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Instability of recent moraines in the Italian Alps. Effects of natural processes and human intervention having environmental and hazard implications

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ABSTRACT. The original structure of a moraine can be substantially modified by a number of processes, which can proceed for hundreds of years or develop almost instantaneously. A study has been conducted on the entire Italian Alpine arc, including an analysis of aerial-photographs, literature review and direct observations, aimed to identify the main processes that reshape moraines. Special attention was paid to cases where human activity was directly affected or implicated in moraine remodelling. Water-driven processes, on the occasion of severe rainfall events or sudden emptying of glacial lakes, proved to be the most hazardous events, initiating high-magnitude debris flows which travelled many kilometres downwards. Landslides, gully erosion and rockglacier, also responsible for moraine reshaping, have a much lower hazard potential. Exogenous processes, although being far the most active, are not the only agents of moraines remodelling: tectonics and human interventions can cause sporadic but sometimes heavy changes of moraine shape.

Key terms: LIA moraines, Remodeling, Hazard, Italian Alps

Introduction

Moraines of the Little Ice Age (LIA, ca. 1450—1850) are generally characterized by their perfect, well-preserved shape. Accurate analysis, however, reveals that they have undergone substantial morphological change since their construction. The chief morphogenetic processes that reshape moraines are significant not only as indications of morphodynamics but also as potential hazard sources in mountainous areas. Not infrequently, these processes can, in fact, negatively impact on human activity, while human action can substantially change moraine shape as well.

FIGURE 1 - Location map of the study area.

Recent rainstorm events have had a direct bearing on the reshaping of moraines, especially on those of the LIA. To assess the effects of these events, the Authors investigated the major natural processes that concur in the remodeling of moraines after deposition. Expanding on the scope of a previous work (CHIARLE & MORTARA, 2001), the present study includes an analysis of aerial photographs of the entire Italian Alpine arc, direct observations and a review of the literature. In this way, the case history has been condensed and updated with specific reference to cases where human activity was directly implicated in moraine remodeling or affected by its effects (FIG. 1).

Types of Processes

The original shape of a moraine is heavily changed by water and gravity-driven processes that either work directly on the moraine itself or start in nearby slopes and eventually affect the moraine.

Action of water

Since the end of the LIA, Alpine glaciers have drastically decreased in surface area (40%) and volume, only temporarily counteracted by the positive pulsations that took place in the 1920s and 1980s. Glacial retreat has bared extensive areas and gradually exposed the steep inside walls of moraines. The abundance of not yet stabilized glacial deposits promotes erosion and transport processes during heavy rains or glacial floods.

In such situations, moraine morphology may be substantially changed by:

- erosion at the foot of the moraine, both on the internal and external walls. During the summer of 2003, modest glacial outbursts produced visible erosions at the foot of the internal wall of the lateral moraine of the Belvedere Glacier (Monte Rosa Group) and the Miage Glacier (Mount Blanc). The downcutting may be very wide and deep, sometimes reaching into the moraine crest (FIG. 2).
- linear erosion due to highly concentrated surface flow along the internal wall of a moraine. Closely spaced gully erosions form and the crest indents, so that the moraine loses its characteristic knife blade profile. This loss may be due to: (a) a reduction in the internal wall slope; (b) a gradual retreat of the ridge crest, with continued adjustment of hiking trails running along it.

  Occasionally, gully erosion processes may trigger debris flows also on the outside wall of the moraine during heavy rains (SMIRAGLIA, 1988; ZIMMERMANN, 1990). For example, a large debris flow issuing from the terminal moraine of the eastern Monte Giovo Glacier was observed on 24 August 1987 (Val Formazza, Western Alps). The debris flow halted 3 km farther downvalley, after severely damaging a crowed camping ground (MORTARA *et alii*, 1995).
- downcutting of terminal/lateral moraines. This generally creates a V-shaped incision of sometimes enormous proportions in the moraine (HAEBERLI *et alii*, 1998; LUGON *et alii*, 2002; MORTARA *et alii*, 1995). In documented cases, abrupt downcutting was followed by debris flows of even hundreds of thousands of cubic meters.

