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MONIQUE FORT (*)

TWO LARGE LATE QUATERNARY ROCK SLOPE FAILURES AND THEIR GEOMORPHIC SIGNIFICANCE, ANNAPURNA HIMALAYAS (NEPAL)

ABSTRACT: FORT M., *Two large late Quaternary rock slope failures and their geomorphic significance, Annapurna Himalayas (Nepal).* (IT ISSN 0391-9838, 2011).

This paper is a contribution to the knowledge of large-scale landslides in the Nepal Himalaya. We present two examples of giant rock slope failures that occurred north of the Annapurna Range, namely the Manang rock avalanche and Thini debris-flows. We show that they correspond most probably to seismically triggered features that have developed in connection with the North Himalayan Fault system activity during inter-stadial and post-glacial periods. Collectively with many other examples, they illustrate the fact that giant landsliding is a major process shaping and maintaining the steepness of the still rising Higher Himalaya Range.

KEY WORDS: Large rock avalanche, Giant Debris flow, Seismo-tectonic trigger, Paraglacial response, Annapurna Himalayas, Nepal.

INTRODUCTION

Large landslides play a prominent role in the denudation history of active orogens at a wide range of spatial and time scales (Korup & Clague, 2009). While both tectonic and climatic forcing causes rapid bedrock uplift and river incision rates, earthquakes, orographically enhanced precipitation, and postglacial debuttressing are generally considered as the main triggers of large landslides (Fort & *alii*, 2009). Predisposing factors include lithology (either bedrock or colluvium) and structural conditions (dip, fracturing, faulting), slope steepness, and relief s.s.. The geomorphic impacts of large landslides depend on the ruggedness of the terrain (confined vs large valleys), on the orographic pattern (transverse vs parallel valley system) and climatic pattern (humid vs arid mountain). Their occurrence is often associated with other phenomena, such as landslide dams with their upstream and downstream effects, or landslide generated waves, which collectively produces distinctive morphological and sedimentological pattern (Evans & *alii*, 2006; Hewitt 2002; Hewitt & *alii*, 2008; Korup & *alii*, 2010).

Large, catastrophic slope failures have recently retained much attention in the northern dry Himalayas and Central Asia, where their occurrence is particularly dramatic in the landscape (Hewitt, 1988, 2001, 2006, 2009; Fort & Peulvast, 1995; Weidinger 2006; Mitchell & *alii*, 2007; Hewitt & *alii*, 2008; Dortch & *alii*, 2009). Often misinterpreted as glacial material, their deposits are now fully recognized as the main components of Himalayan valley-fills (Hewitt, 2009).

This paper is a contribution to the knowledge of large-scale landslides in the Nepal Himalaya. After a short presentation of the Himalayan context, we focus on two examples of giant rock slope failures that occurred north of the Annapurna Range, before discussing their origin and significance in the understanding of the geomorphic evolution of Higher Himalayan mountain system.

HIMALAYAN CONTEXT

Many massive landslides have been reported in the Nepal Himalayas to date, among which several of them have a volume exceeding 1 km^3 in size (table 1). In most cases, the material is composed of unsorted diamicton, in

(*) *University Paris-Diderot, Dpt of Geography, GHSS Case 7001, F-75205 Paris Cedex 13* (e-mail: fort@univ-paris-diderot.fr). *UMR 8586 Prodig, CNRS, 2 rue Valette, F-75005 Paris.*

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TABLE 1 - Large landslides (>10^9 m^3) recorded to date in Nepal Himalayas. (Numbers refer to location in fig. 1)

Mass wasting failure	Volume (10^8 m^3)	Age	Geological context	Type of failure	Nature of material	Geomorphic impact	References
1 Phoksumdo-Ringmo rockslide (Suli Gad valley)	15	30-40,000 yr (Pre-Last Glacial advance)	NHTS (limestones)	In situ collapse	Disintegrated, recemented fragments and blocks	landslide dam lake, volume: 1500 Mm^3	Yagi 1997; Ibetsberger & Weidinger 2000
2 Dhumpu-Kalopani rock-avalanche (Kali Gandaki)	30	29,674 +/– 1022 yr (10 Be); 4,1 +/– 0,6 yr	HHC (augen and biotitic gneisses)	Banc-to-banc rock-slide rock-avalanche	bedrock slabs + breccia and pulverized rocks	landslide dam lake of Marpha, volume: 4000 M m^3	Fort 2000 + pers. unpubl. dates; Zech & *alii*, 2009
3 Pokhara giant rock avalanche/debris flow (Seti khola)	40	500 yr +/– 100 (^{14}C)	HHC Crystallines (gneisses) + NHTS + tills	Catastrophic collapse of Higher Himalayan Thrust Front	Gigantic debris flow (channelized along the Seti khola gorges)	Damming of adjacent, tributary valleys (lakes)	Fort 1987, 1988; Fort & Peulvast 1995
4 Manang rock-avalanche (Upper Marsyangdi khola)	150	Interstadial ? Pre-Last Glacial advance	NHTS (marly and hard limestones)	Catastrophic collapse of recumbant fold axis	diamicton (all clast sizes), recemented breccia	linear, gully erosion + karstic like landforms	Fort 1993; Weidinger 2006; this article
5 Dhikur Pokhari rockslide (Upper Marsyangdi khola)	10	Post Glacial	NHTS (limestones and schists)	In situ collapse	Brecciated cataclastic and recemented blocks	shallow, relict Dhikur pokhari (lake)	Korup & *alii*, 2006
6 Latamrang landslide (Upper Marsyangdi khola)	> 55 (1 already removed)	5400 yr BP	HHC Crystallines (gneisses) + NHTS + tills	Sledge-like sliding	Brecciated cataclastic and recemented blocks	landslide dam lake, volume 160 M m^3	Korup & *alii*, 2006
7 Tsergo Ri rockslide (Langtang khola)	100	34,2 +/– 10,4 (10 Be); 25-40 (TL) 51+/–13 (FT)	HHC (gneisses and intrusive granite)	Post glacial gravity instability	Microbreccia (mylonites and pseudotachylites)	Linear, gully erosion	Barnard & *alii*, 2006; Weidinger & *alii*, 2002; Takagi & *alii*, 2007
8 Khumjung rock- avalanche (Upper Dudh Kosi)	21	Pre-Last Glacial advance	HHC (gneisses)	Post glacial gravity instability	Brecciated cataclastic, blocks		Heuberger, 1986

the form of consolidated breccia that include all sizes of angular clasts, often embedded in an important portion of crushed material. All these characteristics are distinctive of rapid emplacement, favoured by a high momentum impulsed by steep slopes and high relief. In many cases, the massive deposits blocked the river valleys, hence resulting in lake formation either still present or as attested by lacustrine sediments. Documented examples are: (1) in the Kali Gandaki valley the Dhumpu-Kaiku rock avalanche and related Marpha lake (Fort, 1980; 2000); (2) in the Marsyangdi valley the Lamtarang landslide, with a lake up to Chame and Nar khola (Weidinger & Ibetsberger 2000; Pratt-Sitaula & *alii*, 2007); (3) in the Bauli (Suli) Gad valley (Dolpo, West Nepal), the Ringmo landslide at the origin of the Phoksumdo lake, the second largest in Nepal (Yagi, 1997). We present here two more examples that

