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THE JULY 2003 FREBOUGE DEBRIS FLOWS (MONT BLANC MASSIF, VALLEY OF AOSTA, ITALY): WATER POCKET OUTBURST FLOOD AND ICE AVALANCHE DAMMING

ABSTRACT: DELINE P., CHIARLE M. & MORTARA G., *The July 2003 Frébouge debris flows (Mont Blanc Massif, Valley of Aosta, Italy): water pocket outburst flood and ice avalanche damming*. (IT ISSN 1724-4757, 2004).

In July 2003, during a dry period, debris flows occurred on the large polygenic fan (0.85 km^2; elevation difference of 500 m) at the foot of the Glacier de Frébouge (Val Ferret). These events deeply incised the western fan sector and deposited ~ 30000 m^3 of coarse material in the distal part of the fan. The first debris flow on 17 July may have been triggered by a glacial water pocket outburst flood, a not uncommon process in the Mont Blanc massif. The other ones developed in three steps: (i) ice avalanching of a part of the Glacier de Frébouge front; (ii) damming of the proglacial torrent gorge by the ice deposit; (iii) outburst flood due to dam collapse, with debris flow formation. Increasing ice avalanching at the hanging front of retreating glaciers constitutes an important natural hazard factor in alpine high mountain tourist areas.

KEY WORDS: Debris flow, Ice avalanching, Ice dam, Glacial water pocket outburst flood, Mont Blanc Massif, Glacier de Frébouge, Natural hazards.

RIASSUNTO: DELINE P., CHIARLE M. & MORTARA G., *Le colate detritiche del luglio 2003 sul conoide del T. Frébouge (Gruppo del Monte Bianco, Valle d'Aosta): rottura di una sacca d'acqua endoglaciale e sbarramento ad opera di crolli di ghiaccio*. (IT ISSN 1724-4757, 2004).

Nel luglio del 2003, in un periodo privo di precipitazioni, due colate detritiche torrentizie si sono prodotte sul grande cono poligenico (0.85 km^2; 500 m di dislivello) che si apre a valle del Ghiacciaio di Frébouge (Val Ferret). Dopo aver inciso profondamente il settore occidentale del conoide, le colate hanno deposto nella sua porzione distale non meno di 30000 m^3 di materiale a pezzatura grossolana. Il primo episodio, datato 17 luglio, potrebbe essere stato innescato dallo svuotamento improvviso di una sacca d'acqua endoglaciale, fenomeno relativamente frequente nel Massiccio del Monte Bianco. Le colate dei giorni successivi si sono invece sviluppate secondo il seguente schema: (i) crollo di una porzione della fronte del Ghiacciaio di Frébouge; (ii) sbarramento della forra rocciosa percorsa dal torrente proglaciale ad opera del deposito di ghiaccio; (iii) cedimento dello sbarramento di ghiaccio e innesco di ondate di colata detritica. La ricorrente instabilità della fronte sospesa in ritiro del Ghiacciaio di Frébouge merita attenta considerazione sotto l'aspetto del rischio, per la sua collocazione in un'area di intensa frequentazione turistica estiva.

TERMINI CHIAVE: Colata detritica; Crollo di fronte glaciale, Sbarramento di ghiaccio, Svuotamento di sacca d'acqua endoglaciale, Massiccio del Monte Bianco, Ghiacciaio di Frébouge, Rischi naturali.

RÉSUMÉ: DELINE P., CHIARLE M. & MORTARA G., *Les laves torrentielles de juillet 2003 sur le cône de Frébouge (massif du Mont Blanc, Vallée d'Aoste, Italie): vidange de poche d'eau glaciaire et barrage de glace par chute de séracs*. (IT ISSN 1724-4757, 2004).

