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LARGE GLACIER FAILURES IN THE ITALIAN ALPS OVER THE LAST 90 YEARS

Abstract: Chiarle M., Viani C., Mortara G., Deline P., Tamburini A. & Nigrelli G., *Large glacier failures in the Italian Alps over the last 90 years.* (IT ISSN 0391-9838, 2022).

Ice failures are among the least known and least studied mass movements, both because large events are quite rare, and because they usually develop in remote and little-frequented areas. However, the unprecedented transformation of glaciers due to climate change, on the one hand, and the growing human pressure on high-elevation environments, on the other, nowadays require a more careful and in-depth consideration of these hazardous processes, such as tragically highlighted by the collapse of the Marmolada Glacier (Italy) on July 3, 2022. In this context, a review of existing documentation on past glacier failures is essential to learn about their spatio-temporal distribution, the characteristics of the glaciers where the failures occurred and flow properties. In turn, these findings are fundamental to inform the assessment of current and future hazards. The present work contributes to the topic by documenting, cataloguing, and analysing the glacier failures larger than 10,000 m^3 that occurred in the Italian Alps in the period 1930-2022. Sixty-eight glacier failures are documented, which affected 29 glaciers distributed throughout the Italian Alps. The volumes of glacier failures are mostly between 10,000 and 50,000 m^3 (1.1×10^6 m^3 in one case). The events occurred mainly in summer, with a frequency peak in August. The H/L ratio, i.e. the ratio between the vertical (H) and horizontal (L) distances covered by the process, indicator of the mobility of the detached mass, is between 0.33 and 0.80. Although glacier failures can occur during both glacial advance and retreat, we found a sharp increase in the number of documented cases since the 1990s. We are aware that, due to the difficulty of finding information, the dataset provided in this work is only partially representative of the glacier failures that occurred in the Italian Alps in the period considered: nevertheless, it is a useful starting point for studies aimed at assessing hazards related to glacier failure, and for risk mitigation. Given the speed and intensity with which glaciers and their surrounding environments are evolving in response to climate change, their continuous observation is essential, as is the systematic documentation of glacier failure events. Remote sensing data and tools can nowadays facilitate glacier monitoring and the documentation of ice failures: however, field data such as those collected during the annual glaciological surveys of the Italian Glaciological Committee (CGI) remain fundamental for the validation of remote sensing data and numerical models.

Key Words: Glacier failure, Italian Alps, Climate change, Hazard assessment.

Riassunto: Chiarle M., Viani C., Mortara G., Deline P., Tamburini A. & Nigrelli G., *Crolli di ghiaccio di grandi dimensioni nelle Alpi Italiane nel corso degli ultimi 90 anni.* (IT ISSN 0391-9838, 2022).

I crolli di ghiaccio sono tra i processi d'instabilità naturale meno conosciuti e studiati, sia perché eventi di grandi dimensioni sono piuttosto rari, sia perché coinvolgono per lo più aree remote e scarsamente frequentate. Tuttavia, le rapide e profonde trasformazioni dei ghiacciai in atto per effetto dei cambiamenti climatici, da una parte, e la crescente frequentazione e pressione antropica sugli ambienti di alta quota, dall'altra, richiedono oggi una più attenta e approfondita considerazione di questi fenomeni, la cui pericolosità è stata tragicamente evidenziata dal crollo occorso al Ghiacciaio della Marmolada il 3 luglio 2022. In questo contesto, particolarmente importante risulta la documentazione di eventi di instabilità avvenuti in passato, al fine di disporre di informazioni su distribuzione spazio-temporale degli eventi, caratteristiche dei ghiacciai soggetti a crollo e della dinamica dei fenomeni che si originano, dati indispensabili per la valutazione della pericolosità attuale e di scenari futuri. Il presente lavoro intende dare un contributo in questo senso attraverso la documentazione, schedatura e analisi di eventi di crollo di ghiaccio di volume > 10.000 m^3 occorsi nelle Alpi Italiane tra il 1930 e il 2022. Sono stati così documentati 68 eventi che hanno coinvolto 29 ghiacciai distribuiti sull'intero arco alpino. Si tratta per lo più di crolli di dimensioni comprese tra 10.000 e 50.000 m^3 (ma in un caso è stato raggiunto il valore di 1.1×10^6 m^3), avvenuti per lo più in estate, con un picco nel mese di agosto. Il rapporto H/L, cioè il rapporto tra dislivello (H) e distanza orizzon-

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tale (L) percorsi dal fenomeno, indicatore della mobilità della massa di ghiaccio distaccata, è risultato compreso tra 0.33 e 0.80. Benché i crolli di ghiaccio siano fenomeni associati sia alle fasi di avanzata che di regresso dei ghiacciai, lo studio ha rilevato una netta crescita dei casi documentati a partire dagli anni '90. Pur nella consapevolezza che, per la difficoltà di reperire informazioni, il dataset raccolto è solamente in parte rappresentativo dei crolli di ghiaccio avvenuti nelle Alpi Italiane nel periodo considerato, esso può rappresentare un utile punto di partenza per studi volti alla valutazione della pericolosità legata ai crolli di ghiaccio e alla mitigazione dei rischi associati. Considerata la rapidità e l'intensità con cui i ghiacciai e gli ambienti circostanti stanno evolvendo in risposta ai cambiamenti climatici in atto, è fondamentale una loro osservazione continuativa, nonché la documentazione sistematica degli eventi di crollo di ghiaccio. I dati e gli strumenti di telerilevamento possono facilitare il monitoraggio dei ghiacciai e la documentazione degli eventi d'instabilità. Tuttavia, i dati di campo come quelli raccolti durante le campagne glaciologiche annuali del Comitato Glaciologico Italiano restano essenziali ai fini della validazione dei dati di telerilevamento e dei modelli numerici.

Termini Chiave: Crolli di ghiaccio, Alpi Italiane, Cambiamento climatico, Valutazione di pericolosità.

INTRODUCTION

Ice failures are processes commonly associated with glacier dynamics, both during advance and retreat phases. In most cases, break-offs have a low magnitude (10-10^3 m^3, Deline & *alii*, 2012; Giordan & *alii*, 2020), and affect only a small part of the glacier mass, as in the case of serac fall or ice cavity collapse. However, in some cases glacier failures can involve up to almost the entire ice mass, resulting in ice avalanches that can reach impressive magnitudes (up to 10^7 m^3, Evans & *alii*, 2021). Although hazards associated with glacier failures have been known for a long time (Alean, 1985; Dutto & Mortara, 1992; Pralong & Funk, 2006; Jacquemart & Cicoira, 2022), these phenomena are still poorly understood and investigated (Hock & *alii*, 2019). The main reason for this is that glacier failures mostly stop within glacial basins, which are usually located in remote areas, with limited interference with infrastructure and human activities (Chiarle & *alii*, 2021). In addition, the accumulations of glacier failures disappear quickly, within days or weeks (Kellerer-Pirklbauer & *alii*, 2012), making them difficult to recognize and study, unless a significant amount of debris was entrained.

The recent tragic ice failures occurred at Grand Combin (Swiss Alps, May 27, 2022) and Marmolada (Italian Alps, July 3, 2022, fig. 1) glaciers, which caused victims among the mountaineers who were in the path of the phenomena, have abruptly raised the attention of the public and local authorities on these processes, raising questions about the possibility of predicting their occurrence and mitigating the risks, in a context of climate change. In fact, mountain areas are a hot spot of climate change (Pepin & *alii*, 2015): air temperature in the European Alps rose over recent decades at an average rate of 0.3 °C per decade, thereby outpacing the global warming rate of 0.2 °C per decade (Hock & *alii*, 2019). Nigrelli & Chiarle (2021) found even larger warming rates for the periglacial environment of the Alps, i.e. the zone between the timberline and the snow line (French, 2018), where in the period 1990-2019 mean/maximum/minimum temperatures increased of 0.4 °C, 0.6 °C and 0.80 °C per decade, respectively. In addition, the frequentation and human pressure on high elevation environments is constantly growing (Agrawala, 2007).

While aware that the glacial environment is changing at an unprecedented rate (Zemp & *alii*, 2015), with this work we intend to raise attention to the importance of a systematic documentation of glacier failure and of datasets of events to be made available to the scientific community, stakeholders, local administrations, and citizens. These data are necessary to deepen the knowledge on spatio-temporal distribution of glacier failures, and for a reliable assessment of current and future hazard trends. In fact, glacier failures (like all gravity-driven instabilities, mostly due to topography and internal stress distribution), under stable climatic conditions, tend to recur in the same way at the same glaciers. Furthermore, using a "space-for-time" substitution approach, i.e. using contemporary spatial phenomena to understand and model past and future events (Blois & *alii*, 2013; Geyman & *alii*, 2022), the knowledge of what happened or is happening to glaciers located at a given elevation (or at a given latitude) may allow us to draw instability scenarios for glaciers located at higher elevation (or higher latitude).

This paper intends to contribute on the subject by investigating the main events of glacier failure that occurred in the Italian Alps in the period 1930-2022. After an overview of the Italian Alps and of the distribution, characteristics and trend of contemporary glaciers, we will illustrate the main types of ice failure that can affect the Alpine glaciers, also referring to well-documented events in the European Alps and in the world. We than review the main known events for the Italian Alps and analyze their main characteristics in terms of spatio-temporal occurrence, volumes and runout. We conclude by analyzing how ongoing climate change has modified the hazard scenarios associated with glacier failures.