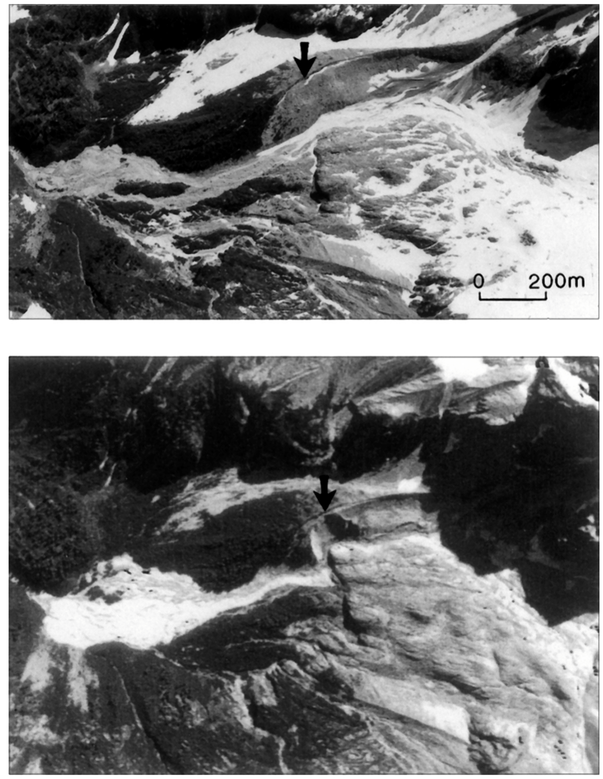

FIGURE 2 - Deep erosion at the base of the inside wall of the right lateral moraine (Presanella Glacier, Trentino-Alto Adige, NE Italy) was caused by a flood of the glacial torrent in August 1987. (Aerial photo, 1991; Conc. Aeron. Mil. – R.G.S. n.385 del 22 nov. 1999).

FIGURE 3 - Strong downcutting on latero-frontal moraine occurred during a rainstorm on September 24th, 1993 (Mulinet Glacier, Piemonte, NW Italy).

FIGURE 4 – Coarse debris accumulation in the Forno Alpi Graie village, following the September 1993 event. Deposit was up to 4 m thick.

When effects are triggered by rainfall, the cause cannot always be attributed to rainfall intensity alone. Local topographic features or contingent circumstances (anomalous contribution of snow- and/or icemelt, glacial deposit saturation, hydrostatic overpressure) may be predisposing or determinant factors even when rainfall is modest. Three examples of this are:

Sissone Glacier Moraine (Valmalenco, Central Alps). On 15/09/1950, after several hours of abundant rainfall, a channel (ca. 600 m long, up to 200 m wide, 60 m deep) opened in the terminal-lateral moraine within around two hours; an enormous debris flow (> 1x 10^6 m^3) buried a more than 10-km-long stretch of the bed of the Sissone Torrent (MORTARA *et alii*, 1995).

Ormelune Glacier Moraine (Valgrisanche, Aosta Valley, NW Alps). During a heavy rainstorm (24/07/1996), the steep fluvioglacial cone at the foot of the glacier was deepened by 20-30 m; a large debris flow (ca. 300,000 m^3) starting in the channel flooded the alluvial plain of the Grand'Alpe Torrent.

Mulinet Glacier Moraine (Graian Alps, NW Alps). During a rainstorm (24/09/1993), a violent debris flow due to strong downcutting of a small stream on the face of the LIA moraine of Mulinet Glacier traveled 4.5 km and hit the village of Forno Alpi Graie. The moraine incision was about 15 m deep (locally up to 50 m in depth), 450 m long and up to 200 m wide. The estimated volume of the removed debris was about 800,000 m^3 (FIGS 3, 4).

Similar forms of erosion can be created by abrupt releases of huge water masses from a glacial lake. Downcutting commonly occurs on the terminal side of the moraine arc enclosing the proglacial lake and can develop over the course of a few hours, sometimes without forewarning. The released water (up to millions of m^3) usually triggers violent torrential floods with elevated debris charges that can travel several kilometers, leaving a path of devastation behind (WALDER & COSTA, 1996).

Moraine dam breaching due to glacial outburst is a feared phenomenon that, while frequent in extra-European mountainous areas, seldom occurs in the Alps. The best known Italian case is related to the proglacial Lago delle Locce (Monte Rosa, Italian eastern side). In three events (13 August 1970, 2 July 1978, 19 July 1979), outburst floods issuing from the moraine- and ice-dammed Lago delle Locce widened the breach initially cut in 1904 through the Belvedere Glacier right lateral moraine near Alpe Pedriola. The 1979 event seriously damaged the Belvedere chairlift and flooded a stretch of the valley bottom 1 km in length, with a mean width of 150 m, almost reaching the hamlet of Pecetto near Macugnaga (DUTTO & MORTARA, 1992; FIG. 5).

