and Wagreich, 2011). The thick conglomerate with Mesozoic clasts suggests local high-relief topography along the eastern margin of the basin (Fig. 7B) as Mesozoic outcrops are mainly concentrated there. Sediments of the basal interval of the Tetang Formation were deposited in alluvial fan and braided river systems. The upper portion of the Tetang Formation was dominated by lacustrine facies comprised by fine-grained laminated carbonate deposits with plant fossils and thus testifies for a decrease in the relief and tectonic activity, resulting in the formation of a predominantly lacustrine environment. The accommodation space for the deposition of sediments in this formation may have been created as a response to normal faulting and footwall uplift associated with STDS because there are no strong evidences for syndepositional movements along local faults (Garzione et al., 2003).

After the deposition of Tetang Formation, these strata were rotated ~ 5° westward before the deposition of the Thakkhola Formation. Consequently, these two formations are separated by an angular unconformity which can be observed in Tetang and Dhinkyo Khola areas (Fig. 3). This angular unconformity records a temporal gap of ≥ 2.5 Ma, beginning at ca. 9.6 Ma and ending at 8 Ma (Garzione et al., 2000). The basal imbricated conglomerate sequence of the Thakkhola Formation rests upon the lacustrine deposits of the Tetang Formation (Fig. 3). The presence of granite clasts in the Thakkhola Formation indicate that the Mustang and Mugu granites (age 17.6 ± 0.3 Ma, Harrison et al., 1997) had been already brought to the surface and were starting to be eroded slightly before the deposition of the Thakkhola Formation. Renewed coarse conglomerate deposition may be attributed to a reactivation of fault systems, the formation of high relief and subsequent alluvial fan deposition. The Thakkhola Formation is distributed mostly in the northern part of the basin starting from Tetang village up to Lomangthang. Its western proximity is bounded by the Dangardzong fault (Fig. 7C) and it forms the main phase of half-graben deposition. Sediments were deposited in alluvial fan, braided river system, fluvio-lacustrine and lacustrine environments. Paleocurrent directions indicate that the sediments were derived from north ranging from NW to NE (Adhikari and Wagreich, 2011). The conglomerate layers in Chaile gaon have up to 10 m in thickness which indicates that fluvial channel sizes of this paleo Kali Gandaki River system was in a magnitude similar to present. The clast sizes in sediments are influenced by local relief and resulting fan systems, e.g, there are larger clasts present at the southwestern margin of the basin along the (active) Dangardzong fault and significant smaller pebbles at the northeastern margin of the basin in the Dhi gaon, associated with increasing amounts of silt layers of a more distal environment. It also indicates that the velocity and capacity of the river(s) was strong in the central part of the basin compared to the northern edge of the basin.

The Sammargaon and Marpha formations were deposited after Middle Pleistocene age (Fig. 2 and 7). The Sammargaon Formation is associated with glacial moraines and it is a glaciofluvial package deposited during Middle Pleistocene glaciations (Fort et al., 1982). Pleistocene-Holocene formations (I.e. Marpha Formation) were largely influenced by the periodic damming of the paleo Kali Gandaki River. However, there are no strong evidences to prove the exact age and cause of damming. Tectonic landslides, glaciers or seismic activity are the most likely possibilities. Iwata (1984) stated that large-scale landslides occurred around Larjung before the Last Interglacial period that were responsible for the damming of the river and formation of the Paleo Marpha Lake. However, tectonic reactivation of the fault- systems like the Main Central Thrust (MCT), South Tibetan Detachment System (STDS) and Dangardzong Fault (DF) may have contributed to the structural dam by either headward erosion through the Higher Himalayan south of STDS or rupture of detachment system and the Higher Himalaya by the Dangardzong fault.

7. Discussion

The facies distributions in extensional basins are mainly controlled by a combination of factors including tectonics, climate, subsidence and sediment supply (e.g., Nichols and Watchorn, 1998). The basin fill of the Thakkhola-Mustang Graben was strongly influenced not only by Himalayan tectonics but also by climatic change during a critical phase in the Miocene period because of the uplift of the Himalayan mountain chain (Clift et al., 2008). Fluvial, fluvio-lacustrine and lacustrine styles of sedimentation are widespread in the Thakkhola-Mustang Graben.