THE ITALIAN ALPS AND GLACIERS IN A CHANGING CLIMATE

The Italian Alps represent the southernmost portion of the Alpine chain, a complex of mountain ranges that form an arc across Western Europe, with a length of around 1200 kilometres, a maximum width of 300 km and an average elevation of about 2500 m a.s.l., with elevation decreasing from West to East. The Italian Alps represent about 27% of the total area of the Alps (51,941 km^2 out of 190,717 km^2). The Alpine drainage divide constitutes the Italian state border almost everywhere. Of the 82 Alpine peaks over 4000 m a.s.l., 37 are, often shared with neighbouring countries, in Italy. The Alps are home to more than 14 million people (4.5 in the Italian Alps, alpconv.org). The region is also among the most visited in the world, with about 60-80 million of tourists each year: in Italy, Alpine areas represent almost 90% of the winter tourist offer, as well as about 10% of the total tourist offer (Bosello & *alii*, 2007). The Alps are facing increasing development pressures, with dramatic growth rates in the transport of people and goods, and a trend

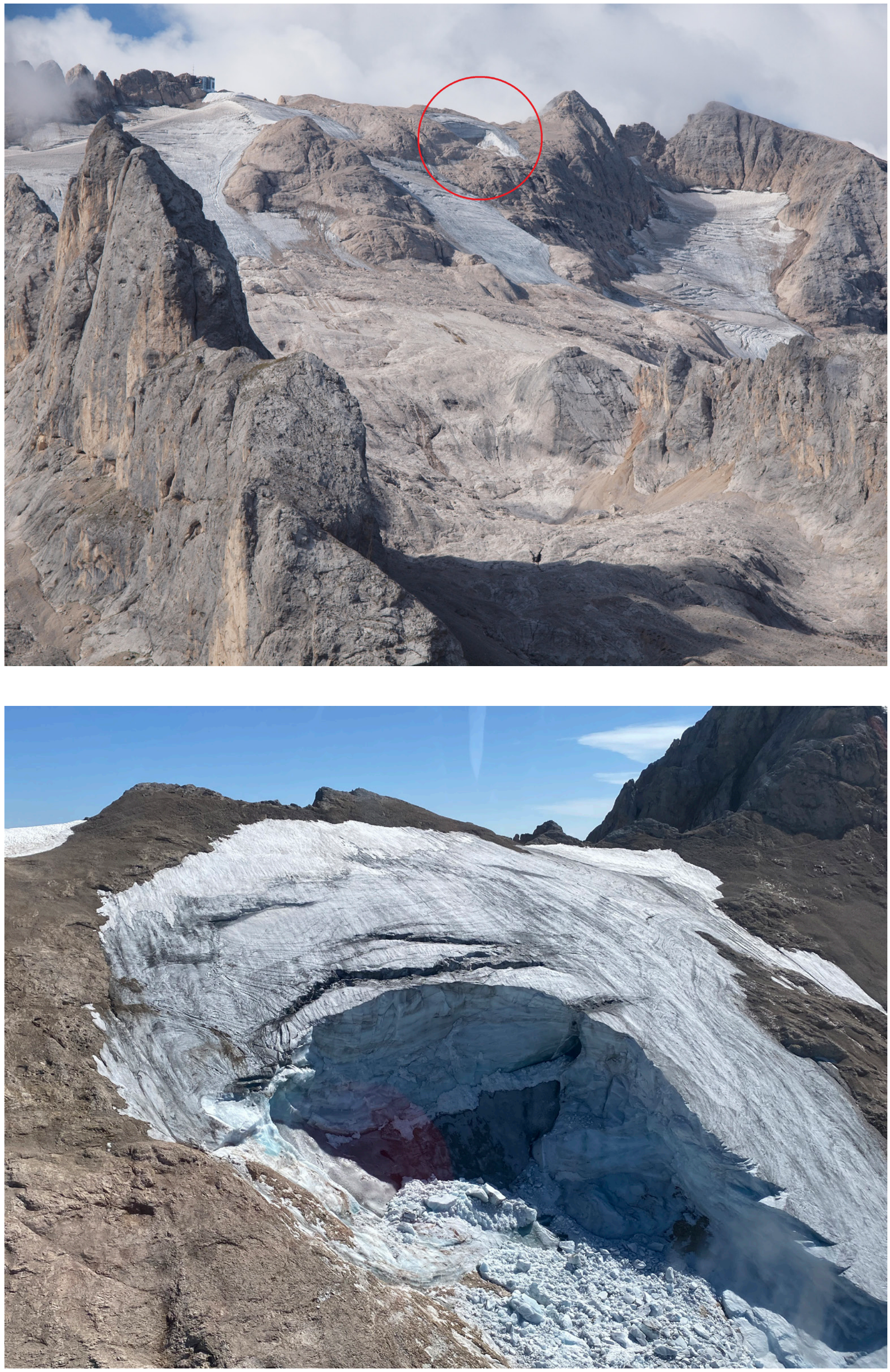

FIG. 1 - Marmolada Glacier, Dolomiti group. The dramatic ice avalanche of 3 July 2022 (event ID 1, tab. 2) originated near the watershed crest (a, in the circle the collapsed ice mass, photo S. Perona, 2022). The detachment scar is clearly visible in b (photo Centro per la Protezione Civile, Università degli Studi di Firenze).

towards the urbanisation of many alpine valleys (Permanent Secretariat of Alpine Convention, 2016). While contributing to economic development, this trend has put pressure on the land, increasingly exposing residents and visitors to natural hazards (Agrawala, 2007).

Salvatore & *alii* (2015), from the interpretation of high-resolution orthophotos taken in 2006-2007, identified on the Italian Alps 967 glaciers covering an area of 387.4 km^2. The most glaciated mountain group is the Ortles massif (134 glaciers covering 76.5 km^2), followed by

Adamello Presanella (43.0 km²), Mont Blanc (38.5 km²) and Monte Rosa (38.4 km²) massifs. These mountain groups also host some of the largest Italian glaciers (Adamello ice plateau, 16.4 km², Forni Glacier, 11.3 km², Miage Glacier, 10.3 km²). In the easternmost sectors, glaciers are much smaller and located within narrow glacial cirques. According to Salvatore & *alii* (2015), over 54% of the Italian glaciers in 2006-2007 were less than 0.1 km², while 29% ranged between 0.1 and 0.5 km², and only the remaining 16% of glaciers had larger areas. Glaciers in the 2-5 km² class covered the largest surface area (about 25% of the total glaciated area). According to Smiraglia & *alii* (2015) only 25 glaciers in the Italian Alps can be classified as "valley glacier", while the majority are classified as "mountain glacier" (57%) and "glacieret" (40%). Most of the glaciers face towards North: however, if we consider the exposure of glaciated areas, they are quite equally redistributed between northern aspects (from West to Northeast, with a peak for the North aspect) and the southern ones (from Southwest to East, with a peak for Southeast exposures). The elevation of glacier fronts and the mean elevation of the Italian glaciers decrease from West to East: the latter ranges from about 2600 to 3800 m a.s.l. in the West, and from about 1800 to 2800 m a.s.l. in the easternmost sections (Salvatore & *alii*, 2015).

The same authors compared their data with those reported in the first systematic glacier inventory of the Italian Alps (CNR-CGI, 1959, 1961a, 1961b, 1962) and found that, in 2006-2007, 181 glaciers were extinct, 470 glaciers remained integer, while 171 glacial bodies fractionated, generating 243 new glaciers. As a consequence, in over 40 years the total number of glaciers has increased (+147 glaciers), while the glaciated area has decreased by about 27% (-140 km², despite the short period favorable to glaciers from the 1960s to 1980s; Nigrelli & *alii*, 2015). Going back in time, Zemp & *alii* (2008) quantified the loss of glaciated area in the Alps at about 50% from the peak of the Little Ice Age (about 1850 CE) to 2000. A study carried out by Lucchesi & *alii* (2014) revealed that 63% of glaciers and 78% of the glaciated area vanished in the same period in the Western Italian Alps. Zemp & *alii* (2008) calculated that, in the same period, Alpine glaciers lost approximately two thirds of their volume. Glacier shrinkage in the Alps continued unabated throughout the 21st century, as documented by a recent inventory realized with Sentinel-2 images by Paul & *alii* (2020), who found a 14% reduction of glacier surface area from 2003 to 2015. Data gathered from satellite imagery and referred to the 2006-2016 period quantify in -0.87 ± 0.07 m of water equivalent the annual rate of glacier loss in Central Europe (Zemp & *alii*, 2019). Maritime glaciers in the Julian Alps represent an exception to the general trend of reduction, since they have undergone a stabilization since the mid-2000s, which has been explained with a higher sensitivity to precipitation changes rather than to air temperature warming (Carturan & *alii*, 2013; Colucci, 2016). A similar resilience has been assessed for glaciers in the Orobie (Scotti & *alii*, 2014).

TYPES OF GLACIER FAILURES

Glacier failures are generally classified based on bedrock topography, failure mode, and temperature inside the ice body but in particular at the ice/bed contact (fig. 2, Alean, 1985; Faillettaz & *alii*, 2015). For this reason, under stable climatic conditions, glacier instability affects the same glaciers in the same way. For example, the Allalin Glacier (Valais-CH), which in Mattmark caused in 1965 the most tragic ice avalanche ever recorded in the European Alps, broke off again in 2000, in a very similar way (Faillettaz & *alii*, 2015). The term "avalanching glaciers" was expressly coined by Pralong & Funk (2006) to indicate glaciers undergoing a periodic or occasional release of ice by break-off mechanisms. However, climatic variations, which affect glacier geometry (by controlling their advance or retreat) and their thermal conditions, can modify the type, timing, and spatial distribution of glacier instability (Allen & *alii*, 2022). Moreover, as for all natural processes, the distinction between the different types of failure, useful for process investigation and hazard assessment, is not always clear-cut, and there are intermediate types (Alean, 1985). Regardless of the type of instability and of the mechanisms of failure initiation, once detached the ice mass usually rapidly disintegrates producing a highly mobile, high-velocity flow of fragmented ice (GAPHAZ, 2017).

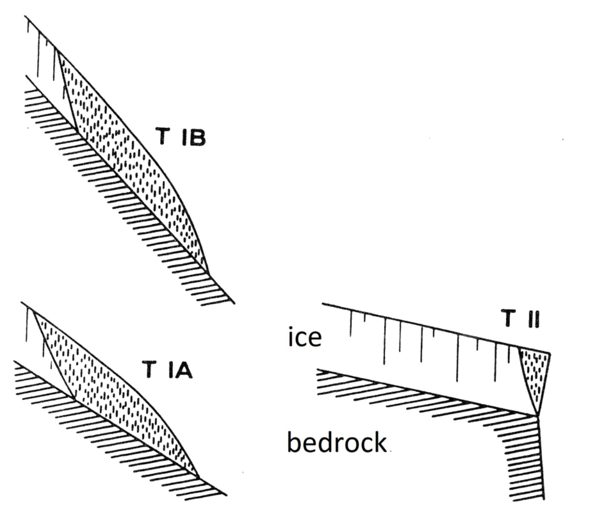

FIG. 2 - Types of starting zones (modified from Alean, 1985). Type IA starting zone is at the pressure melting-point. Type IB starting zone is frozen to the bedrock. Type II starting zone develops in correspondence of a slope break. Dashed: ice expected to break-off.

Wedge failure at a hanging glacier front

The most common type of glacier failure is the break-off of ice lamellas from glacial fronts or ice cliffs located on a sharp break of slope of the bedrock (T II, Alean, 1985, fig. 2; "wedge fracture" of Pralong & Funk, 2006). For this type of failure, single-event volumes are mostly in the range 10-10^3 m^3 (Deline & *alii*, 2012; Giordan & *alii*, 2020). According to Alean (1985), all known ice failures of this type have volumes of less than 4×10^5 m^3: the author hypothesizes that lateral mechanical coupling limits the width of lamellae that can fall from wide hanging glaciers. Huggel & *alii* (2004) proposed that unstable volumes in a cliff-type situation can be estimated from cliff length (L), width (W), and thickness/depth (D). The distances travelled depend roughly on the volume of detached ice (Alean, 1985), and are generally between a few hundreds and a thousand meters (Deline & *alii*, 2012). Thermal conditions at the ice/bed interface are not relevant in this type of failure (Pralong & Funk, 2006) and, in fact, events do not show a specific seasonality (Alean, 1985), even though the greater dynamics of glaciers during the warm season, even at high elevations (Dematteis & *alii*, 2021b), explains a greater frequency of this type of failure during the summer. This type of break-off usually affects only a limited sector at the foot of the rock step where the ice cliff is formed, and therefore is not a threat for inhabited areas or infrastructure. However, due to their frequency and unpredictability, these processes can pose a serious threat to mountaineers and skiers (Mourey & *alii*, 2019), as tragically recalled by the break-off of a serac at the Grand Combin Glacier at 3400 m a.s.l. on May 27, 2022 at 6:20 a.m., which killed 2 of the 17 climbers who were passing under the serac at the time. Given the low magnitude, glacier failures of this type are rarely reported, unless there are consequences for people, and little studied (fig. 3).

