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Little Ice Age glacial systems and related natural instability processes in the Orco Valley (North-Western Italy)

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ABSTRACT

Glaciated and recently (post-Little Ice Age) deglaciated areas are very dynamic environments, undergoing continuous changes, in particular as a consequence of climatic fluctuations and cryosphere changes. The intense geomorphic activity that takes place here conditions natural hazard, sediment transport and tourist fruition. A geo-morphological mapping with applicative purposes has to take into account the peculiarities and the dynamism of these specific areas. We here propose a methodological approach based on the interpretation of a multitemporal set of aerial photos (from 1983 to 2012), in a GIS environment, with application to the sectors modeled by Little Ice Age glaciers in the upper Orco Valley (NW Italy). The result is a geo-morphological map focused on the elements that are most relevant for application purposes, complemented by a map of the spatio-temporal distribution of the natural instability processes identified in the study area for the reference period, aimed to highlight the recent dynamism of the geomorphological elements in the map.

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Western Alps; Gran Paradiso Massif; Little Ice Age; glacier; geomorphology; natural instability

1. Introduction

Glacial and periglacial areas are very dynamic environments, as a result of the incessant geomorphic activity carried out by glaciers during their advances and retreats, in response to climate fluctuations (Ballantyne, 2002; Giardino, Mortara, & Chiarle, 2017; Martini, Brookfield, & Sadura, 2001; Zasadni, 2007). This dynamism leads to a widespread and recurrent natural instability that controls sediment transfer (Curry, Cleasby, & Zukowskyj, 2006) and may become hazard (Evans & Clague, 1994; Geertsema & Chiarle, 2013; Huggel, Carey, Clague, & Käab, 2015). In this framework, hazard assessment requires a detailed and updated picture of the geological and geomorphological setting. This has become urgent in recent years, given the dramatic changes affecting the high mountains, in response to an accelerated global warming (Zemp et al., 2015). Particular attention should be given to areas of recent (since the end of the ‘Little Ice Age’ glacierization – LIA, around 1865; Painter et al., 2013) and very recent (last 2–3 decades) deglaciation: here, rocks and deposits have come to light, which were previously buried by ice and therefore not exposed to atmospheric processes (e.g. frost/thaw cycles) and to gravitational instability phenomena (Chiarle, Geertsema, Mortara, & Clague, 2011; Deline, Gardent, Magnin, & Ravanel, 2012; Giardino, Perotti,

Bacenetti, & Zamparutti, 2013). Being in disequilibrium with current environmental conditions at the ground/atmosphere interface, recently deglaciated areas are, thus, particularly prone to instability (Deline et al., 2015; Huggel, 2009; Paranunzio, Laio, Nigrelli, & Chiarle, 2015). The term ‘Little Ice Age’ was originally coined by Matthes (1939), referring to glacier regrowth in the Late Holocene, later renamed ‘Neoglaciation’ by Porter and Denton (1967). Nowadays, the term LIA refers to the latest glacier expansion of the Late Holocene, during historical time (13th to mid-19th centuries; Grove, 2004). While some authors argue that this term should only be used in a glaciological sense (Clague, Menounos, Osborn, Luckman, & Koch, 2009), often the term LIA has been introduced in a climatic context, referring to a shorter cold and snowy time interval (1570–1900 AD, Matthews & Briffa, 2005). In any case, glaciers in the northern hemisphere reached their maximum Holocene extent during the LIA (Orombelli, 2011); in the Alps, this was reached mostly in the final 1850/1860 AD advance (Ivy-Ochs et al., 2009). The LIA moraines are often imposing and well-preserved landforms, clearly marking this phase of glacial expansion, before present-day deglaciation. Many data exist for the Alps, where glaciers lost since then almost 50% of their total area (Zemp, Haeberli, Hoelzle, & Paul, 2006), while further research

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is needed for the Mediterranean mountains, where glaciers were also common during the LIA (Hughes, 2014). In different sectors of the Italian Alps, post-LIA glacier retreat has been highly variable, dependent on latitude and local topoclimatic factors, which strongly control glacier evolution, especially in Mediterranean mountains (Hughes, 2018). In the Julian Alps (Eastern Italy), e.g. present ice cover is one-fifth of the LIA one, but appears resilient to climate warming, due to geomorphological factors (Colucci, 2016). In the Maritime Alps, only some ice patches and semi-buried ice lenses remain of 30 LIA glaciers (Federici & Pappalardo, 2010). Moving towards north, glacier reduction in the Western Alps has been less dramatic, being about 80% of the original LIA extent in the Orco Valley (Nigrelli, Lucchesi, Bertotto, Fioraso, & Chiarle, 2015), and about 60% in the Aosta Valley (Curtaz, Motta, Théodule, & Vagliasindi, 2014).