Another example is the abrupt outburst of an endoglacial water body inside the Brenva Glacier (July 1928) that caused a breach that still interrupts the regular geometry of the right lateral moraine. Also, large breaches identified by aerial photo analysis of terminal moraines in the Italian Alps can be attributed to glacial outbursts or intensive gully erosion processes. Examples are the moraines of the glaciers of Western Breuil (Gran Paradiso Group, Western Alps), Eastern Levadé (Adamello Group, Central Alps), Western Pasquale (Cevedale Group, Central Alps). The size of some downcutting erosions in the LIA moraines described above may appear extraordinary, but a unique case is that of the Rio Casare (Trento Province, Eastern Alps). During a catastrophic rainfall event in September 1882, this small torrent (basin surface 2 km^2) changed its

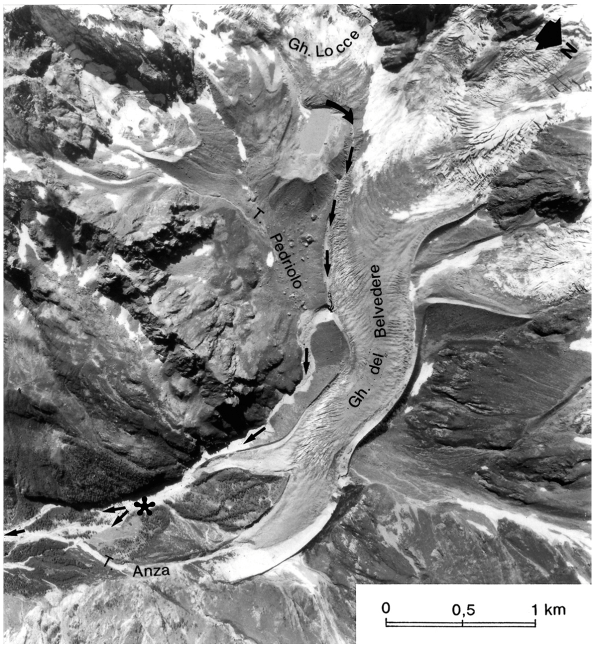

FIGURE 5 – Black arrows outline the path of the 1979 outburst debris flow issuing from the proglacial Lago delle Locce (Monte Rosa Group, NW Italy). The chair lift station damaged during the event is located by the asterisk (Aerial photo, 1979; Conc. Aeron. Mil. – R.G.S. n.385 del 22 nov. 1999).

path and cut a new channel in a Pleistocene moraine terrace up to 80 m deep, carrying away around 5 million m^3 of sediment. Three years later, the Rio Casare deepened by another 20 m following a rainstorm (GORFER, 1991; MARAGA & MORTARA, 1996). Unlike the other cases described here, although this large incision did not affect recent glacial deposits, it exemplifies the unpredictable intensity of erosion processes on glacial deposits.

Action of gravity

Landslides can substantially modify the original moraine form. Gravity acts more strongly on the internal wall of a moraine (dry wall moraine), where morphogenetic processes start when the glacier no longer supports the moraine. At this site, small portions of cemented deposit may collapse, whereas rotational sliding involves larger portions. Two noteworthy examples have been observed in the large right lateral moraine of the Belvedere Glacier (Monte Rosa, north eastern side).

1) Some time before 1889, a wide portion of the moraine slid along an inclined surface (ca. 40°) toward the glacier and halted 10-20 m below its original position (HAEBERLI, 1985). Following the collapse, an unusual intramoraine depression (ca. 300 m long) with extremely asymmetrical sides formed.

2) Several hundreds of meters upvalley a comparable phenomenon was observed in an aerial photograph taken in 1951, during a period of marked glacier contraction. The photo shows a straight moraine portion (ca. 200 m long) dislocated from the moraine ridge and resting against the right side of the glacier. The portion of glacial deposits detached as a whole and remained unchanged until around 1954, a period of minor glacial dynamics. Readvance during the late 1960s lent new strength and mobility to the glacier, which completely dismantled the detached moraine portion. The surprising unity of the two collapsed stumps indicates that the glacial sediments were highly cemented (ice-cemented moraine).

