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Monique Fort, Regis Braucher, Didier Bourles, Valery Guillou, Lila Nath Rimal, et al.. Geomorphic impacts, age and significance of two giant landslide dams in the Nepal Himalayas: Ringmo-Phoksundo (Dolpo District) and Dhampu-Chhoya (Mustang District).. EGU General Assembly 2014, Apr 2014, Vienne, Austria. 1 p. hal-01262118

HAL Id: hal-01262118

<https://hal.science/hal-01262118>

Submitted on 26 Jan 2016

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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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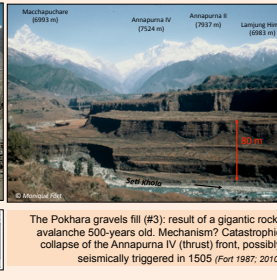
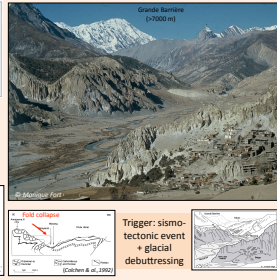
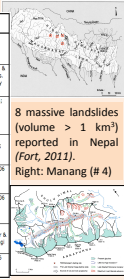


1. INTRODUCTION: MAIN ISSUES

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 downstream landforms and process evolution in upstream catchments. Their occurrence mostly results from three different potential triggers: earthquakes, post-glacial debultrussing, 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.

From Fort, 2012

How weaning feature	Volume (10 ⁶ m ³)	Age	Geological context	Type of material	Nature of the failure	Geomorphic impact	References
1. Phoksundo (Dolpo District)	~100	~1000 ± 100 ka	HMC (greyish to greenish)	Brittle, clastic	Brittle failure, topographic	Large lake, 3600 m asl, 4.5-5 km ²	Fort 1997, 2000; Braucher 2000
2. Ringmo (Dolpo District)	~100	~1000 ± 100 ka	HMC (greyish to greenish)	Brittle, clastic	Brittle failure, topographic	Large lake, 3600 m asl, 4.5-5 km ²	Fort 1997, 2000; Braucher 2000
3. Phoksundo (Dolpo District)	~100	~1000 ± 100 ka	HMC (greyish to greenish)	Brittle, clastic	Brittle failure, topographic	Large lake, 3600 m asl, 4.5-5 km ²	Fort 1997, 2000; Braucher 2000
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9. Phoksundo (Dolpo District)	~100	~1000 ± 100 ka	HMC (greyish to greenish)	Brittle, clastic	Brittle failure, topographic	Large lake, 3600 m asl, 4.5-5 km ²	Fort 1997, 2000; Braucher 2000
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2. DATING METHODS: COSMIC RAY EXPOSURE DATING

AMS measurements of the ³⁶Cl and ¹⁰Be concentrations were performed at the 5 MV national AMS facility ASTER located at CEREGE, Aix en Provence, France. All ³⁶Cl concentrations were normalized to the KNSTD1600 calibration material (³⁶Cl/³⁵Cl = 1.6*10⁻¹² provided by K. Nishizumi) and all ¹⁰Be concentrations were normalized to the SRM 4325 NIST reference material with an assigned ¹⁰Be/⁹Be value of (2.79±0.03)*10⁻¹¹. The ³⁶Cl decay constant of (2.303 ± 0.016)*10⁻⁶ a⁻¹ corresponds to a half-life (T_{1/2}) of (3.014±0.021)*10⁵ years and the ¹⁰Be decay constant of (4.987±0.036)*10⁻⁷ a⁻¹ to a half-life of (1.39±0.01)*10⁶ years. Analytical uncertainties include the counting statistics, machine stability (~0.5%) and blank correction, the associated ³⁶Cl/³⁵Cl blank ratio being ~10⁻¹⁴ and the ¹⁰Be/⁹Be blank ratio ~2*10⁻¹⁵. Cosmic ray exposure ages derived from these cosmogenic nuclide concentrations were calculated using production rates corrected for topographic shielding following Dunne *et al.* (1999) and scaled to the sites position (latitude, altitude) using the Stone scheme (Stone, 2000) from a sea level and high latitude production rate of 4.5±0.3 atoms of ¹⁰Be g⁻¹(SiO₂)⁻¹yr⁻¹ for ¹⁰Be and integrating all production pathways (spallation, including a spallation production rate of 42.0 ± 2.0 atoms of ³⁶Cl g⁻¹Ca⁻¹ yr⁻¹ and at sea level and high latitude, thermal neutron, muon captures and radiogenic production) and the rock's chemical composition for ³⁶Cl.