To be suitable for hazard assessment purposes, the geological/geomorphological maps of glacial and periglacial environments should be realized at a proper scale (1:10,000 or higher) and with criteria highlighting the proneness of the mapped features to instability (Turconi, Tropeano, Savio, De, & Mason, 2015).

We applied this approach to the glaciated and recently (post-LIA) deglaciated areas at the head of the Orco Valley (Figure 1), for which we provide detailed maps (Main Maps), that have been conceived as a tool for the identification of areas prone to natural instability in a context of climate warming, while maintaining rigorous cartographic standards.

The geomorphological mapping has then been complemented with a multitemporal analysis, based on the comparison of aerial photos taken in the period 1983–2012. This analysis allowed to identify the natural instability processes that developed in the study area during that period, with the aim to highlight the recent dynamism of the geological and geomorphological elements represented in the maps. A map showing the spatio-temporal distribution of the starting points of the natural instability processes recognized in the study area through this multitemporal analysis has also been produced. The spatial occurrence of geomorphological elements and the spatio-temporal distribution of instability processes are comparatively analyzed, in order to i) assess the geomorphological conditions favoring the development of natural instability, and ii) identify recent trends of instability. We conclude highlighting the implications of this study for geomorphological mapping oriented to hazard assessment in glaciated and recently deglaciated mountains.

2. Geographical, geological, and climatic setting

The Orco Valley is one of the most glacierized valleys of the Piemonte region, in the North-Western Italian

Alps. The valley has a general orientation W-E and borders to the North with the Aosta Valley, with which it shares the highest mountain (Gran Paradiso, 4061 m a.s.l.). To the West, the Orco Valley borders with France, and the dominant mountains are the Levanne Massif (Levanna Centrale, 3619 m a.s.l.). The Orco Valley has an extent of about 620 km², but for this study we considered only the parts of the valley shaped by the LIA glaciers (53 km² in total), at an elevation between 2250 and 4020 m a.s.l.

The Orco Valley is part of the Alpine Axial Belt (Penninic Domain): the study area is dominated by the lithotypes of the Gran Paradiso Massif, mainly augen-gneiss and secondly fine-grained gneiss (Piana et al., 2017). Rocks of different types, belonging to Oceanic Units (in prevalence carbonate schists and micaschists), can only be found in the westernmost end of the valley. The combination of tectonic uplift and low erosion rates, due to rock hardness (DiPietro, 2018), is responsible for the high elevation of the mountain ridges that border the head of the valley and, consequently, of its high degree of glacialization.

The entire Orco Valley has been deeply sculpted by Pleistocene glaciers. However, as in other parts of the Alps (Ehlers & Gibbard, 2004), traces of these glaciations are rare, due to rapid glaciers downwasting (Ivy-Ochs et al., 2009) and subsequent deep erosional phases. Depositional evidences of these glaciations have been reported in the lower part of the Orco Valley and at its mouth on the piedmont (Carraro & Giardino, 2004). At the alpine valleys heads, including the study area, the traces of these glacial phases have been mostly overwritten by glacial readvances occurred during the LIA. Nowadays, the glacial landscape has been partly modified by gravitational and fluvial processes, which are becoming increasingly important as glaciers shrink and paraglacial processes develop, modifying the former glaciated environments (Ballantyne, 2002).

The climate in the Orco Valley is characterized by cold-dry winters and warm-wet summers. The mean annual temperature observed at one of the most representative meteorological stations (Ceresole Reale station, 1579 m a.s.l., 45°25'48"N, 07°14'40"E, observation period 1934–2012) is 4.7°C. Mean monthly temperatures show a unimodal trend: the hottest month is July with 14.3°C and the coldest is January with −4.6 °C. Total annual precipitation is 1082 mm. The mean monthly precipitation has two maxima, the principal one in autumn, 345.3 mm, and the secondary one in spring, 322.2 mm, and two minima, with the principal one in winter, 149.8 mm, and the secondary one in summer, 265.0 mm (Nigrelli & Audisio, 2010). Recent studies have shown a significant warming trend in the mean annual maximum and minimum temperatures, respectively 0.05°C/year and 0.04°C/year (1950–2012 period), while total annual precipitation shows no clear trends (Nigrelli et al., 2015).