The outside wall of a moraine is more prone to debris sliding; in some cases glacial sediments flow as rock glaciers, a phenomenon that indicates the presence of an ice core inside the moraine (VERE & MATTHEWS, 1985). The gradual melting of underground ice may also cause the crest to split, resembling multiple orders of moraines which are, in fact, genetically linked to glacial advances of decreasing intensity instead.

Moraine ice-core melting was probably involved in a landslide a few meters deep that mobilized about 40,000 m^3 of debris from the inside wall of the right lateral moraine of the Forni Glacier (Ortles-Cevedale Group) in the summer of 2003. This mass movement seriously damaged the glaciological path to the glacier established in 1995 (M. PELFINI *et alii,* 2004). Large landslides due to melting underground ice were reported by PERETTI (1932) in 1931 in the upper right moraine of the Grand Sertz Glacier (Gran Paradiso Group).

Moraine deformation is not always apparent on the surface; indirect evidence may reveal active processes. This is the case of the terminal moraine of the Locce Glacier (Monte Rosa). In 1958 the small Rifugio Paradiso was built on a cement slab at the crest of the moraine. Unsuspected underground ice slowly melted, irremediably destabilizing the refuge, so that it was eventually abandoned in 1975 (HAEBERLI, 1992; FIG. 6).

Slope instability processes overrunning moraines

The form of a moraine can also be changed by gravitational processes that trigger externally to the moraine. Landslides, debris flows and avalanches can fill the depression between the valley slope and the outside wall of a moraine. As the depression fills, the detritus cones create a morphological link between the slope and the moraine. In this way, later landslides, debris flows or avalanches can transfer debris to the foot of the inside wall of the moraine and ultimately to the glacier if still present.

In the spring of 1986, a large landslide (ca. 200,000 m^3) detached from the right side of the Val Veny (Mount Blanc). After crossing the river of the valley bottom, it partially ran up the outside wall of the right lateral moraine of the Miage Glacier (MORTARA & SORZANA, 1987). Two years later, this glacier was affected by a large rockfall issuing from a tributary basin. The rockfall traveled the entire width of the glacier, obliterating two big ice-cored medial moraines. Similar effects are produced over much longer time periods when active rock glaciers transversally

FIGURE 6 – Tilted Rifugio Paradiso (2271 m a.s.l.) on frontal moraine containing underground ice (Locce Glacier, Monte Rosa, NW Italy).

overlap moraines. Spectacular examples can be observed in LIA and tardiglacial moraines in the Aosta Valley (e.g. Grand Neyron Glacier, Gran Paradiso Group).

Sometimes, large landslides (hundreds of thousands or millions of m^3) triggering inside a glacial basin can move along the glacier surface until they overrun terminal/lateral moraines. Several effects may result:

- planing of the moraine crest (e.g. Brenva rock-ice avalanche, Mont Blanc Group, 18 January 1997: BARLA *et alii,* 2000);
- breaching of the terminal moraine arc following landslide impact (e.g. Felik rock-ice avalanche, Monte Rosa Group, 14 August 1936: BOTTINO *et alii*, 2002);
- accretion of the outside wall of the moraine, when the landslide entrains debris outwards; the landslide accumulation overlies the moraine, reducing its slope. Discriminant features are the different textures of the two deposits, the stage of lichen growth, and sometimes the lithology. Three generations of landslide accumulation (14th century?, November 1920, January 1997) were recognized by DELINE (2001) on the distal side of the right lateral moraine of the Brenva Glacier. The recognition of such geomorphological evidence is also important for assessing the frequency of large landslides spreading outside glacial basins (FIG. 7).

Deep-seated gravitational deformation linked to deglacialization may involve lateral moraines adjoining

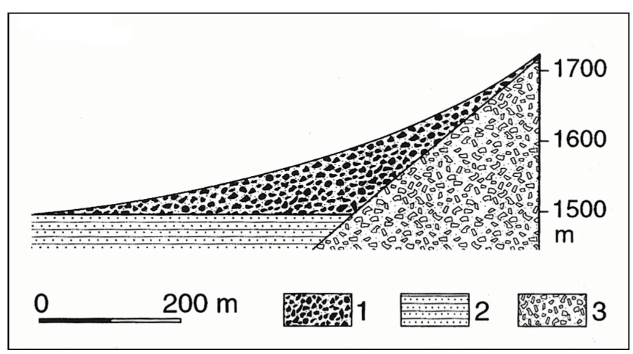

FIGURE 7 – Cross-section of the right lateral moraine of the Brenva Glacier. Morphological setting of the external flank has been modified by landslide accumulation overflowing moraine ridge. LEGENDA: 1. Landslide accumulation; 2. Fluvioglacial deposit; 3. Glacial deposit of the lateral moraine (courtesy of P. DELINE).

mountainsides. In New Zealand, following the marked glacial retreat of the last 20 years, several valley slopes are deforming jointly with LIA moraines (BLAIR, 1994). In Italy, a tardiglacial moraine of the Laghetto dei Forni (Ortles-Cevedale Group) is partially dislocated due to slow, extensive sliding of the bedrock (POZZI *et alii*, 1991).

