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Geomorphic impacts, age and significance of two giant landslide dams in the Nepal Himalayas: Ringmo-Phoksundo (Dolpo District) and Dhampu-Chhoya (Mustang District).

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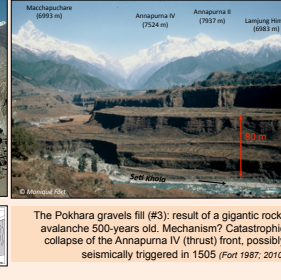
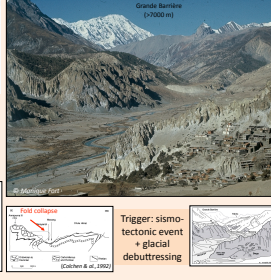
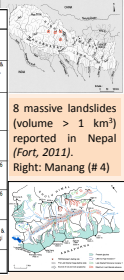
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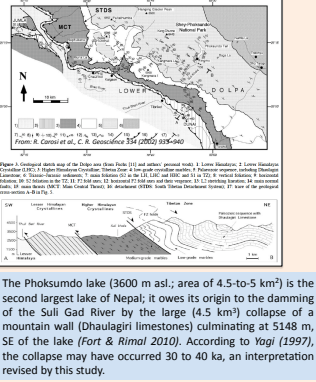
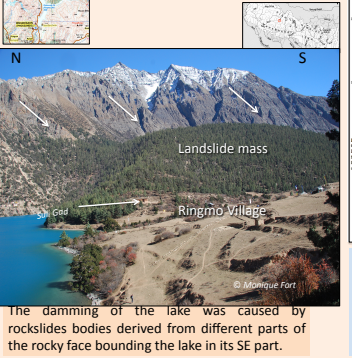
1. INTRODUCTION: MAIN ISSUES

Large catastrophic slope failures have recently retained much attention in the northern dry Himalayas (Hewitt 2009). They play a prominent role in the denudation history of active orogens at a wide range of spatial and time scales (Korup & Clague, 2009), and they impact durable landforms and process evolution in upstream catchments. Their occurrence mostly results from three different potential triggers: earthquakes, post-glacial debudding, and permafrost melting. We focus on two examples of giant rock slope failures that occurred across and north of the Higher Himalaya of Nepal and assess their respective influence on the regional, geomorphic evolution.

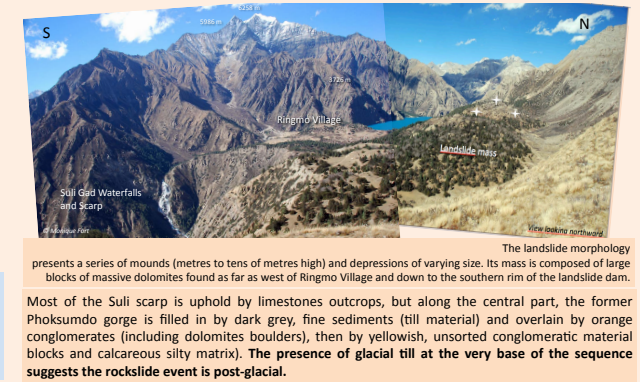
Mass wasting feature	Volume (10 ⁶ m ³)	Age	Geological setting	Type of slope	Nature of material	Geomorphic impacts	References
1. Hemant (1958-2000)	10	1958-2000	HMC (greyish sandstone)	Steep collapse	Blocky, angular, silty sandstone	Interruption of the Kali Gandaki river, formation of a lake (1998)	Fort 1987, Weinger 2000
2. Jhuwotang (2002-2009)	30	2002-2009	HMC (greyish sandstone)	Steep collapse	Blocky, angular, silty sandstone	Interruption of the Kali Gandaki river, formation of a lake (2002)	Fort 2002, 2009
3. Rujina ghat (2003-2009)	40	2003-2009	HMC (greyish sandstone)	Steep collapse	Blocky, angular, silty sandstone	Interruption of the Kali Gandaki river, formation of a lake (2003)	Fort 2003, 2009
4. Marpha (2009-2010)	100	2009-2010	HMC (greyish sandstone)	Steep collapse	Blocky, angular, silty sandstone	Interruption of the Kali Gandaki river, formation of a lake (2009)	Fort 2009, 2010
5. Marpha (2010-2011)	100	2010-2011	HMC (greyish sandstone)	Steep collapse	Blocky, angular, silty sandstone	Interruption of the Kali Gandaki river, formation of a lake (2010)	Fort 2010, 2011
6. Marpha (2011-2012)	100	2011-2012	HMC (greyish sandstone)	Steep collapse	Blocky, angular, silty sandstone	Interruption of the Kali Gandaki river, formation of a lake (2011)	Fort 2011, 2012
7. Marpha (2012-2013)	100	2012-2013	HMC (greyish sandstone)	Steep collapse	Blocky, angular, silty sandstone	Interruption of the Kali Gandaki river, formation of a lake (2012)	Fort 2012, 2013
8. Marpha (2013-2014)	100	2013-2014	HMC (greyish sandstone)	Steep collapse	Blocky, angular, silty sandstone	Interruption of the Kali Gandaki river, formation of a lake (2013)	Fort 2013, 2014
9. Marpha (2014-2015)	100	2014-2015	HMC (greyish sandstone)	Steep collapse	Blocky, angular, silty sandstone	Interruption of the Kali Gandaki river, formation of a lake (2014)	Fort 2014, 2015
10. Marpha (2015-2016)	100	2015-2016	HMC (greyish sandstone)	Steep collapse	Blocky, angular, silty sandstone	Interruption of the Kali Gandaki river, formation of a lake (2015)	Fort 2015, 2016