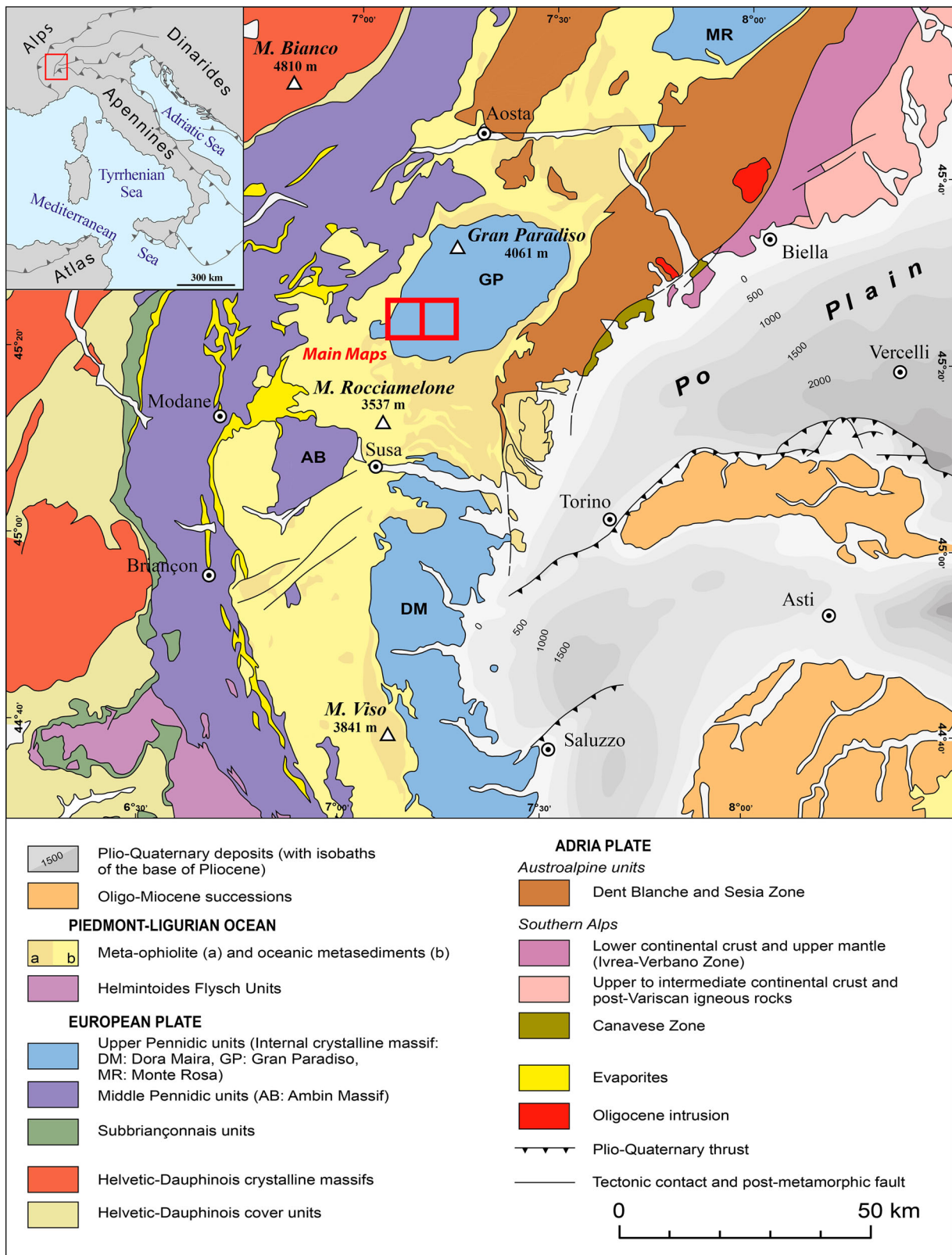


Figure 1 . Geological map of the Western Alps (modified from Bigi et al., 1990). The red insets show the investigated areas represented in the Main Maps.

3. Data and methods

The limits of the areas involved by LIA glaciers in the Orco Valley have been obtained from Lucchesi, Fioraso, Bertotto, and Chiarle (2014), and are outlined in the schemes A1 and B1 in the Main Maps. The geomorphology of the study area has been obtained from

the interpretation of a multitemporal set of aerial photos (Table 1) and represented in a GIS. The geomorphological mapping through remote sensing, rather than through traditional field surveys (although some field check was also carried out), allowed a homogenous mapping. At the same time, the use of a

Table 1 . List (from oldest to newest) and main characteristics of the sets of aerial photos that have been considered for this work. SI-P: stereoscopic images, printed; OP-O: orthophotos, available on-line.