Ongoing glacial dynamics

A recent example of moraine remodeling is exquisitely connected with the dynamics of the Belvedere Glacier (Monte Rosa Group). Between 2000 and 2003, the glacier developed an astonishing surge-type movement (a unique case in the Alps) due to accelerated flow, thus becoming dramatically compressed and deformed. The ice started to override or push through the right lateral moraine (HAEBERLI *et alii*, 2002). Moraine bulgings are continuously monitored because of the risks that potential moraine breaching and abrupt outbursts of pressurized glacial water pose to the many tourists visiting this mountain resort.

Other Causes of Remodeling

While exogenic processes are by far the most common and most active factors in remodeling the shape of moraines, tectonic and human activities also play a morphogenetic role that, while episodic, is not negligible.

Tectonics

The prominent "saw toothed" profile of the crests of some tardiglacial moraines is a recognized surface feature of tectonic forces. Spectacular examples in the Swiss Alps include the moraines near the sources of the Ticino River and those near Bodmen, where a system of subparallel faults dissects the glacial deposits with displacements of 5-10 m (STRECKEISEN, 1965). In the Central Italian Alps, counter slope scarps in some late-glacial moraines have also been attributed to tectonic activity (FORCELLA & OROMBELLI, 1984; GUGLIELMIN & NOTARPIETRO, 1991; TIBALDI, 1998).

Human intervention

The need to mitigate the destructive effect of natural phenomena originating in glacial areas may require the construction of prevention works on moraines (HAEBERLI, 1992). The use of caterpillars or similar means generally leads to major morphological and environmental modifications. Significant examples include the moraines of the Locce Glacier (Monte Rosa Group) and the Chérillon Glacier (Matterhorn Group).

Terminal moraine of the Locce Glacier. To keep the level of the Locce proglacial lake low, the site of dangerous outbursts during the decade 1970-1979, an artificial outlet was constructed by excavating a large, deep V-shaped trench (ca. 200 m long) into the moraine (TROPEANO *et alii*, 1999).

Moraine of the Chérillon Glacier. The northern part of the village of Cervinia is threatened by large avalanches originating from the Chérillon and Mont Tabel glaciers. Around 1985, a gigantic dam was built inside the LIA moraine to ensure the safety of the valley bottom (FIG. 8). The structure was anchored by deeply excavating the internal walls of the two lateral moraines. The artificial embankments of loosely cohesive sediments expose the moraine to erosion and landslide processes.

The installation of hydroelectric plants in glacial basins usually introduces works of great environmental impact into the landscape (artificial dams, yards, etc.) that not infrequently interfere with the moraines.

Moraine of the Hohsand glaciers (Ossola Valley, Western Alps). After an artificial dam was built in 1952, the proglacial area and the front of the two Hohsand glaciers, which are separated by a medial ice-cored moraine, were gradually submerged. Within a few years, very active calving processes severely fragmented the glacier fronts and the moraine resting under the water level (MAZZA & MERCALLI, 1992).

Construction of yards and chairlifts for summer skiing also impact negatively on moraines. A good example of this is the profound remodeling of the LIA moraines of the Scorluzzo Glacier within the Stelvio Pass tourist area (Central Alps). It is also interesting to note that road construction over the Stelvio Pass in the first half of the 19th century already cut through the tardiglacial moraines of the glacier.

Quarrying in glacial deposits has led to minor morphologic changes in moraines. Examples include mining of the Z'mutt Glacier frontal moraine (Swiss Alps) and the foot of the right lateral moraine of the Brenva Glacier (Mount Blanc Group).

Conclusions

Building on an ample case history of the Italian Alps, the aim of the present study was to identify the major processes that can significantly remodel recent (LIA) moraines. Water seems to play a decisive role in mobilizing sometimes huge amounts of sediment (tens or hundreds of thousands of cubic meters) during intense rainfall events or sudden glacial outbursts. The most prominent effect is moraine downcutting, sometimes measuring tens of meters in depth.