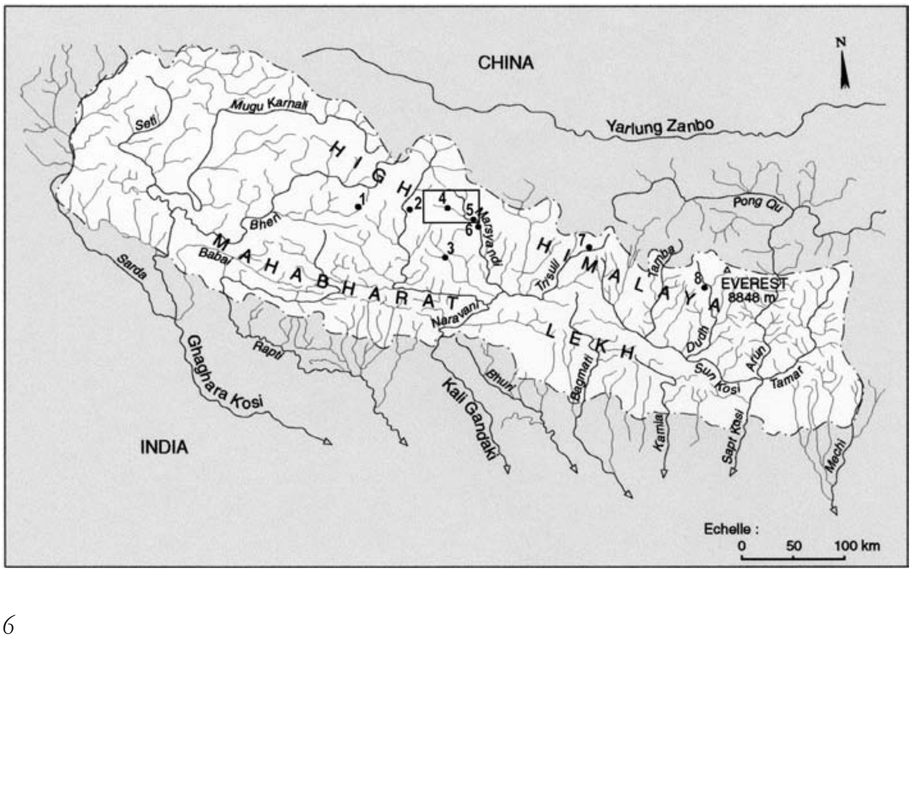

FIG. 1 - Map of Nepal and location of large-scale slope failures. 1: Phoksumdo-Ringmo; 2: Dhumpu-Kalopani; 3: Pokhara; 4: Manang; 5: Dhikur Pokhari; 6: Latamrang; 7: Tsergo Ri; 8: Khumjung. Box delineates fig. 2.

illustrate well mountain slope instability caused by the constant interplay between tectonic activity, postglacial debuttressing and possible climate change.

We focus on the northern flank of the Annapurna Himal. The study area can be considered as an area of transition for at least three reasons. (1) It lies due north of the deep (> 4000 m) gorges sections that cut across the Higher Himalayan massifs of Manaslu (8163 m) - Annapurna (8091 m) - Dhaulagiri (8172 m) peaks, from East to West respectively. (2) Although the area considered stands well below (< 4500 m) the present glaciation limit (5500-5600 m) as it already belongs to the dry, continental Himalaya, most of it was affected by the Late Pleistocene glaciation (Fort, 2004). (3) Geologically, the area spans over the upper Higher Himalayan Crystalline (HHC) Sequence (including gneisses and metasedimentary marbles) and the low-grade Tibetan Sedimentary Sequence (TSS), deformed by north verging folds (Colchen & *alii*, 1986). Both units are separated by the North Himalayan Detachment Fault (NHDF), otherwise called South Tibetan Detachment System (STDS), a prominent family of normal faults affected by a down to the north displacement (Burchfield & *alii*, 1992; Godin, 2003). These three characteristics make this north Himalayan belt, an area prone to large-scale rock failures.

We will concentrate on two adjacent, east-west oriented valleys. (1) The upper Marsyangdi valley presents a series of distinctive large-scale slope failures, upstream of Bagarchap, where the valley parallels the orientation of the Annapurna Range. From down- to upvalley, two large failures have already been documented: the Lamtamrang landslide and Dhikur Pokhari rockslide (Weidinger & Ibetsberger, 2000; Pratt-Sitaula & *alii*, 2004; Weidinger, 2006; Korup & *alii*, 2006). Upvalley the most prominent feature is the gigantic Manang-Braga rock avalanche/debris flow (Hagen, 1968; Fort, 1993, 2004; Weidinger, 2006). (2) Beyond to the West, the Thini valley (tributary of the Kali Gandaki) develops north of the Tilicho peak (7134 m) and Nilgiri North peak (7061 m): most of it is also filled with large, debris-flow type of deposits (Fort, 2000). The last two, Manang and Thini examples, are described below.

THE GIANT MANANG ROCK AVALANCHE

Field evidence

The upper Marsyangdi valley is filled in by a large, thick, diamictic formation that crops out from the extreme West of the valley, at the foot of the Tilicho pass (4990 m), down to the village of Gyaru (3400 m), on a distance of > 30 km. These deposits fossilize entirely the valley bottom, and extend as inliers into adjacent tributary valleys (Sabje and Julu kholas) (fig. 2). The deep dissection of the present fluvial network reveals a deposit about 250 m thick in average, as measured close to Braga and Ngawal villages (3660 m) (fig. 3). On the basis of available outcrops and extensive fieldwork, the original volume of this formation was assessed to be of about 15 km^3.