Year	Provider (date of release)	Type	Quality
1983	ALIFOTO (11/01/1984)	SI-P	Snow on the ground/good
1988	IGM (20/03/1989)	SI-P	Snow on the ground
1991	IGM	SI-P (infrared)	Not useful
2001	Portale Cartografico Nazionale	OP-O	Quite good
2005/ 07	ALIFOTO – Comunità Montana Val Soana	SI-P	Good
2006	Portale Cartografico Nazionale	OP-O	Very good
2006	ARPA Piemonte	SI-P	Good
2010	Regione Piemonte	SI-P / OP-O	Very good
2012	Portale Cartografico Nazionale	OP-O	Good

multitemporal set of images allowed to (i) overcome local visibility problems caused by shadows, clouds, or snow cover, that can be encountered on a single flight and (ii) assess the dynamism of the geomorphological elements, by identifying the sectors that are recurrently subject to natural instability.

The aerial photos have been visualized by means of an analogical stereoscopic viewer, while digital orthophotos have been imported and analyzed directly in the GIS project created on purpose for this work. Stereoscopic viewing allowed an accurate tridimensional characterization of landforms, essential for their classification. On the other hand, orthophotos have been useful to locate and outline these landforms in the WGS 84 geographical reference system.

The good quality and high-resolution of the images and the above-mentioned methodology allowed an accurate and detailed analysis of the study area, which was carried out at the scale 1:5000. The geomorphological maps presented here (A2 and B2 in the Main Maps) have been produced at the scale 1:15,000, while the maps showing the spatio-temporal distribution of instability processes (A3 and B3 in the Main Maps) are provided at the scale 1:20,000.

3.1. Geomorphology of the Little Ice Age glaciated area

The geomorphological maps (A2 and B2 in the Main Maps) were created following the methodology proposed by Lucchesi, Giardino, and Perotti (2013), i.e.:

- identification of the major landforms, using the latest aerial photos of good quality available in our set (years 2006–2012);
- genetic interpretation of landforms and definition of the boundaries between the different geological bodies, based on their morphology and environmental context;

- GIS mapping of the observed landforms and of the geologic bodies, with the creation of three shapefiles (punctual, linear, and areal), containing, respectively, the points, lines and polygons representing the landforms and geologic bodies identified in the investigated areas;
- description of polygons, lines and points within the GIS database, associated with corresponding symbols to the map legend;
- superposition of the three shapefiles to create a geomorphological map.

In consideration of the specificity of the study area and of the purposes of our work, we mapped the following elements:

Glaciers. Their extent is updated to 2010, based on the latest available orthophotos where all glacial margins are well exposed. We distinguished three types of glacial cover: debris-free ice, ice with a thin debris cover and debris-covered ice. Debris-free glaciers have different behavior with respect to debris-covered ones (Scherler, Bookhagen, & Strecker, 2011); in addition, debris cover on glaciers is a clear indicator of slope instability (Deline, 2009). We also mapped crevasses, as indicators of glacier activity.

Glacial deposits and landforms. We distinguished the following types of glacial deposits: LIA till, discontinuous LIA till, pre-LIA till, and LIA-moraine deposit (Figures 2 and 3). LIA and pre-LIA till have been mapped separately, because of their different geotechnical properties, besides the different chronological information associated to them. When till formed ridges and mounds, we have mapped it as moraines: glacial deposits in the moraines are thick and coarse, and these characteristics condition the type and magnitude of the instability processes that can develop from them (Clague & Evans, 2000). We also mapped the moraine ridges and the edges of glacial cirques, which are associated with steep slopes, representing geomorphological elements prone to natural instability development.

Permafrost-related deposits and landforms. Specific attention has been paid to the identification and mapping of protalus ramparts, rock glacier deposits and ridges, because of their importance as permafrost indicators (Cremonese et al., 2011). Moreover, under specific climatic and topographic conditions, rock glaciers may represent a source of loose sediment, ready to be mobilized from different types of geomorphic processes, including debris flows (Lugon & Stoffel, 2010; Schoeneich et al., 2015).

Gravitational deposits and landforms. Landslides and talus have been mapped separately: a landslide accumulation is the product of a single-event slope failure, while talus is the result of multiple block falls and small rock falls. Talus fans have been mapped, if clearly recognizable, to highlight the most active channels for

