

Recent debris flow occurrences associated with glaciers in the Alps

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Received 12 August 2005; accepted 21 July 2006

Available online 9 January 2007

Abstract

Debris flows from glacier forefields, triggered by heavy rain or glacial outbursts, or damming of streams by ice avalanches, pose hazards in Alpine valleys (e.g. the south side of Mount Blanc). Glacier-related debris flows are, in part, a consequence of general glacier retreat and the corresponding exposure of large quantities of unconsolidated, unvegetated, and sometimes ice-cored glacial sediments. This paper documents glacier-related debris flows at 17 sites in the Italian, French, and Swiss Alps, with a focus on the Italian northwest sector. For each case data are provided which describe the glacier and the instability. Three types of events have been recognized, based on antecedent meteorological conditions. Type 1 (9 documented debris flows) is triggered by intense and prolonged rainfall, causing water saturation of sediments and consequent failure of large sediment volumes (up to 800 000 m³). Type 2 (2 debris flows) is triggered by short rainstorms which may destabilize the glacier drainage system, with debris flow volumes up to 100 000 m³. Type 3 (6 debris flows) occurs during dry weather by glacial lake outbursts or ground/buried ice melting, with debris flow volumes up to 150 000 m³. A data base of historic cases is needed in order to advance process understanding and modelling, and thus improve hazard assessment.

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Keywords: debris flow; glacial outburst floods; climate change; European Alps

1. Introduction

Ice avalanches, emptying of glacial lakes and englacial water bodies as well as glacier surges are infrequent, yet recurrent events in the normal evolution of a glacier as it advances and retreats (Dutto and Mortara, 1992). These phenomena also pose a risk to inhabitants and infrastructure in valleys, some of which are frequented by large numbers of tourists (e.g. Ferret

and Veny valleys on the Italian side of the Mount Blanc Massif). High velocities (up to 200 km/h), long travel distance (up to tens of kilometers) and large volumes (up to millions of cubic meters) are compounded by the complete absence of precursor phenomena in some cases. These events leave a record in the geomorphology of the affected areas, but are soon forgotten by residents (Mortara and Chiarle, 2005). Reports of suddenly arising highly critical situations in the Alps (Margreth and Funk, 1999; Barla et al., 2000; Dei Cas et al., 2004; Deline et al., 2004; Kääh et al., 2004) and the catastrophic Kolka–Karmadon rock/ice slide in the Russian Caucasus (Huggel et al., 2005) have highlighted the danger these events pose.

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Glacier-related debris flows are, in part, a consequence of general glacier retreat and exposure of large quantities of unconsolidated, unvegetated, and sometimes ice-cored glacial sediments. These sediments are easily mobilized by floods resulting from heavy precipitation, snowmelt, and glacial lake outbursts (Zimmermann and Haeberli, 1992; O'Connor and Costa, 1993; Evans and Clague, 1994; Haeberli et al., 1997).

Any method, either empirical, statistic or deterministic, aimed at assessing debris flow hazards, is based, or tested, on data gathered from past events (Huggel et al., 2004). Glacier-related debris flows are, in many cases, poorly documented, as they often occur in remote, uninhabited areas. The present paper aims at partially filling this gap by providing data and

analyses on 16 events which occurred in the European Alps in the last 25 years. Additionally, the Sissone debris flow which occurred in 1950 and is the largest debris flow documented in Italian glacierized areas (Fig. 1) is discussed. The presented data set can thus be a contribution to the development or testing of methods for glacial debris flow hazard assessment.

2. Study area and data

The study area includes the Italian, French, and Swiss Alps, with a focus on the northwestern Italian sector, because of the high concentration of glaciers in that area and because of the authors' familiarity with it (Fig. 2). Only events that mobilized at least thousands of cubic

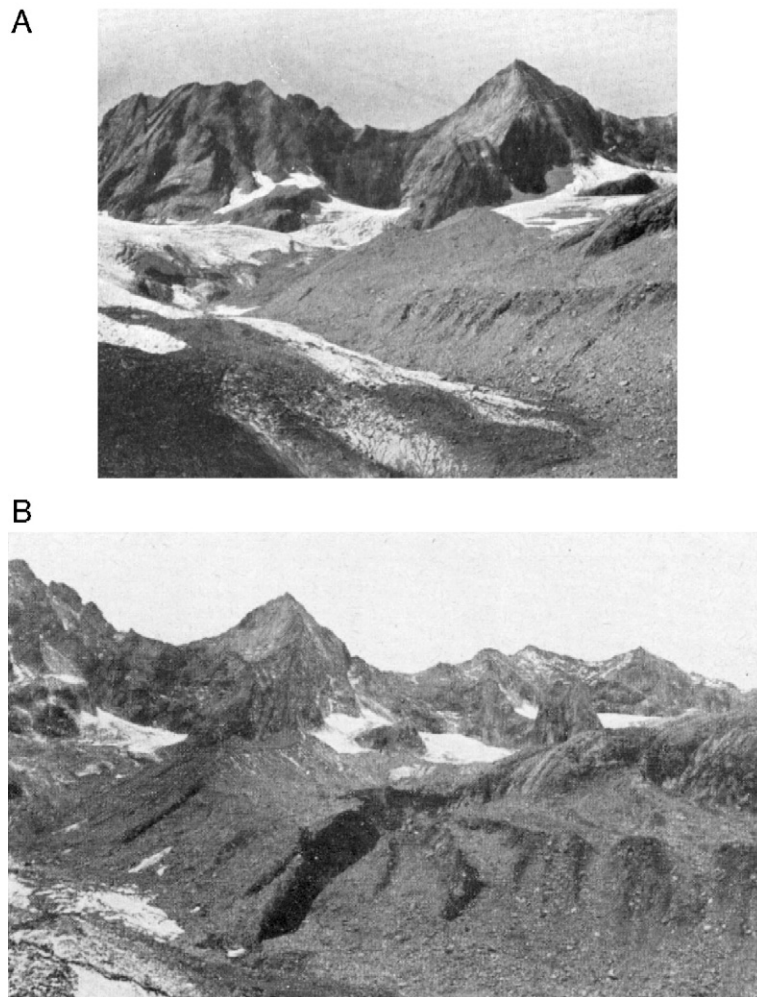


Fig. 1. Breach in the moraine of Sissone Glacier (site 10), which formed in September 1950 (B). Photo A shows the moraine prior to the breach (from Nangeroni, 1951).