The topographical surface of this deposit displays a slightly rough morphology, with small mounds (< 5 m high) and hollows (a few metres deep). However, clear glacial landforms are locally superposed to the diamictic deposit in the form of morainic ridges, either clustered as frontal system such as at the junction with the Julu khola,

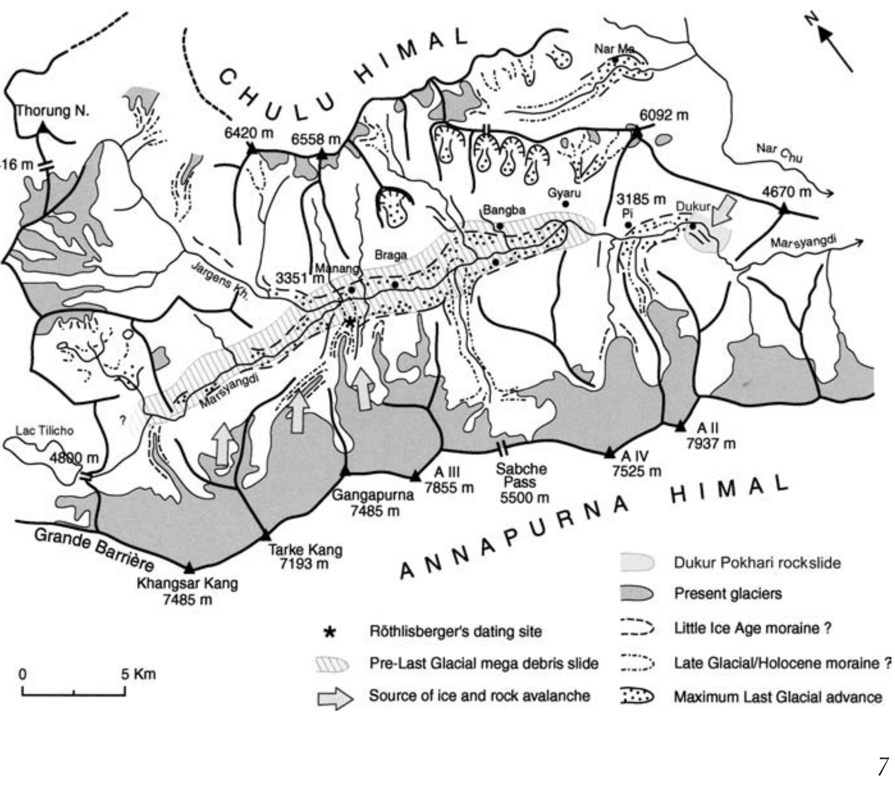

FIG. 2 - Map of Upper Marsyangdi valley. The giant rock-avalanche buried most of the valley, and was later on carved out by Last Glacial and Holocene glacier advances.

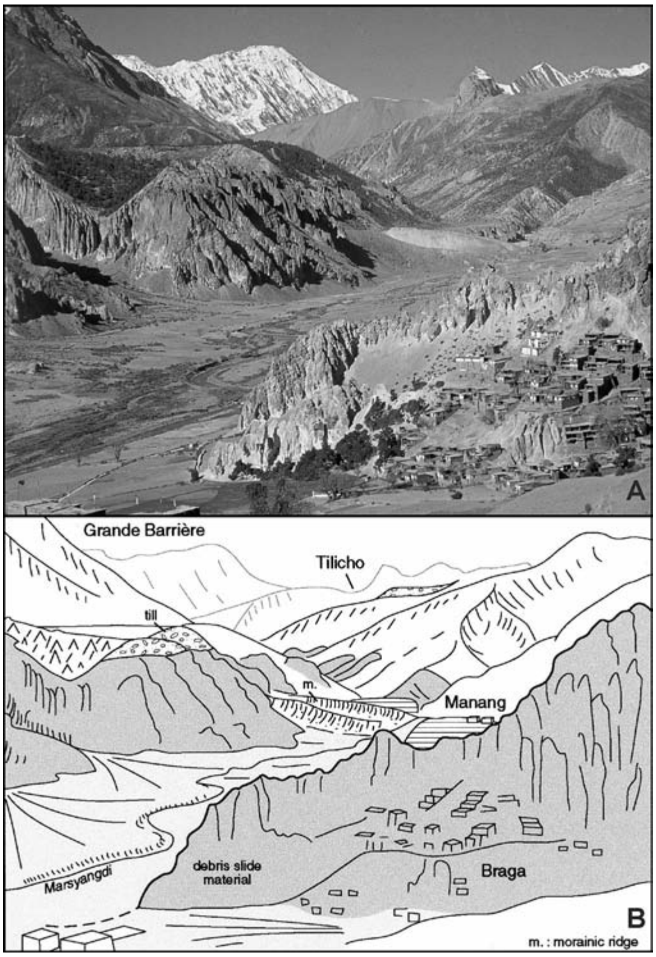

FIG. 3 - Morphology of the Upper Marsyangdi, from East of Braga village looking upstream to the Tilicho Pass (4990 m). Photo (A) and its interpretation (B). The rock-avalanche deposit originated from the northern flank of the Annapurna Himal (left side) and filled in the entire Upper valley (fig. 2). Note the widespread, dissected outcrops of the Manang rock-avalanche deposit, and the superimposed tills of the assumed Last Glacial stage. The Late Holocene moraine (m.) of the Gangapurna glacial tongue and its lake (see fig. 6), opposite to Manang village. (© M. Fort, 1977).

or as lateral longitudinal ridges (right bank of Marsyangdi, downstream of Manang village).

The diamicton is composed of very angular limestone clasts, derived from the Bangba marly limestones and Ordovician-to-Devonian Tilicho limestones (TSS, Bordet & *alii*, 1975; Godin, 2003). The deposit is composed of very large blocks (> 100 m^3), massively fractured at all scales (fig. 4), embedded in a matrix of powdery consistency, the percentage of which is relatively low and is mainly concentrated in the lower part of the filling. The matrix may locally appear in the upper part either as dykes, injected into fractured rocks, or as pockets with contorted outlines. A distinctive characteristic of the deposit is the consolidation of the entire mass by post-depositional cementation, certainly due to its limy components (fig. 4b and c). This has later been exploited by selective weathering, particularly along fractures network, resulting in specific erosional landforms such as badlands, or towers and pinnacles, much similar to karstic modelling (fig. 3 and 4a).

In contrast, the superficial, morainic material is quite loose (although slightly compacted), composed of a much larger proportion of matrix in which subrounded blocks of varying lithology (reflecting the geology of the upper catchment) are embedded. This, together with the morphology, provides good distinctive elements to separate both materials.

Interpretation

Hagen (1968) was the first to interpret the diamicton as a massive mass-movement, whereas Bordet & *alii* (1975) considered it as till material. We showed that this formation corresponds to the runout of a catastrophic rock avalanche formation (Fort, 1993; 2004).