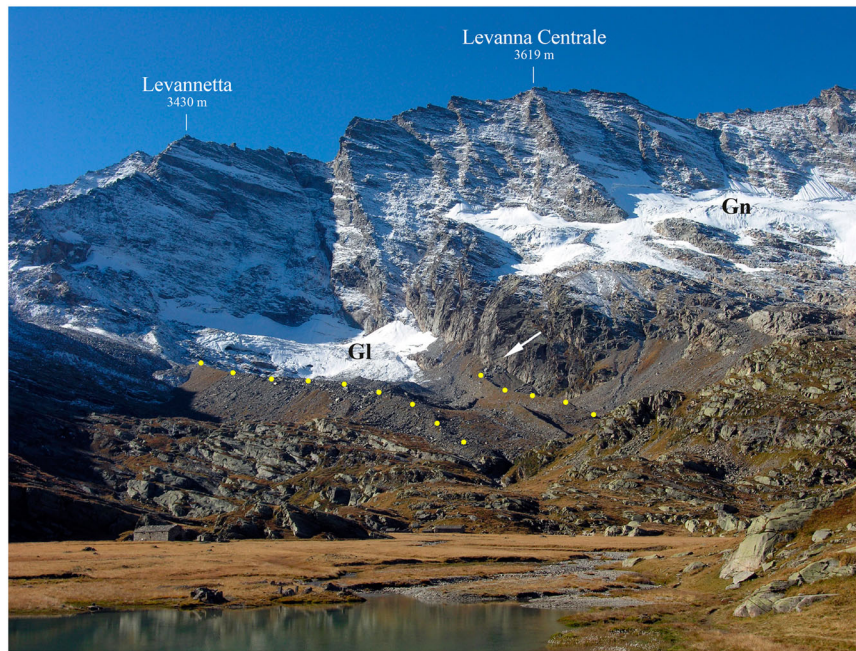


Figure 2. View of the north face of the Levanne Massif (right side of the upper Orco Valley). G1 and Gn indicate the Levannetta and the Nel glaciers, respectively. Yellow dots highlight the Little Ice Age moraine ridges of the Levannetta Glacier. The white arrow indicates a rock fall accumulation that involved the moraine ridge. The alluvial plain of Alpe di Nel is visible in the foreground. Photo taken from Guglielmo Jervis hut (2249 m a.s.l.), view looking SSW.

debris production. Debris-rich snow-avalanche accumulations have also been mapped, because they also reveal an active debris production from the slope.

Torrential and debris-flow deposits and landforms. Debris-flow deposits and channels have been mapped separately from torrential ones only if features leading to a clear attribution to the type of process (e.g. levees) were present. Debris-flows are very dangerous processes, given the suddenness, the high peak discharge and the destructive potential of this type of process (Hungre, Evans, Bovis, & Hutchinson, 2001). Alluvial fans have also been mapped.

Mixed deposits and related landforms. In some cases, a debris accumulation is the result of multiple processes acting on a slope (snow avalanches, landslides, torrent activity): in this case, it has been classified as ‘mixed deposit’, and the related form as ‘mixed fan’.

Bedrock. Considered the extreme lithological uniformity of the study area (augen gneiss of the Gran Paradiso Unit), bedrock has been mapped as undifferentiated.

Lakes. They are a common element in areas shaped by glaciers, in particular during phases of glacier retreat (Viani, Giardino, Huggel, Perotti, & Mortara, 2016). In particular conditions, lakes can develop outburst flood, which is one of the most hazardous processes in glacial and periglacial environments (Evans & Clague, 1994). For this reason, lakes are considered an important feature of the landscape and included in the geomorphological map.

Closed depressions and very large blocks. Closed depressions in periglacial environments undergoing

cryosphere degradation may indicate ground ice melting, and therefore are of particular interest for the purposes of this work. Very large blocks are important reference points for remote sensing analyses and field measurements.

3.2. Maps of the slope instability events

The maps illustrating the spatio-temporal distribution of natural instability processes in the study area (A3 and B3 in the Main Maps) were created according to the following steps:

- photo-interpretation of all available, good quality aerial images (7 flights from 1983 to 2012, see Table 1), to identify the evidences of the major instability events occurred in the study area, for each time step;
- attribution of the events to the following typologies: rockfall/landslide, debris-rich snow-avalanche, debris flow, debris slide (i.e. instability process developed from a debris accumulation).
- Afterwards, the attention has been focused on the starting zone of each slope instability event, because this is the most relevant information for assessing the proneness to failure of the mapped geological bodies. The following steps were carried out on this regard:
- GIS mapping of the starting zones of the slope instability events, represented by points placed in the highest part of the source area. The geometry of the starting points indicates the type of