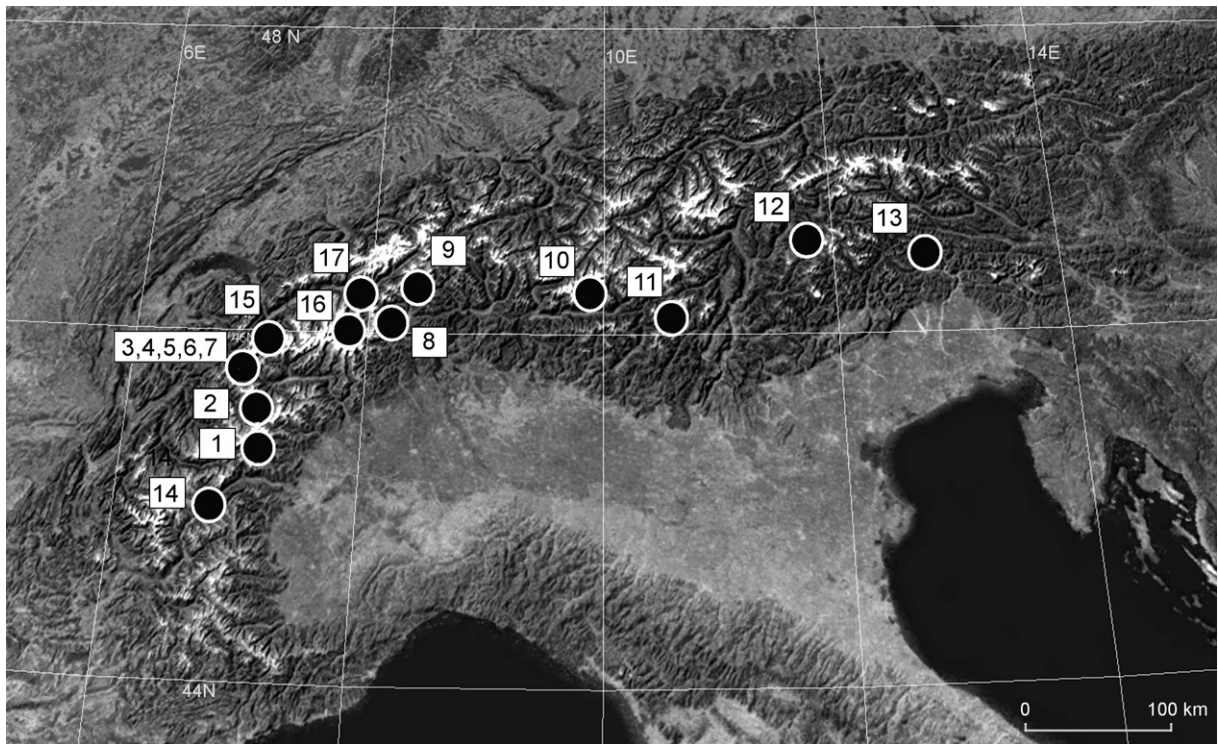


Fig. 2. Map showing locations of the case histories.

meters of debris are considered. At sites of recurrent events, reference is made to the largest or best documented event.

For each case, we provide several simple parameters that describe the glacier (Table 1), and the

instability (Table 2). Data were also collected on elevation and triggering mechanism, duration of the debris flow and ensuing damage. Analysis was completed using aerial photographs, field observation, and a review of the literature. We assembled data in a

Table 1

Summary and glacier characteristics of analysed cases. M: mountain glacier; V: valley glacier; G: glacieret

Site	Country	Massif	Glacier	Type	Area (km ²)	Slope (°)	Orientation
1	Italy	Levanne	Mulinet	M—Cirque	0.46	15	NE
2	Italy	Rutor	Ormeleura	M—Cirque	0.89	20	NE
3	Italy	Monte Bianco	Freny	M—Cirque	1.42	26	SE
4	Italy	Monte Bianco	Rochefort	M—Cirque	1.08	28	S
5	Italy	Monte Bianco	Pra' Sec	M—Niche	0.16	35	S
6	Italy	Monte Bianco	Grandes Jorasses	M—Cirque	0.89	34	S
7	Italy	Monte Bianco	Frebouge	M—Cirque	2.30	10	SE
8	Italy	Monte Rosa	Belvedere	V—Compound basin	5.58	10	NE
9	Italy	Monte Leone	Monte Giove Orientale	M—Cirque	0.12	24	NE
10	Italy	Bernina	Sissone	M—Cirque	0.78	24	E
11	Italy	Adamello	Presanella	V—Compound basin	3.59	18	N
12	Italy	Monte Pelmo	Pelmo	G—Ice apron	0.07	22	SE
13	Italy	Jôf di Montasio	Montasio Occidentale	M—Niche	0.08	22	N
14	France	Chambeyron	Chauvet	M—Ice apron	0.15	17	NW
15	Switzerland	Monte Bianco	Dolent	M—Cirque	1.50	25	E
16	Switzerland	Alphubel	Weingarten	M—Cirque	2.00	19	SW
17	Switzerland	Fletschhorn	Bodmer	M—Niche	0.64	29	N