En juillet 2003, en l'absence de précipitations, deux laves torrentielles se sont produites sur le grand cône polygénique (0.85 km^2; 500 m de commandement) qui se développe en contrebas du Glacier de Frébouge (Val Ferret). Incisant profondément la surface de son secteur occidental, elles ont déposé au moins ~ 30000 m^3 de matériel grossier dans la partie distale du cône. Le premier épisode du 17 juillet pourrait avoir été déclenché par la vidange brutale d'une poche d'eau sous-glaciaire, processus relativement fréquent dans le massif du Mont Blanc. Les autres laves torrentielles ont été engendrées par la séquence suivante: (i) écroulement d'un secteur du front du Glacier de Frébouge (séracs); (ii) barrage de la gorge du torrent proglaciaire par le dépôt de glace (embâcle); (iii) rupture du barrage de glace (débâcle) et formation de bouffées de lave torrentielle. L'instabilité récurrente du front suspendu d'un glacier en retrait comme celui de Frébouge participe d'un accroissement des risques naturels dans un espace à forte fréquentation touristique estivale.

MOTS CLÉS: Lave torrentielle, Ecroulement de front glaciaire, Barrage de glace, Vidange de poche d'eau glaciaire, Massif du Mont Blanc, Glacier de Frébouge, Risques naturels.

INTRODUCTION

With the development of major alpine roads and resorts has come an ever larger summer influx to tourist areas in large alpine valleys where steep, elevated and largely glacierized versants are subject to highly active geo-

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morphic processes. In addition, instability processes as just one effect of global warming on mountain morphodynamics, may increase in frequency and/or magnitude, posing greater risks from the natural hazards in high elevation tourist alpine valleys.

During July 2003, while small ice avalanches occurred elsewhere nearby, debris flows ran on the large fan that develops at the foot of the Glacier de Frébouge, reaching one of the recreation spots in the Val Ferret. After the hanging front of Glacier de Frébouge experienced a large ice avalanche in September 2002 (Deline & *alii*, 2002), these much smaller but repeated ice avalanches of 2003 show the present instability of the glacial front. Starting with the a presentation of the studied area, our paper describes the deposits of the 2003 debris flow succession and concludes with a discussion of the possible mechanisms of phenomena initiation. We were surveying the involved area two hours before the onset of the 17 July debris flows, which were partly filmed by geologists of the Région Autonome Vallée d'Aoste (RAVA) from a helicopter; the deposits and forms related to these events were studied the next day. Three days later from a distant but dominant place, we witnessed a new debris flow. One month later, the depositional and erosional features were surveyed again.

THE GLACIER DE FREBOUGE AND FAN CHARACTERISTICS

With an area of 2.3 km^2 in 1970 (Vivian, 1975), the Glacier de Frébouge is one of the medium-sized hanging glaciers on the south-east (Italian) flank of the Mont Blanc massif (fig. 1). The headwalls of this mountain glacier with a compound basin culminate from 3480 m asl (Col des Hirondelles) up to ~ 4150 m (Grandes Jorasses). During the Little Ice Age (LIA), it covered a part of the present large downstream fan, with its frontal moraines standing between 1750 and 1950 m of elevation (fig. 2). Since the