FIG. 3 - Grandes Murailles Glacier, Aosta Valley. Frontal view of the glacier: in the circle, the sector recurrently subject to large ice collapses (event ID 51, tab. 2, photo A. Cotta Ramusino, 1978).

Slab failure on a bedrock with constant slope

The largest glacier failures, very rare indeed, are those that occur along bedrock with a constant slope (T I, Alean, 1985, fig. 2), on a ramp or below a terrace (Pralong & Funk, 2006). Faillettaz & *alii* (2015), assuming that basal properties drive the nature of the instability, distinguish three types of processes, depending on whether the ice/bed interface is in condition: a) of permafrost, b) partially temperate, c) temperate.

Cold-based glaciers - At the highest elevations, glaciers are sealed to the permafrost-affected bedrock by frost, and can therefore lie on slopes up to 45°-50° steep (T IB, Alean, 1985, fig. 2). In this case, glacier instability results from creeping of the ice mass under the action of gravity, causing a progressive internal deformation that changes the glacier geometry. This type of failure occurs periodically at the same glaciers and represents the main ablation process for cold-based hanging glaciers located at high elevations (> 3200 m a.s.l. in the Alps), where melting is absent or occasional. These failures occur in any season; however, in some cases, a combination of heavy snowfall was observed in the preceding period and unusually mild temperatures on the day of the event or in the days immediately before: melt water infiltrating in the crevasses might have been the final trigger (Paranunzio & *alii*, 2015). Detached volumes are usually of the order of 10^3-10^5 m^3 (Funk & Margreth, 1999). For the Taconnaz Glacier, located in the French Alps between 4300 and 3300 m a.s.l. on a Northwest facing slope, 20° to 40° steep, the largest documented event (11 August 2010) had a volume of 278,500 m^3 (Vincent & *alii*, 2015). The Taconnaz Glacier is among the best studied cold-based glaciers internationally, together with the Weisshorn Glacier in Switzerland, a cold ramp glacier located between 4500 and 3800 m a.s.l. on a Northeast facing slope, 45° steep (Pralong & Funk, 2006). The studies carried out on these glaciers, in particular on seismic records and surface displacements, have allowed considerable advances in the understanding of this type of processes ((Faillettaz & *alii*, 2008; Gilbert & *alii*, 2015). According to Faillettaz & *alii* (2015), processes leading to glacier failure include the initial development of microcracks within the ice body a few meters above the bedrock; once they reach a critical size, these microcracks merge, producing log-periodic oscillations. At this point, the glacier cannot adapt anymore to the evolution of the internal damage, and an ice failure occurs.

In the Italian Alps, the major documented glacier failures of this type are those released by the Whymper Serac (Grandes Jorasses Glacier), subject to periodic ice break-offs from a 40-45° slope, at an elevation of 4200-3900 m a.s.l., at the top of the South face of the Grandes Jorasses (Mont Blanc massif). The volumes of ice released are generally of the order of 10^4 m^3 (fig. 4): however, in the night between May 31 and June 1, 1998, a large part of the serac detached and travelled horizontal and vertical distances of about 3000 m and 2200 m, respectively (Cerutti, 1997; Faillettaz & *alii*, 2016). Based on helicopter-borne GPR surveys, an ice thickness of about 30 m, out of a total thickness of the hanging glacier of 60 m, was involved in the collapse, for an estimated total volume of collapsed ice of about 120,000 m^3

FIG. 4 - Grandes Jorasses Glacier, Mont Blanc Massif. The fractures in the frontal part of the Whymper Serac are clearly visible (a), from which the ice detachments of October and November 2020 (b) originated (events ID 2-3, tab. 2, photos Fondazione Montagna Sicura, 2020).

(IMAGEO, 2010). Following this event, the glacier has been intensively studied and monitored for the risk posed to the Val Ferret valley bottom, a very popular tourist destination, both in winter and in summer (Margreth & Funk, 1999; Margreth & *alii*, 2011; Faillettaz & *alii*, 2016; Dematteis & *alii*, 2021a; Perret & *alii*, 2021). This glacier is also responsible for the deadliest ice failure event in the Italian Alps, before the Marmolada tragedy: on August 2, 1993, at 4:15 a.m., an ice break-off of 80,000 m^3 killed eight mountaineers climbing the normal route of the Grandes Jorasses from the Boccalatte Hut (Cerutti, 1997; Faillettaz & *alii*, 2016).

Polythermal glaciers - These glaciers retain warm ice in their interior, where the ice is thick and is warmed to the pressure melt point, and cold ice around their margins where ice is thin (Glasser, 2011). The presence of liquid water within the glacial mass can cause rapid localized warming at the ice/bed interface, leading to local decoupling of the glacier from the bed that can initiate a destabilization of the entire glacier. In this case, the detachment surface develops at the ice/bed contact, and can then propagate inside the ice mass (Faillettaz & *alii*, 2015). This type of instability is quite rare, but large ice volumes (typically 10^5-10^6 m^3) can be released (Pralong & Funk, 2006). In agreement with the role played by liquid water in triggering glacier instability, these phenomena show a clear seasonality. According to Faillettaz & *alii* (2015), the largest event of this type in the European Alps occurred at the Altels Glacier (Switzerland) on September 11, 1895: it mobilized a volume of ice of 4×10^6 m^3, had a runout of 3900 m and an estimated speed of 430 km/h. In the mid-19^{th} century, it was a cold-based glacier, located on a 35° to 40° steep ramp, at an elevation of 3630-3000 m a.s.l. Based on the results of numerical modeling, Faillettaz & *alii* (2011) hypothesized that the glacier instability could have initiated by a rapid localized warming at the glacier-bed interface. A similar mechanism could be responsible for the initiation of the giant, unprecedented collapse of the entire lower parts of two adjacent glaciers that occurred in western Tibet in July and September 2016, causing sudden large-volume detachment of low-angle (mountain) glaciers that mobilized ice volumes of 68 and 83×10^6 m^3, respectively. The investigations conducted by Kaab & *alii* (2018) concluded that the twin collapses were caused by climate- and weather-driven factors, acting on a polythermal and soft-bed glacier.

In Italy, similar conditions may have caused the glacier failure occurred on the Monte Rosa East face in 2005, which produced the largest ice avalanche ever documented in the Italian Alps, and one of the largest of the European Alps over the past 100 years (fig. 5; Tamburini & *alii*, 2013). On August 25, a huge ice slab of about 1.1×10^6 m^3 detached at an elevation between 3820 and 3580 m a.s.l. The ice mass quickly fragmented, becoming an ice avalanche that further entrained debris, snow and ice along its path. The ice avalanche travelled a horizontal distance of 3200 m and a vertical one of 1700 m (angle of reach: 28°). Most of the ice/debris mixture stopped at the foot of the rock wall, spreading over the upper part of the Belvedere Glacier tongue and filling the depression that once hosted the Effimero Lake (Tamburini & Mortara, 2005). The anemometer of an automatic weather station located near the right edge of the accumulation zone recorded a peak of wind speed of 140 km/h associated with the avalanche. The ice detachment started from a sector of the Monte Rosa East flank that had undergone strong changes in

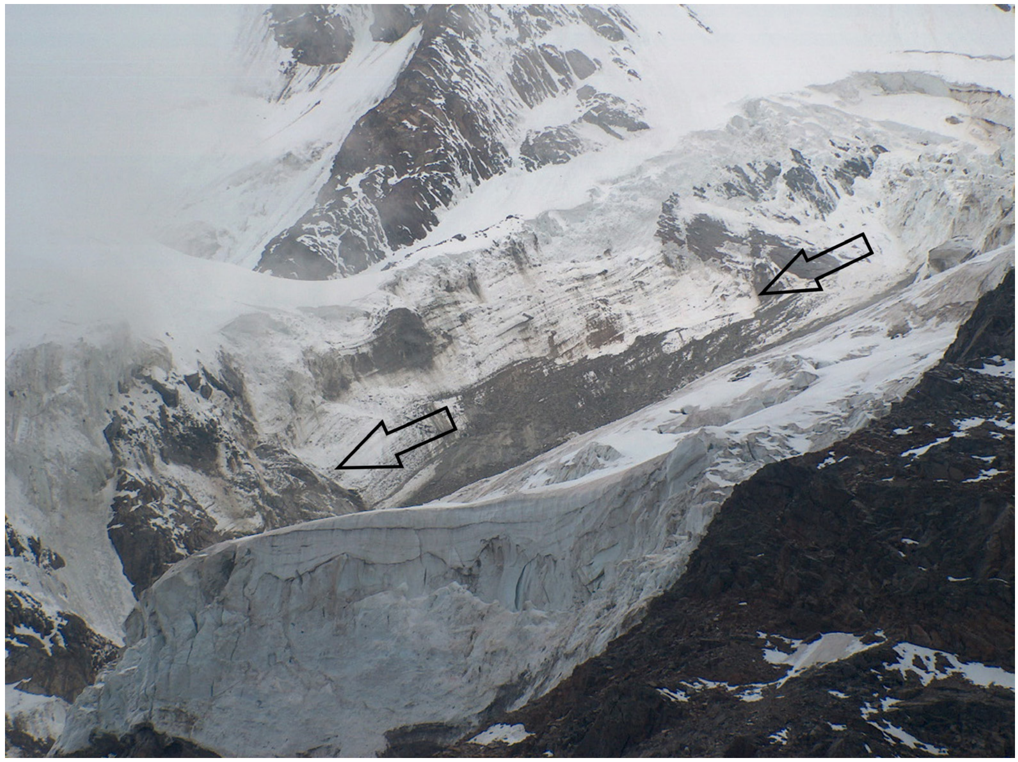

FIG. 5 - Monte Rosa Glacier, Monte Rosa massif. Detail of the starting zone of the very large ice avalanche of August 2005 (event ID 33, tab. 2; in the background, arrows show the direction of the movement of the detached ice mass; photo L. Fischer, 2005).

previous years (Fischer & *alii*, 2011). According to Huggel (2009), in the hanging glacier which failed, despite being originally cold-based, polythermal to temperate conditions may have established at some distance behind the front, causing glacier instability: the presence of water flowing in the scar after the detachment supports this hypothesis (Paranunzio & *alii*, 2015).

