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Erosion assessment in the middle Kali Gandaki (Nepal): A sediment budget approach

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ABSTRACT

Active mountains supply the largest sediment fluxes experienced on earth. At mountain range scale, remote sensing approaches, sediments provenance or stream power law analyses, collectively provide rough long-term estimates of total erosion. Erosion is indeed controlled by rock uplift and climate, hence by a wide range of processes (detachment, transport and deposition), all operating within drainage basin units, yet with time and spatial patterns that are quite complex at local scale. We focus on the Kali Gandaki valley, along the gorge section across the Higher Himalaya (e.g. from Kagbeni down to Tatopani). Along this reach, we identify sediment sources, stores and sinks, and consider hillslope interactions with valley floor, in particular valley damming at short and longer time scales, and their impact on sediment budgets and fluxes. A detailed sediment budget is presented, constrained by available dates and/or relative chronology, ranging from several 10 kyr to a few decades. Obtained results span over two orders of magnitude that can best be explained by the type and magnitude of erosional processes involved. We show that if large landslides contribute significantly to the denudation history of active mountain range, more frequent, medium to small scales landslides are in fact of primary concern for Himalayan population.

Key words: Himalaya, Kali Gandaki, erosion, landslide, sediment budget

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INTRODUCTION

Solid particles transported by rivers dominate the mass transported out of continents to oceans. This is particularly true in steep, active mountains that supply the largest sediment fluxes experienced on earth, as estimated at global scale (Milliman and Syvitski 1992; Summerfield and Hulton 1994; Gaillardet and Galy 1999). At mountain range scale, total erosion is often estimated by using different approaches (stream power law, remote sensing approaches, or sediments provenance analysis), which provide rough long-term estimates. Sediment budgets are controlled by rock uplift and climate, hence by a wide range of erosion processes (detachment, transport and deposition), all operating within drainage basin units (hillslopes and talwegs). The time and spatial patterns of these processes can be quite complex, and should be documented at a more local scale to understand the succession of stages/sections of efficient sediment transfer with stages/sections of sediment storages, depending on landforms (both present and inherited ones) and water fluxes. Such patterns are commonly observed in the Himalayas, where the sediment cascade is particularly efficient, as favoured by high, glaciated peaks, together with narrow valleys and steep hillslopes, in a monsoon-contrasted, climatic context (Fort 1987a; Fort and Peulvast 1995; Pratt-Sitaula et al. 2004). At local scale, landslides interaction with valley bottom may cause river channel diversions, short-lived dams and sediment traps, whereas remnants of ancient landslides may play an important role in the location of present instabilities and the control of sediment fluxes (Fort et al. 2009). Thus a sediment budget approach appears appropriate to understand the links between sediment mobilisation, transport, storage and yield (Slaymaker 2003) and to specify the varying pathways and processes involved in the sediment cascade (Fort et al. 2010a). In this paper, we aim to document what are the geomorphic processes that animate the sediment fluxes connecting sedimentary stores and what are the main coupling patterns we observe in such active mountain areas. The volumes of debris stored, eroded and exported by the Kali Gandaki in its middle reach (upper Myagdi and lower Mustang Districts, Nepal Himalayas) are assessed for the last thousands years up to present.

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SEDIMENTARY BUDGET AND SEDIMENT CASCADE APPROACH

Our understanding of the denudation in the Himalayan Range is based on studies carried out at different time/spatial scales. Métivier et al. (1999) assessed the global denudation rate of the mountains of Central Asia via the resulting volumes of sediments stored in the large continental (Tarim, Qinghai) and marine basins surrounding them (Indus and Bengal fans, China sea, etc.). At the Himalayan scale, Galy and France-Lanord (1999) measured geochemical fluxes and sediments carried by rivers then trapped in foreland basins and marine fans. At watershed scale (i.e. Marsyangdi catchment, Nepal Himalayas), Garzanti et al. (2007) attempted at quantifying sand provenance through heavy minerals, hence defining the zone of maximum erosion, whereas in the same valley, Pratt-Sitaula et al. (2004) tried defining the alternance of alluviation events and incision stages on the basis of fluvial terrace, straths and radiometric dating (Pratt-Sitaula et al. 2007). By analyzing the relationships of sediment transport with daily river and precipitation data, Andermann et al. (2012) estimated the suspended sediment denudation rate of the Kali Gandaki to be 2.8 mm/yr, the largest among the major drainages of Nepal.

Our study focuses on shorter time span and spatial scale. The approach is based on two complementary concepts, sediment budget and sediment cascade through the geomorphic system, which can be subdivided into sub-systems (e.g. rockwalls, hillslope, valley bottom). The concept of sedimentary budget (Fig. 1) implies the identification of sediment sources, sediment stores and

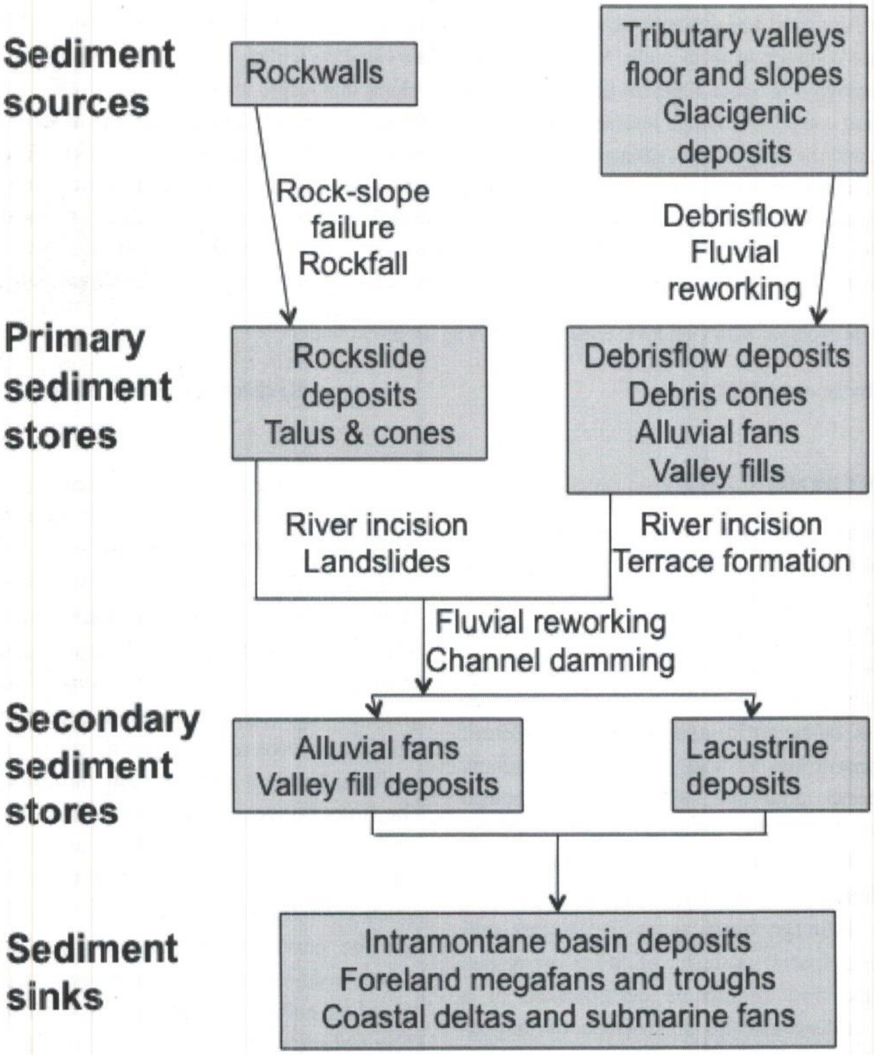


Fig. 1: Sedimentary budget concept. The grey boxes represent sediment stores. Sediment fluxes connecting stores are animated by different geomorphic processes.

sinks. In Himalayan valleys such as the Kali Gandaki valley, most sediment sources are rocky mountain slopes (rockslope failures and rockfalls, or/and rock weathering) adjacent to the valley floor, and tributary valleys (debris derived from rockslopes and/or from inherited glacigenic deposits). Set into motion by sismo-tectonic and/or climatic events, the loose debris is reworked and transported by slope processes (landsliding) or fluvial processes, and may be deposited in primary sediment stores, either as landslide debris or as secondary stores such as alluvial or lacustrine fills. The different sediment sources and stores are connected through sediment cascades (Fig. 2), i.e., debris and water fluxes that transit from the different elements of the geomorphic system: mountain slopes, gullies, valley floor, and river channel, at different spatial and time scales. These connections may be alternately efficient or not, and this functioning is documented through the estimation of the volumes of debris eroded and exported by the Kali Gandaki since the formative failures that impounded the valley at different sites.

RESEARCH AREA

We focus on a specific reach of the Kali Gandaki valley (Fig. 3), i.e., from downstream of Tatopani (Myagdi District) up to Kagbeni (Mustang District), from the transition between the Lesser and Greater Himalayas (Upreti and Yoshida 2005) up to the metasediments of the "Tibetan series" (Colchen et al. 1986). More specifically, from Tatopani up to the north of Dana, the upper Lesser Himalayan sequences display an alternation of slates-phyllites bands with quartzites, affected by various mylonitic facies while approaching to the MCT zone. Further to the north, the Higher Himalayan Crystalline (HHC) sequences (including mica-gneisses, calcareous gneisses and augen gneisses) are taking over up to Kalopani, where the low-grade Tibetan Sedimentary Sequence (TSS), mostly metasedimentary marbles, predominate and are deformed by north verging folds (Upreti and Yoshida 2005; Colchen et al. 1986). This Kali Gandaki section spans across two major structures: to the south, the Main Central Thrust (MCT), between the upper Lesser Himalaya and the lower part of the Greater Himalaya; to the north, the North Himalayan Detachment Fault (NHDF), otherwise called South Tibetan Detachment System (STDS), a prominent family of normal faults along the contact between HHC and TSS affected by a down to the north displacement (Burchfield et al. 1992; Godin 2003).