Bordet's interpretation (1975) of this massive deposit as till material cannot be a priori ruled out: the hypothesis of a large glaciation with ice tongues filling the entire Marsyangdi valley might be plausible considering the elevation of the Marsyangdi valley floor (> 3000 m) and its short distance (5-10 km) to the glaciated peaks (> 7000 m), well above the glaciation limit. In this glacial interpretation however, such a thick formation would correspond to a basal till; indeed, both the structural strike and the marly limestones lithology of the valley might have favoured glacial overdeepening and the development of a thick tillic sole, as formerly described in the far West Nepal by Heim and Gansser (1939). However the sections observed did not display any preferential grain orientation that would be consistent with the supposed west-east ice flow direction, as depicted elsewhere in Pakistan as distinctive of till material (Derbyshire, 1984; Owen & Derbyshire, 1988). In fact, the petrography of limestone's clasts observed along the left bank does not reflect the geology of the southern flank of the Chulu Himal, as would be expected from glacially derived material. Yet, internal micro-shearing does exist but it is oriented parallel and down to the valley (fig. 4c), hence suggesting some post-depositional stress release, incompatible with a valley still occupied by a glacial tongue.

For all the above reasons we consider these massive deposits as the result of a large slope failure, an interpretation initially proposed by Hagen (1968). In fact, the homogeneity of the petrography, the relatively low percentage of matrix mostly concentred in the lower part, the local occurrence of melt-water figures together with a deposit spread over long distance without any significant change in structure and thickness would be in favour of a large, catastrophic rock avalanche deposit that evolved into a gigantic debris-flow filling a deglaciated valley. More specifically, the origin of the material suggests a generalized collapse of the fold hinge of the northern flank of the Annapurna (Khangsar Kang, Tarke Kang Gangapurna and Annapurna III peaks) (fig. 2 and 5), which may have also incorporated some crushed glacier-ice, hence water, into the huge mass of debris favouring in turn its larger spreading. The very large extent of the deposit, together

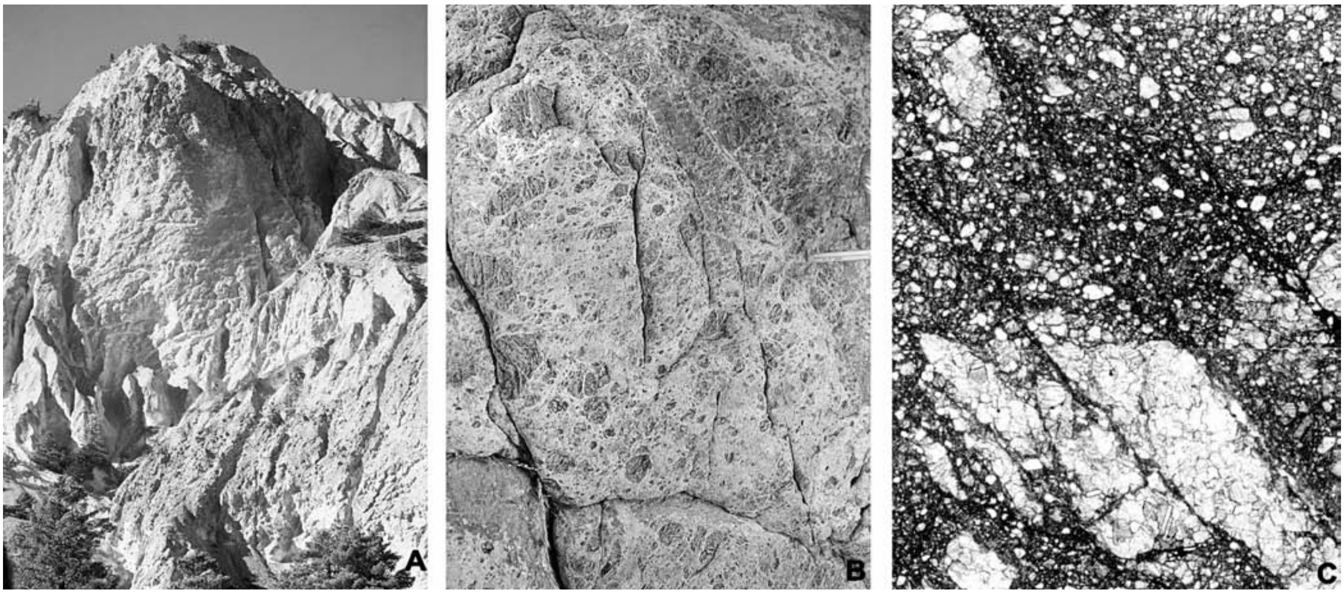

FIG. 4 - Material of the Manang rock-avalanche. A: General outcrop (height of about 100 m) displaying massive brecchiated, fractured material modelled in pinnacles and towers. B: Small scale outcrop (width: 50 cm); note the en-echelon cracks, and the internal cracks affecting the dark limestone clasts. C: Micro-fabric revealing the heterometric, clastic matrix affected by shearing planes oriented down to the valley (width: 2,5 cm). (© M. Fort, 1977).

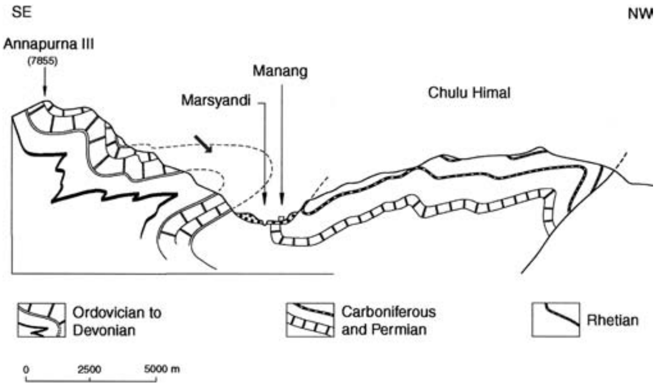

FIG. 5 - Geological cross section of the Marsyangdi valley (completed after Colchen, in Bordet & *alii*, 1975). Note the general, northward verging structures, hence the asymmetry of the valley. Arrow indicates the failure movement and direction.

with the continuity of its fabric all along the valley, collectively suggests a regional trigger such as an earthquake that could have affected the entire length of the valley (see below the discussion).