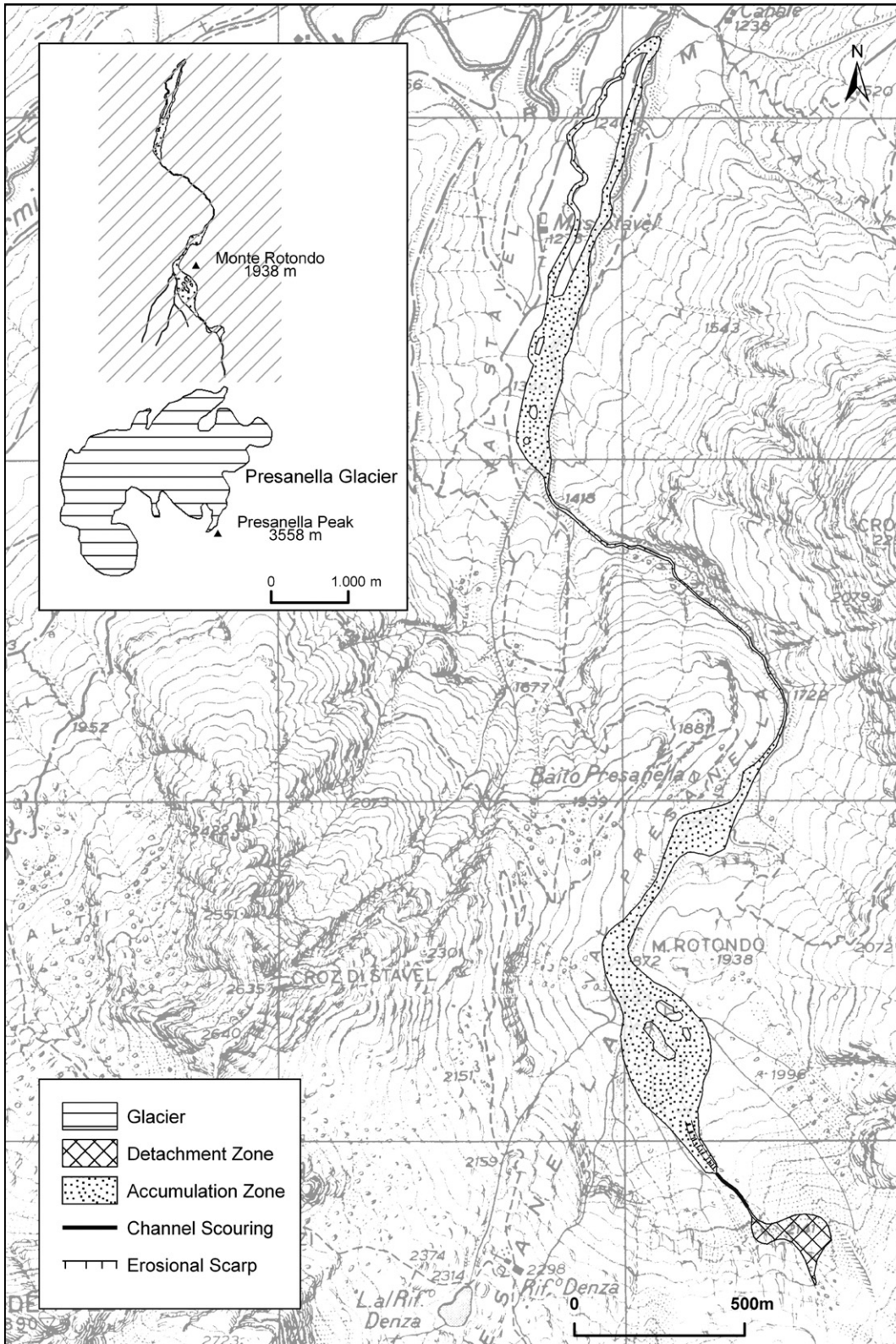


Fig. 3. Map showing path of the debris flow that initiated in the forefield of Presanella Glacier (site 11) in August 1987.

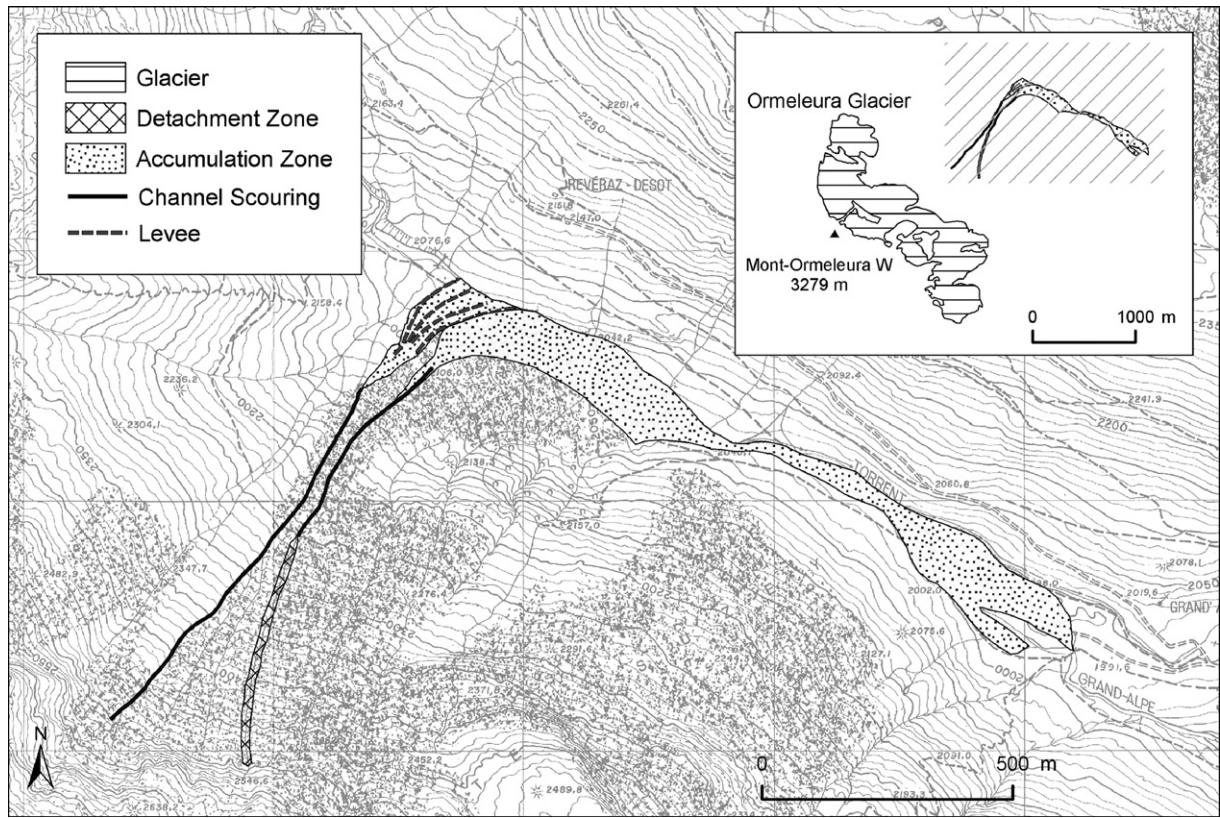


Fig. 4. Map of the debris flow that occurred in the forefield of Ormeleura Glacier (site 2) in July 1996.

GIS (Figs. 3–5). A brief description of each event is provided in Table 3.

3. General characteristics of debris flows in glacial environment

Several general inferences can be drawn from our analysis of the events that we have studied (Table 2). Most debris flows initiated at high elevation, ranging from 2000 to 3000 m a.s.l. Starting zones correspond to the uppermost occurrence of large quantities of loose debris along proglacial stream channels. In some cases (Ormeleura, Freney, Rochefort, Prà Sec, Grandes Jorasses, Frébourg, Presanella) these sediments consist of thick, steeply-inclined fluvioglacial deposits and till, often located at the foot of a steep rock face below glacier fronts. Otherwise, Mulinet, Monte Giove, Montasio, Pelmo, Dolent, Weingarten, and Bodmer debris flows initiated with the failure of Little Ice Age end moraines: stagnant ice outcropped in Mulinet, Pelmo, and Montasio moraine breaches. In two cases (Belvedere, Sissone), processes initiated from lateral moraines.

Source zones are up to 600 m long and 200 m wide; erosion depths range from meters to decameters (maximum erosion depths of 50 m and 60 m have been reported for events at Mulinet and Sissone glaciers, respectively). The mobilized volumes range from several thousand cubic meters to one million cubic meters, and the deposit area is generally less than 0.5 km².

The duration of the debris flows is commonly 1–3 h.

Travel distances range from 1 to 6 km. Mobility, expressed as the ratio of the vertical travel distance to the length of travel (H/L) is a function of the specific geomorphologic context and amount of water input involved in the debris flow. The lowest values of this parameter (0.13 and 0.15) are for the events at Ormeleura and Sissone glaciers; the highest (0.50 and 0.52) are for the events at Montasio and Chauvet glaciers. The values for the Ormeleura and Sissone events correspond to the average slopes of 7° and 8.5°, respectively, lower than the minimum value of 11° proposed for debris flows resulting from lake outbursts in the Swiss Alps (Rickenmann and Zimmerman, 1993; Huggel et al., 2002).