Temperate glaciers - Tongues of temperate glaciers on steep slopes can undergo instability due to sliding: in this case, the subglacial hydrology plays a fundamental role, and the rupture occurs at the ice/bed contact. Meltwater infiltration can lubricate the glacier bed and lower the effective pressure at the ice/bed interface, thereby decreasing basal friction. This condition can cause an acceleration of the glacier flow, initiating a so-called "active phase". Based on in-depth investigation of some case studies, Faillettaz & *alii* (2015) conclude that, in addition to the onset of an active phase, four criteria have to be met for this type of glacier failure to occur: 1) a critical geometrical configuration of the glacier tongue; 2) a distributed subglacial drainage network; 3) a reduction of drainage network efficiency, following a period of decreased runoff; 4) a final pulse of subglacial water flow that triggers the catastrophic failure. This type of failure has been observed to affect glaciers on slopes steeper than 25° (Pralong & Funk, 2006). In some cases, the glacier tongue only undergoes one very large break-off, preceded or followed by several minor ones (fig. 6). In other cases, during an active phase several minor break-offs occur, which together cause the detachment of a large volume of ice from the glacier tongue (Alean, 1985; Giordan & *alii*, 2020). Given the primary role of meltwater, it is not surprising that these events show a

FIG. 6 - Frébouge Glacier, Mont Blanc massif. Front view of the September 2002 ice avalanche (event ID 37, tab. 2; in the rectangle, the detachment scar). The accumulation cut the path to the Gervasutti bivouac (photo P. Deline).

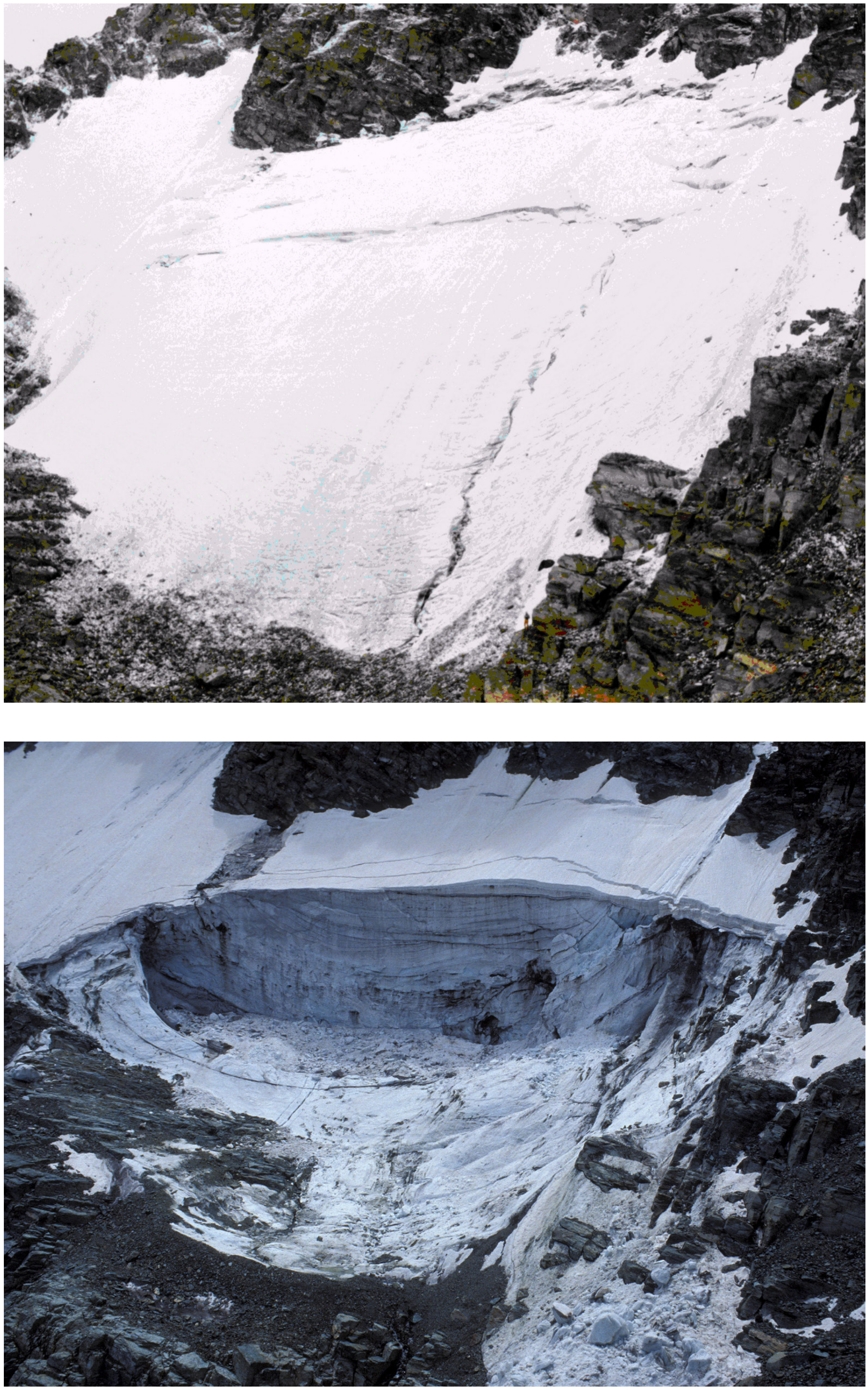

FIG. 7 - Superiore di Coolidge Glacier, Monviso massif. (a) the glacier in 1987 (photo M. Vanzan); (b) detachment scar of the July 1989 ice avalanche with exposure of the bedrock (event ID 48, tab. 2; photo R. Tibaldi, 1989).

clear seasonality, concentrating in the July-October period. Based on the documented events, the volumes released by this type of failure are slightly smaller than those from polythermal glaciers. In the European Alps, the largest and most tragic documented event is the aforementioned failure of the terminal part of the Allalin Glacier (about 2×10^6 m^3) on August 30, 1965, which travelled a vertical distance of 400 m and run for a further 400 m across the valley bottom (Faillettaz & *alii*, 2015), killing 88 employees at the Mattmark dam construction site (Röthlisberger, 1977). The glacier has a temperate tongue, which ranged in elevation from 2800 to 2200 m a.s.l. during most of the last century, resting on a 27° slope. Another ice avalanche of 1 $\times 10^6$ m^3 detached from the Allalin Glacier front on July 31, 2000 (Deline & *alii*, 2021).

In the Italian Alps, the largest documented event of this type is the break-off on July 6, 1989 of 200,000 m^3 of ice from the Superiore di Coolidge Glacier (northern side of the Monviso, fig. 7; Dutto & *alii*, 1991). The detachment occurred along a crevasse, which was observed since 1986 at an elevation of 3195 m a.s.l (fig. 7a). The ice avalanche descended a vertical distance of 950 m, with a runout of 1200 m (angle of reach: 38°): as for the 2005 ice avalanche at the Belvedere Glacier, runout could have been longer without the Chiaretto Lake depression along the avalanche path. The signal recorded by a nearby seismic station made it possible to estimate an ice-avalanche speed between 90 and 130 km/h.

The collapse of the Marmolada Glacier, which on July 3, 2022 hit a group of 11 climbers heading to Punta Penia, shows surprising similarities with this event. As the Superiore di Coolidge Glacier, before detachment the collapsed glacier appeared as a flat ice mass, apparently devoid of dynamics, and cut by some crevasses. Based on evidence from videos available online, the initial ice avalanche was followed and overcome by a highly mobile mixture of ice, water and debris, with an estimated runout of about 1600 m, and a vertical distance of 750 m. The collapsed ice mass has approximately the same exposure (North) as the Superiore di Coolidge Glacier (Northeast) and a similar elevation of the detachment scar (3200 m a.s.l.), as well as a striking similarity of occurrence date.

Paranunzio & *alii* (2015) found that the collapse of the Superiore di Coolidge Glacier followed a very snowy winter, was preceded by a rapid increase in temperatures in the previous 2-3 days, while the final trigger was most likely a heavy thunderstorm. On the contrary, the collapse of the Marmolada Glacier followed a winter with scarce snowfalls, but a two-month period (May-June) with temperatures several degrees above the average, which reached 10 °C on the day of the event (ARPA Veneto, 2022). In both cases we can hypothesize that the collapse was due to the building of water pressures at the ice/bed interface, favored by the geometry of the bedrock and by frost conditions at the glacial margins, which prevented water runoff. In conclusion, if the triggering mechanism looks similar, the origin of the water responsible for the overpressures is different: from snow melting and rainfall, in the case of the Superiore di Coolidge Glacier, from snow and ice melting, in the case of the Marmolada Glacier.

In recent years, great concern aroused from the evolution of the Planpincieux Glacier, a temperate glacier on the Italian side of the Mont Blanc massif. The glacier, facing Southeast and with an area of about 1 km^2, starts from an elevation of about 3600 m a.s.l. and ends in two temperate lobes (elevation range: 2900-2600 m a.s.l., slope: 32°). The right one hangs on a rock step and is subject to recurrent break-offs in summer and early autumn (Giordan & *alii*, 2020). Since 2013, this lobe has been constantly monitored, following the opening of a large crevasse in October 2011 and the consequent threat posed to the underlying Val Ferret valley floor. This made it possible to better define the dynamics of this glacier, and in particular of its frontal sector, in order to predict large break-offs and manage the related risks (Giordan & *alii*, 2020; Dematteis & *alii*, 2021b).

MAJOR GLACIER FAILURES IN THE ITALIAN ALPS

Data and methods

The main source of information on glacier failures in the Italian Alps, especially until the year 2000, have been the reports on the annual glaciological surveys promoted by the Italian Glaciological Committee (CGI). During the annual glaciological surveys, carried out at the end of the ablation season, the volunteers of the CGI, in addition to measuring the variations of the glacial fronts, collect photos and observations of the glaciers and of surrounding areas. Since 1928, the reports are published in a dedicated section of the CGI Bulletin (CGI, 1928-1977; 1978-2020). These reports are therefore a valuable source of information on glacier failures (fig. 8), processes usually poorly documented and analyzed from a risk perspective, given the remote location of most Italian glaciers, with limited interference with human activities and infrastructure. Further information was collected from aerial images, scientific publications, reports, unpublished documentation provided by CGI and glaciological volunteer operators, regional geoportals, media.

While other sources of information usually deal only with major events, the reports of the CGI glaciological surveys contain information on glacier failures of all magnitudes, from small break-offs observed during the surveys, to large ice avalanches that have substantially changed the morphology of the glaciers and/or of the proglacial areas. A systematic analysis of those reports allowed to collect over 600 mentions of glacier failures in 90 years in the Italian Alps, which will be the subject of further investigation. Considering the objectives of this work, we have only considered events larger than 10,000 m^3: this is in fact the minimum volume of events that have caused damage or risk to people or structure/infrastructure in the Italian Alps. When a volume estimate was not available, an assessment of the relevance of the event was necessarily made based on the interpretation of the available images and maps, and/or descriptions provided (fig. 9). This inevitably implies a degree of arbitrariness, which however we believe was more likely to lead to the exclusion of events with a volume greater than 10,000 m^3, for which too general information was available, than to the inclusion of events with a volume lower than that threshold.