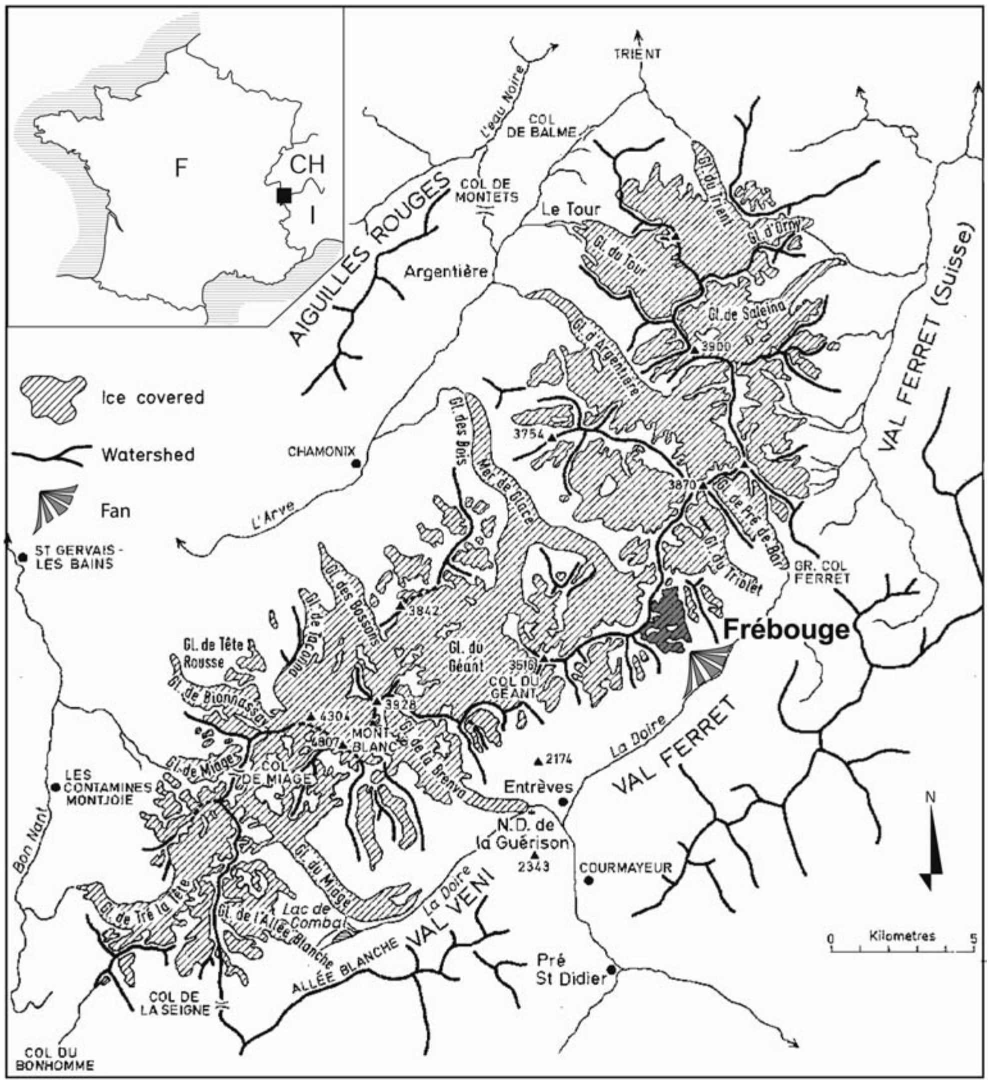

FIG. 1 - Location map (after Grove, 1988, modified). Glacier de Frébouge is dark grey glacier.

FIG. 2 - Frébouge debris flow deposits map (from terrestrial photographies). 1: Glacier de Frébouge front and portal; 2: proglacial torrent (a: downstream section; b: up stream section); 3: 17 July ice avalanche deposits; 4: limit of September 2002 ice avalanche deposit; 5: new incised channel; 6: 17 July debris flow deposit (a: coarse deposit; b: detrital veneer); 7: debris flow levees; 8: 20 July debris flow deposit; 9: LIA moraines (L_1, L_2, L_3 generations); 10: Frébouge polygenic fan area. Box: 17 July ice avalanche deposits, in order of occurrence. [topographical map 1:10000; contours: 10 m. *Archivi topocartografici della Regione Autonoma Valle d'Aosta Permit n. 52 (18.08.1999)*].

end of the LIA, Frébouge has experienced a 1600 m glacial withdrawal, with its present front located on a steep rockwall at an elevation of 2500-2550 m.

The Frébouge fan covers an area of ~ 0.85 km^2 (fig. 2). It develops from 1650 to 2150 m of elevation, with a mean gradient of 17° (24°, 18° and 11° in the apical, central and distal parts, respectively). Being one of the polygenic fans characteric of this versant, the Frébouge fan results from the combination of several processes: torrential bed load transport, debris flow, rock fall, rock avalanche, snow avalanche and ice avalanche. For instance, in the late afternoon of 18 September 2002 a part (~ 0.1 x 10^6 m^3) of the Glacier de Frébouge front avalanched (Deline & *alii*, 2002). The ice avalanche descended 400 m of the steep rock step below the front and covered a large area on the apex of the polygenic fan, down to an elevation of 1855 m, while a few ice boulders reached lower elevations, coming to rest 100-150 m ahead of the front of the main mass (fig. 2); detrital material on the fan surface was reworked.