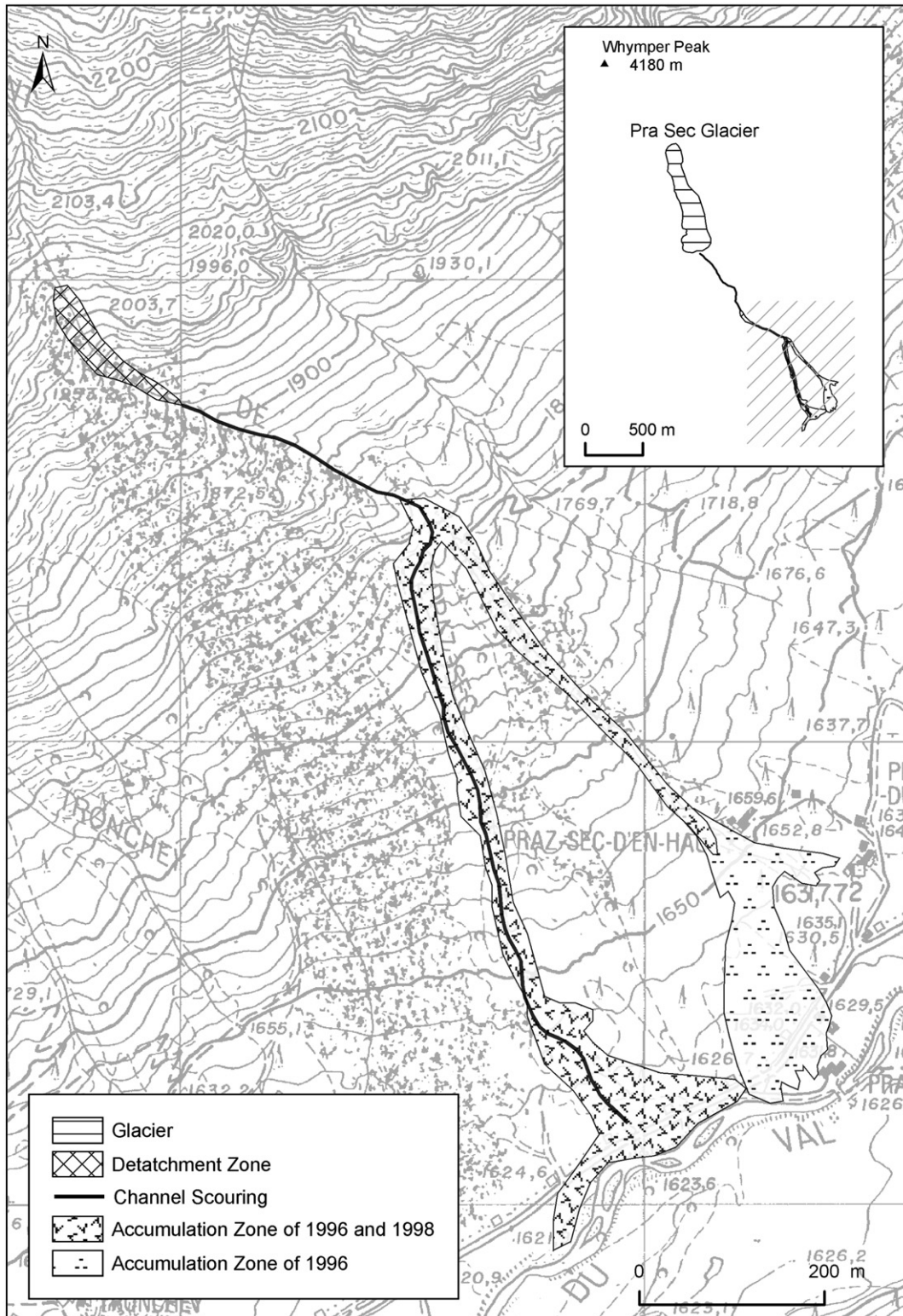


Fig. 5. Map showing paths of the debris flows that occurred at the front of Prà Sec Glacier (site 5) in 1996 and 1998.

Table 2

Parameters and data for analysed debris flows. DZ: detachment zone; AZ: accumulation zone. H/L: ratio of the vertical travel distance to the length of travel

Site	Date	Rainfall	Starting elevation (m a.s.l.)	Volume (10^3 m ³)		Length (m)		Total runoff (m)	H/L	Width (m)		Depth (m)		Event duration (h)	Initiation mechanism	Damage
				DZ	AZ	DZ	AZ			DZ	AZ	DZ	AZ			
1	9/24/1993	Heavy and prolonged	2525	800		450	2450	5660	0.24	200	356	15–50	1–4	2	Moraine saturation	Flooding of the Forno Alpi Graie, damage to roads and waterworks
2	7/24/1996	Heavy thunderstorm	2500	300		470	1600	4010	0.13	20	120	20–30			Moraine saturation	
3	Winter 1983–84	None	2350					1600	0.47						Water pocket release	Damage to a road and a bridge
4	7/12/1991	Thunderstorm (3 h)	2600	100		1500	3400		0.31	100		5–6	> 1.5		Water pocket release	Damage to municipal road
5	7/31/1998	Thunderstorm (20 min)	2020		190	780	1200		0.33	240					Water pocket release	Damage to regional road, flooding of the Pra Sèc hamlet
6	8/11/1986	Thunderstorm (1 h)	2000	15							10	1.5			Water pocket release	Damage to the regional road, flooding of campsite
7	7/17/2003	None	2080	30		1300	1330		0.31	120		Mean 1 max >3	> 1.5		Water pocket release	
8	7/19/1979	None	2200	> 150				3000	0.27	150				3	Glacial lake outburst	Destruction of the Belvedere chairlift
9	8/24/1987	Heavy and prolonged	2350	10				3000	0.36						Moraine saturation	Flooding of campsite
10	9/15/1950	1 day copious rainfall	2380	> 1000	600			5000	0.15	200	Up to 60	Up to 30		2.5	Moraine collapse	Destruction of 3 buildings and 4 bridges
11	08/1987	Heavy rainfall	2200			360	4060	4570	0.20		260					
12	9/14/1994	Heavy and prolonged (115 mm in 2 days; max. intensity 10 mm/15 min)	2185	200		270		1650	0.34	110		25			Moraine and talus saturation	Flooding of National Road 251
13	8/16/1999	Heavy thunderstorm	2150	Thousands of m ³		350		2000	0.50		15–20	3			Moraine saturation	Flooding of tens of thousands of m ²
14	7/25/1997	None	2700	Thousands of m ³		1100		2300	0.52					2.3	Glacial lake outburst	Flooding of the Chauvet Valley
15	7/10/1990	None (250 mm in the 40 days preceding the event)	2610	30	40			2400	0.42		up to 15			10	Water pocket release	1 person injured, destruction of a campsite, flooding of the l'A Neuve hamlet
16	6/25/2001	None	3060	25–40	20–30			5050	0.20						Glacial lake outburst	12 million EUR damage, destruction of bridge at Täschalp, flooding of Täsch village
17	9/24/1994	Heavy rainfall	2300	100							10–20					Damage to infrastructure

4. Triggers and debris flow characteristics of the studied cases

Most debris flows occurred during the months of July, August, and September. The events can be subdivided into three groups, based on antecedent meteorological conditions.