A southward paleoflow was the main controlling factor for the sediment dispersal and deposition, filling an asymmetric graben-like depression bounded by faults (Fort et al., 1982; Garzione et al., 2003; Adhikari and Wagreich, 2011).

The lower alluvial units of the Tetang Formation (Upper Miocene, ca. 11 and 9.6 Ma) is composed of thick massive and imbricated conglomerate beds interbedded with some silt layers, which represents alluvial or small braided river facies. This sequence gradually alternated with pebbly sand and silt layer with some imbricated conglomerate layers, formed by braided river facies towards the upper portion. Clast-rich debris flow transitional to stream flow systems deposited such kinds of sediments with channel fill and gravel bars geometries. Carbonate layers in the upper part of this formation consists of algal mats with ostracods representing a shallow lake environment (Adhikari and Wagreich, 2008). Carbonaceous clay with some plant fossils were formed by the accumulation of in situ vegetation and plant material. Fining upward sequences in the upper portion of the Tetang Formation, a few meters to tens of meter thick, formed by gradual migration or abandonment of channels and sediment supply. Mainly carbonates with some sandstones and mudstones clasts are present on the Tetang Formation, which are derived from the eastern Mesozoic basement. The southeast portion of the graben near Tetang and Dhinko Khola section also has a similar provenance.

The basal conglomerate unit of the Thakkhola Formation (Upper Miocene-Pliocene, ca. 8 - 2 Ma) rests with an angular unconformity above the Tetang Formation. Basal conglomerate beds are composed of mainly shale, sandstone, quartzite of Paleozoic and Neogene granite clasts. This unit is composed of coarsening upward sequences, which suggests a progradational style of fan development. Braided fluvial system deposited imbricated conglomerate and sand layers in the middle of the Thakkhola Formation. Thick (12 to 15 m) mudstone sequences (Fig. 6C) were deposited above the imbricated conglomerate layer, sandstones and red mudstones on the upper part characterizing a progressive change in environmental conditions from lacustrine to low sinuosity river probably due to decreasing tectonic activities (e.g. Einsele, 1992). Lacustrine carbonates are present between 350 to 425 m (Fig. 5B) at different intervals above the imbricated conglomerate and stratified sandstone in the Thakkhola Formation. Garzione et al. (2003) also reported different lacustrine intervals in this formation and interpreted them as lakes due to a periodic damming of a southward-flowing river system. The upper alluvial unit represents imbricated braided-river conglomerates with sandstones and siltstones, which can be traced for more than 1 km. Mainly sandstones, shales and quartzites clasts are present in the conglomerate layers with southward-flowing paleoflow direction (Fig. 5B). Sandstones, shales, slates, phyllites, mudstone and some Mesozoic carbonate clasts are dispersed in the conglomerate beds on the middle and center part of the basin. Paleoflow directions show that these sediments were derived from the western Paleozoic basement highlands (Adhikari and Wagreich, 2011). Marl beds are distributed in a wedge shape in Dhi gaon, which indicate the north-eastern edge of the graben.

The overlying Middle Pleistocene Sammargaon Formation is a package of angular and unsorted, well-indurated diamictic conglomerate with silt layers. Hurtado et al. (2001) described these conglomerates as a glacial till and Fort et al. (1982) interpreted this formation as a product of Middle Pleistocene glaciations. Very gentle (5-7°) dipping of fine-grained sandstones and siltstones beds occur on the base of the Upper Pleistocene Marpha Formation and some conglomerate layers in the upper portion. Mainly quartzite, sandstone, slate, granite and carbonate clasts are dominant in the conglomerate with maximum 37 cm clast size, which are deposited in fluvio-lacustrine environment. Fine sandstone to mudstone of the Marpha Formation was deposited in the Paleo Marpha lake after the damming of the Kali Gandaki River (Iwata, 1984). Braided river system was active during the deposition of the Holocene Kaligandaki Formation and it is in cut and fill relation with Marpha Formation.