TRACK AND DEPOSIT OF THE 17 JULY DEBRIS FLOWS

At around 14.00 on 17 July 2003, downstream from the Glacier de Frébouge, the water of a Doire tributary darkened, due to a flood on the Frébouge fan. At least two others debris flows formed until 15.30. A field survey the next day showed that a flow avulsion had affected the ordinary channel (C_1) at the fan apex and incised a new channel (C_2), ~ 10 m wide and 2-5 m deep; coarse material and sand-rich patches were deposited, locally containing numerous rounded ice particles (pebbles to metric blocks) which account for up to ~ 50% of the volume. Downstream from the main LIA morainic complex (1800-1850 m asl), the C_2 incision stopped and deposition became predominant (fig. 2):

- Some overflows occurred on the C_2 east bank and formed wide detrital veneers. A 20-150 m wide coarse detrital band formed along C_2, which terminated by a thin sandy-pebbly fingered deposit in the distal part of the fan; a torrent diramation jointed the C_1 distal deposit.
- Coarse material settled along the upper section of C_1. At the main LIA complex, two 200 m long, 2-3 m high lateral levees of metric boulders formed along C_1. Downstream, (i) a thin debris fingered deposit formed on the C_1 east bank; (ii) a thin, 20-50 m wide detrital band formed along C_1, its sandy cover contained ice particles (as testified by strong porosity and metric depressions in the deposit after melting). A 3-4 m^3 rounded block located at 1725 m asl, absent in the autumn of 2002, might have rolled from the glacier front before the 17 July event.

The whole deposit of the 17 July debris flows covers an area of ~ 0.1 x 10^6 m^2 (fig. 2). Its thickness ranges from 0.05 m to 1.50 m, exceeding 3 m at the highest levees. Its minimal volume can therefore be roughly estimated at 3 x 10^4 m^3. Although the deposit is very heterometric, a rough granulometric gradient can be observed along the accumulation area, with coarser material abandoned in the upper fan portion. Several springs which appeared in the distal part of the fan testify to a rise in the water table.

The 17 July debris flow event lasted more than 1.30 hour, with at least three phases of peak discharge. During one (the second?) of these phases, the minimal C_2 discharge can be estimated (via observation of the Doire de Ferret discharge on the RAVA film) at 2-5 m^3/s. During what was probably the last (third?) phase of the debris flow, the proglacial torrent discharge upstream from the ice deposit remained constant.

At 14.00 on 20 July, a new debris flow occurred: during more than 1 hour, a strong detrital load remained in the flow cause of the sapped channel banks, with some small avulsions. In contrast to the large 17 July deposit, the 20 July deposit was reduced to a thin detrital sheet on the distal part of the fan, along a westernmost newly incised short channel (fig. 2).

THE MECHANISMS OF THE FREBOUGE DEBRIS FLOW INITIATION

The proglacial torrent damming by ice avalanches

During the filmed last period of the 17 July debris flows and on 20 July, a pulverized ice deposit generated by a small ice avalanche (< 1000 m^3) from the eastern part of the glacier front dammed the rocky gorge and the upper section of channel C_2, reducing the downstream flow. As the water concentration in the ice deposit increased, it 'slushed' with a mean velocity (estimated from the RAVA film) of 2 m/s on 17 July, before stopping at ~ 2000 m of elevation (fig. 2). Then, a brown-coloured debris flow started, while upstream, the normal flow deeply incised the ice deposit. Very dark at the flood peak, the debris flow travelled along channel C_2 at a mean velocity (estimated from the RAVA film) of 5-8 m/s; its front was formed by a succession of waves, some meters wide and ~ 1 m high, that travelled at an estimated velocity of 2-3 m/s. After the bulk of the debris flow had passed, ice particles settled on the channel edges.