Geomorphologically, the Kali Gandaki valley is mainly V-shaped, with very narrow gorge segments controlled by N10° oriented dip slopes (dip gradient varying between 30° to nearly 90°) alternating with limited wider areas, bounded by unstable, debris-covered slopes (slope gradient <30°) corresponding to older landslide material most prone to be re-mobilized (Fort 1987b; Fort et al. 1987; White et al. 1987). The valley bottom displays a narrow floor with discontinuous patches of aggradational terraces of late Pleistocene and Holocene age (Dollfus and Usselmann 1971; Fort 1974; 1993; 2000; Yamanaka and Iwata 1982; Monecke et al. 2000); in addition very discontinuous patches of old alluvial formations can still be found perched several hundred meters high above the present river bed (Dollfus and Usselmann 1971; Fort 1974; 1993), suggesting the magnitude of river incision after their deposition.

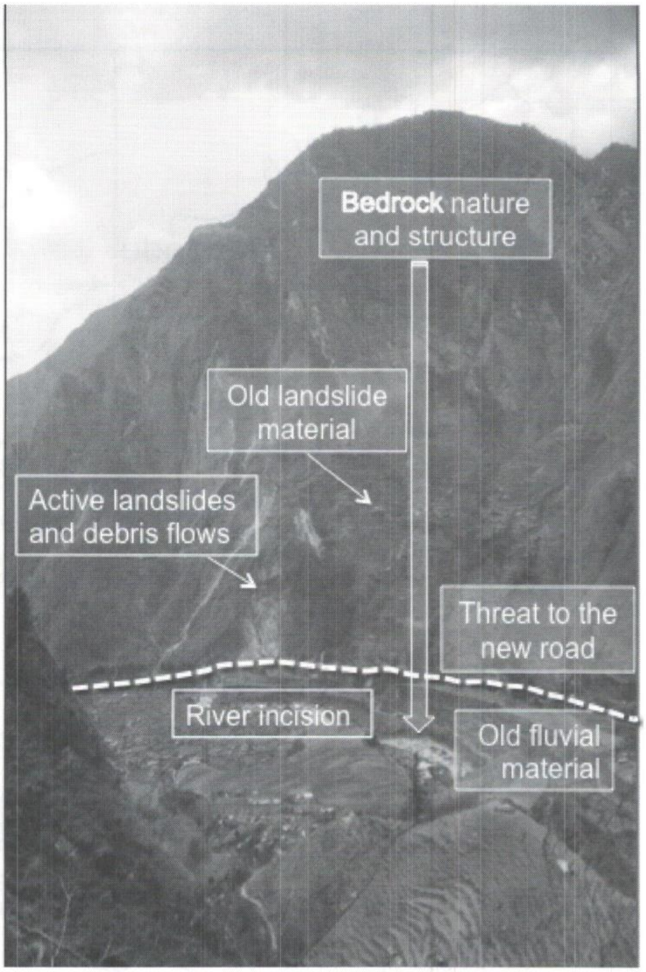


Fig. 2: Sediment cascade concept, including upslope-to-downslope fluxes, and upstream-to-downstream fluxes.

The valley appears as a fragmented river system (sensu Hewitt 2002) interrupted by a series of landslides and/or large debris flow fans that temporary blocked the sediment conveyance of solid discharge to the downstream reaches (Fig. 3). From north to south, the main landslide barriers are as follows. The prehistoric, giant (10^9 m^3) Dhampu-Chhoya rock avalanche (Fort 1974, 2000) dammed the upper Kali Gandaki, with complex relationships with the Late

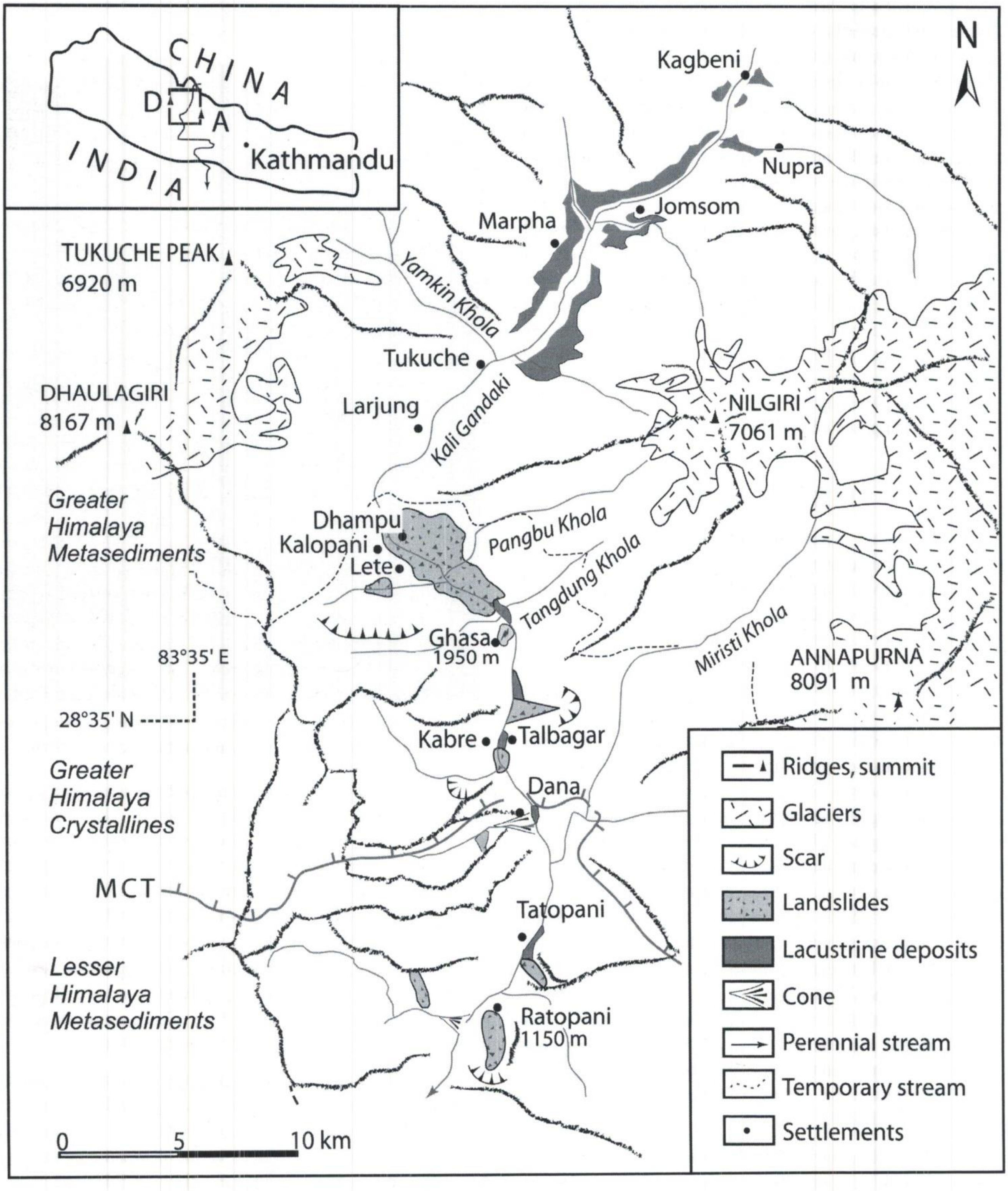


Fig. 3: The middle Kali Gandaki River and location of main studied features.

Pleistocene ice tongues derived from the Dhaulagiri (8167 m) and Nilgiris (7061 m) peaks. Both the rock avalanche and glaciers controlled the former "Marpha Lake" deposits that extend upstream from Tukuche up to Kagbeni (Fort 1980; Iwata et al. 1982). Adjacent to the Dhampu-Chhoya rock avalanche, the Kalopani one correspond to a more recent event, the distal debris of which having formed the widespread Lete-Kalopani cone. Further down the valley is interrupted by the Ghasa landslide (postdating the Dhampu-Chhoya one; Fort 2000; Zech et al. 2009), then by the undated Pairothapla-Talbagar and Kopchepani landslides dams (Fort et al. 2010b). Other modern features are still actively, partly and/or temporarily impounding the valley: the two debris cones of the Ghatte (Dana) and Dhoba kholas, both supplied by the right bank tributaries of the Kali Gandaki, and the 1998 Tatopani landslide (Fort et al. 2010b). In addition, large sediment storages in the form of terraces are found all along the studied area: we will refer mostly to the large set of terraces developed at the junction between the Miristi Khola and the Kali Gandaki (Monecke et al. 2000).

METHODS

Sediment is routed through storage reservoirs: sediment fluxes are inferred from the variation of the volume of the reservoirs, according to their age when available. On the basis of diachronic (1974-1982-1993-2000-2008) geomorphic surveys and field mapping, along with aerial photographs, topographic map analysis, and with the recent help of DEM facilities, we reconstructed the extent of the landslide deposits, the nature (lacustrine and alluvial) and volume of the sedimentary traps, and the evolution of the landslide masses. We established the cross section of landslide masses in the valley and characterized the material (size, sorting). The volume of sediments released by the mountain slope was assessed, including the debris cones (the very dam), and the sedimentary wedges resulting from superficial reworking and redistribution of debris. We also estimated the volume of debris eroded and exported by the Kali Gandaki since the failure. All sediment export calculations were based upon simple geometric landforms (Campbell and Church 2005): talus, cone, etc. Basic measurements (height, width, etc.) were adapted to the field area, and surveyed with a Leica laser telemeter and hand-help GPS.

RESULTS

We present below results that include the most prominent sediment storages of the considered valley section. We selected them according to their type, volume and age, according to previous investigations.

Dhampu-Chhoya rock-avalanche, and the "Marpha Lake"

We consider here the upstream part of the Kali Gandaki valley, north of Ghasa up to Kagbeni. It is difficult to single out one feature, because the Dhampu-Chooya rock avalanche, together with the legacies of the "Marpha Lake", cannot be totally understood without considering the complex interactions between these two features and the last Quaternary glaciation (Fig. 4).