Debris failures can often occur on both walls of the moraine. These usually slowly evolving phenomena are probably linked to ice cores melting inside the moraine, and sometimes resemble rock glacier flow-type. Rapid landslides may involve the inside wall of moraines, where closely spaced gully erosion favors the collapse of the more cemented debris portions.

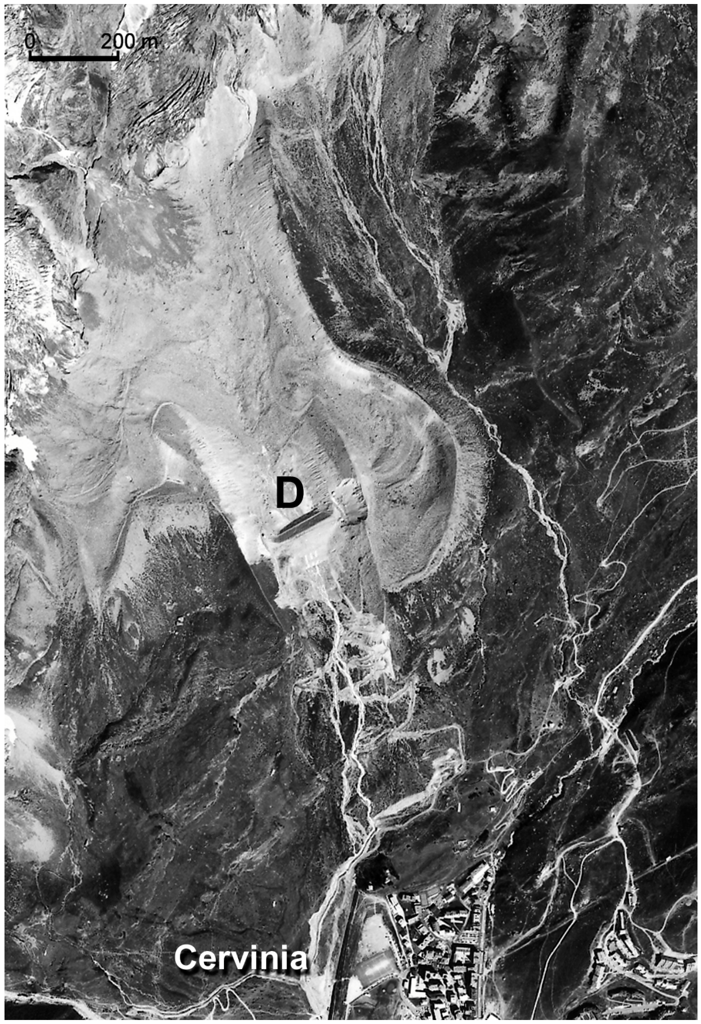

FIGURE 8 - Grand snow avalanche dam (*D*), protecting the Cervinia built-up area (2006 m a.s.l.). The structure was anchored to the internal moraine wall of the Chérillon Glacier (Aosta Valley, NW Italy), with important excavation works (Aerial photo, 1991; Conc. Aeron. Mil. – R.G.S. n.385 del 22 nov. 1999).

Moraine preservation also depends on the distance of the moraine from the surrounding valley side: the shorter the distance, the higher the probability that external solid transport from landslides, avalanches or debris flows triggering externally to the moraine will seal the depression between the valley side and the outside wall of the moraine, obliterating its original shape.

Human activity, whether motivated by economic development of an area or by defense against natural hazards, may change the shape of moraines through extensive excavation and filling activity. This case series illustrates that the original moraine structure may be changed by sudden events or by continuous processes having different development times, sometimes spanning centuries. Rapidly evolving phenomena can be associated with important morphologic effects and hazards implications, as in intensive moraine downcutting followed by debris flows. Such phenomena have been increasingly reported in glacial areas throughout the world. They are associated with the present phase of global warming that seems to be accelerating glacial retreat, which started at the end of the LIA, and be making metastable moraines and debris bodies in the permafrost belt (EVANS & CLAGUE, 1994; WEGMANN *et alii*, 1998).

This collection of case histories provides a useful reminder for hazard assessment and land use planning in glacial and periglacial areas. Nevertheless, it must be remembered that rapidly evolving phenomena starting from recent moraines can travel many kilometers, thus also threatening the valley bottom below, where human presence is greater.

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