Glacial water pocket outburst floods in the Mont Blanc massif

Three distinct ice deposits at the fan apex on 17 July (fig. 2) suggest that damming of the present main proglacial torrent by ice avalanches was the process that led to the formation of most of the July 2003 debris flows. But a glacial water pocket outburst flood (WPOF) may be suspected to have triggered the first 17 July debris flow.

WPOFs are common in alpine mountain glacierized areas and account for 30-40% of the glacial floods during and after the Little Ice Age (LIA) in the Swiss Alps (Haeberli, 1983). A water pocket can form: (i) inside a glacier, in the closed-off remnants of crevasses or conduits (Paterson & Savage, 1970); (ii) on a rough bed, where a high input of water due to hot or rainy weather can switch a linked-cavity network (i.e. water-filled subglacial cavities linked by orifices) to a conduit system, able to flood (Walter & Driedger, 1995); (iii) on a flat bed, where subglacial cupolas form due to a smaller hydraulic potential which corresponds to a depression in the glacier surface (Nye, 1976).

WPOFs mainly occur during the warm season (Haeberli, 1983), as shown by the months of occurrence of the WPOFs during the last century at the Mont Blanc massif glaciers (fig. 1), an alpine area particularly affected by this kind of process (Vivian, 1975; Chiarle, 2000; Eglin, 2004): June (A Neuve, 1898; Argentière, 1904; Planpincieux, 1929), July (Bossons, 1939, 1949, 1963, 1997, 1999; Brenva, 1928, 1929; Mer de Glace, 1969; Pélerins, 1949; Tête Rousse, 1892; Tour, 1920; Trient, 1911, 1930, 1933, 1942, 2001, 2002, 2003), August (Bossons, 1892, 1942, 1944, 1985; Nantillons, 1934; Praz Sec, 1981; Taconnaz, 1892; Trient, 1960), September (Bossons, 1970; Mer de Glace, 1920; Taconnaz, 1921), while a WPOF affected the Glacier des Pélerins during the summer of 1893. Only two events are known to have occurred in other months: in April (Frêney, 1984) and May (Bossons, 1920).

WPOF at the Glacier de Frébouge on 17 July 2003?

Several elements support the hypothesis for a WPOF as a triggering agent for the first 17 July debris flow:

- The Frébouge debris flow did not only occur in July, like most of the recorded WPOFs mentioned above, but rather during the extremely hot summer of 2003, that began at the end of May (Chiarle & *alii*, 2004).
- WPOFs are often associated with steep hanging glaciers (Haeberli, 1983). Although Frébouge is not a steep glacier, the upper areas in the compound basin show steep surfaces.

- Extreme values of outburst volume and peak discharge of Swiss alpine WPOFs are in the order of 1-2 x 10^6 m^3 and 100-200 m^3/s, respectively (Haeberli & *alii*, 1989). The Frébouge values during the first 17 July debris flow are unknown, but its peak discharge and flood volume might be much higher than the above-mentioned values of the possible second debris flow, as suggested by: (i) the deep large channel C_2 incised upstream in the main LIA morainic complex; the last 17 July debris flows and the 20 July debris flow might simply have dug channel C_2 formed during the first 17 July debris flow; (ii) downstream, as shown by the RAVA film, the bulk of the deposit along channel C_2 seems to have been in place before the end of the possible second 17 July debris flow. Thin overflow deposits along the Doire de Ferret near Lavachey show a ~ 20 m Doire width and a ≥ 1 m rise at the flood peak. With a minimal flood velocity of 4-5 m/s, this suggests a ≥ 80-100 m^3/s proglacial Frébouge torrent discharge.
- A witness said that the proglacial torrent briefly stopped flow at the glacier portal just before the start of the first 17 July debris flow; another witness reported a loud noise (O. Tajola, *pers. comm.*).