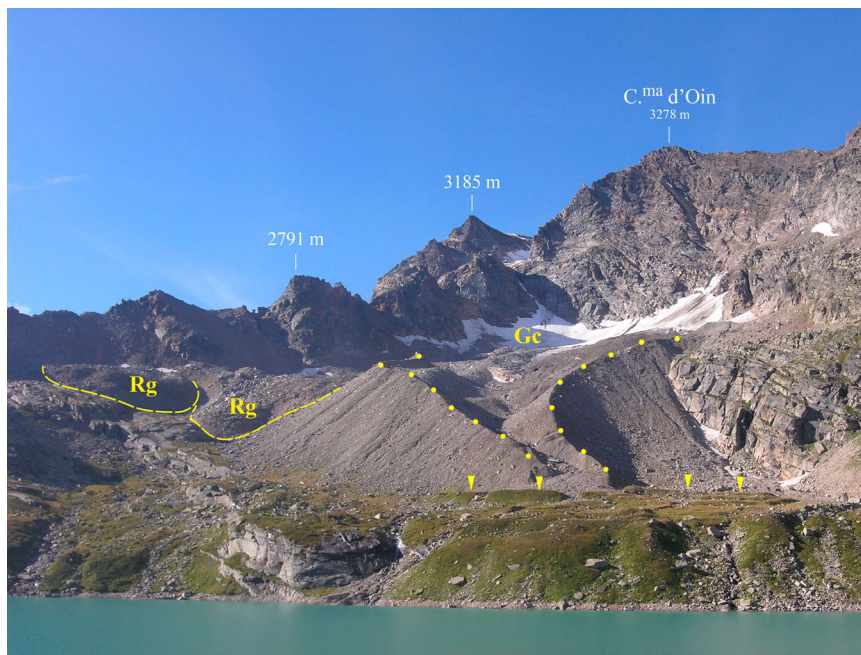


Figure 3 . View of the impressive Little Ice Age moraine system (yellow dots) of the Capra Glacier, on the North-Eastern slope of the Cima d'Oin – Cima della Valla drainage divide (right side of the upper Orco Valley). Note the absence of vegetation cover and the presence of gully erosions on the outer sides of the moraines. Gc indicates the present-day Capra Glacier. Rg: rock glacier. Yellow triangles highlight some frontal moraines of Late-glacial age. Photo taken from the northern shore of the Serrù Lake, visible in the foreground (2290 m a.s.l.), view looking SSW.

instability process, while their color identifies the year of the flight on which the instability event was recognized for the first time;

- superposition of the shapefile of the starting points on a simplified geomorphological map, including bedrock, deposits, glaciers, and lakes.

4. Results and discussion

4.1. Geomorphological analysis

The extent of the mapped areas are unevenly distributed on the right and left sides of the upper Orco Valley, 15.9 and 36.7 km², respectively. This reflects the larger extent of the LIA glacial cover on the left flank of the Orco Valley (26 glaciers, covering an area of 14.6 km²), with respect to the right one (7 glaciers, covering an area of 8.5 km²). This disparity is due to the different elevation of the left and right flanks of the valley: the former is dominated by the Gran Paradiso Massif (4061 m a.s.l.), while the latter is carved in the Levanne mountain group (maximum elevation 3619 m a.s.l.). Despite the higher elevation, the unfavorable exposure of the left flank of the Orco Valley towards S-SE caused a more pronounced glacier retreat (−73% from the peak of the LIA to 2010) with respect to the right side (−69% in the same period), facing NE. The overall glacier shrinkage in the study area since the peak of the LIA (−71%) is greater than the mean value found for the Aosta Valley (−60%), located immediately to the North, but is the lowest found for the

Western and South-Western Piedmont Alps (Nigrelli et al., 2015). Remarkably, one-third of the glacial surface is nowadays covered with debris, a value which is much higher than the mean one found for the Italian Alps (12% in 2006; Salvatore et al., 2015). The high percentage of glacial surface covered by debris in the study area may be explained with a combination of rapid ice melt and high-relief, along with high denudation rates, supplying large quantities of debris (Mihalcea et al., 2006).

In the study area, 12.4% of the surface is occupied by glaciers, while lakes represent only the 0.4%. Bedrock outcrops and deposits occupy almost equivalent areas (41% and 46%, respectively). These values are intermediate between those found for the Aosta Valley, where bedrock outcrops represent 2/3 of the deglaciated areas since the peak of the LIA (Curtaz et al., 2014), and those found for the Western and South-Western Piedmont Alps, where over 70% of the recently deglaciated areas are covered with debris (Lucchesi et al., 2014). This might be due to the much higher and steeper reliefs that characterize the Aosta Valley, compared to the South-Western Alpine sector, which do not favor debris accumulation. The Orco Valley has orographic characteristics that are intermediate between the Aosta Valley (with massifs such as the Mont Blanc – 4809 m a.s.l.) and the South-Western Italian Alps (Monviso, 3841 m a.s.l.; Argentera Massif, 3297 m a.s.l.), which may account for the observed balance between rock outcrops and debris accumulations.