3. RINGMO-PHOKSUNDO SITE



The Phoksundo lake (3600 m asl.; area of 4.5 to 5 km²) is the second largest lake in Nepal; it owes its origin to the damming of the Suli Gadi River by the large (4.5 km²) collapse of a mountain wall (Dhaulagiri limestones) culminating at 5148 m, SE of the lake (Fort & Rimal 2010). According to Yagi (1997), the collapse may have occurred 30 to 40 ka, an interpretation revised by this study.



The landslide morphology presents a series of mounds (metres to tens of metres high) and depressions of varying size. Its mass is composed of large blocks of massive dolomites found as far as west of Ringmo Village and down to the southern rim of the landslide dam. Most of the Suli scarp is upheld by limestones outcrops, but along the central part, the former Phoksundo gorge is filled in by dark grey, fine sediments (fill material) and overlain by orange conglomerates (including dolomite boulders), then by yellowish, unsorted conglomeratic material blocks and calcareous silty matrix. The presence of glacial till at the very base of the sequence suggests the rockslide event is post-glacial.

Sample ID	Sample weight (g)	% CaO	147Sm/147Nd (10 ⁻¹⁰)	147Sm/147Nd (ppm)	147Sm/147Nd (10 ⁻¹⁰)	Exposure Age of surface (unreworked surface)	Uncertainties
PHOK 1	67.29	55.19%	133.8	33.64	2.79	6.98	6987 ± 566
PHOK 2	69.08	54.76%	382.0	24.08	4.58	9.8	20882 ± 1887
PHOK 3	72.05	54.59%	314.9	10.42	13.62	39.5	20889 ± 1661

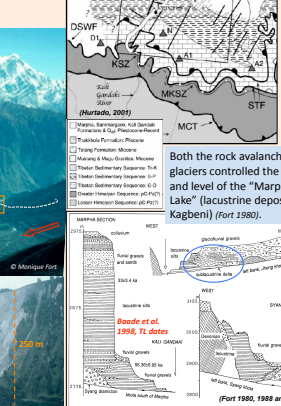
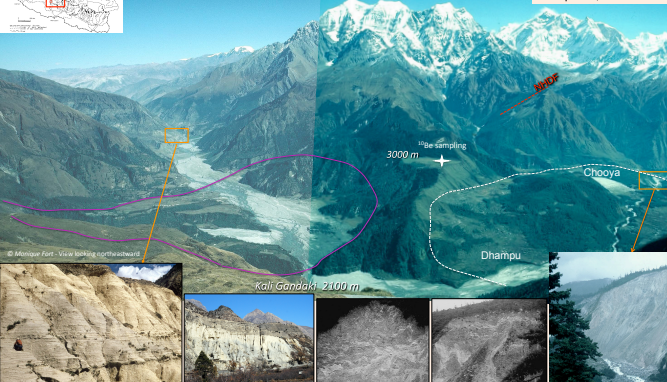
Two consistent ³⁶Cl ages of 20,885 ± 1675 argue for a sinele, massive event of para-glacial origin