However, others parameters contradict the hypothesis for a WPOF having triggered the first 17 July debris flow:

- No WPOF has ever been recorded for the Glacier de Frébouge.
- Unlike a typical WPOF, which lasts from hours to days due to progressive enlargement of subglacial channels during the flood (Haeberli & *alii*, 1989), the first phase of the 17 July debris flow lasted less than half an hour.
- Only around one hour after the first debris flow, the rockwall below the Glacier de Frébouge portal was dry (except for the usual stream bed and runnels of water), whereas a very recent WPOF should have left it wet. Moreover, fresh ice surface and ice particles on small rockwall benches which are markers of a recent WPOF, were not observed at or below, respectively, the glacier portal.

CONCLUSIONS

The strong retreat of glacier fronts in high mountain areas during the post-LIA period is generating new morphodynamic processes that may sometimes increase natural hazards. While several glaciers of the Mont Blanc massif have repeatedly produced WPOFs, with the first 17 July debris flow, the Glacier of Frébouge might have experienced its first known WPOF. Because it affects steep hanging glacier fronts, ice avalanching may pose an important risk for the numerous tourists to the area, especially during the summer (Deline & *alii*, 2002). Ice damming of a proglacial torrent by an ice avalanche deposit can result from this process when two topographical conditions are present: (i) a steep rockwall below the front and (ii) a gorge section drained by the proglacial torrent. On 17 and 20 July 2003, several ice avalanche deposits accumulated at the bottom of the Frébouge rockwall and on the fan apex, and they produced all except perhaps one of the debris flows. The existence of a well-developed serac network at the Frébouge front suggests that the July 2003 events could reoccur, while numerous glaciers of the Mont Blanc massif may produce proglacial torrent damming, like the glaciers de la Lex Blanche, du Breuillat, de Frêney, de Triolet, de l'A Neuve and du Tour.

REFERENCES

CHIARLE M. (2000) - *Analisi dei pericoli naturali in ambiente glaciale*. PhD, Politecnico di Torino, 206 pp.

CHIARLE M., MORTARA G., MERCALLI L. & DELINE P. (2004) - *Summer 2003 climate anomaly: instability processes in the Italian glacial and periglacial environment*. EGU Assembly, Nice, April 2004.

DELINE P. (2002) - *Etude géomorphologique des interactions entre écroulements rocheux et glaciers dans la haute montagne alpine: le versant sud-est du massif du Mont Blanc*. PhD, Université de Savoie, 365 pp.

DELINE P., CHIARLE M. & MORTARA G. (2002) - *The front ice avalanching of Frébouge Glacier (Mont Blanc Massif, Valley of Aosta, NW Italy) on 18 September 2002*. Geogr. Fis. Dinam. Quat., 25 (2), 101-104.

EGLIN Y. (2004) - *Retrait récent des glaciers et risques naturels d'origine glaciaire dans le massif du Mont Blanc*. Unpublished study report, Université de Savoie, 97 pp.

GROVE J. (1988) - *The Little Ice Age*. Methuen, London, 498 pp.

HAEBERLI W. (1983) - *Frequency and characteristics of glacier floods in the Swiss Alps*. Ann. Glaciol., 4, 85-90.

HAEBERLI W., ALEAN J.-C., MÜLLER P. & FUNK M. (1989) - *Assessing risks from glacier hazards in high mountain regions: some experiences in the Swiss Alps*. Ann. Glaciol., 13, 96-102.

NYE J.F. (1976) - *Water flow in glaciers: jökulhlaups, tunnels and veins*. Journ. Glaciol., 17, 181-207.

PATERSON W.S.B & SAVAGE J.C. (1970) - *Excess pressure observed in a water-filled cavity in Athabasca Glacier, Canada*. Journ. Glaciol., 9, 103-107.

VIVIAN R. (1975) - *Les glaciers des Alpes occidentales*. Allier, Grenoble, 513 pp.

WALDER J.S. & DRIEDGER C.L. (1995) - *Frequent outburst floods from the South Tahoma Glacier, Mount Rainier, USA: relation to debris flows, meteorological origin and implications for subglacial hydrology*. Journ. Glaciol., 41 (137), 1-10.

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