FIG. 8 - Salarno Glacier, Adamello massif. View of the long path of the September 1957 ice avalanche: the detachment scar is highlighted by the star (event ID 57, tab. 2; photo C. Saibene, 1957).

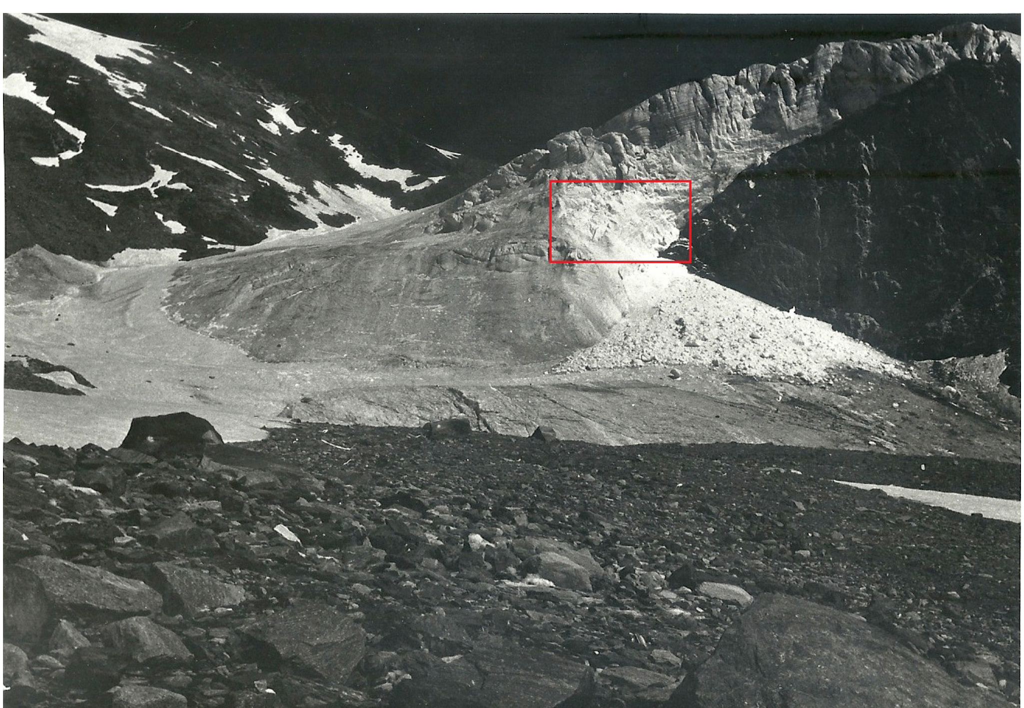

FIG. 9 - Rosim Glacier, Ortles-Cevedale massif. The 1977 failure was generated by the vertical and crevassed left side of the glacier (event ID 52, tab. 2; rectangle, photo F. Secchieri, 1977).

For each event, the following information was reported or calculated, whenever possible: date, hour, (maximum) elevation of the detachment zone, (minimum) elevation of the accumulation zone, runout, coordinates of the detachment point, volume, vertical (H) and horizontal (L) distance covered by the phenomenon, tan α (H/L), damage, synthetic description of the event, source of the information.

The information on the elevation of the detachment and accumulation zone, on the runout, and on H and L are in some cases provided by the documents themselves, but sometimes they have been obtained, on the basis of the information available, by means of GIS, mostly using the tools ("geolocation" and "measurement") available in the geoportals of regional and autonomous province administrations, or in Google Earth. In the same way, we assigned geographical coordinates to the events which, apart from some specific cases, are inevitably only indicative and correspond to the highest point hypothesized for the detachment. Of course, the assignment of these coordinates was more and more complex, as the events were older, due to the increasing difference between the morphology and geometry of the current glaciers and those of glaciers at the time of failure: in order to minimize errors, as far as possible, reference was made to the historical aerial images available on the geoportals of regional and autonomous province administrations, or to maps and photos close to the year of failure.

Results

The research led to the identification of 68 major glacier failures that affected 29 different glaciers of the Italian Alps in the period 1930-2022 (fig. 10). Tab. 1 shows the characteristic data of the 29 glaciers, while tab. 2 lists the 68 documented events, with their main characteristics. A brief description of the events (where available) and sources of information are reported in tab. 1S. For about half of the glaciers only one major event has been identified, while for 10 glaciers (34%) two major events are documented. Only for the Frêney, Palon de la Mare, Grandes Jorasses and Planpincieux glaciers a greater number of major events have been reported (respectively 4, 6, 8, 15). If we analyze the number of events per decade (fig. 11a), we can see that from 1930 to 1990 this number is between 1 and 6; decades with a greater number of events (1930s, 1950s, 1970s) alternate with decades with fewer events (1940s, 1960s, 1980s). However, starting from the 1990s, the events per decade are between 8 and 20, with a clear positive trend: also the decade 2020s, with 8 cases in 3 years, seems to follow this trend. As regards the seasonal distribution (fig. 11b), data (available only for 54 events, 79%) indicates a clear concentration in the summer period (JJA, 33 events, 60%, of which 19 in August), followed by autumn (SON, 14 events), winter (DJF, 4 events), and spring (MAM, 3 events). The elevation of the detachment scar is known for 67 events: most detachments occurred in the 2500-3500 m elevation range (48 events, 72%), however some glacier failures occurred at lower (9 events) and higher (10 events) elevations. Information, even approximate, on the volume of glacier failures is available only for 40 events (59%, fig. 12a). About two thirds of them have a volume between 10,000 and 50,000 m^3, while there are 5 events in the volume class 50,000-100,000 m^3 and 4 events in the range 100,000-150,000 m^3; only 1 event had a volume between 150,000 and 200,000 m^3, while 5 events exceeded 200,000 m^3, with the largest event (Monte Rosa 2005) reaching 1,100,000 m^3. The mobility of processes is commonly described in the literature by the parameter H/L, or tan α: the lower the value of this ratio, the greater

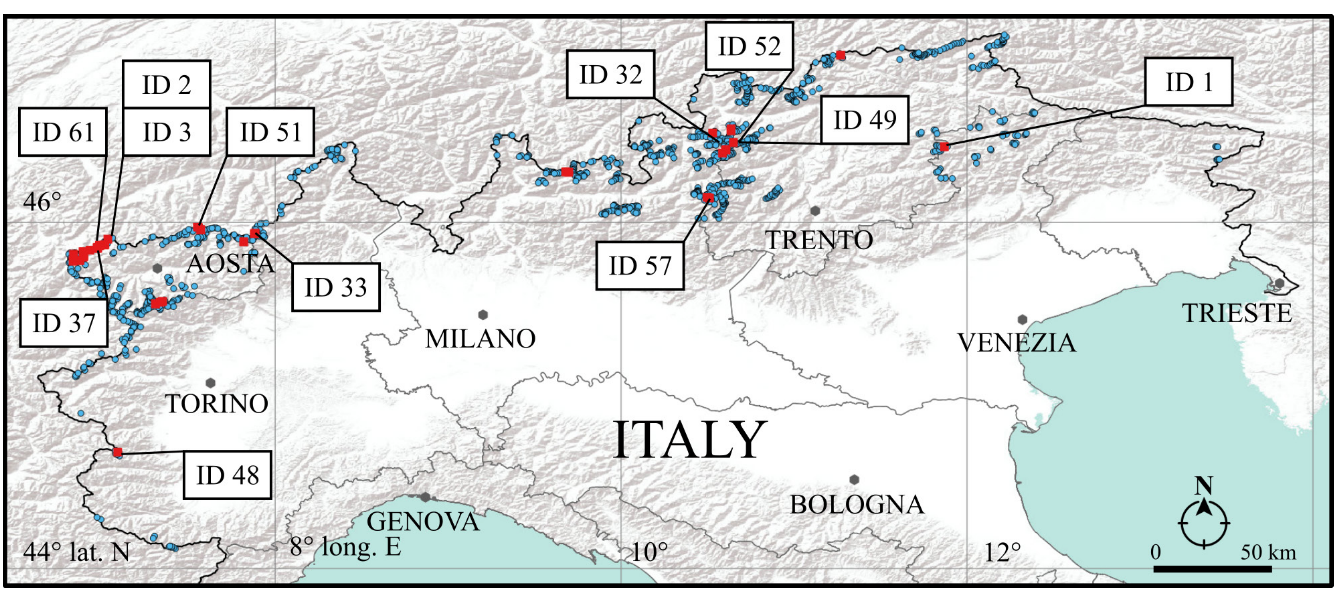

Fig. 10 - Location of the Italian glaciers (blue circles; grey circles in the printed version) and of the major glacier failures (red squares; black squares in the printed version) documented in the Italian Alps for the period 1930-2022. The labels (ID #) refer to the number of glacier failure events, as numbered in tabs. 2 and 1S, which are shown in the Figures and mentioned in the text.

TABLE 1 - Location and main characteristics of Italian glaciers with documented glacier failures. CGI code: glacier code according to the inventory of Italian glaciers (CNR-CGI, 1959); WGI code: glacier code according to the World Glacier Inventory (1989); Name: glacier name according to CNR-CGI (1959); Latitude and Longitude: coordinates of the centre of the glacier, referred to the WGS84 datum and reported as decimal degrees; Type: type of glacier according to the WGI classification; Coordinates, type, area, maximum elevation, and aspect are from Smiraglia and Diolaiuti (2015) and referred to the period 2007-2011; data with one asterisk: from Salvatore & *alii* (2015) and referred to the period 2006-2007; data with two asterisks: from CNR-CGI (1961) and referred to the period 1957-1958; n. events: number of events documented for each glacier in this work.