The giant, persistent rock-avalanche dam of Dhampu-Chhoya is largely described and commented in Fort (2000). It should be mentioned that this rock-avalanche corresponds to an event different from the more recent Kalopani debris-avalanche cone and fan (as in Weidinger 2006) derived from Sarpang Dhuri, whose debris and associated deposit are cut-and-fill into the older Dhampu-Chhoya rock-avalanche runout.

The apparent areal extent of the Dhampu-Chhoya rock-avalanche is about 10 km^2 (Fig. 4). It reaches a thickness of at least 300 m, as observed along the left bank of the Kali Gandaki between Chhoya and Kaiku (Fig. 4C). The base of the material, mostly hidden by scree and rubble covering the foot of the slope, is below or close to the level of the present bed of the river, and suggests a minimum displaced volume of approximately 1 km^3. The failed mass is made of granitic gneiss material, hence is derived from the right side of the Kali Gandaki river, namely the Kaiku ridge (~3300-3400 m). The latter is much lower than the Bandarjung Turture Danda (~4000 m) west of Ghasa while it should be higher as regards to the geological and morphological structure of the Higher Himalaya. This large collapse of the Kaiku ridge was most probably triggered in relation to the activity of Northern Himalayan Detachment Fault (Fort 2000; 2011). According to recent dating, it was emplaced about 30,000 years ago (Zech et al. 2009; 10Be, R. Braucher and D. Bourlès, personal communication; Fort et al. in prep.) across the narrow gorge of the Kali Gandaki River, hence ensuring dam stability and longevity (Fig. 4A and C), and persistent aggradation by the Kali Gandaki, associated to a braiding pattern. The dates recently obtained make the geomorphic evolution of this valley section more complex than expected, as discussed below.

Indeed another important event was the development of a large lake upstream, the Marpha Lake (Fort, 1980) that extended more than 23 km in length, flooding the entire Kali Gandaki valley and its tributaries as inliers from Tukuche up to Kagbeni (lake top at about 3000 m). In the type locality (Marpha), the depth of lacustrine deposits is close to 200 m (Fort 1980), probably a minimum thickness (Fig. 4B). Dates of lacustrine sediments between Marpha and Syang span

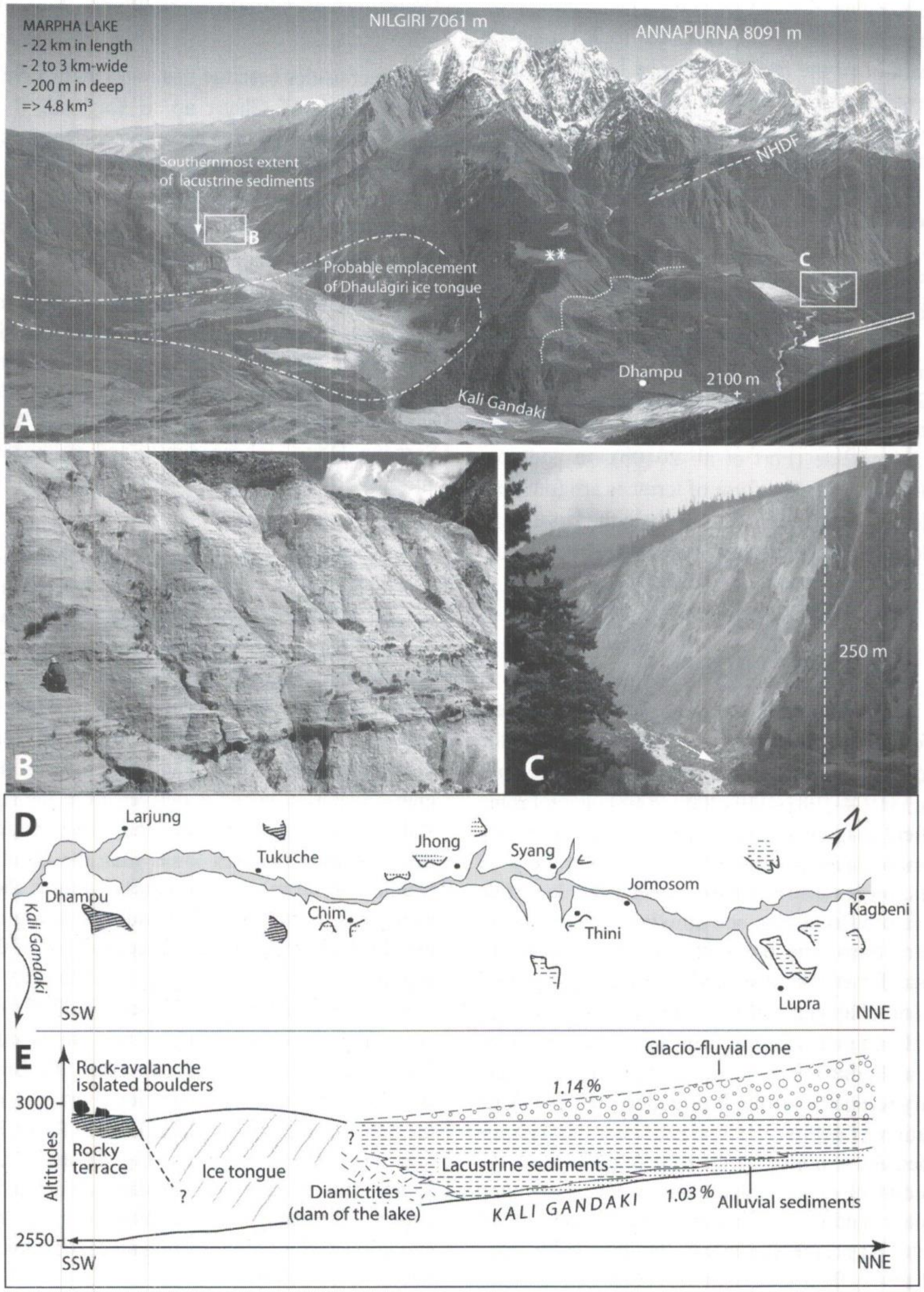


Fig. 4: The large, prehistoric Dhampu–Chhoya rock avalanche. (A) View from the east face of Dhaulagiri). The collapsed mass (several failure events are not excluded) failed along the North Himalayan Detachment Fault (NHDF) and blocked durably the Kali Gandaki River; the ice tongue issued from Dhaulagiri (8172 m) might have controlled the lake level. Asterisk indicates the location of 10Be sampling. (B) Lacustrine sediments, Marpha section; (C) Section of the Kali Gandaki left bank exhibiting the fractured rock-avalanche material; (D) The present braided channel of the Kali Gandaki (in grey) and perched remnants of lacustrine-alluvial deposits, as superposed in (E) Lacustrine sediments derived from upstream and from glaciated tributary valleys, with interfingering with retrogressive alluvial fan facies, until Kali Gandaki alluvial deposits prograde downstream during and after complete filling of the lake.

over stages of the Last Glaciation: according to Baade et al. (1998) and to Baade (2000), the lake was in existence from 56.4±6.94 ka up to 32.7±3.8 ka BP (OSL dates), a time span large enough that might have included two lacustrine stages as suggested by Iwata (1984). Clearly however, the lacustrine episode ended soon before the Dhampu-Chhoya rock-avalanche failure.

This discrepancy in the dating of both lacustrine and failure events raise the issue of the nature of the lacustrine dam: rock-avalanche, as initially thought (Fort 1974; 1980; Baade 2000) or possibly a glacier tongue (Fort 2000)? During the last glaciation (Fort 2004), a glacier tongue issued from the east face of Dhaulagiri (8167 m) most probably reached the Kali Gandaki valley bottom (i.e. calcareous breccia plastered along the left bank of the Kali Gandaki, north of Dhampu) (Fig. 4A). Yet, a glacial tongue is not resistant and persistent enough to dam and contain such a large lake (>4 cubic kilometres; Fort 2000). In order to match the level of the lake together with morphological and sedimentary remnants on the one hand (Fig. 4D and 4E), with the OSL dates of lacustrine sediments and 10Be dates of Dhampu-Chhoya rock-avalanche on the other hand, we end up with the following hypothesis: another massive rock-failure, older (>30 ky) than the Dhampu-Chhoya one that we dated, might have formed the initial dam, whereas the adjacent Dhaulagiri glacier tongue controlled the lake level hence the lake sedimentation. Alternatively, we may question the dating methods and their reliability, and/or consider the possibilities of sediment reworking or weathering that might have brought more uncertainty on the exact timing of these different events. The fact that both Zech et al. (2009) and our team (together with R. Braucher and D. Bourlès) have obtained consistent cosmonuclide dates, from different samples and different laboratories, provides very good evidence of a chronologically, well constrained Dhumpu-Chhoya rock-avalanche event, i.e. about 30,000 years ago. Conversely, dating of lacustrine sediments has not been crosschecked to date, and some uncertainty cannot entirely be ruled out.

From the above discussion, the assessment of sediment budget and fluxes should be established as follows. If incision of the lacustrine sediments could not began before 32.7±3.8 ka BP (youngest age of lacustrine deposits), incision was further delayed by the Dhampu-Chhoya rock-avalanche that occurred at about 30 ka 10Be. In addition, we reasonably assumed that exportation of lacustrine sediments was controlled by the Dhaulagiri ice-tongue thickness, and by progressive and/or fluctuating restoration of full conveyance when the Kali Gandaki valley bottom became ice-free, i.e., after the Last Glacial Maximum. We can consider it occurred at ~18–24 ka (i.e. Marine Oxygen Isotope Stage 2, or MIS-2) as in the other parts of the Himalayas (Owen 2009), without ruling out other smaller glacier advances during Holocene that might have temporarily impounded sediment export. The emplacement of the former Dhaulagiri and Tukuche Peak ice tongues is now occupied by younger, thick debris-flow deposits underlying the terraces and cultivated fields of Larjung and Khobang (Fig. 5).