This catastrophic failure is not firmly chronologically constrained to date. However, the relative succession of different events that occurred in the valley may be reconstructed as follows (Fort, 1993, 2004; fig. 6). It seems that the pre-existing morphology of the upper Marsyangdi, was already deeply incised and might have corresponded to a former glacial trough before it was buried under the rock avalanche deposit (average thickness of 250 m). Hence the question remains whether this event may have a paraglacial origin. Then the valley and the rock avalanche deposit were partly carved out by another glacial advance, as

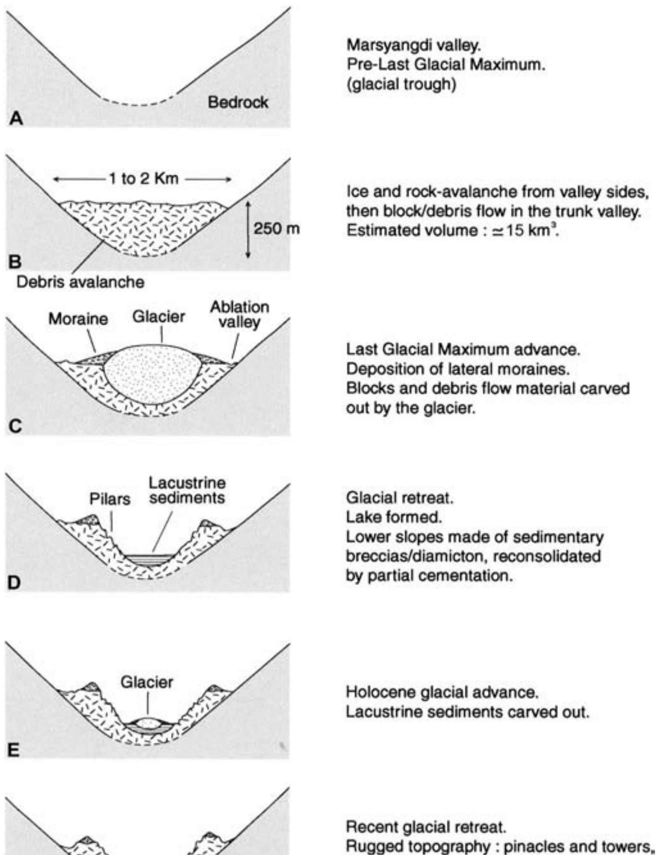

FIG. 6 - Series of sketches reconstructing the succession of events characteristic of the evolution of the Upper Manang valley during and after the last glaciation (adapted from Fort, 1993).

attested by the lateral moraines superimposed on the rock avalanche deposit. Thereafter the main glacier trunk retreated whereas some tributary glaciers were still locally damming the Marsyangdi valley, as attested by outcrops of lacustrine beds upstream of Manang village. Holocene glacial advances followed at around 4600-2350 yr BP, 3000-2350 yr BP, and about 1200 BP, according to ^{14}C dates by Rothlisberger & Gey (1986) who dated the well-shaped, frontal morainic complex opposite to Manang village (fig. 7). We can therefore consider that this large-scale rock avalanche probably occurred during an inter stadial period belonging to the Last Glacial.

THE THINI-SYANG-JOMOSOM GIANT DEBRIS-FLOWS

Field evidence

Westwards, beyond the Tilicho Pass (the westernmost part of the Upper Marsyangdi catchment), the Thini khola and Langpogyun valleys, two adjacent left bank tributaries of the Kali Gandaki, develop north of the Nilgiri North Peak (7061 m) and Tilicho Peak (7134 m) (fig. 8). Their relief is particularly steep (4200 m relief from the peaks to the < 12 km distant confluence), limiting the extent of the present glaciation to overhanging, cold-based, slope-glaciers (fig. 9). These two river valleys are in fact entrenched into a massive debris accumulation about 400 m thick that constitutes the Thini formation (Fort, 1993; 2000).

This deposit corresponds to diamictic material composed of glacially derived and rockfall products, overtopped by morainic ridges shaped by small, more recent (presumably Holocene) glacial tongues. Composed of predominantly calcareous shales and pelites interstratified with dolomitic and quartzitic bands (Silurian to Permian metasedimentary upper series of the TSS Higher Himalaya; Bordet & *alii*, 1971; Godin 2003), the 70° steep mountain wall is subject to rockfalls, the magnitude of which is very much influenced by a northward vergent folded structure, the «Nilgiri anticline» (Colchen & *alii*, 1986), similar to the one referred to in the Marsyangdi valley (fig. 5).

The Thini formation, representing a volume of about 6 km^3, is very rich in angular clasts of various sizes (mostly Ordovician dark gray, micritic Nilgiri limestones), embedded in a marly matrix, the presence of which locally favoured the cementation, hence discontinuous consolidation into breccia (Fort, 2000). The exposed sections exhibit a complex alternation of diamictic beds, some being coarser, more poorly sorted and less layered than others (fig. 10). Basal contacts of layers are generally planar, and reflect rapid phases of aggradation, without significant interruption that would have resulted in their dissection and in the presence of erosional, channelized basal contacts.

Interpretation

In contrast to Kuhle's (1982) and Wagner's (2005) interpretation as purely glacial deposits, we interpreted these thick deposits as a succession and/or an imbrication of several debris flows, the layered ones representing the local facies of glaciofluvial deposits whereas the thicker and poorly sorted ones reflecting unusual, massive coarse inputs of rock- and ice-falls caused by events of larger magnitude (Fort, 2000). Such a thick, continuous aggradation was however facilitated by the presence, more than 30 km downstream of the Kali Gandaki, of a large blockage controlling the local base level. This blockage was caused by the 3 km^3 Dhumpu rock avalanche and was possibly reinforced by the presence of Dhaulagiri ices down to the Kali Gandaki valley (fig. 8; Fort, 2000). This resulted in a >30-

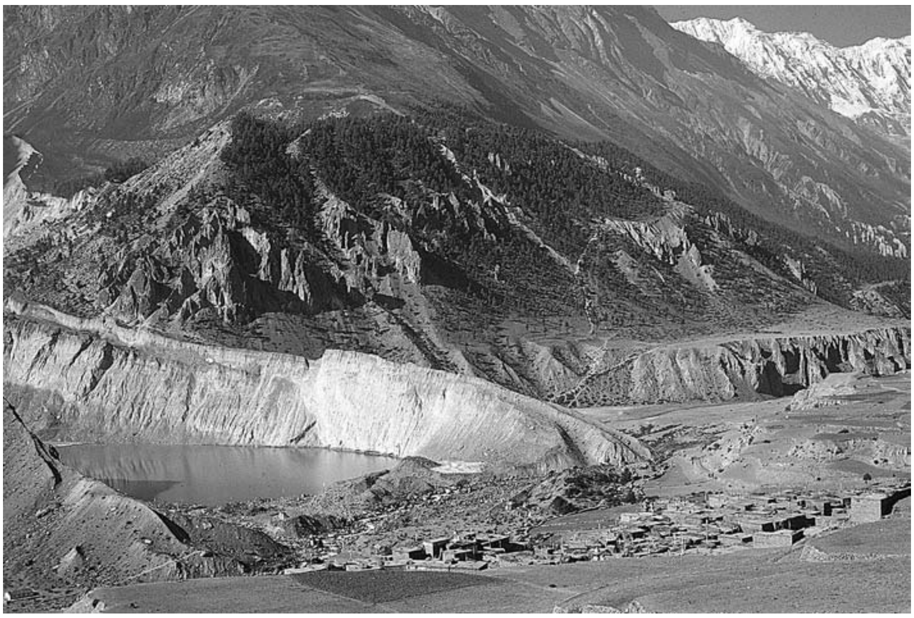

FIG. 7 - The Holocene frontal, morainic system and related lake of Manang. This system was built by a glacial tongue issued from the North face of the Gangapurna (7455 m) and Annapurna III (7685 m) peaks. (© M. Fort, Fall 1977).