The first group comprises events that occurred during heavy and prolonged rainfall. It includes the debris flows in the basins of Mulinet, Ormeleura, Monte Giove, Pelmo, Grandes Jorasses, Western Montasio, and Bodmer glaciers. Failure probably was triggered by saturation of the debris cover due to infiltration of rainwater. The presence of buried glacier ice within the debris (Fig. 6), documented for Mulinet, Pelmo and Western Montasio events, may have facilitated failure and/or affected the geometry of the detachment zone (Zimmermann and Haeberli, 1992). In each of the above-mentioned cases, rain water played a primary role in triggering debris flow, as testified by the concomitant occurrence of other instability processes in surrounding areas, out of the glacial basin. The Sissone debris flow was also triggered by heavy rainfalls but, in this case, no other failures occurred in the surrounding areas, which suggests that rainfall may not have been the only triggering factor.

The second group includes two events (Prà Sec and Rochefort) triggered by a brief local rainstorm that caused no other failures in the surrounding areas (Fig. 7). The debris flows may have been caused by rapid water input to the glacier bed from rainfall. Rain alone may not have triggered the debris flows, but may have induced high water pressures that linked water

pockets in the glaciers (Walder and Driedger, 1995). It is noteworthy that these streams are repeatedly subject to debris flows (see Table 3).

The third group includes debris flows triggered by the sudden emptying of ice-marginal lakes (Belvedere, Chauvet, Weingarten) or englacial water pockets (Frenay, Frébourg, Dolent). In these cases, the debris flows occur in dry weather, and in only one case (Dolent) was there abundant rainfall in the weeks preceding the event that may have destabilized the glacial deposits involved in the failure. In some cases (e.g. Belvedere and Frébourg), high air temperatures likely contributed large amounts of melt water, potentially modifying the dynamic of the glaciers and destabilizing surrounding sediments.

A major difference among the three groups of debris flows is the time at which the events occurred. Debris flows of types 2 and 3 occurred during the first half of the summer, between late June and July, at the onset of snowmelt (Haeberli, 1983).

In contrast, group 1 debris flows occurred during the second half of summer, between late July and September, the time of heavy rainfalls in the Alps. As the transient snow line rises in summer, the snow-free area increases, and hence the area of catchment that responds rapidly to rainfall. Rainfall-induced floods are therefore most likely to be largest between mid-August and mid-September (Fig. 8), when thermally induced runoff is at a maximum and subglacial channels are well developed (Collins, 1998).

Another important difference is the magnitude of the events. Debris flows of group 1 have the highest magnitude (800 000 m³ at Mulinet), whereas debris



Fig. 6. A deep breach developed in the end moraine of Western Montasio Glacier, on 14 September 1993, exposing buried glacier ice.

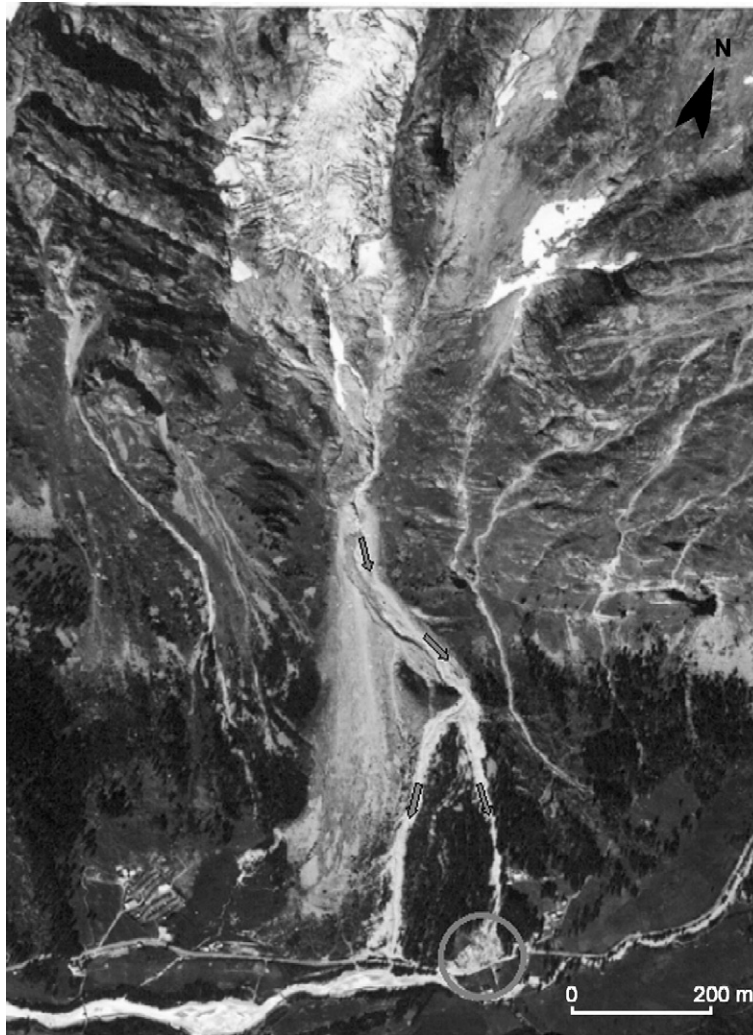


Fig. 7. Aerial photograph of the lower portion of the glacierized basin of Prà Sec Torrent (site 5). Arrows show the path of debris flows that occurred on 24 July 1996 and 31 July 1998. The circle locates a campsite that was dismantled after it was hit by a similar event in 1981.

flows of groups 2 and 3 are generally tens of thousands of cubic meters: the Belvedere debris flow, which mobilized over $150\,000\text{ m}^3$, was the largest event among those of groups 2 and 3. Debris flows triggered by glacial outbursts, however, are not always smaller than rainfall-induced events. The sudden release of a water pocket beneath Tête-Rousse Glacier (Mount Blanc, France) in 1892 mobilized over $600\,000\text{ m}^3$ of debris (Mougin, 1904). Klattasine Lake, a moraine-dammed lake in British Columbia, catastrophically drained sometime between June 1971 and September 1973, releasing about $1.7 \times 10^6\text{ m}^3$ of water from the lake. Escaping waters trenched the moraine and mobilized large quantities of sediment along the channel and valley margins and the flood

rapidly evolved in a debris flow that travelled 8 km downstream (Clague et al., 1985).