Nowadays, most of the lacustrine sediment is removed, and valley incision by the Kali Gandaki River formed a series of stepped terraces (downwasting of the ice tongue? stages of rock-avalanche dam incision?) cut into the lacustrine deposits, with abundant supply of debris from the slopes (Fig. 6). Near Kagbeni (2900 m), the lacustrine beds pinge out and are progressively replaced by the fluvio-deltaic prism that underlies the >200 m high terraces of the Kali Gandaki, 14C dated by Hurtado et al. (2001). Assuming a minimum lake volume of 4 cubic kilometres and a maximum time span of 20 ka (no incision before), we calculated that more than 80% of the former lacustrine sediment is eroded, giving a large figure of sediment removal (min. exportation rate of 200,000 m^3/yr). Indeed, this incision rate is quite dramatic, yet favoured by the very erodible type of sediment (silts). Export nowadays is very limited, and mostly depends on catastrophic shifting of the Kali Gandaki from one side to another side of the valley.

Pairothapla-Talbagar debris avalanche

The Talbagar debris avalanche, also referred to as Pairothapla, is located on the left bank of the valley (Lat. 28°34'14"N and Long. 83°38'25"E, southernmost Mustang District) along a 2000 m high mountainslope, cut into the Greater Himalayan crystallines (Colchen et al. 1986) where weaker biotite and hornblende rich bands alternate with steeper calcareous gneiss (Upreti and Yoshida 2005). The Pairothapla-Talbagar debris avalanche (about 16 million m^3) dammed the Kali Gandaki gorges at their narrowest, probably a few centuries ago according to the thin weathering soil horizon (dating under progress), hence forced the sedimentation upstream with a resulting lake of estimated 9-14 million m^3 in volume (Fort et al. 2010b). Lacustrine silts and sands are coarsening upstream ward and laterally with alluvial and slope sediment influxes. The left bank of the Kali Gandaki river displays a very actively eroded, 100 m thick debris avalanche section. It is composed of a diamicton including very large blocks (>350 m^3) and fine crushed, gneissic material composed of the superposition of two debris avalanche events, of an assumed age of four hundreds and one hundred years respectively (see discussion in Fort et al. 2010b). The Kali Gandaki River restored its

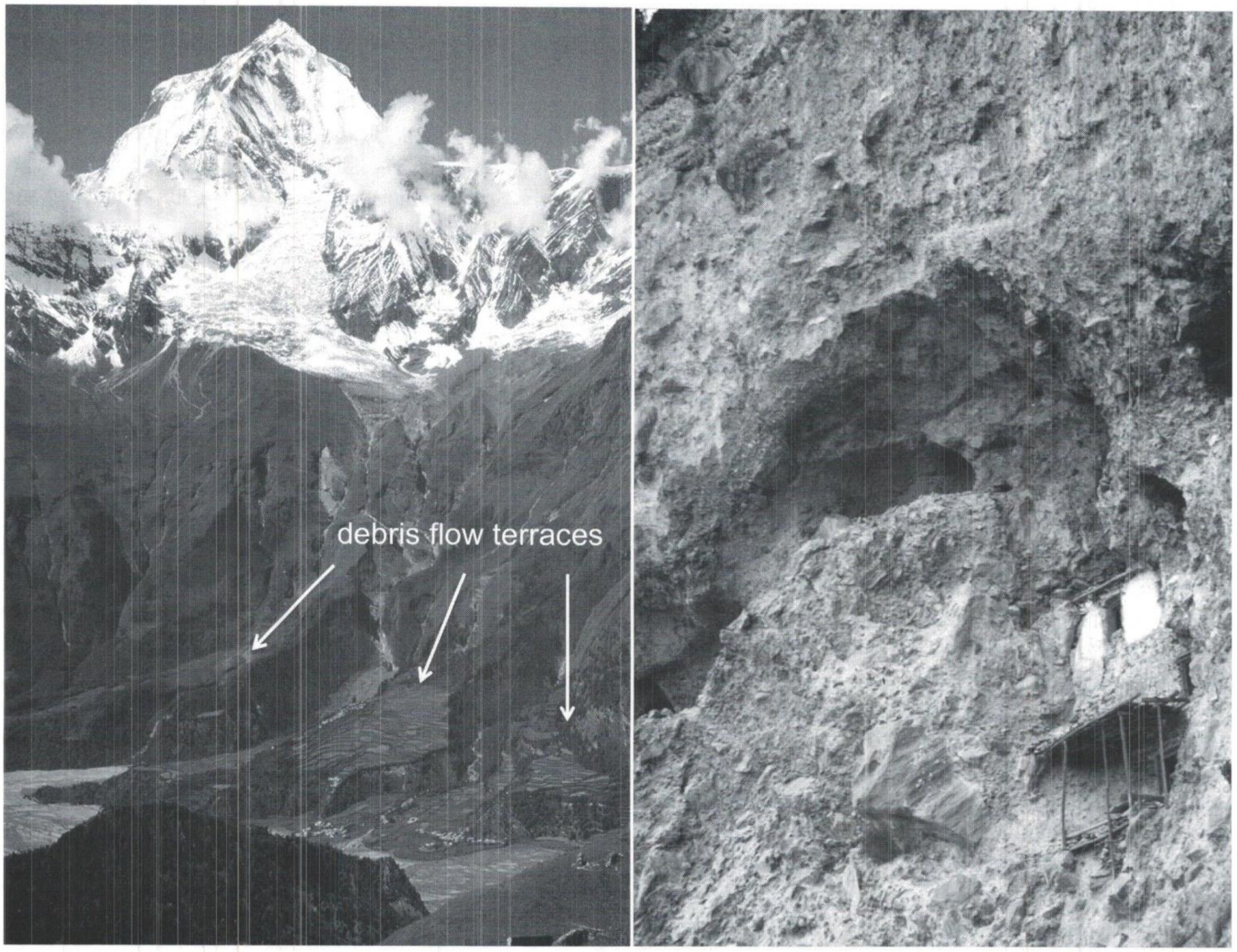


Fig. 5: East face of Dhaulagiri (8172 m), with debris-flows terraces of Larjung and Kobang (left) at ~2500-2600m, and detail of debris-flow material near Khobang (right).

continuity by cutting through the debris then incising the bedrock underneath, with the development of a spectacular epigenetic gorge.

Downstream, after the breaching of the first dam, a large (11 million m^3) sedimentary wedge formed that is now dissected (remnant: 4 million m^3). The breaching of the second dam following a second debris avalanche event and subsequent valley damming, led to the formation of new cut-and-fill terrace ($2.3x10^6$ m^3), a large part of it is already removed (present remaining volume: $0.8x10^6$ m^3). The synthesis of our calculation (Fig. 7) shows that more than 63% of the initial volume of the upper terrace has been removed, a figure that represents a rate of combined incision-exportation of about 6000 m^3/yr, assuming a 400-year age for the formative event. For the lower terrace (100-year old), the percentage of removal is about the same (60%), yet the combined incision-exportation rate is much higher (13,000-15,000 m^3/yr). The fact that this rate is calculated on a shorter period is for us good evidence that most of the erosion work is instantaneously carried out during the outburst of landslide dams, so that coupling between mountain slopes and river is efficient and, finally, the work accomplished by the river is steadier between two "extreme" events.

Alluvial examples

Two alluvial examples, the first one along a large tributary (Ghatte khola) debris flow cone built up at the junction with the Kali Gandaki, and the second one corresponding to a large set of Holocene and modern terraces built at the Miristi/Kali Gandaki confluence, show that sediment stores related to fluvial/torrential transport and deposition may also be quite impressive.