The most abundant deposits are glacial deposits (56% of the mapped deposits, covering 26% of the study area). They are mostly composed of supraglacial melt-out till and secondly of flow till, deposited during the LIA. The maximum advance of LIA glaciers is generally marked by sharp end-moraine systems, free of vegetation. Sometimes, pre-LIA glacial deposits have also been recognized and mapped. Gravitational deposits cover less than 8% of the study area; they consist mainly of rock/block-fall accumulations, sometimes organized in talus slopes/cones. Gravitational deposits are proportionally more abundant on the left side of the Orco Valley, likely as a consequence of the higher relief of this flank. Debris-rich avalanche accumulations, instead, were mostly found on the right side of the valley. This picture is consistent with the outcomes of a study carried out by Regmi and Watanabe (2009): they detected a seasonal rockfall activity on the north-facing slopes, which experience a small diurnal range of rock surface temperatures and seasonal freeze-thaw; the other aspects, which undergo frequent diurnal freeze-thaw, were characterized instead by the infrequent release of large debris and year-round rockfall activity. Several rock glaciers have also been identified, and they are more abundant on the right flank of the Orco Valley, in shaded zones. They generally develop from LIA glacial deposits: they can be found just below a glacier front, or on a side of a moraine ridge (e.g. Capra Glacier right lateral moraine), or in deglaciated areas (e.g. Col Perduto extinct glacier). The location of rock glaciers in the study area does not allow to shed light on the open debate about the genesis of these features (Monnier & Kinard, 2015).

4.2. Starting points of natural instability processes

The multitemporal aerial-photo interpretation led to identify over 1400 starting points of natural instability processes (Figure 4). As already mentioned, the year associated with each starting point is that of the first flight on which the event was observed. Normally, the event should have occurred in the interval between the observation year and the year of the previous flight. However, the quality of the image may have hampered the observation of a specific event, that was then recognized on a subsequent flight: in this regard, the date associated to a specific event has to be considered as a minimum age. Debris-rich snow avalanches represent an exception: they must have occurred in the same year of the aerial photo, since their evidence is destined to be canceled the next winter by new snowfalls.

The type of natural instability that has been most frequently recognized are debris flows (Figure 5a) and debris-rich snow-avalanches, which together

account for almost 80% of the events inventoried for this work. The total number of debris flows and debris-rich snow-avalanches identified is about equivalent, however, debris flows prevail in the period 1983–2001, while debris-rich snow avalanches generally exceeded the number of debris flows in the following years (Figure 4). On this regard, it should be mentioned that heavy precipitations with devastating consequences were recorded in the Orco Valley in September 1993 and October 2000 (Nigrelli & Audisio, 2010): in both cases, the high elevation of the 0°C isotherm caused the occurrence of instability processes also at high altitude (see, e.g. the huge debris flow from the Mulinet Glacier moraine, on September 1993; Mortara, Dutto, & Godone, 1995). For what concerns the distribution of debris-rich snow-avalanches, it must be noticed that the spring/summer 2012 has been one of the warmest ever recorded in the Piemonte region.

The identification of rock-falls on aerial photos is challenging, as they are generally small and often add to existing deposits. Therefore, the number of rock-fall starting points that have been mapped is certainly underestimated. However, a cluster of events was observed in 2006, a year characterized by a month of July with marked thermal anomalies (up to +4 °C) on the Italian and French Alps, with values that in several places exceeded the historical highs. Important rock falls have been documented in the Alps in that period (Paranunzio et al., 2015) (Figure 5b, c).

Finally, the analysis of the spatial distribution of the starting points pointed out that more than a half are located on rock slopes. This observation is consistent with the conclusions of several studies, which point out how rock walls are particularly prone to instability, in particular in a context of climate change, due to their high slopes, and to the fractures that convey heat through fluids circulation (Gruber & Haeblerli, 2007). Rock falls represent a common paraglacial process, related to stress redistribution in a deglaciated rock slope (Ballantyne, 2002; Fischer, Käab, Huggel, & Noetzli, 2006). The starting points of several debris flows, and of some debris-rich avalanches, are located in deposits of various types, in particular till, torrential or gravitational deposits. Rock glaciers, areas with discontinuous till, landslide accumulations, and dead ice do not host, instead, a significant number of starting points, probably because of their low slopes.

5. Concluding remarks

In this work, we propose a geomorphological map specifically intended as a support to applied studies in glaciated and recently deglaciated areas, in particular for purposes of natural hazard assessment. However, this map can provide valuable base information also for studies, e.g. of sediment yield, water resources, tourism development.