CGI code	WGI code	Name	Latitude (°N)	Longitude (°E)	Type	Area (km²)	Max. elev. (m a.s.l.)	Aspect	events (n.)
20	IT4L01481003	Superiore di Coolidge	44.671389	7.089722	Glacieret	0.03	3271	N	1
108	IT4L01512018	Superiore di Patrì	45.540000*	7.354000*	Mountain	0.29*	3529*	NW*	2
109	IT4L01512020	Coupé di Money	45.531000*	7.349000*	Mountain	1.51*	3587*	NW*	1
112	IT4L01512022	Tribolazione	45.525000	7.285556	Mountain	5.07	3888	NE	2
209	IT4L01517004	Lex Blanche	45.784167	6.817778	Mountain	3.32	3880	SE	2
213	IT4L01517006	Miage	45.811667	6.845833	Valley	10.47	4668	SE	2
218	IT4L01517009	Frêney	45.814444	6.885000	Mountain	1.16	4044	S	4
219	IT4L01517011	Brenva	45.830278	6.884722	Mountain	5.77	4800	SE	1
221	IT4L01517013	Toula	45.841667	6.926111	Mountain	0.64	3341	SE	1
225	IT4L01517018	Planpincieux	45.857500	6.973611	Mountain	1.08	3657	SE	15
226	IT4L01517019	Grandes Jorasses	45.860004	6.982510	Mountain	0.58	4200*	S	8
229	IT4L01517022	Frébouge	45.872778	7.007500	Mountain	2.07	3561	SE	2
234	IT4L01517027	Triolet	45.899444	7.021944	Mountain	3.61	3532	SE	1
259	IT4L01522024	Tza de Tzan	45.977778	7.562222	Valley	3.27	3790	S	2
260	IT4L01522027	Grandes Murailles	45.956667	7.586103	Mountain	6.26	4000	W	2
304	IT4L01502002	Lys	45.908611	7.832778	Valley	9.58	4323	S	1
323	IT4L01211009	Monte Rosa	45.937000*	7.887000*	Mountain	1.84*	4550*	NE*	2
399	IT4L01104023	Orientale della Rasica	46.294167	9.682222	Glacieret	0.02	2984	SW	1
401	IT4L01104026	Pizzo Torrone Est	46.286667	9.698889	Glacieret	0.05	2860	S	2
507	IT4L01137023	Palon della Mare	46.413333	10.607222	Mountain	1.06	3666	SW	6
507.1	IT4L01137024	Forni	46.392222	10.591111	Valley	11.34	3673	N	2
603	IT4L01024006	Corno di Salarno	46.146324**	10.498979**	Mountain	0.08**	3300**	S**	1
604	IT4L01024006	Salarno	46.142336**	10.513857**	Mountain	0.38**	3050**	SW**	2
730	IT4L00112122	Vedretta Alta dell'Ortles	46.457222	10.680278	Mountain	1.26	3299	N	1
732	IT4L00112126	Cevedale	46.455556	10.629167	Valley	3.47	3733	NE	1
751	IT4L00112405	Fuori di Zai	46.543333	10.636111	Mountain	0.29	3488	N	1
754	IT4L00112408	Rosim	46.525833	10.641111	Mountain	0.56	3406	NW	1
880	IT4L00121204	Montarso	46.966389	11.254167	Mountain	1.26	3135	E	1
941	IT4L00101101	Marmolada	46.438611	11.867778	Mountain	1.28	3254	N	1

the mobility of the event (Corominas, 1996). The value of this parameter was determined only for 38 events (56%) and ranges between 0.80 and 0.33 (fig. 12b): the greatest number of events (10) falls into the class 0.70-0.80, and then gradually decreases as the value of tan α decreases (9 events in the class 0.60-0.70, 8 events in the range 0.50-0.60; 6 events in the class 0.40-0.50 and 3 events in the class 0.30-0.40). The lowest value (0.33) was reached by the collapse of the Torrone East glacieret in 2009, while only 2 events have values equal to 0.80. By a fortunate series of circumstances, only 7 of the 68 identified events resulted in casualties or damage.

DISCUSSION

The dataset presented in this work is the most complete list of events ever published on glacier failures in the Italian Alps, and it considerably expands the datasets available so far on a national scale (Dutto & Mortara, 1991; Gridabase, 2003), implemented with this study (Nigrelli & *alii*, 2023). It is a relevant dataset even when compared with similar datasets published for other Alpine regions and around the world (Alean, 1985; Pralong & Funk, 2006; WGMS, 2022). In particular for events occurred before 2000, the compilation of this dataset was made possible thanks to the reports of the

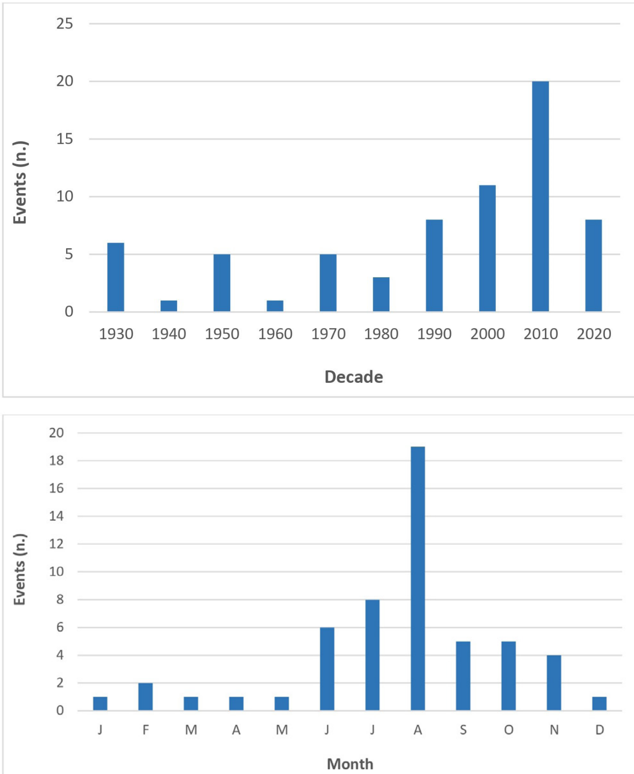

FIG. 11 - Temporal distribution of glacier failures. Number of events: a) per decade, b) per month.

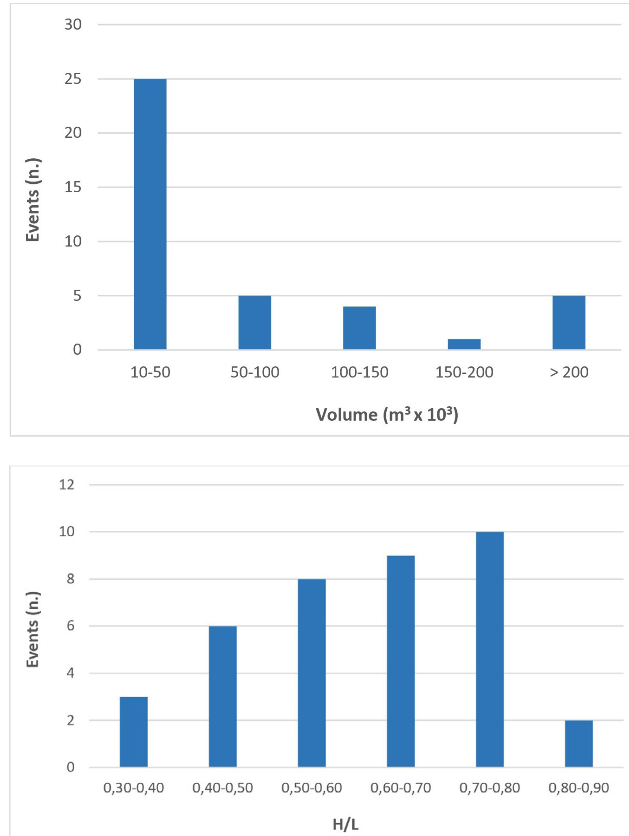

FIG. 12 - Properties of documented glacier failures. Number of events: a) per class of volume; b) per class of H/L value.

annual glaciological surveys promoted and published by the CGI. However, we are aware that this dataset is only partially representative of glacier failures that have occurred in the Italian Alps in the considered period. It is no coincidence, in fact, that the three glaciers for which the greatest number of events are documented are glaciers subject to monitoring and/or in-depth investigation, due to specific risks: in the case of the Grandes Jorasses and Planpincieux glaciers due to the threat they pose to the Val Ferret (Giordan & *alii*, 2016; Giordan & *alii*, 2020; Dematteis & *alii*, 2021a), and in the case of Palon de la Mare to the Branca Hut (fig. 13; Maggioni & *alii*, 2018). Furthermore, as already mentioned in section "Data and methods", the reports of the CGI glaciological surveys in several cases did not have sufficient information to allow to evaluate the magnitude of the reported glacier failures, which we therefore did not include in this dataset as a precaution: in some cases, however, it was possible to get photos and clarifications from the glaciological volunteer operators, which made it possible to better characterize the reported phenomena. Conversely, in case glacier failures were inferred from the observation of ice accumulations, and not observed and documented directly, it is possible that events included in this dataset are rather the result of a sequence of smaller events that overlapping each other have built an important accumulation of ice: in this case, flow lobes were used as a diagnostic feature to distinguish accumulations due to a single large event from accumulations due to the superimposition of successive small ice failures. Furthermore, since the main objective of CGI glaciological surveys is to measure the fluctuation of glacier fronts, it is up to the sensitivity of the individual operators to report news or evidences of glacier failures: however, it can reasonably be assumed that major glacier failures, which significantly modified the morphology of glaciers and/or proglacial areas, could hardly have been ignored. Finally, the glaciological surveys normally take place between mid-August and mid-September, so events occurring in the other periods of the year may escape observation. Since 2009, thanks to the attention gained towards these and other phenomena of natural instability in the high mountains in a context of climate change, the reports of the annual CGI glaciological surveys contain a specific section listing glaciers that underwent natural instability and/or significant morphological changes.

Nevertheless, we believe that the limits and biases described above do not affect some of the analyses performed on the dataset. In particular, there is no reason why the fluctuation in the number of events observed in the decades from 1930s to 1980s should depend on such limits and biases. This fluctuation does not even show an apparent correlation with the fluctuation of air temperature in that period (Acquaotta & *alii*, 2015): we can therefore conclude that this fluctuation is related to the dynamics of individual glaciers. On the other hand, the sharp increase in the number of events since 1990s may stem in part from a greater attention to glacial environments, as also noted

TABLE 2 - Main glacier failures in the Italian Alps in the period 1930-2022. Events are numbered by date, from the most recent to the oldest one. CGI code: glacier code according to the inventory of Italian glaciers (CNR-CGI, 1959; name of glaciers is given in tab. 1); Sector: sector of the glacier where the failure occurred; Year, Month, Day, of the glacier failure: "00" when not known; time: time of the day of glacier failure; Longitude and Latitude: coordinates of the highest point of the detachment zone; Max. elev.: maximum elevation of the detachment zone; Min. elev.: minimum elevation of the deposition zone; L: length of the glacier failure path (runout); H: vertical distance of the failure path; H/L: tan α, α = angle of reach; n.a.: data not available.