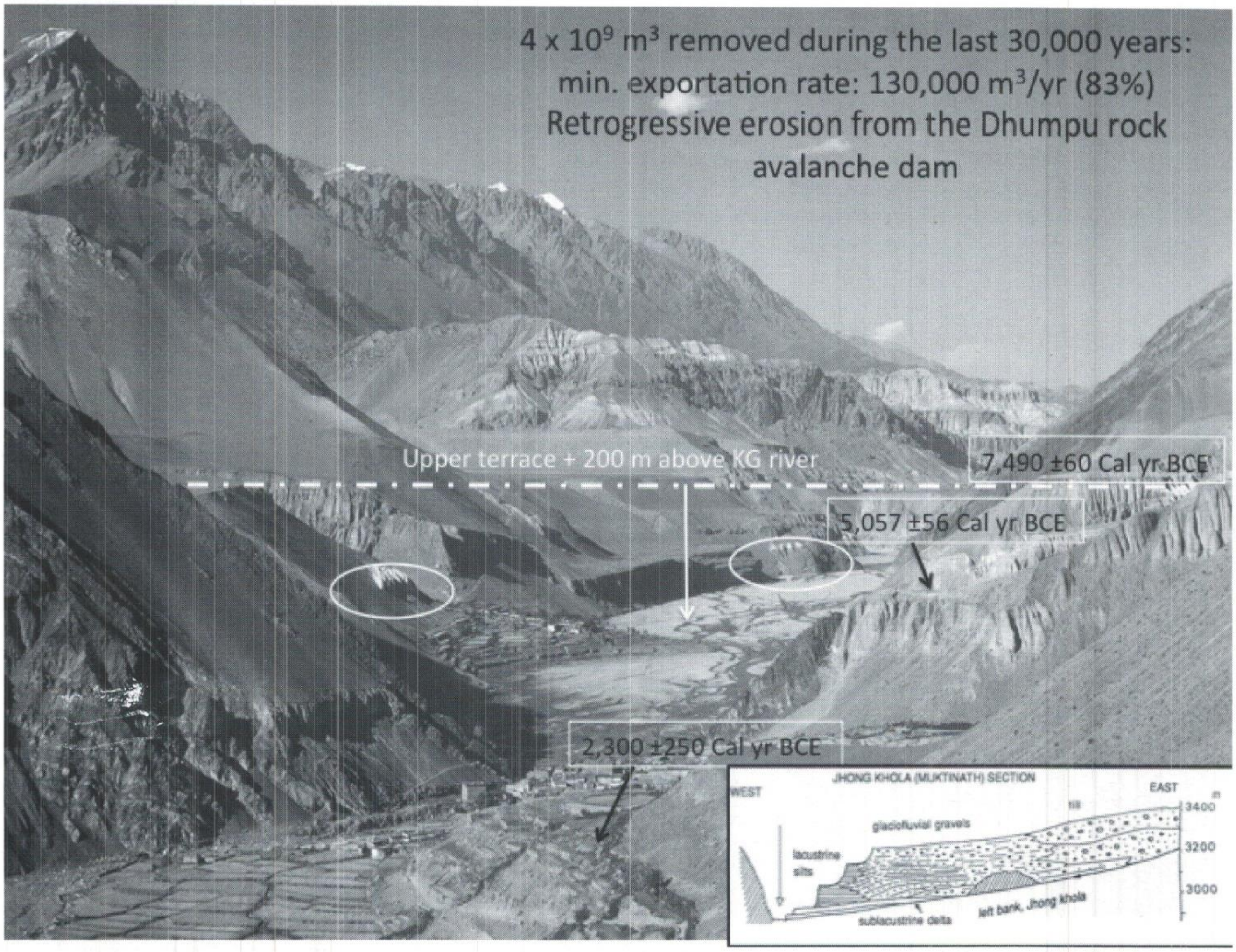


Fig. 6: Morpho-sedimentary pattern near Kagbeni and calculated Holocene sediment removal rates; 14C dates from Hurtado et al., 2001. Box: section along the Jhong khola, left tributary of the Kali Gandaki, from Fort 1980).

The Ghatte khola, a right bank tributary of the Kali Gandaki, drains a small (7.8 km^2), steep (37%), east-west elongated catchment, characterised by a pronounced asymmetry striking perpendicular to the northward general dip of the Himalayan structures (Fig. 8 A). At the junction with the Kali Gandaki, the Ghatte khola has built up a large debris fan (1.5 km wide and 2 km long). Developed in the upper Lesser Himalaya Formation close to the MCT zone (Colchen et al. 1986; Upreti and Yoshida 2005), the 70° steep counter dip scarps (mostly quartzites, left bank) of the Ghatte catchment contrast with the >40° steep dip slopes (aluminous schists, right bank). These latter are affected by active translational slides that are most often triggered by heavy cloudbursts distinctive of the pre-monsoon season (Fort 1974). Depending on their size, the slide masses may clog for a few hours the upper narrow valley of the Ghatte stream upstream, until a sudden, landslide lake outburst flood (LLOF) occurs and generates sporadic, sometimes fairly destructive debris-flow events (Fort 1974; Fort et al. 2010b) (Fig. 8B). These latter have caused the progressive aggradation of the confluence debris-flow fan, encroaching over the Kali Gandaki alluvium, as exhibited along the left bank of the fan nearby the village of Dana. Modern erosion along the fan banks caused by successive LLOFs (they occur every two-three years) together with aggradation of the channel bottom are both good evidence of the transient sediment flux and continuous reworking of sediment storages by the river. The fact that the Ghatte khola debris fan is in direct connection with the Kali Gandaki river allows a high rate of removal during and just after the monsoon season, with an export rate varying between 30% and more than 60% of the original landslide debris, depending on monsoon precipitation intensity and amount, hence on stream discharge.

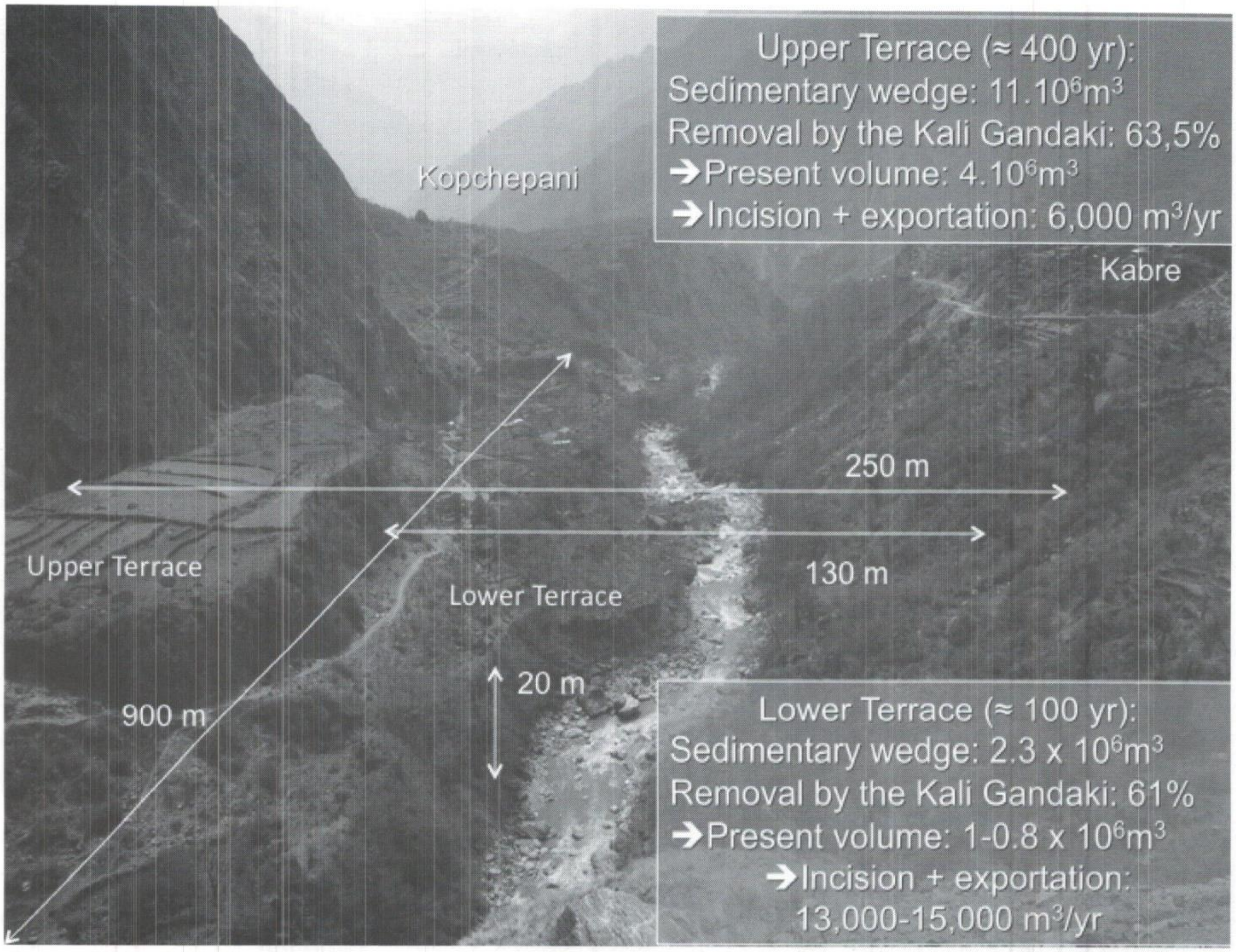


Fig. 7: Sedimentary wedges downstream of Pairothapla-Talbagar debris avalanche and later sediment removal.