FIG. 8 - Map of the Kali Gandaki valley across the Higher Himalaya, between Dhaulagiri and Nilgiri-Annapurna Himal (location in fig. 1, including the site 2 of Dhumpu-Kalopani). The Thini valley extends north of Nilgiri and Tilicho peaks. The recent Jomosom Formation corresponds to a catastrophic debris flow (modified and completed after Fort, 2000).

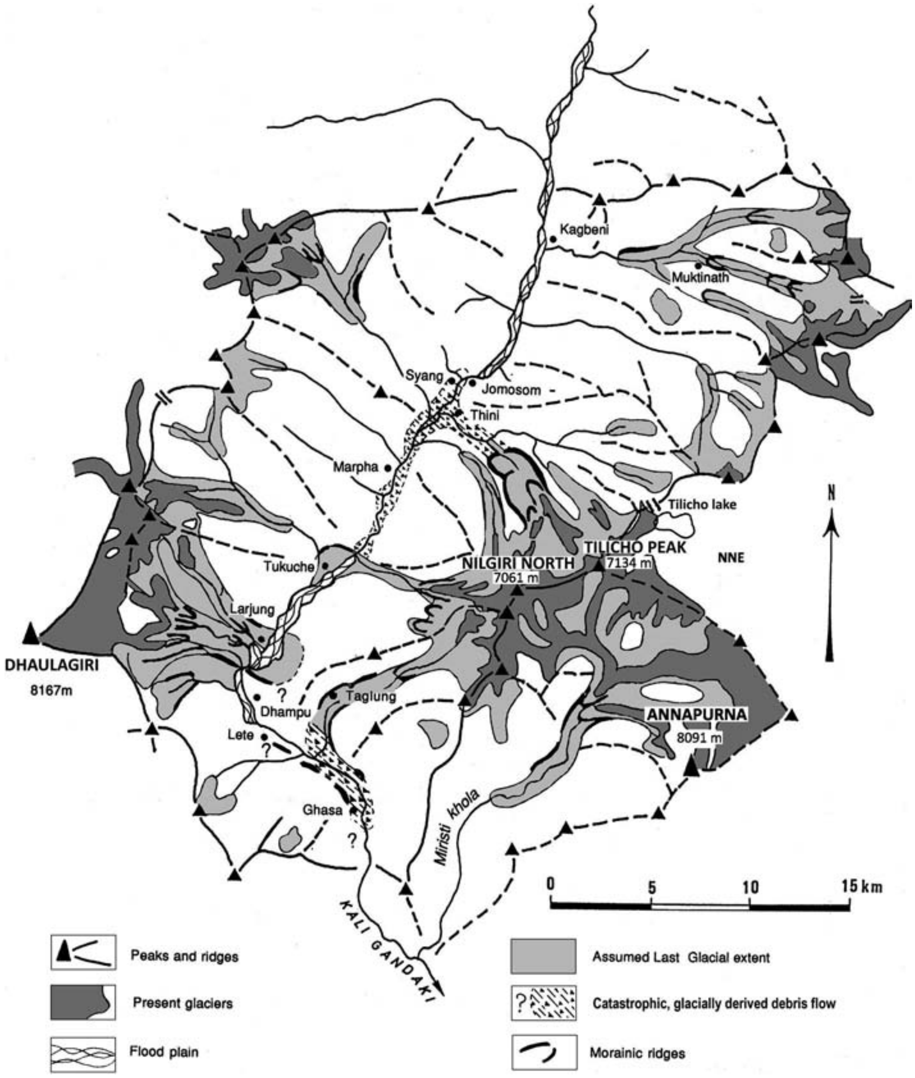

FIG. 9 - The north face of Tilicho peak (7134 m), with the Tilicho Pass (4900 m) on the left, and the Nilgiri North peak (7061 m) on the right (not entirely visible). The wide Thini valley is filled in by a complex, 400-metre thick formation made of glacially derived and rockfall products overtopped by morainic ridges (see fig. 8), and reworked catastrophically by large debris flows. White box locates figure 10 (© M. Fort, 1978).

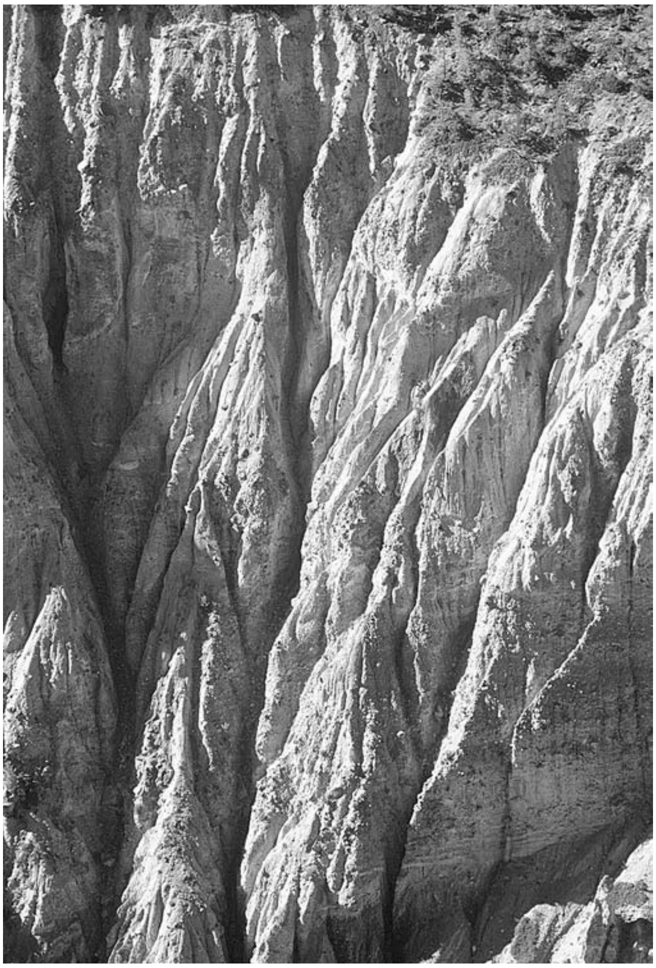

FIG. 10 - Section across Thini formation (height: 50 m). The predominantly massive, diamictic mass exhibits a few slightly stratified layers (lower part) reflecting the presence of a minimum content of water. (© M. Fort, 1978).

km long lake that controlled for several ten thousand years the level of this valley (Fort, 1980), hence preventing the possibility of downcutting across the Thini formation by meltwater streams (the Langpogyung and Thini tributaries).