5. Discussion

All studied debris flows started at the uppermost occurrence of large accumulations of loose debris along proglacial stream channels. These sediments form undifferentiated till or lateral/end moraine deposited during the Little Ice Age, or fluvio-glacial apron of the same age. In the considered geographic context, thus, climate change can influence debris flow occurrence by glacier retreat and consequent exposure of large quantities of unconsolidated and unvegetated glacial sediments, that can be easily mobilized by glacial

Table 3
Brief description of analysed events

Site	Date	Description	References
1	9/24/1993	Heavy rainstorm triggered incision of the Little Ice Age moraine of Mulinet Glacier (15–50 m deep, 450 m long, and up to 200 m wide). The resulting debris flow travelled over 5 km before striking the village of Forno Alpi Graie (estimated volume of mobilized debris about 800 000 m ³).	Mortara et al., 1995
2	7/24/1996	The steep fluvioglacial cone at the foot of the Ormeleura Glacier was deepened 20–30 m during a heavy rainstorm. A large debris flow (about 300 000 m ³) flooded the Grand'Alpe alluvial plain.	Mortara and Chiarle, 2005
3	Winter 1983–84	Release of a probable englacial water pocket at the front of the steep Freney Glacier triggered a debris flow that reached the valley bottom. A road and a bridge were damaged by debris.	Chiarle, 2000
4	7/12/1991	A rainstorm triggered the release of an englacial water pocket and a large debris flow (>100 000 m ³) at the snout of Rochefort Glacier. The debris flow spread out on an alluvial fan and blocked a 400-m stretch of road on the valley bottom. A similar event recurred in 2003.	Dutto and Mortara, 1992
5	7/31/1998	A debris flow originated in the basin of the small and steep Prà Sec Glacier following a rainstorm and probable release of englacial water (ice blocks mixed in the debris deposit). The debris flow threatened houses and blocked a 100-m length of the road on the valley bottom. Other similar events occurred in 1965, 1981, 1986, 1989, 1996 and 1997.	Chiarle, 2000
6	8/11/1986	A rainstorm triggered a debris flow in the Ponte stream. The stream channel was incised 10 m in places, and coarse debris partially covered the alluvial fan to a depth of about 1.5 m. A campsite was flooded. Other similar events occurred in 1987 and 1997. The Ponte stream basin was the site of a major glacial outburst flood in 1841.	Mortara and Turitto, 1989
7	7/17/2003	In July 2003, during dry weather, debris flows occurred at the foot of Frébouge Glacier. The flows deeply incised the alluvial fan and deposited about 30 000 m ³ of coarse sediment. The first debris flow on July 17 may have been triggered by the release of an englacial water pocket. The other debris flows developed in four stages: (1) ice avalanching from the front of the Glacier de Frébouge; (2) damming of the proglacial gorge by the avalanched ice; (3) outburst flood due to dam collapse; and (4) debris flow formation. A previous debris flow occurred in 1996.	Deline et al., 2004
8	7/19/1979	Proglacial Lago delle Locce drained through Locce Glacier. The escaping water followed the right margin of Belvedere Glacier, cut through its lateral moraine, and triggered a debris flow that seriously damaged a chairlift and flooded a 1-km length of the valley bottom, almost reaching the hamlet of Pecetto near Macugnaga. Similar, but less severe events occurred in 1904, 1970, and 1978.	Dutto and Mortara, 1992
9	8/24/1987	During heavy and prolonged rain, a debris flow initiated from the end moraine of Monte Giove Glacier and travelled 3 km downvalley, partially destroying a campsite.	Mortara et al., 1995
10	9/15/1950	After several hours of heavy rain, a channel (ca. 600 m long, up to 200 m wide, and 60 m deep) opened in the moraine of Sissone Glacier. A large debris flow (>1 million m ³) buried over 10 km of the bed of Sissone stream up to 30 m deep. A refuge, 2 huts, and 4 bridges were destroyed. The debris flow was the largest involving glacial deposits in Italy.	Mortara et al., 1995
11	8/24/1987	Following heavy rains, runoff eroded the proximal flank of the lateral moraine of Presanella Glacier, triggering a debris flow that spread out and flooded the proglacial plain.	Mortara and Chiarle, 2005
12	9/14/1994	At the end of a brief, although intense rainstorm, a debris flow initiated in the upper part of a large talus apron on the northern slope of Mt. Pelmo. Talus covered a small body of stagnant ice, part of the buried toe of Val d'Arcia Glacier. 200 000 m ³ of material moved downslope, interrupting National Route 251.	Del Longo et al., 2001
13	8/16/1999	The end moraine of Western Montasio Glacier was deeply incised (15–20 m deep and about 350 m long) following heavy rain in 1999, triggering a debris flow. The debris flow reached the valley bottom and widened the channel section 4 to 5 times in some places. The alluvial fan and the vegetated alluvial plain were covered by debris up to 3 m deep over an area of tens of thousands of square meters.	Piemontese, 2000
14	7/25/1997	A thermokarst lake (94 000 m ³) in the forefield of Chauvet Glacier suddenly drained, causing an outburst flood that mobilized debris in the Chauvet gully. The debris blocked Ubaye River, 1100 m below, and caused a wave 1 m high that endangered camp sites along the river. Similar outburst floods occur about every 20 yrs: 1936, 1956, 1970, 1991.	Assier and Evin, 1998
15	7/10/1990	Collapse of part of the terminal moraine of Dolent Glacier triggered a 40 000-m ³ debris flow that threatened l'A Neuve hamlet and a campsite in the Val Ferret (Mount Blanc). Debris flow pulses continued for 10 h. Slow release of a water pocket in the glacier, snowmelt and rainfall in the weeks before the event contributed to the failure of the moraine dam.	Lugon et al., 2000
16	6/21/2001	Parts of the village of Täsch were damaged or destroyed by a debris flow at a time of dry weather. An elevated water level due to snowmelt or an ice jam at the outlet channel of Lake Weingarten initiated incision of the moraine dam. 25 000–40 000 m ³ of debris were entrained along the uppermost 1 km of the outburst path. The debris flow spread out at the apex of a fan flooding the village.	Huggel et al., 2004
17	9/24/1994	Heavy precipitation initiated a deep breach in the moraines of Bodmer Glacier. 100 000 m ³ of debris were eroded, initiating a debris flow in Lauigrabe stream. The debris flow destroyed a bridge and road in the village of Simplon Dorf, and caused further damage in the settlement of Gabi.	Rouiller, 1994; Haeblerli et al., 1998



Fig. 8. Oblique view of the deposit of a debris flow that started from the moraine breach in the front of Western Montasio Glacier (site 13) on 14 September 1993. The event was very similar to the one that occurred in August 1999.

floods. In the Italian Alps, the formation of moraine-dammed lakes is not a major process that follows glacier retreat, as opposed to other geographic areas (Lliboutry et al., 1977; Yamada, 1998; Reynolds, 1998; Clague and Evans, 2000; O'Connor et al., 2001).

The role of ground ice melting in sediment failure and debris flow initiation is hardly assessed, and interstitial as well as massive ground ice can only be detected by specific site investigations (e.g. bottom temperatures of winter snow cover—BTS, geoelectrical, electromagnetic, and seismic soundings; Haeberli and Epifani, 1986; Hauck, 2001). The presence of ice cores can influence the stability of the moraines, where

important ice masses may be preserved beneath moraine cover, as glaciers retreat. An example of the role that massive ground ice can play in triggering glacial floods is the debris flow that occurred in fair weather on 29 July 2005 in Val di Fosse (eastern Italian Alps). Melt of a buried ice mass, exposed in a 20-m-long detachment zone at 3000 m a.s.l., triggered a debris flow (15 000 m³) that flowed downslope for over 1 h.