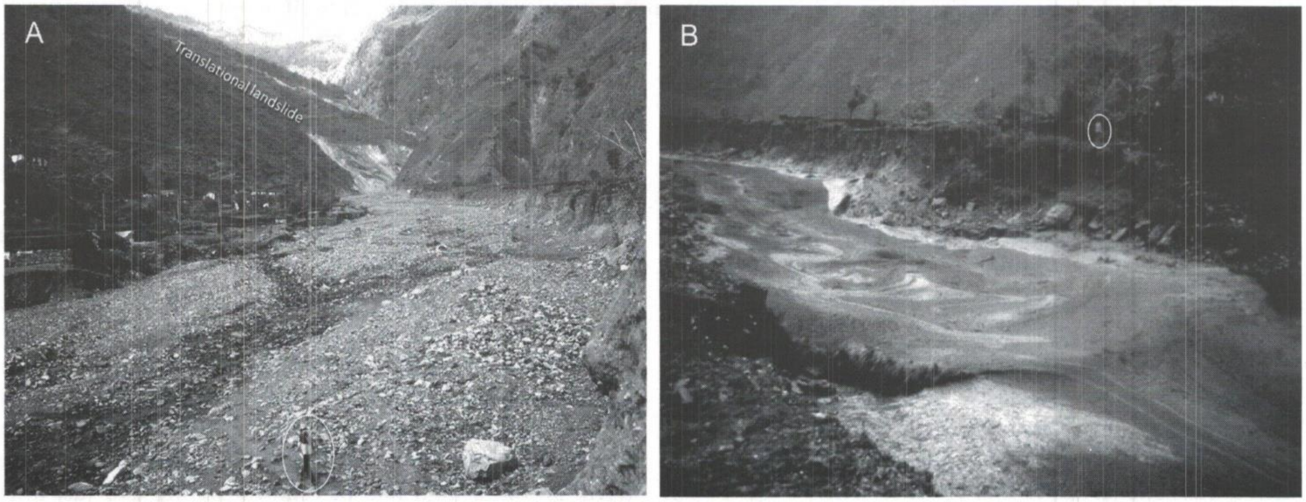


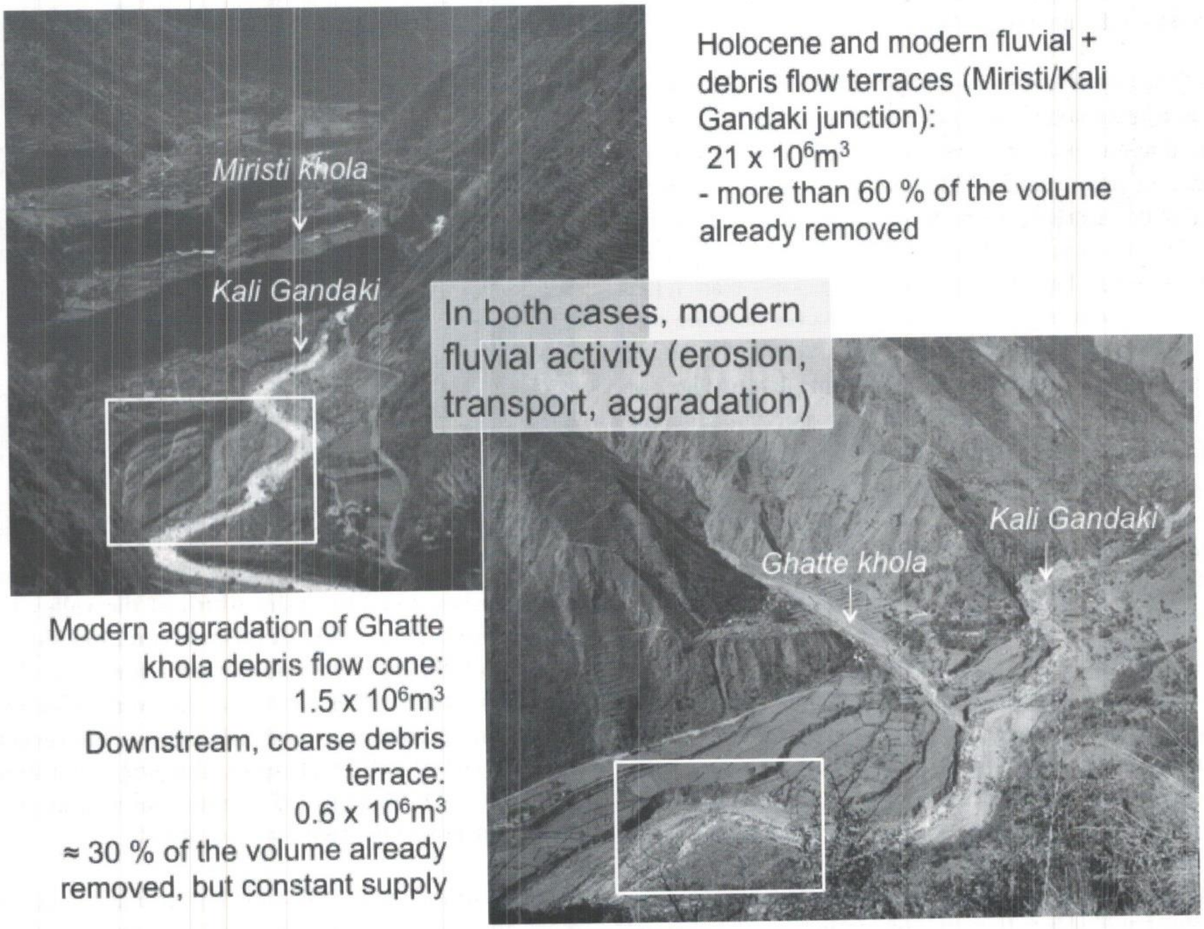
Fig. 8: (A) Asymmetric Ghatte khola watershed, characterized by rapid sediment fluxes with time in response to landslide events occurring upstream, hence causing both changes in channel width (15m in 1974, 35m in 2009) and in bed surface morphology (short term alternation of aggradation/incision stages, in a regional trend of river incision). (B) Debris flow event as witnessed in May 1974.

The second example is the set of Holocene and modern terraces (max. relative elevation +20 m) built up at the Miristi/Kali Gandaki confluence; it has been extensively described and dated by Monecke et al. (2001). These authors show that these terraces are the result of complex cut-and fill aggradation, with lithofacies evidencing an alternation of fluvial and debris flows units. They interpret these debris flows as sedimentary responses to climate changes in connection with stages of glacier melting and/or final deglaciation, without totally ruling out the possibility of being a response to earthquake or glacial-lake outburst floods. Alternatively, our observations in the upper Miristi catchment suggest the debris flow units might also be a response to landslide dam outburst floods that occurred in the upstream part of the Miristi khola and its tributaries (Ghaleti khola) (Fort 1993; Zech et al. 2009). Whatever the interpretation of these debris flows events, it is important to note that a significant part of the original terrace deposit representing a volume of about 21x10^6 m^3 has been removed by further incision and lateral shifting of the Kali Gandaki river (Fig. 9): we estimated the volume removed to be ~60%, that would represent an average rate of 1260 m^3/y, a value that indeed does not represent the reality of what has probably been operated by sporadic, impulsive flood events, as suggested by the last example.

1998 Tatopani landslide

A last example corresponds to the 1998 Tatopani, rainfall triggered landslide that affected the quartzites and phyllites (mostly green chloritoschists) of the upper part of the Lesser Himalaya formations (Sikrikar and Piya 1998). This slope has experienced a series of retrogressive, large scale, failures during the recent decades (Fort et al. 2010b), and is affected in depth by slow rock creep (Voelk 2000). In 1998 however, the failed mass was significant enough to impound the Kali Gandaki flow for a few hours (Fig. 10).

The volume of the landslide (1.1 x 10^6 m^3), landslide dam (0.7x10^6 m^3) and lake (1.5x10^6 m^3) were assessed by Fort et al. (2010b) together with the volume of the eroded breach by



Holocene and modern fluvial + debris flow terraces (Miristi/Kali Gandaki junction):
21 x 10^{6}m^3
- more than 60 % of the volume already removed

In both cases, modern fluvial activity (erosion, transport, aggradation)

Modern aggradation of Ghatte khola debris flow cone:
1.5 x 10^{6}m^3
Downstream, coarse debris terrace:
0.6 x 10^{6}m^3
≈ 30 % of the volume already removed, but constant supply

Fig. 9: Sediment removal affects both Holocene terraces of the Miristi-Kali Gandaki confluence, and the active Ghatte khola junction fan with the Kali Gandaki.

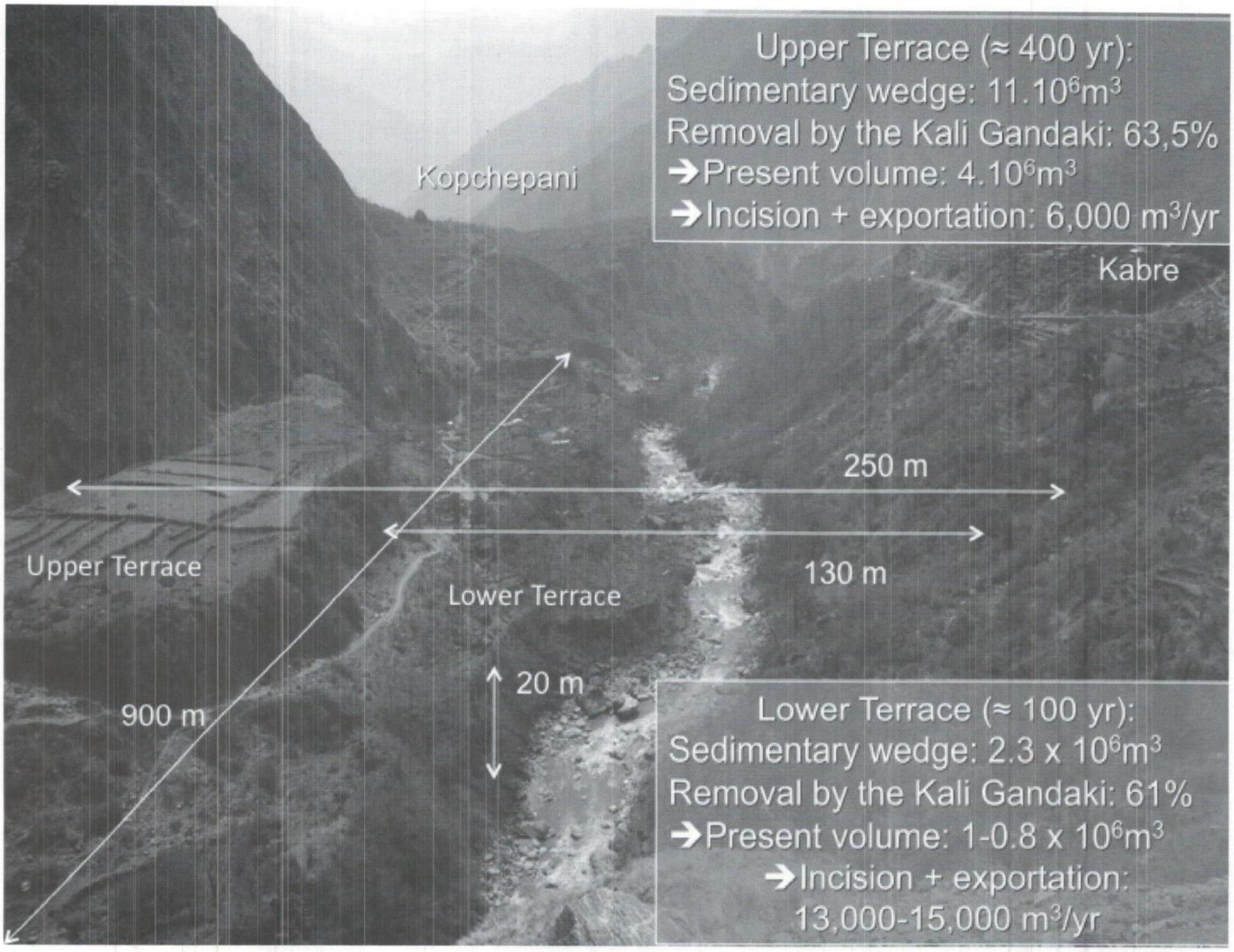


Fig. 7: Sedimentary wedges downstream of Pairothapla-Talbagar debris avalanche and later sediment removal.