Field assumptions are confirmed by cosmic ray exposure dating: the landslide dam was formed in response to the collapse of the limestone cliff in one single, massive event. The ³⁶Cl dates confirm the para-glacial/post-glacial origin of the failure, an event that fits well with the last chronologies available on the Last Glacial Maximum in the Nepal Himalaya (Owen & Dortch 2014). IRSL dating of silts suggests a progressive trend to dryness of these Northern Himalayan regions from Late Pleistocene to Holocene.

Note on Infrared Stimulated Luminescence (IRSL) dating

The IRSL samples, PHOK 2 and PHOK 3, were collected respectively at the top and the bottom of the silty deposits, below the surface soil. IRSL measurements were performed at Montreaux Laboratory by S. Balescu, S. Huot and M. Lamotte. The corrected IRSL ages of PHOK 2 and PHOK 1, respectively 4.7 ± 0.3 ka and 12.6 ± 0.7 ka, are stratigraphically consistent (Fort et al., 2013).

4. DHAMPU-CHHOYA SITE



The Dhampu-Chhoya rock avalanche (10⁶ m³, area extent 10 km²) was derived from the northward failure of the Kailay ridge, upheld by north-dipping, upper crystalline of the Higher Himalaya (Fort 1974; 2000). It dammed the Kali Gandaki River, with complex interactions with the Late Pleistocene ice tongues derived from the Dhaulagiri (8167 m) and Nigirisi (7061 m) peaks. Both the rock avalanche and glaciers controlled the existence and level of the 'Marpha Lake' (lacustrine deposits up to Kagbeni) (Fort 1980). The discrepancy in the dating of both lacustrine and failure events raise the issue of the nature of the lacustrine dam: (i) rock-avalanche as initially thought (Fort 1974; 1980; Baoude 2000) or (ii) possibly a glacial tongue controlling the lake level (Fort and Cossart 2013); (iii) repeated failures cannot be ruled out (Zech et al., 2010).

The fact that both Zech et al. (2009) and our team (Fort et al., in prep.) have obtained consistent exposure duration to cosmic ray, from different samples and different laboratories, provides very good evidence of a chronologically, well constrained Dhampu-Chhoya rock-avalanche event, i.e. about 30,000 years ago. Conversely, dating of lacustrine sediments has not been cross-checked to date, and some uncertainty cannot entirely be ruled out.

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5. COMPARISONS and CONCLUDING REMARKS

Phoksundo-Ringmo

- Efficient drainage blockage, but no backwash sedimentation (predominant carbonates + low discharge)
- Prominent knick point: karst + boulder pavement reducing incision => prominent hanging valley
- Triggering factor: glacial retreat («para-glacial collapse»), cf. ³⁶Cl dates

Dhampu-Chhoya

- Efficient drainage blockage, and extensive lacustrine sedimentation (glacial sediment reworking + Spitit shales + glacial- and snow-melt discharges)
- Knick points and associated epigenetic gorges + braided Kali Gandaki valley: delayed incision => relatively hanging valley
- No climate forcing, cf. ¹⁰Be dates => Triggering factor related to the North Himalayan Detachment Fault + foliation dip of Upper Himalayan Gneisses
- Complex interplay between glaciers and mountain wall collapses (Fort 2000)

Both examples confirm that giant landslides play a significant role in the: - Destruction of Himalayan topography (Fort 1988), - Bedrock protection from river incision (Korup et al. 2010), - Delay of sediment transport outward from the mountain zone (cf. sediment storages & budgets; Fort & Cossart 2013; Blithe J. B. Korup O., 2013) - Local controls exerted by topography and climate (eg. magnitude of glaciation + snow <-> discharge) + lithology (eg. sediment supply <-> storage)