The largest events in our sample were triggered by heavy and prolonged rainfalls (group 1). Debris flows that have occurred at the glaciers Mulinet, Sissone, Pelmo and Ormeleura reached volumes among the highest in the Alps (Rickenmann and Zimmermann,



Fig. 9. Coarse debris accumulation in the village of Forno Alpi Graie, following the 24 September 1993 debris flow (site 1). The deposit was up to 4 m thick.

1993; Marchi and Tecca, 1996). This fact is most likely due to the extreme sediment saturation produced by prolonged rainfalls, which caused the failure of large sediment volumes. Closely related to debris flow volumes, is the impressive size of detachment zones. Breaches incised in the Mulinet, Sissone, and Pelmo moraines measured thousands of m^2 in cross-section; these values are remarkable, if compared with the maximum cross-section area of 500 m^2 found for Switzerland by Haeblerli (1983) for erosion channels produced by glacial outbursts in suitable materials, and by Zimmermann (1990) for the 1987 periglacial debris flows in Switzerland. In order to compare the data we have found with other literature cases we can also determine the sediment yield rate (ϵ), which is determined as the ratio between the total volume amount and the length of the detachment zone. Proceeding in this way, we find that for the Sissone and Mulinet debris flows ϵ is 1700, while ϵ is less than 750 for large Alpine moraine dam breaches described by Huggel et al. (2002).

Reliability of the data listed in Table 2 is variable. Some data have been obtained by accurate photogrammetric measurements (e.g. breach dimensions at the Mulinet Glacier, Mortara et al., 1995) or by field surveys carried out by the authors. In other cases, values were estimated (e.g. debris flow magnitude at the Sissone Glacier, Nangeroni, 1951), obtained from technical/scientific documents or derived from event maps from which the data quality could not be assessed. Thus, generally speaking, data reported in Table 2 have to be considered with due caution.

For Table 2, some information about detachment/accumulation zone's features could not be obtained and, as a consequence, data analysis and interpretation are limited accordingly. In some cases, data quantity and quality could be improved with additional field or remote sensing investigations. Unfortunately, in many cases original debris flow features have been modified or erased, making it difficult to assess their original dimensions. Finally, the scarcity of high altitude meteorological stations in Italy and France represents an important constraint for the assessment of climatic parameters as triggers.

6. Conclusions

If we compare our data set, which accounts events that occurred in the last 25 years, with extensive historical investigations of debris flows from glacier forefields in the Italian Alps (Dutto and Mortara, 1992), debris flows seem to be increasing in frequency at the margins of glaciers. This fact can be explained by the

increased availability of loose sediment for transport in debris flows and, in some cases, by the formation of moraine-dammed lakes, as a consequence of twentieth-century glacier retreat. Debris flows from glacier forefields are among the largest in the Italian Alps. The extremely high sediment yield rates (up to $1700 \text{ m}^3/\text{m}$) along moraine breaches in the detachment zone of debris flows are an important finding that will change presently established hazard assessment procedures. The water source may be either heavy precipitations, sudden glacial lake outbursts, or the melt of ground ice or buried ice bodies (Harris and Gustafson, 1993). Of the 17 events in the European Alps reported in this paper, six occurred during dry weather and two others occurred at a time when rainfall was insufficient to trigger the debris flow. On average, debris flows during dry weather were smaller (150000 m^3) than those triggered by intense rainfall (less than 800000 m^3). Massive ground ice in glacial and colluvial deposits is an especially insidious element, due to its invisibility and its role in destabilizing sediments.

Data collected and analysed in the present paper demonstrated that debris flows from glacier forefields can pose serious hazards because of their magnitude and mobility (Fig. 9), as well as their unexpectedness, in case of events triggered by glacial outburst. For a better comprehension of process characteristics, predisposing factors, and triggering mechanisms, accurate studies on future events are needed. An expansion of the network of high altitude meteorological stations would much improve the knowledge about the role of climatic factors in process triggering; for this purpose, meteorological radars also are a promising source of data.

Knowledge gathered from the analysis of past events can now be applied for hazard assessment, which requires the combined consideration of glacier location and characteristics, topographic and geomorphological setting of glacier forefields, availability of loose sediments along proglacial channels as well as climatic and morphodynamic trends in the studied areas.

Acknowledgements

The authors thank Furio Dutto (Civil Defense Service, Turin Province) for his contribution to the methodological approach, and Hanspeter Staffler and Claudio Volcan (Public Works Service, Bolzano Province) for information on the Val di Fosse debris flow. The authors thank also John Clague and Wilfried Haeblerli for the time they spent in intensively reviewing the manuscript, and Guido Nigrelli and Stephan Gruber for their valuable comments.