The last of these large events is recorded in the Jomosom Formation (Fort, 2000). This diamictic formation, cut-and-fill into the Thini formation, reached the bottom of the Kali Gandaki and underlies the lower terrace of the Kali Gandaki. This is good evidence that its setting occurred much more recently than the Thini Formation, most probably during the late Holocene period, after partial erosion of the Dhumpu rock avalanche dam. The formation extends from the northern edge of Jomosom locality (2750 m) down to the entrance of Tukuche village (2500 m) (fig. 8); in fact, it controls the present narrowing (<15 m) of the Kali Gandaki channel, otherwise characterized by a dramatic, 0.5-to->1 km wide, braided pattern (an effect of the persistence of the Dhumpu dam downstream of the valley).

Despite its recent levelling following irrigated-fields development, urbanization, airstrip and road building, the Jomosom Formation remains quite conspicuous in the landscape because of its dark colour and hummocky topography (conical hills). This 25-30 m thick material is very poorly sorted, matrix-rich into which very large blocks are embedded (fig. 11). The petrography of the blocks again indicates a clear origin from the steep North face of the Nilgiri North Peak. Such a widely distributed formation, split into lobes spread both upstream and downstream from the original source, is distinctive of a catastrophic, instantaneous mode of setting (Fort 2000) that occurred long after the retreat of glaciers from the lower part of the Langpogyung and Thini valleys. It therefore appears as a good modern analogue of what might have occurred in the Langpogyun-Thini valleys several times in the past.

FIG. 11 - Jomosom Formation outcropping along both banks of the Kali Gandaki river (view from Jomosom bridge, looking south; 2750 m). Note in the middle ground the white, lacustrine sediments of Marpha (see other references in Fort, 2000), and in the background the peaks of Dhaulagiri (8172 m, left) and Tukuche (6920 m, right). (© M. Fort, 2009).

DISCUSSION

A complex origin

The above examples of Manang rock avalanche, Thini mega debris flow and related, very recent Jomosom debris flow are representative of large scale features that are geographically associated with the geodynamic context of the High Himalayan Range. Their volume together with their sedimentological and petrographic characteristics cannot be interpreted as ordinary features, i.e. as the results of either single landsliding or glacial material.

There are several predisposing factors that may explain the presence of such large rockslope failures. Firstly, the structural north-eastward oriented folded structures (Nilgiri anticline) together with subvertical fractures and stratigraphic and/or lithologic discontinuities, offer weakness planes along which collapse may develop (fig. 5, fig. 12b). Secondly, the poorly resistant, shaly-dolomitic outcrops of the Silurian-Devonian «Sombre Formation» (Bordet & *alii*, 1971) have facilitated the deep incision of these two valleys either by glacial or fluvial erosion. The resulting, pronounced steepness of the mountain front makes it particularly prone to large-scale slope instability, whatever reworked or not by glacially influenced dynamics (including pure glacial and glacio-fluvial activity). Thirdly, this area is sited in the influence zone of the South Tibetan Detachment System (see below).

The trigger mechanism of these two events, rock avalanche and debris-flow, is not resolved. Among possible candidates, we do not think high-intensity rainstorms or slope undercutting are relevant factors in this north-Himalayan environment. Similarly, intense and rapid snowmelt episodes or permafrost degradation would not appear adequate to destabilize in one single event such a huge volume, specially when considering the vertical zonation along these steep, north-oriented mountain walls. Conversely, post-glacial debuttressing and/or seismic shaking would appear as good triggers to explain large-scale rock slope failure in these two adjacent valleys.

Post-glacial, paraglacial debuttressing is certainly a good triggering factor, as demonstrated in many mountain areas, in Western Himalayas (Hewitt, 2009), North American (Evans & Clague, 1994) or in the European Alps (Ivy-Ochs & *alii*, 2007; Cossart & *alii*, 2008). In fact, this hypothesis must be evaluated with regard to the general structure of the Himalayan Range. Most of the present seismotectonic activity occurs south of the Himalayas along the different thrust fault planes connected in depth along a major detachment plane (Lavé & Avouac, 2001; fig. 12a). Yet the northern side of the Himalayas is also affected by large, north-dipping extensional structures, referred to as the South Tibetan Detachment System (Hodges & *alii*, 1996) or as the North Himalayan Detachment Fault (Colchen & *alii*, 1986). Locally known as the Annapurna detachment (Godin 2003), this fault is localized at the contact between the lowermost part of the TTS and the uppermost part of HHC, and should therefore also be considered as a potential zone of great instability, all the more efficient in the vicinity of high mountain peaks (fig. 12b). This fault system, together with stratigraphic and/or petrographic