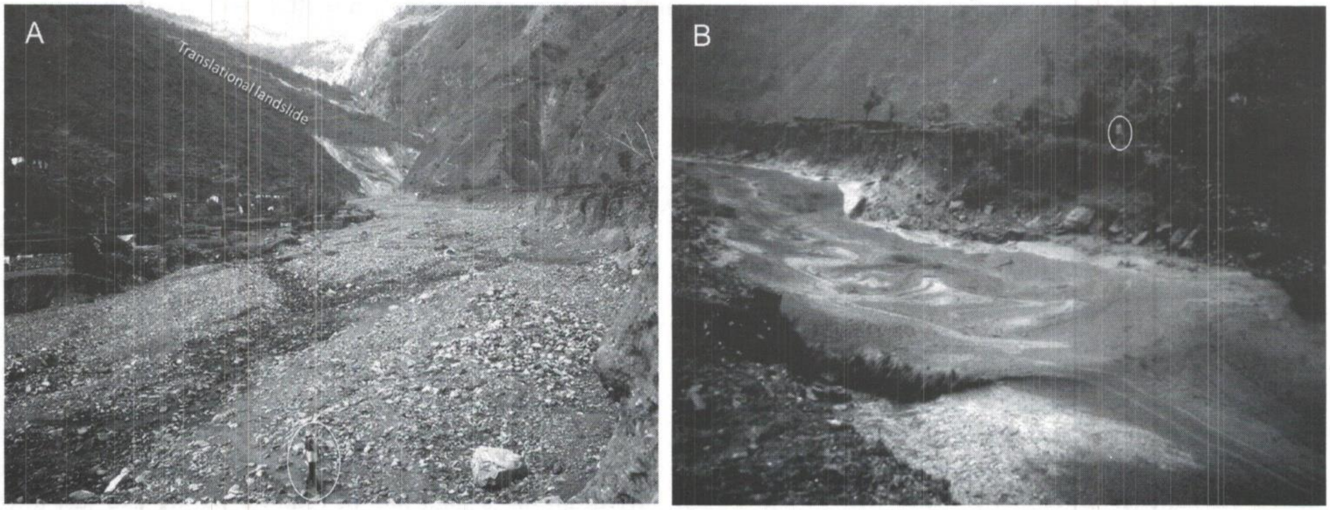


Fig. 8: (A) Asymmetric Ghatte khola watershed, characterized by rapid sediment fluxes with time in response to landslide events occurring upstream, hence causing both changes in channel width (15m in 1974, 35m in 2009) and in bed surface morphology (short term alternation of aggradation/incision stages, in a regional trend of river incision). (B) Debris flow event as witnessed in May 1974.

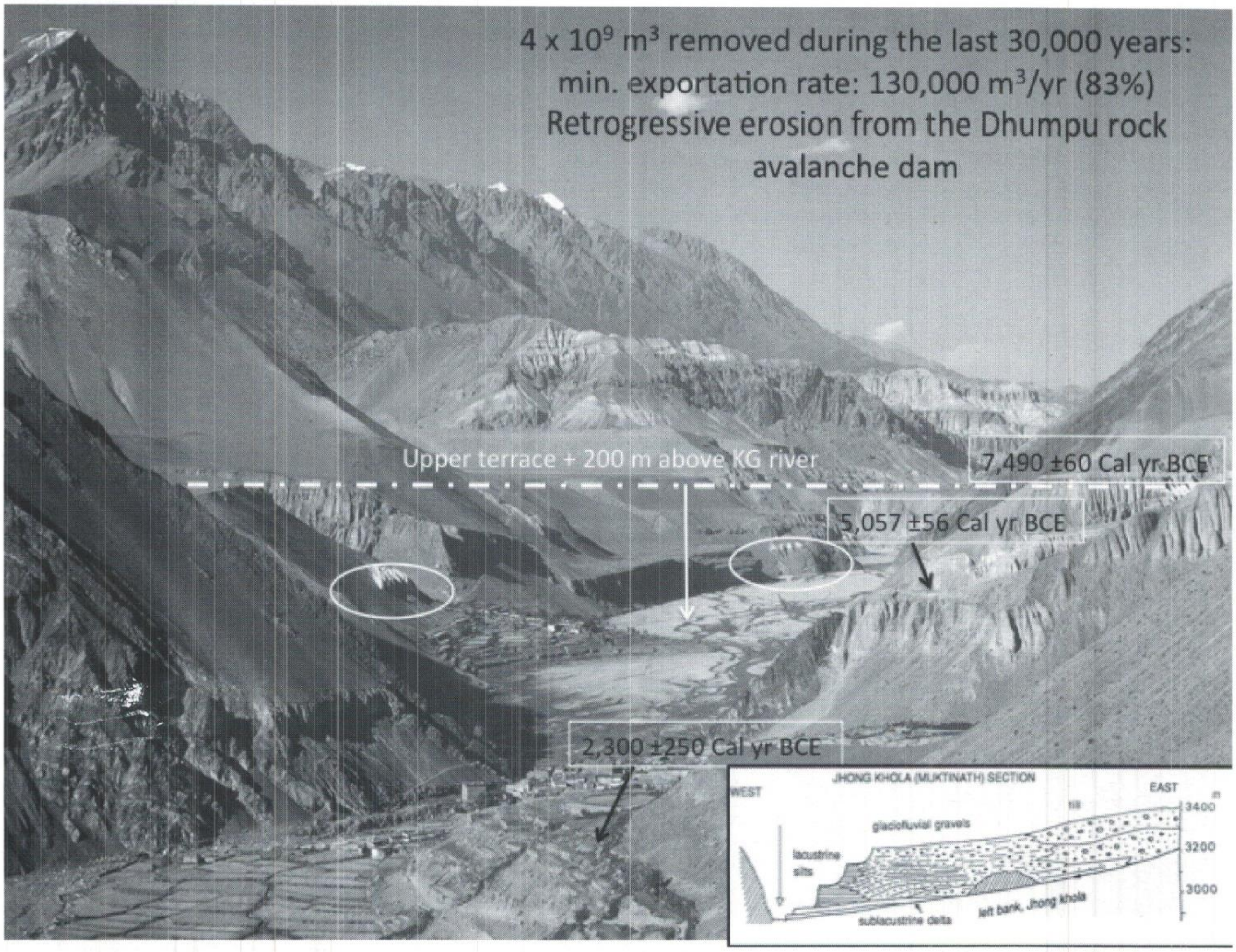


Fig. 6: Morpho-sedimentary pattern near Kagbeni and calculated Holocene sediment removal rates; 14C dates from Hurtado et al., 2001. Box: section along the Jhong khola, left tributary of the Kali Gandaki, from Fort 1980).

The Ghatte khola, a right bank tributary of the Kali Gandaki, drains a small (7.8 km^2), steep (37%), east-west elongated catchment, characterised by a pronounced asymmetry striking perpendicular to the northward general dip of the Himalayan structures (Fig. 8 A). At the junction with the Kali Gandaki, the Ghatte khola has built up a large debris fan (1.5 km wide and 2 km long). Developed in the upper Lesser Himalaya Formation close to the MCT zone (Colchen et al. 1986; Upreti and Yoshida 2005), the 70° steep counter dip scarps (mostly quartzites, left bank) of the Ghatte catchment contrast with the >40° steep dip slopes (aluminous schists, right bank). These latter are affected by active translational slides that are most often triggered by heavy cloudbursts distinctive of the pre-monsoon season (Fort 1974). Depending on their size, the slide masses may clog for a few hours the upper narrow valley of the Ghatte stream upstream, until a sudden, landslide lake outburst flood (LLOF) occurs and generates sporadic, sometimes fairly destructive debris-flow events (Fort 1974; Fort et al. 2010b) (Fig. 8B). These latter have caused the progressive aggradation of the confluence debris-flow fan, encroaching over the Kali Gandaki alluvium, as exhibited along the left bank of the fan nearby the village of Dana. Modern erosion along the fan banks caused by successive LLOFs (they occur every two-three years) together with aggradation of the channel bottom are both good evidence of the transient sediment flux and continuous reworking of sediment storages by the river. The fact that the Ghatte khola debris fan is in direct connection with the Kali Gandaki river allows a high rate of removal during and just after the monsoon season, with an export rate varying between 30% and more than 60% of the original landslide debris, depending on monsoon precipitation intensity and amount, hence on stream discharge.

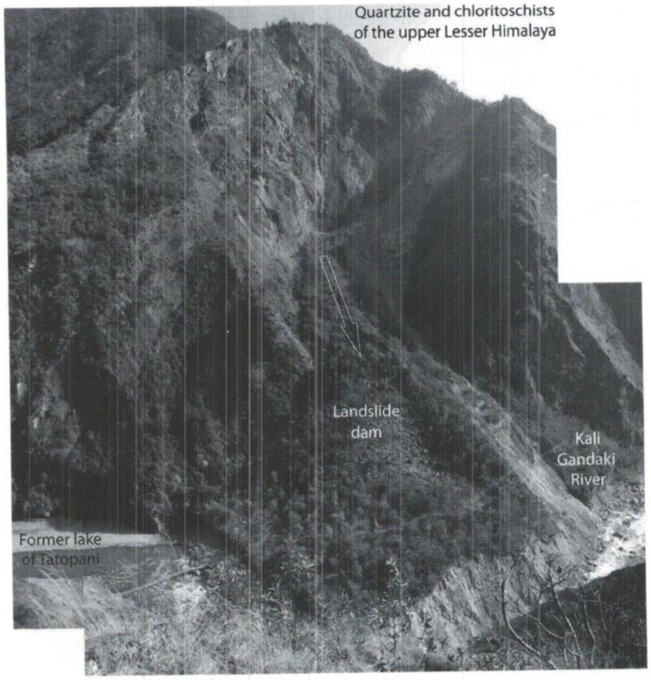


Fig. 10: The Tatopani landslide and the remnants of the backwater lake upstream (left).

the Kali Gandaki across the dam (0.2×10^6 m^3). We showed that the lake breaching was not catastrophic but progressive (it lasted approximately 3 hours), resulting in an increasing injection of both coarse and fine solid discharge that partly aggraded downstream in the form of a sedimentary wedge or prism, and encroached downstream on the alluvial plain as the landslide breach further enlarged. Less than 1 km-long, this accumulation represented however no more than 10% of the debris removed from the breach: the largest blocks (>4 m^3) are remnants of the sedimentary wedge and are still clustered near the landslide dam and eroded banks, whereas the remaining, finer particles were flushed away by the Kali Gandaki river. The resulting diversion of the river on its right bank, caused the undercutting of the Holocene terrace deposits and the partial removal of colluvium, hence revealing the evidence of former landslide dam outburst events (Fig. 11).