References

- Assier, A., Evin, M., 1998. The July 25th 1997 Glacial Outburst at the Chauvet Glacier, Haute-Ubaye, France. 2° Alpine Glaciological Meeting, Grenoble, France.
- Barla, G., Dutto, F., Mortara, G., 2000. Brenva Glacier Rock Avalanche of 18 January 1997 on the Mount Blanc Range, northwest Italy. *Landslide News* 13, 2–5.
- Chiarle, M., 2000. *Analisi dei pericoli naturali in ambiente glaciale*. Unpublished, PhD thesis, Politecnico di Torino, Italy.
- Clague, J.J., Evans, S.G., 2000. A review of catastrophic drainage of moraine-dammed lakes in British Columbia. *Quaternary Science Reviews* 19, 1763–1783.
- Clague, J.J., Evans, S.G., Blown, I.G., 1985. A debris flow triggered by the breaching of a moraine-dammed lake, Kattlasine Creek, British Columbia. *Canadian Journal of Earth Sciences* 22, 1492–1502.
- Collins, D.N., 1998. Rainfall-induced high-magnitude runoff events in highly-glacierized Alpine basins. *Hydrology, Water Resources and Ecology in Headwaters*. Proceedings of the HeadWater '98 Conference. International Association of Hydrological Sciences, vol. 248, pp. 69–78.
- Dei Cas, L., Mannucci, G., Tropeano, D., 2004. Thurwieser, 18 settembre 2004, frana la cima in Alta Val Zembrù. *Sopra il Livello del Mare* 17, 16–21.
- Deline, P., Chiarle, M., Mortara, G., 2004. The July 2003 Frébouge debris flow (Mont Blanc Massif, Valley of Aosta, Italy): water pocket outburst flood and ice avalanche damming. *Geografia Fisica e Dinamica Quaternaria* 27, 107–111.
- Del Longo, M., Finzi, E., Malgaro, A., Godio, A., Luchetta, A., Pellegrini, G.B., Zambiano, R., 2001. Responses of the Val D'Arcia small dolomitic glacier (Mount Pelmo, Eastern Alps) to recent climatic changes. *Geomorphological and geophysical study*. *Geografia Fisica e Dinamica Quaternaria* 24, 43–55.
- Dutto, F., Mortara, G., 1992. Rischi connessi con la dinamica glaciale nelle Alpi Italiane. *Geografia Fisica e Dinamica Quaternaria* 15, 85–99.
- Evans, S.G., Clague, J.J., 1994. Recent climatic change and catastrophic geomorphic processes in mountain environments. *Geomorphology* 10, 107–128.
- Haerberli, W., 1983. Frequency and characteristics of glaciers floods in the Swiss Alps. *Annals of Glaciology* 4, 85–90.
- Haerberli, W., Epifani, F., 1986. Mapping the distribution of buried glacier ice—an example from Lago delle Locce, Monte Rosa, Italian Alps. *Annals of Glaciology* 8, 78–81.
- Haerberli, W., Wegmann, M., Vonder Muhl, D., 1997. Slope stability problems related to glacier shrinkage and permafrost degradation in the Alps. *Eclogae Geologicae Helvetiae* 90, 407–414.
- Haerberli, W., Hoelzle, M., Suter, S., Frauenfelder, R., 1998. Fluctuations of glaciers 1990–1995. International Association of Hydrological Sciences/United Nations Environment Programme/United Nations Educational, Science and Cultural Organisation, vol. VII, 51.
- Harris, A.S., Gustafson, A.C., 1993. Debris flow characteristics in an area of continuous permafrost, St. Elias Range, Yukon Territory. *Zeitschrift für Geomorphologie (Neue Folge)* 37, 41–56.
- Hauck, C., 2001. *Geophysical methods for detecting permafrost in high mountains*. Mitteilungen VAW 171 Zürich.
- Huggel, C., Käab, A., Haerberli, W., Teysseire, P., Paul, F., 2002. Remote sensing based assessment of hazards from glacier lake outbursts: a case study in the Swiss Alps. *Canadian Geotechnical Journal* 39, 316–330.
- Huggel, C., Haerberli, W., Käab, A., Bieri, D., Richardson, S., 2004. An assessment procedure for glacial hazards in the Swiss Alps. *Canadian Geotechnical Journal* 41, 1068–1083.
- Huggel, C., Zraggen-Oswald, S., Haerberli, W., Käab, A., Polkvoj, A., Galushkin, I., Evans, G.S., 2005. The 2002 rock/ice avalanche at Kolka/Karmadon, Russian Caucasus: assessment of extraordinary avalanche formation and mobility, and application of QuickBird satellite imagery. *Natural Hazards and Earth System Sciences* 5, 173–187.
- Käab, A., Huggel, C., Barbero, S., Chiarle, M., Cordola, M., Epifani, F., Haerberli, W., Mortara, G., Semino, P., Tamburini, A., Viazzo, G., 2004. Glacier hazards at Belvedere Glacier and the Monte Rosa East face. *Italian Alps: processes and mitigation*. Proceedings International Symposium Interpraevent 2004, Riva di Trento, Italy, pp. I/67–I/77.
- Lliboutry, L., Morales Arnao, B., Schneider, B., 1977. Glaciological problems set by the control of dangerous lakes in Cordillera Blanca, Peru, I. Historical failures of morainic dams, their causes and prevention. *Journal of Glaciology* 18 (79), 239–254.
- Lugon, R., Gardaz, J.-M., Vonder Mühl, D., 2000. The partial collapse of the Dolent glacier moraine (Mont Blanc Range, Swiss Alps). *Zeitschrift für Geomorphologie (Neue Folge), Supplement-Band* 122, 191–208.
- Marchi, L., Tecca, P.R., 1996. Magnitudo delle colate detritiche nelle Alpi Orientali Italiane. *Geoingegneria Ambientale e Mineraria* 33 (2/3), 79–86.
- Margreth, S., Funk, M., 1999. Hazard mapping for ice and combined snow/ice avalanches—two case studies from the Swiss and Italian Alps. *Cold Regions Science and Technology* 30, 159–173.
- Mortara, G., Chiarle, M., 2005. Instability of recent moraines in the Italian Alps. Effect of natural processes and human intervention having environmental and hazard implications. *Giornale di Geologia Applicata* 1, 139–146.
- Mortara, G., Turitto, O., 1989. Considerazioni sulla vulnerabilità di alcuni siti adibiti a campeggio in ambiente alpino. Proceedings International Congress on Geoengineering “Suolosottosuolo”, Politecnico di Torino, Torino, Italy, vol. II, pp. 137–144.
- Mortara, G., Dutto, F., Godone, F., 1995. Effetti degli eventi alluvionali nell'ambiente proglaciale. La sovraincisione della morena del Ghiacciaio del Mulinet (Stura di Valgrande, Alpi Graie). *Geografia Fisica e Dinamica Quaternaria* 18, 295–304.
- Mougin, P., 1904. *Les poches intra-glaciaires du glacier de Tête-Rousse*. La Géographie, Bulletin de la Société de Géographie, Masson, Paris.
- Nangeroni, G., 1951. La frana di Val Sissone (15 Settembre 1950). *Natura* 42, 11–17.
- O'Connor, J.E., Costa, J.E., 1993. Geologic and hydrologic hazards in glacierized basins in North America resulting from 19th and 20th Century global warming. *Natural Hazards* 8, 121–140.
- O'Connor, J.E., Hardison III, J.H., Costa, J.E., 2001. Debris flows from failures of neoglacial-age moraine dams in the three sisters and Mount Jefferson Wilderness Areas, Oregon. U.S. Geological Survey Professional Paper 1606.
- Piemontese, L., 2000. Sconquasso d'agosto in Montasio. *Le Alpi Venete* 1, 71.
- Reynolds, J.M., 1998. High-altitude glacial lake hazard assessment and mitigation: a Himalayan perspective. In: Maund, J., Eddleston, M. (Eds.), *Geohazards in Engineering Geology*. Geological Society Engineering Group Special Publication, vol. 15, pp. 25–34.

- Rickenmann, D., Zimmermann, M., 1993. The 1987 debris flows in Switzerland: documentation and analysis. *Geomorphology* 8, 175–189.
- Rouiller, J.D., 1994. Murgang Lauigrabe/Bodmergletscher (Gemeinde Simplon). Technical report, Baudepartement Kantons Wallis, Sion.
- Walder, J.S., Driedger, C.L., 1995. Frequent outburst floods from the South Tahoma Glacier, Mount Rainier, U.S.A.: relation to debris flows, meteorological origin and implications for subglacial hydrology. *Journal of Glaciology* 41, 1–10.
- Yamada, T., 1998. Glacier lake and its Outburst Flood in the Nepal Himalaya. Data Center for Glacier Research, Monograph n. 1, Tokyo.
- Zimmermann, M., 1990. Debris flows 1987 in Switzerland: geomorphological and meteorological aspects. *Hydrology in Mountainous Regions: Part II*. International Association of Hydrological Sciences, vol. 194, pp. 387–393.
- Zimmermann, M., Haerberli, W., 1992. Climatic change and debris flow activity in high mountain areas—a case study in the Swiss Alps. *Catena. Supplement* 22, 59–72.