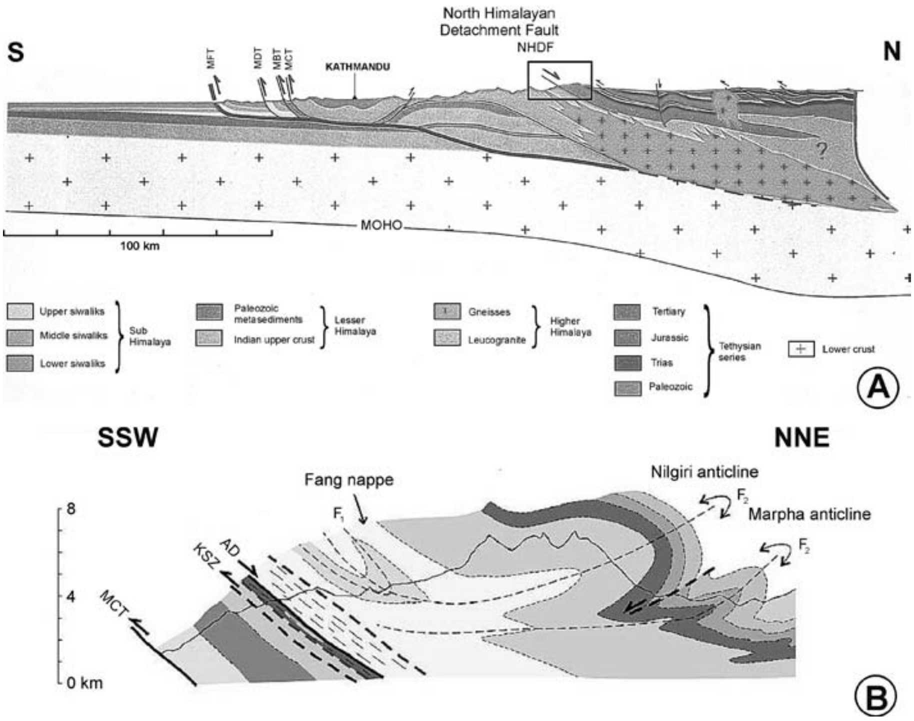

FIG. 12 - Geodynamic context favourable to the occurrence of large landslide. A: At Himalayan scale, a combination of high local relief, adequate lithology and major structural (detachment) planes, as well expressed along the northern flank of the Greater Himalaya (section modified after Lavé and Avouac, 2001); Box showing emplacement of fig. 12B; B: North-east vergent Nilgiri fold, a structural pattern favourable to catastrophic collapse in a context of deglaciation (modified after Godin, 2003).

discontinuities (big. 5; big. 12b) may potentially be reactivated by an earthquake the magnitude of which do not need to be exceptional to cause giant catastrophic rock slope failure in this area of very high local relief.

Therefore, our assumption is that there is a strong structural control on the location and occurrence of these two adjacent large-scale rock failures, along the 40 km long mountain front, from Annapurna II (Marsyangdi valley) to Nilgiri North Peak (Kali Gandaki valley). This would favour a seismic shaking as the most likely trigger, but we recognize that the lack of chronological data does not permit to constrain better this hypothesis or to rule out the post-glacial, paraglacial hypothesis as well. In this latter figure, the anticline structure hence the repetition of the same stratigraphic beds in both the upper and lower parts of the mountain face did not permit to say whether or not the collapse was derived from the formerly glaciated, lower slope segments of this uniformly steep north face. Eventually, both factors may have contributed concurrently if the earthquake occurred in a context of recent deglaciation.

Comparison with other giant landslides reported in Nepal Himalaya to date

The different surveys carried in Nepal Himalayas on large landslides do not cover the whole country, most of which remaining of difficult access; we therefore suspect many more large-scale rock failures still remain to be discovered. Yet, it appears that there are several common grounds to the eight, large-scale failures inventoried in Nepal to date (tab. 1). They are all located in valleys with steep topographic gradient, that may exceeds > 4000 m for the Khumjung rock avalanche, and even > 5500 m for the Pokhara giant debris flow. Also, for seven of them the potential sliding surfaces are located along distinctive lithologic discontinuities. For instance, the Tsergo Ri rockslide (Langtang Himal) originated in an horizon of young leucogranite intrusions at the top of the HHC close to the STDS (Weidinger & *alii*, 1996; Schramm & *alii*, 1998; Weidinger & Korup, 2009). The Dhumpu rock avalanche similarly developed in the upper HHC augen gneisses, very close to the NHDF (Fort, 2000). The Dhikur rockslide (Weidinger, 2006) failed along a curved stratigraphic discontinuity within the steep dipping, west oriented fold planes of Pisang (Bordet & *alii*, 1975). Note that the Tsergo Ri rockslide and the Dhumpu rock avalanche occurred at 51±13 Ka (Takagi & *alii*, 2007) and 29,500±1000 Ka (Fort & *alii*, unpubl. data) respectively, i.e. between the two subpeaks (70 and 20 Ka) of the Würm glacial period (Owen, 2009).

The giant debris flow of Pokhara may appear as an «anomaly»: generated from the south of Annapurna IV Peak (7855 m), it developed perpendicular, across and in the opposite direction of the thrust dip. It corresponds to a catastrophic collapse of the very steep, glaciated mountain wall, and filled the entire Pokhara valley. It was most probably triggered by the 1464 earthquake (Nepali calendar, i.e. in 1505 AD) that also damaged the capital town of Lalitpur in the Kathmandu valley (see ^{14}C ages, Fort 1987). In this case, stress release was favoured by sub-vertical tension faults that distinctively develop across the entire Annapurna Himalaya. In fact, similar, very large debris-flows were reported along the southern flank of this mountain, as described along the Madi khola down to Kusma sited at the confluence with the Kali Gandaki (Fort, 1976; 1993), and along the Marsyangdi khola downstream of Khudi Bazaar (Yamanaka & Iwata, 1982), where the debris-flow was emplaced 4300+/–130 years B.P. These events suggest that such rapid episodes of rock wall collapse evolving into giant debris flows are quite common features at a 10^{4-5} yr time scale; they do appear as the mean process maintaining the steepness of the Higher Himalaya all along the still rising MCT thrust front (Fort, 1987; 1988).

CONCLUDING REMARKS

The large rockslide failures presented here illustrate what appears as a major process shaping the Himalayas of Nepal. Their location in the Manang and Thini valleys confirms the fact that such giant landslides are concentrated in the smallest, but steepest parts of mountain ranges (Korup & *alii*, 2007), where maximum material strength may not resist indefinitely to gravitational forces. Their identification and occurrence in a geographic setting already marked by some degree of aridity, together with their location in the sedimentary domain of the Tibetan series, and the proximity of a major structural zone of discontinuity, collectively favour both the good preservation of evidence and the large volume of accumulated material.

Our study sites confirm general statements on the significance of large magnitude low frequency events. Recognized as formative events, i.e. as responsible for shaping the landscape (Brunsden & Jones 1984), at least for the last hundred thousand years, they are considered as contributing significantly to the denudation history of active mountain ranges (Fort, 1987; 1988; Fort & Peulvast, 1995; Pratt-Sitaula & *alii*, 2004; Korup & *alii*, 2007; Hewitt, 2009; Hewitt & *alii*, 2008; Dortch & *alii*, 2009), even though more frequent, medium scale landslides are of primary concern for Himalayan villagers (Fort & *alii*, in press).

Future research should be oriented to fill the gaps in this preliminary inventory of large rockslide failures of the Nepal Himalayas. Dating should also be a priority in order to better specify the conditions, either seismic and/or climatic, of their formation and trigger, and it would also help assessing the frequency of these giant features for a better understanding of their role in the Himalayan range evolution. Examples of recent (10^{2-3} yrs) giant debris flows (e.g. Pokhara, Jomosom) suggest these features may well remain a major potential threat to densely populated Himalayan basins and/or valleys.

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