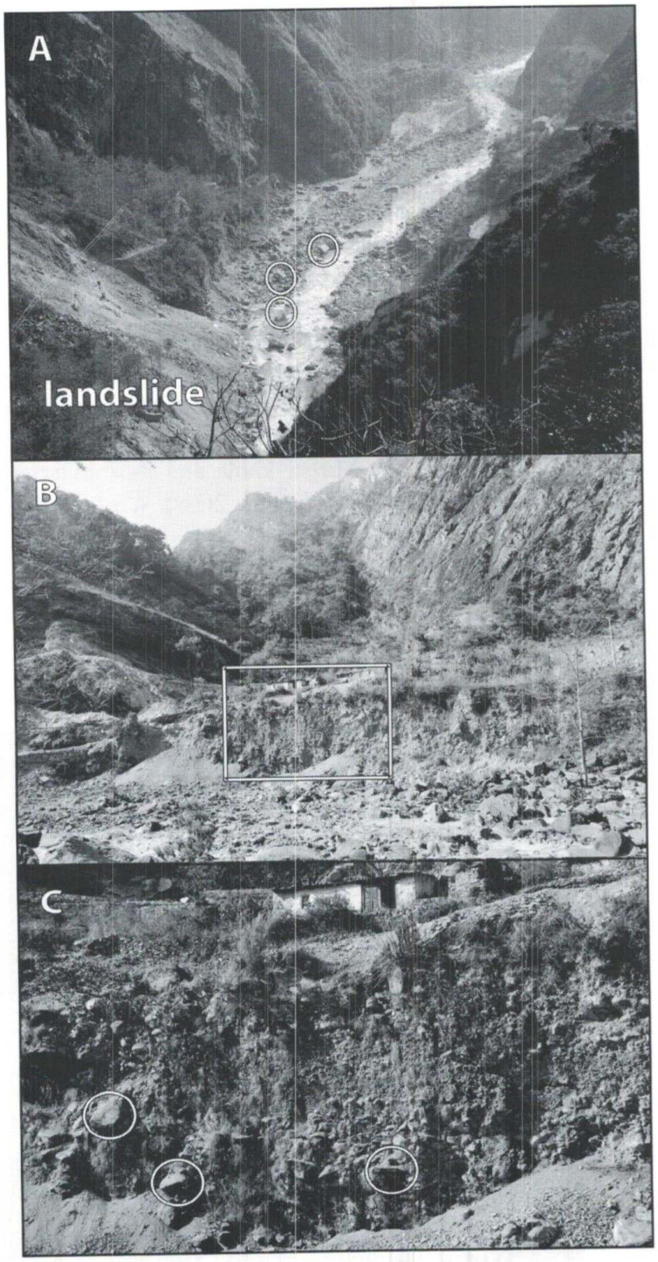


Fig. 11: Downstream effects of the Tatopani landslide dam erosion. (A) The entire width of the valley bottom was affected along 1500 m downstream, but the largest boulders (circles) were transported a few tens of meters only. (B) Eroded bank following the lake outburst: note the endangered houses and fields above the recent fan-terrace. (C) Detail (rectangle), showing large boulders embedded into the alluvial terrace material as evidence of former landslide dam outburst floods.

The 1998 event was very short in time: the breach of the dam represents debris removal of 66,666 m^3/hour. Over the next fifteen years, the landslide mass has been further affected by shallow translational slides during each rainy seasons, supplying a continuous flux of debris (mostly pulverized slates) to the Kali Gandaki river, yet very limited (~3 orders of magnitude lower) if compared to the 1998 event. Indeed, the "regular" monsoon high flows are insufficient to remove the larger boulder lags that are now armouring the channel bed, whereas the landslide mass is getting progressively stabilized by revegetation (*Alnus Nep.* sp). Debris would be remobilized again only by higher magnitude events, most often related to an off-normal supply of debris (i.e., landslides and/or debris flows) that might occur upstream, and generate debris pulses that would in turn increase the density and the transport capacity, hence the efficiency of the flow downstream.

SEDIMENTARY BUDGET

We end up with a tentative sedimentary budget that encompasses many features from the oldest and the largest stores (Dhampu-Chhoya rock-avalanche, more than one billion cubic meters) to the most recent features (Tatopani landslide, Dana debris-flow) we observed along the middle Kali Gandaki valley (Fig. 12).

This figure is far from being complete, but shows events that developed at different time scales. More precisely, it gives an order of magnitude (~10% error margin) of the importance of landsliding, a process that appears as the major debris supply to river channels. This sketch also highlights the fact that river damming by large scale, stable landslides at least doubles the possibility of sediment trapping in lakes (see the volume ratio between both landslides and lakes). At a finer scale, the adjustment of the longitudinal profile by retrogressive erosion provokes a progressive re-connection of the sediment cascades interrupted by dams. Exportation of the sediments of the landslide mass occurs first, followed by the exportation of the sediments stored within the aggradational plain created upstream of the dam. This second phase is probably associated with a significant rise in the sediment yield as sediments deposited upstream of the dam (silts in many cases) can be easily removed. The second stage may occur rapidly (probably a few millenia after the creation of the dam) and more than two thirds of the total amount of debris may finally be eroded away. Conversely, smaller, geologically "ephemeral" landslides reduce temporarily the width of the active channel, hence favouring a good connectivity between hillslope and river channel, therefore the rapid export of the material supplied by the slopes and/or small landslides tributary watersheds. More generally, it seems that high magnitude events reset the sediment cascade, and offset very temporarily the amount of sediment fluxes together with their morphological imprint.

More observations and measurements are requested to refine this general figure. This valley, as many other ones of this central part of the Himalayas, are certainly among the best places to test the sediment budget approach.

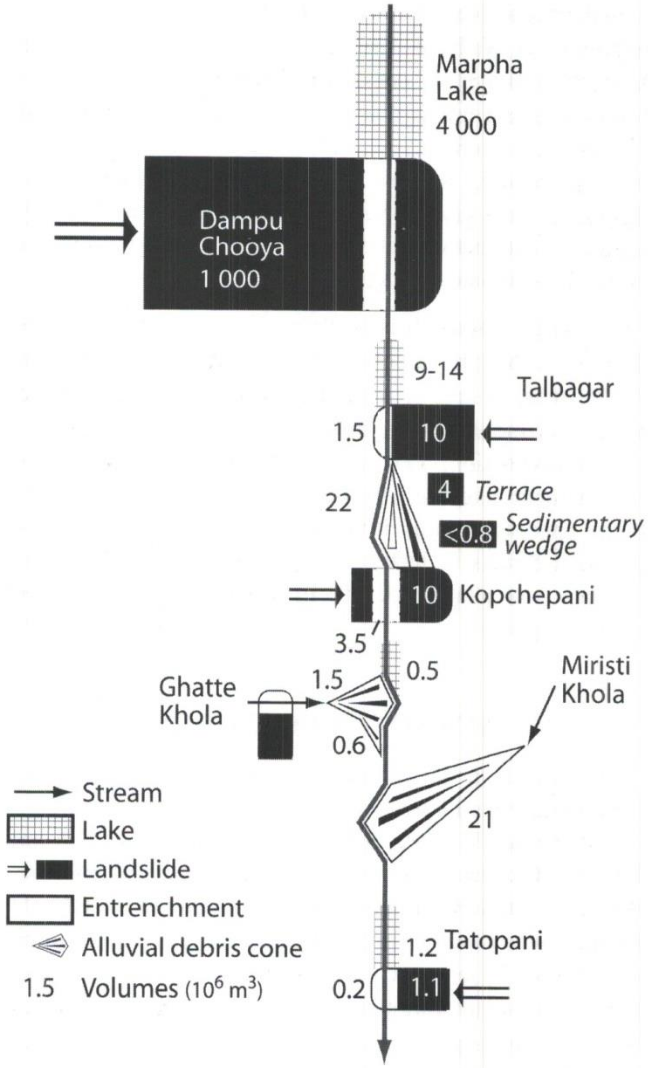


Fig. 12: Sedimentary budget of the Middle Kali Gandaki valley. The sediment stores appear in black boxes, whereas other numbers refer to volumes of sediment removal from initial stores (completed after Fort et al. 2009).

CONCLUDING REMARKS

Obtained results regarding erosional rates span over two- to three orders of magnitude that can best be explained by the type and frequency of erosional processes involved. In fact, within a given reach, most of erosion is accomplished as pulses triggered by landslide collapses and/or outburst events, all the more rapid that debris involved is loose and erodible. Alternation of alluviation events and incision stages can then be reconstructed, and their relation with sismo-tectonic and/or climatic triggering events suggested, according to the time scale considered.

Our study suggests that landsliding plays a major role in the overall process of denudation and sediment transfer outward from the mountain zone. Debris supplied by the adjacent mountain slopes to the river channel are either directly carried away by the river or are a cause of blockage, the duration of which depends on the stability of the landslide dam or on the volume injected by tributaries at their junction with the trunk river. In all cases there is an efficient sediment trapping. Yet, we have also seen that as soon as the blockage fails, the removal of debris can be extremely rapid, then followed by a more regular mode of debris transfer. Indeed, control factors on sediment fluxes act at local scale: dam material nature, bedrock lithology, channel slope, river discharge for a given period. More generally, it indirectly suggests that tectonic and related downcutting forcing is larger than climate forcing.

If large landslides contribute significantly to the denudation history of active mountain range (Hewitt et al. 2008), more frequent, medium to small scales landslides are in fact the largest suppliers of debris that may directly impact population. This suggests that in a very dynamic environment like the Himalayas, a sediment budget and fluxes approach is a useful tool for assessing and managing potential threats to human settlements and infrastructures that are increasingly developing along these Himalayan valley corridors.

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