Event ID	CGI code	Sector	Year	Month	Day	Time	Longitude	Latitude	Max. elev. (m)	Min. elev. (m)	Runout (L) (m)	Vertical distance (H) (m)	H/L tan α	volume (m^3)
1	941	Punta Rocca	2022	07	03	13:45	11.858292	46.435248	3200	2450	1600	750	0.47	65,000
2	226	Whymper Serac	2020	11	12	n.a.	6.985837	45.867360	4050	2500	2200	1550	0.70	20,000
3	226	Whymper Serac	2020	10	18	n.a.	6.985837	45.867360	4050	2500	2200	1550	0.70	20,000
4	225	right lobe	2020	08	00	n.a.	6.974656	45.849132	2650	n.a.	n.a.	n.a.	n.a.	> 10,000
5	225	right lobe	2020	07	00	n.a.	6.974656	45.849130	2650	n.a.	n.a.	n.a.	n.a.	> 10,000
6	225	right lobe	2020	06	00	n.a.	6.974650	45.849136	2650	n.a.	n.a.	n.a.	n.a.	> 10,000
7	225	right lobe	2020	06	00	n.a.	6.974651	45.849131	2650	n.a.	n.a.	n.a.	n.a.	> 10,000
8	219	Gendarme Rouge Serac	2020	02	08	n.a.	6.877297	45.835477	4000	n.a.	n.a.	n.a.	n.a.	100,000
9	225	right lobe	2019	08	00	n.a.	6.974652	45.849132	2650	n.a.	n.a.	n.a.	n.a.	> 10,000
10	225	right lobe	2019	07	00	n.a.	6.974660	45.849140	2650	n.a.	n.a.	n.a.	n.a.	> 10,000
11	507.1	Western	2018	10	01-10	n.a.	10.585805	46.400377	2350	n.a.	n.a.	n.a.	n.a.	n.a.
12	225	right lobe	2018	10	23	n.a.	6.974659	45.849139	2650	n.a.	n.a.	n.a.	n.a.	15,000
13	225	right lobe	2018	08	00	n.a.	6.974660	45.849126	2650	n.a.	n.a.	n.a.	n.a.	> 10,000
14	221		2017	08	22	afternoon	6.930312	45.839199	2900	n.a.	n.a.	n.a.	n.a.	30,000
15	507		2017	04	00	n.a.	10.606127	46.417850	3300	2550	1500	750	0.50	10^5
16	225	right lobe	2017	10	10	n.a.	6.974580	45.849138	2650	n.a.	n.a.	n.a.	n.a.	19,300
17	225	right lobe	2017	08	29	n.a.	6.974656	45.849136	2650	n.a.	n.a.	n.a.	n.a.	54,900
18	225	right lobe	2017	08	01	n.a.	6.974655	45.849135	2650	n.a.	n.a.	n.a.	n.a.	37,700
19	234		2016	07	25	n.a.	7.032541	45.902861	2900	2650	700	250	0.36	n.a.
20	225	right lobe	2016	08	14	n.a.	6.974654	45.849134	2650	n.a.	n.a.	n.a.	n.a.	30,000
21	225	right lobe	2015	08	14	n.a.	6.974657	45.849137	2650	n.a.	n.a.	n.a.	n.a.	13,500
22	226	Whymper Serac	2014	09	23, 29	n.a.	6.985837	45.867360	4050	n.a.	n.a.	n.a.	n.a.	105,000
23	225	right lobe	2014	06	00	n.a.	6.974657	45.849137	2650	n.a.	n.a.	n.a.	n.a.	> 10,000
24	732		2013	00	00	n.a.	10.649823	46.461256	2830	n.a.	n.a.	n.a.	n.a.	n.a.
25	259		2012	00	00	n.a.	7.556651	45.974498	3100	2850	360	250	0.69	> 18,000
26	213	Glacier du Dôme	2012	06	17	18-19	6.834433	45.813573	2650	2450	500	200	0.40	n.a.
27	730		2010	08	01	n.a.	10.530373	46.516313	3200	1700	2500	1500	0.60	n.a.
28	304		2010	07	29	n.a.	7.817360	45.887686	2450	n.a.	n.a.	n.a.	n.a.	n.a.
29	401		2009	08	20-ante	n.a.	9.697554	46.289488	2850	2750	300	100	0.33	n.a.
30	325	Canalone Marinelli	2007	08	12	n.a.	7.883226	45.939712	3400	2300	1900	1100	0.58	n.a.
31	259		2007	00	00	n.a.	7.555115	45.972262	2950	n.a.	n.a.	n.a.	n.a.	n.a.
32	507	Rosole flow	2006	08	21	10:45	10.606267	46.419551	3300	2700	880	600	0.68	10^4
33	325		2005	08	25	2:36	7.878422	45.935524	3820	2100	2700	1720	0.64	1,100,000

Event ID	CGI code	Sector	Year	Month	Day	Time	Longitude	Latitude	Max. elev. (m)	Min. elev. (m)	Runout (L) (m)	Vertical distance (H) (m)	H/L tan α	volume (m^3)
34	225	right lobe	2005	11	18-ante	n.a.	6.974665	45.849112	2650	1885	1100	765	0.70	20,000-30,000
35	209		2004	05	10-16	n.a.	6.833379	45.776364	2420	2050	850	370	0.44	n.a.
36	229		2003	07	17-20	n.a.	7.016593	45.869950	2500	2000	700	500	0.71	> 10,000
37	229		2002	09	18	afternoon	7.016015	45.869139	2500	1855	1200	645	0.54	100,000
38	507	Rosole flow	2002	08	25	night	10.606346	46.419547	3300	2660	1000	640	0.64	60,000-80,000
39	401		2000	08	11	10:30	9.697231	46.290006	2950	2350	1400	600	0.43	n.a.
40	507	Rosole flow	1999	10	23-25	n.a.	10.605850	46.419820	3300	2625	1200	675	0.56	40,000-50,000
41	226	Whymper Serac	1998	06	01	n.a.	6.985724	45.867437	4000	1750	3170	2250	0.71	150,000
42	226	Whymper Serac	1997	01	24-25	n.a.	6.985724	45.867437	4000	2000	2500	2000	0.80	25,000
43	399		1996	09	00	n.a.	9.680002	46.292000	2780	n.a.	n.a.	n.a.	n.a.	n.a.
44	226	Whymper Serac	1996	07	11-14	n.a.	6.985538	45.867144	4000	n.a.	n.a.	n.a.	n.a.	24,000
45	213	Miage Lake	1996	08	09	n.a.	6.871428	45.779425	2015	n.a.	n.a.	n.a.	n.a.	7000-16,000
46	226	Whymper Serac	1993	08	02	4:15	6.985724	45.867437	4000	3100	1350	950	0.70	80,000
47	507	Rosole flow	1993	03	00	n.a.	10.605820	46.419978	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
48	20		1989	07	06	22:45	7.089680	44.672330	3200	2265	1200	935	0.78	200,000
49	507	Rosole flow	1986	02	16-18	n.a.	10.605819	46.419977	3250	2450	1900	800	0.42	n.a.
50	260		1980	00	00	n.a.	7.569323	45.956650	2750	2400	500	350	0.70	n.a.
51	260		1978	00	00	n.a.	7.569507	45.956261	2750	2400	500	350	0.70	n.a.
52	754		1977	00	00	n.a.	10.635390	46.528900	3000	n.a.	n.a.	n.a.	n.a.	n.a.
53	751	Cima Ventana flow	1975	09	00	n.a.	10.635760	46.541850	3300	n.a.	n.a.	n.a.	n.a.	n.a.
54	218		1974	11	00	n.a.	6.889266	45.800516	2350	1700	1500	650	0.43	10^5
55	218		1971	11	00	n.a.	6.889376	45.800687	2350	1670	1350	680	0.50	n.a.
56	604		1969	00	00	n.a.	10.509850	46.140922	3000	n.a.	n.a.	n.a.	n.a.	n.a.
57	604		1957	09	05	afternoon	10.509532	46.141445	3000	2400	1700	600	0.35	80,000-100,000
58	218		1956	06	24-25	night	6.891948	45.801645	2400	1670	1300	730	0.56	10^5
59	209		1956	08	09	noon	6.833576	45.776083	2380	2130	500	250	0.50	n.a.
60	603		1955	00	00	n.a.	10.499366	46.143525	3050	2600	700	450	0.64	n.a.
61	226	Whymper Serac	1952	12	21	n.a.	6.985724	45.867437	4000	1550	4000	2450	0.61	>1,000,000
62	108		1941	00	00	n.a.	7.349087	45.543486	3150	n.a.	700	n.a.	n.a.	>28,000
63	880		1935	00	00	n.a.	11.269530	46.966555	2500	n.a.	n.a.	n.a.	n.a.	n.a.
64	108		1934	00	00	n.a.	7.348431	45.543434	3150	1820	2100	1330	0.63	n.a.
65	218		1933	08	08	morning	6.890059	45.801372	2380	1770	1100	610	0.55	n.a.
66	112		1933	00	00	n.a.	7.302204	45.533264	2650	2350	400	300	0.75	n.a.
67	109		1931	00	00	n.a.	7.334930	45.538663	2650	2530	150	120	0.80	n.a.
68	112		1930	00	00	n.a.	7.301726	45.532999	2740	2300	680	440	0.65	n.a.

by Viani & *alii* (2016) with regard to glacial lakes, and from the increased availability of information (particularly regarding the 2010 and 2020 decades): however, in our view these factors cannot completely explain this trend, which on the other hand coincides perfectly with the rapid increase in air temperature recorded since the 1990s and still ongoing (IPCC, 2021, Nigrelli & Chiarle, 2021). Based on the analysis of our dataset, the progressive increase in the frequency of glacier failures over the last three decades is the only clue of a possible impact of climate change on glacier instability. Further analyses, considering the elevation, volume, runout and seasonality of break-offs, pointed out some slight trends towards an increase over time in the elevation and runout, a decrease in volume and an anticipation of the seasonality of the glacier failures. However, the low correlation coefficients ($R^2 < 0.03$), do not allow these trends to be considered statistically significant. Only a systematic documentation of future events will allow clear trends in these and other properties of glacier failures to be identified, and possibly attributed to climate change.

Conversely, we believe the seasonal distribution of events is significant, with an increase in activity starting in June, a marked peak in August, a rapid decrease in autumn and few documented events in winter and spring. As already mentioned above, the peak of events reported in August is partly explained by the period in which the glaciological surveys take place, and in general by the higher summer frequentation of the high mountains. However, this distribution is also indicative of the type of glaciers of the Italian Alps. In fact, only a minority of glaciers are located at high elevations and can therefore be considered "cold", while most Italian glaciers can be considered "temperate". Since only cold glaciers are not affected by seasonal temperature fluctuations, as their instability is related to the internal deformation of ice bodies, it is logical that the dynamics of most Italian glaciers is instead linked to the seasonal temperature fluctuation and to the presence of liquid water inside the glacial bodies and at the ice/bed interface (see section "Types of glacier failures"), which drives glacier instability and failure. In this regard, it should be recalled that winter and spring events, despite being rare events, are among the most dangerous glacier failures, because they can trigger massive ice-and-snow avalanches: this is what is supposed to have happened e.g. in December 1952 in Val Ferret (ID 61, tab. 2), and what happened in 1986 and 2017 at the Palon de la Mare Glacier (events ID 49, 15, tab. 2). Even if, as mentioned above, it is not possible to recognize an evident trend in the seasonality of occurrence of glacier failures, it is interesting to note that no events were documented in spring before 1986. Still about timing, despite the little information in this regard, the research has highlighted that it is not possible to identify a more favorable time of day for the triggering of ice failures, since events took place indifferently during the night, in the morning, afternoon and evening: this observation is in agreement with the case studies analyzed by Alean (1985), and is likely related with the temporal scale of short-term ice thermodynamics, which cannot reach the hourly scale due to thermal offset.