Several evidences from the sedimentary infill of the Thakkhola-Mustang Graben suggest that the climate was warm and relatively humid during the deposition in Miocene times. In general, the presence of alpine trees like *Pinus*, *Picea Tsuga* and *Quercus* with steppe elements like *Artemisia*, *Compositae*, *Chenopodiaceae*, *Plantago* and *Poaceae* suggests overall warm climate in the southern part of Tibet (Adhikari, 2009). Coniferous pollen grains (*Pinus*) are dominant in the Tetang Formation. The presence of *Keteleeria* in the Tetang Formation may indicate a warm climate and *Betula*, *Quercus* and *Juglans* suggest temperate forest conditions, implying some humidity (Adhikari et al., 2010). The presence of high percentages of *Plantago*, *Poaceae*, *Artimisia* and *Chenopodiaceae* in the Thakkhola Formation indicates a drier climate with mostly steppe vegetation, probably caused by the Himalayan barrier and uplift of the Tibetan Plateau. This formed a water vapor barrier, so that the water vapor carried by the south west monsoon could not reach the Tibetan Plateau, leading to the decrease in rainfall and gradual vegetational change to arid grasslands in the Thakkhola-Mustang Graben. Pollen data from Linxia and Quidam basins also suggest aridification in late Miocene time (Ma et al., 1998 and Wang et al., 1999).

Organic plant material from the Thakkhola and Tetang formations yielded stable carbon isotope ($\delta^{13}C$) values between -21.87 to -26.64 ‰ VPDB, indicating the presence of C3 vegetation. However, the $\delta^{13}C$ values from the carbonates range between -0.62 to 11.08 ‰ in both Tetang and Thakkhola formations, indicating mix vegetation of C3 and C4 plants (Adhikari et al., 2010). Also, the abundance of carbonate nodules in the

Thakkhola Formation compared to the Tetang Formation indicates drier conditions during the deposition of the Thakkhola Formation (Adhikari, 2009, and Garzione et al., 2003).

The $\delta^{18}O$ value of carbonates from the Thakkhola-Mustang Graben ranges from -13.5 ‰ to -24.96 ‰ VPDB (Adhikari, 2009). These values are similar to the modern precipitation in this region inferred from surface water in small catchment (Garzione et al., 2000). Furthermore, applying a lapse rate of -0.41‰/100m (Poage and Chamberlain, 2001) yields an estimate for the paleoelevation of ca. 3300 m (Marpha Formation) to 6100 m (Thakkhola Formation), indicating that the Thakkhola-Mustang Graben had already achieved an elevation near the present day value by 11 Ma. Results of Rowley et al. (2001) from modeling the changes in the isotopic composition of Himalayan precipitation with elevation as a Rayleigh distillation process corroborate our results.

8. Conclusions

The Thakkhola-Mustang Graben in the central Nepal Himalaya is interpreted as a subsiding half-graben structure which evolved during the Middle Miocene to Quartenary along a north-south striking main boundary normal fault, the Dangardzong Fault. The eastern and western Paleozoic and Mesozoic highlands are the main source for the Neogene to Quaternary sediments of the graben fill.

Facies association, lithofacies and architectural elements indicate that the Miocene-Pliocene graben fill was deposited in alluvial fan, braided river, fluvial-lacustrine (low sinuosity) and lacustrine environments.

The evolution of the Thakkhola-Mustang Graben fill is mainly controlled by tectonic movements such as mountain uplift and basin subsidence, and by the interplay of tectonics with the climatic evolution. Coarse alluvial and fluvial deposits due to high mountainous relief predominate, and are interbedded with intermittent lake deposits probably due to damming processes. First indications on paleoelevation by stable isotopes suggest that it was already in the range of today's values during the Late Miocene. Palynology indicates an evolution from warm and more humid to more arid conditions during the Late Miocene-Pliocene ending finally in a glacial period during Middle Pleistocene. Further detailed studies of the Neogene extensional graben fills of the Himalaya may provide a more detailed insight into the interplay of tectonics, i.e. uplift, erosion and basin subsidence, and climate of the area.

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