Sample ID	Sample weight (g)	% CaO	³⁶ Cl/ ³⁵ Cl (10 ⁻¹²)	Cl (ppm)	Cl (10 ⁻⁶ g/g)	Exposure Age of surface (unreduced surface) (ka)	Uncertainties
PHOK COS 1	67.29	55.18%	133.8	33.64	2.79	6.8	6987
PHOK COS 2	69.08	54.70%	382.0	24.08	4.58	19.8	20882
PHOK COS 3	72.05	54.59%	314.9	10.42	13.62	39.5	28889

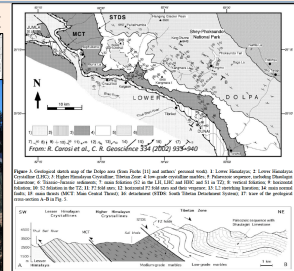
Two consistent ³⁶Cl ages of 20,885 ±1675 argue for a sinele, massive event of paraclacial origin

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 paraclacial/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.

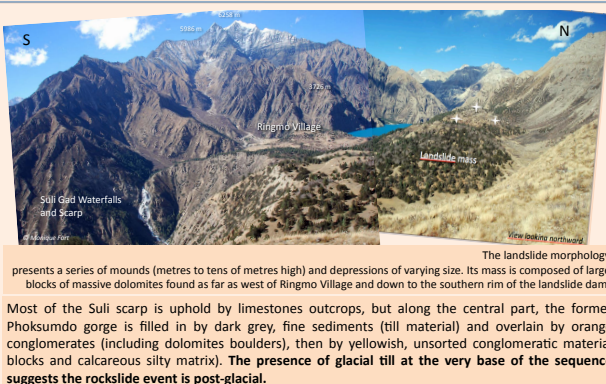
Note on Infrared Stimulated Luminescence (IRSL) dating

The IRSL samples PHOK 2 and PHOK 1, were collected respectively at the top and the bottom of the silt deposit, below the surface soil. IRSL measurements were performed at Montreal laboratory by S. Balescu, S. Huot and M. Lamothe. 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).

3. RINGMO-PHOKSUNDO SITE

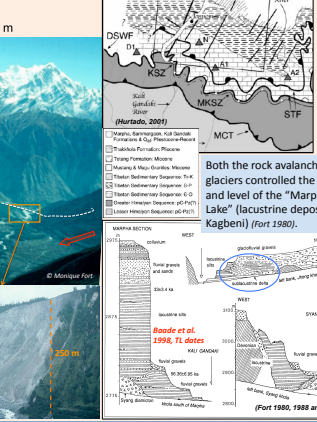
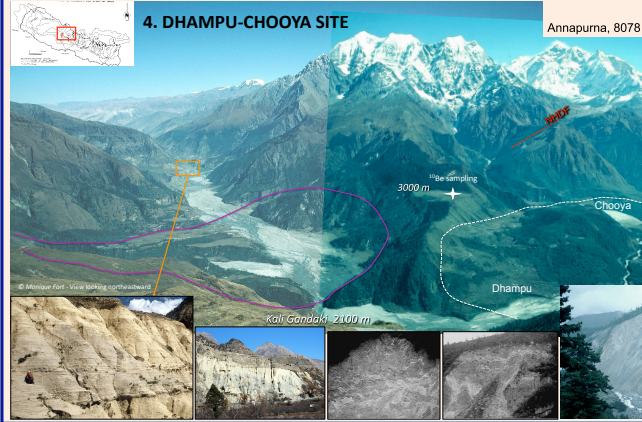


The Phoksundo lake (3600 m asl.; area of 4.5- to 5 km²) is the second largest lake of Nepal; it owes its origin to the damming of the Suli Gad River by the large (4.5 km²) collapse of a mountain wall (Dhaulagiri limestones) culminating at 5148 m, SE of the lake (Fort & Rimal 2010). According to Yagi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



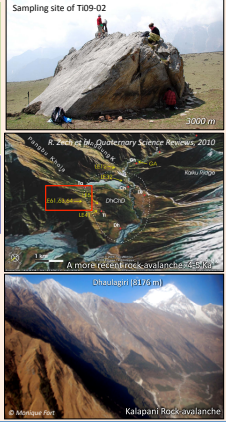
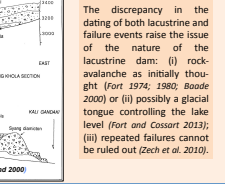
The landslide morphology presents a series of mounds (metres to tens of metres high) and depressions of varying size. Its mass is composed of large blocks of massive dolomites found as far as west of Ringmo Village and down to the southern rim of the landslide dam. Most of the Suli scarp is upheld by limestones outcrops, but along the central part, the former Phoksundo gorge is filled in by dark grey, fine sediments (till material) and overlain by orange conglomerates (including dolomites 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.

4. DHAMPU-CHHOYA SITE



The Dhampu-Chhoya rock avalanche (10⁹ m³), area extent 10 km² was derived from the northward failure of the Kaliu ridge, upheld by north-dipping, upper crystalline lines 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 Nilgiri (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 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.

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 («paraglacial collapse»), cf. ³⁶Cl dates
Dhampu-Chhoya
- Efficient drainage blockage, and extensive lacustrine sedimentation (glacial sediment reworking + Spiti 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; Blöthe *et al.* 2013)
- Local controls exerted by topography and climate (eg. magnitude of glaciation + snow <=> discharge) + lithology (eg. sediment supply <=> storage)

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