The highest volume reached by a glacier failure in the Italian Alps (Belvedere 2005, 1.1 M m^3, event ID 33) is among the highest ever reported for the European Alps, surpassed only by the collapses of the Altels Glacier (CH) in 1895, which probably had similar process initiation mechanisms, and of the Allalin Glacier (CH) in 1965. The number of events for the different volume classes partly follows the distribution observed for other types of natural instabilities (e.g. landslides), with an exponential decrease in the number of events for increasing volumes (Tebbens, 2020). However, in the case of this dataset, if most of the events (25, 63%) have volumes in the range 10,000-50,000 m^3, the number of events in the higher volume classes is quite constant: this trend can be explained considering that, while it is true that the number of events decreases as the volume increases, large events are unlikely to go unnoticed, so they are more likely to be reported. Considering the characteristics of the Italian glaciers and their current evolution, and what is documented in other Alpine regions, the volume reached by the Belvedere glacier failure can be considered a reference value for the maximum order of magnitude of glacier failures in the Italian Alps. Much higher volumes are documented for glacier failures in the literature (Alean, 1985; Kaab & *alii*, 2018; Jacquemart & *alii*, 2020), but refer to very different geographic and climatic contexts, where glaciers can be much larger.

Finally, regarding the mobility of glacier failures, the comparison with the data reported by Alean (1985) shows how the lowest value of tan α in our dataset (0.33) is very close to the lowest value (0.30) found by Alean for the Swiss Alps. This value (0.30) can therefore reasonably be considered the limit value for the mobility of ice avalanches in the Alps, as also suggested by Allen & *alii* (2022). Significantly lower values (0.10) are documented in the literature, but refer to events of tens of millions of m^3 that occurred in geomorphological and climatic contexts very different from the Alpine one (Kaab & *alii*, 2018). On the other hand, our dataset contains several higher values (up to 0.80) than those reported by Alean (maximum value = 0.63): this can be explained considering that Alean (1985) only analyzed ice avalanches (minimum volume = 200,000 m^3), while our dataset also contains smaller glacier failures, with lower mobility. As found for landslides (Corominas, 1996; Devoli & *alii*, 2009), and as far as can be inferred from the limited number of cases for which data are available, there is a positive correlation between volume and runout of glacier failures: in our dataset, however, this correlation is only observed for events smaller than 100,000 m^3, while larger events seem to escape the trend. In some cases (Grandes Jorasses and Palon de la Mare, with values equal to 0.70 and 0.68 respectively) it is possible that the ice temperature played a role: Maggioni & *alii* (2018) demonstrated that ice temperature significantly affects ice avalanche mobility in numerical models, determining whether or not meltwater is produced by friction during the ice flow. In other cases (Belvedere 2005, event ID 33; Coolidge 1989, event ID 48) the limited mobility (0.64 and 0.78, respectively) compared to the large volumes involved (1.1 and 0.2 M m^3, respectively) can be attributed to geomorphological constraints, i.e. the presence of a depression at the foot of the slope where the detachment took place, which stopped the ice avalanche. In this regard, however, it should be kept in mind that if the depression at the base of the Monte Rosa East slope had still been occupied by the Effimero Lake, the effects of the 2005 glacier failure could have been amplified, generating a dangerous flood wave: the presence of glacial lakes at the base of potentially unstable glaciers is a factor to be carefully considered in the assessment of hazards associated to glacier failures, due to the possibility of generating cascading effects (Viani & *alii*, 2022). An example is the outburst flood of August 12, 1997 triggered by the detachment of about 3×10^6 m^3 of ice from the lower part of Diadem Glacier in the southern Coast Mountains of British Columbia. The collapsed ice fell into the Queen Bess Lake, producing a large displacement wave that overtopped and breached the Little Ice Age terminal moraine and flooded the west fork of Nostetuko River valley below the dam (Clague & Evans, 2000).

In the framework of the annual glaciological surveys of the Italian Glaciological Committee, the development of circular collapse features on the surface of glaciers is increasingly reported, in particular (but not exclusively) in the frontal, flat sectors. These features, called "calderoni" in Italy, commonly bordered by characteristic concentric crevasses, result from the action of en/subglacial meltwaters that create cavities at the ice/bedrock contact, with subsequent collapse of the roof of the cavities: they usually prelude and contribute to the disintegration of glacier fronts. Although out of scope, it is worth mentioning that "calderoni" represent an overlooked risk for mountaineers and skiers: in fact, despite the effects are very localized, important volumes of ice can be mobilized. In the night between 24 and 25 August 2020, the opening of a large cavity onto the Mandrone Glacier (Adamello, Central Italian Alps) made news and mountaineers were warned about possible risks. According to ARPA Lombardia (2020) the cavity had a surface of about 10,000 m^2, a diameter of about 100 m, and a maximum depth of 15 m: the collapsed volume of ice was estimated to be around 120,000 m^3. The cavities formed in recent years on the surface of the Forni Glacier (Central Italian Alps) are exemplary in this regard, and have been thoroughly studied (Azzoni & *alii*, 2017; Egli & *alii*, 2021).

CONCLUDING REMARKS AND FUTURE SCENARIOS

The dataset presented in this work is the largest ever published collection of glacier failure events in the Italian Alps, and perhaps the largest regional dataset, publicly available, globally. The compilation of this dataset was possible in particular thanks to the systematic observation of the main Alpine glaciers carried out in the framework of the annual glaciological surveys promoted by the Italian Glaciological Committee and published since 1928. This dataset is certainly only partially representative of the glacier failures that have occurred in the Italian Alps in the last 90 years. Despite this, a preliminary analysis allowed to highlight some significant features of glacier failures in the Italian Alps. First of all, it is evident that the number of cases has increased significantly since the 1990s, in parallel with the rapid, ongoing increase in air temperature. The close relationship between air temperature trend and destabilization of Italian glaciers is also suggested by the seasonal distribution of the events, mostly concentrated in summer, with a marked peak in August. Conversely, the diurnal cycle of air temperature does not seem to be a decisive factor for the initiation of glacier failures. Volumes of documented glacier failures are mostly in the order of 10^4 m^3, however events of a few hundred thousand m^3 are also documented, and the 2005 Belvedere ice avalanche (1.1×10^6 m^3) is one of the largest ever documented in the European Alps. The mobility is only partly related to the detached ice volumes, due to local geomorphological constraints, and possibly also controlled by the temperature of the collapsed ice. However, it is possible to define a tan α (H/L) range between 0.33 and 0.80 (corresponding to a slope range between 18° and 39°) for the Italian glacier failures, in line with the values obtained in other parts of the European Alps. The dataset compiled in this work could be further enriched through a systematic analysis of the aerial images of the Italian Alps (available starting from 1945) and of the photos taken from the ground (photographical archives), despite the difficulty in many cases to distinguish between ice avalanches and snow avalanches, and between accumulations formed by a single large event or a sequence of small events. However, the high number of events reported in sites where monitoring and/or in-depth investigations are carried out due to risks associated with glacier instability demonstrates how systematic monitoring/observation of ice bodies would significantly increase the number of case studies of glacier failures. This would allow for more accurate and statistically sound estimates of volumes, runout, frequency, etc. of glacier failures in the Italian Alps and their trend over time, crucial information for hazard assessment and risk mitigation.

Climate change is rapidly and drastically modifying the distribution, extent, geometry and properties of Italian glaciers, more vulnerable than other glaciers in the European Alps due to unfavourable exposure, small size, and decrease in precipitation south of the Alps (Brunetti & *alii*, 2009). In the long term, under the current climatic trend, the Italian glaciers will disappear, and with them the associated hazards - whereas new ones related to the paraglacial dynamics could develop. In the meantime, however, it is necessary to face present hazards, which are also undergoing rapid and radical changes. Some glaciers that in the past underwent major failures are now extremely small and, even in the event of further destabilization, will not produce collapses as large as in the past (e.g. Superiore di Coolidge Glacier). Other glaciers, retreating, move away from the rock steps that predispose their fronts to break-offs (e.g. Frébouge Glacier). In general, the slowdown of many glaciers reduces the supply of ice to the glacier front and therefore make break-offs less frequent and smaller (e.g. left lobe of the Mon Tabel Glacier). In other cases, however, the loss of connection between the accumulation basin and the glacial tongue can cause the positioning of the active glacial front on rock steps, predisposing to repeated ice failures (e.g. Lys Glacier). Furthermore, on several occasions, glacier front

Fig. 13 - Palon de la Mare Glacier, Ortles-Cevedale massif. Panoramic view of the path of the August 2006 ice avalanche (event ID 32, tab. 2): the white arrow indicates the stop point (photo G. Cola). In the background the Branca Hut (circle).

detachment has occurred concurrently with ice thinning, perhaps because the ice mass no longer exerted sufficient pressure on the bedrock, facilitating the decoupling of the glacier tongue from the bed. The increased amount of meltwater circulating within and at the base of glaciers due to warm air temperatures can lead to an acceleration of the glacier dynamics (e.g. Planpincieux Glacier). Specific attention should be given to cold-based glaciers: their thermal regime could change in the future, creating the conditions for glacier failures with different behaviour than in the past (e.g. Whymper Serac). Finally, the interaction between glaciers and surrounding environments must be considered: the rock walls at the glaciers' margins, deprived of glacial support and subject to changes in the permafrost regime, are increasingly prone to failure (Giardino & *alii*, 2017; Lucchesi & *alii*, 2019; Deline & *alii*, 2021). Rockfalls that occur along the margins of the glaciers, falling on them, can entrain glacier ice, or even cause the glacier to collapse, producing dangerous rock-ice avalanches (e.g. Brenva Glacier, Barla & *alii*, 2000; Deline & *alii*, 2015; Pizzo Cengalo rock-ice avalanche, Walter & *alii*, 2020). On the other hand, the constant increase in the number and extent of glacial lakes can increase the hazard as glacier failures can trigger dangerous chain processes (Viani & *alii*, 2022).

In conclusion, hazard assessment from glacier failures, now as in the future, requires a careful analysis of the relationships between glaciers and the geomorphological setting of the host basins and surrounding areas, and must be continuously updated based on glacier evolution (Nigrelli & *alii*, 2013). The systematic and continuous observation of glaciers is nowadays facilitated by remote sensing data and tools (e.g. Paul & *alii*, 2020), which however must be complemented by field data, especially in the case of small and/or debris-covered glaciers such as most of the Italian glaciers. Finally, numerical models can provide valuable insights to assess current hazards and to anticipate future ones (Viani & *alii*, 2020), but must be validated against documented case studies for optimal performance. We hope that this work will stimulate similar studies in other regions of the European Alps and around the world, in order to fill the current lack of information on glacier failures.

SUPPLEMENTARY MATERIAL

Supplementary material associated with this article can be found in the online version at: http://gfdq.glaciologia.it/045_1_02_2022/

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