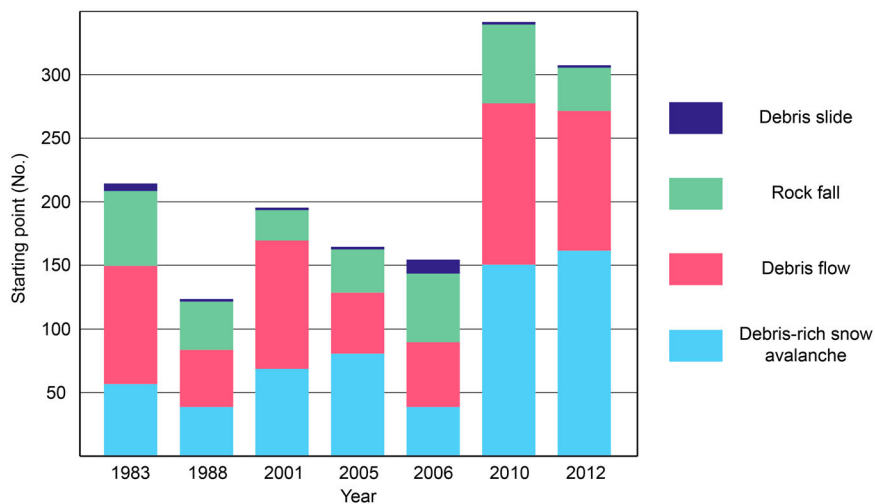


Figure 4 . Temporal distribution of the instability events in the Orco Valley from 1983 to 2012.

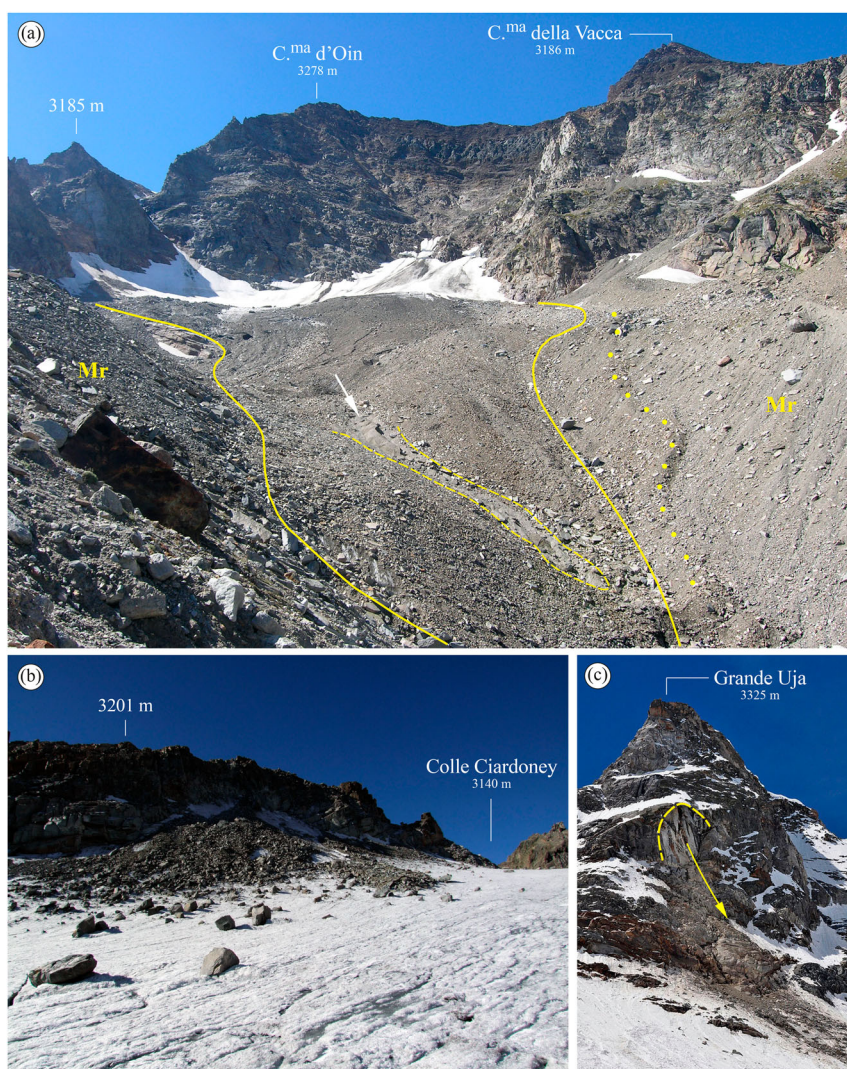


Figure 5 . (a) View of the Capra Glacier (outlined by the yellow lines), widely mantled by a thick debris cover. Mr indicates the inner sides of the Little Ice Age moraines. A recessional moraine is visible on the right (yellow dots). The white arrow highlights a outburst mudflow originated in the August 2010 from some kettle holes in the distal portion of the glacier. Photo taken from the right-lateral moraine ridge (2550 m a.s.l.), view looking SSW. (b) Rock falls involving fractured orthogneiss of the Gran Paradiso Massif, along the right border of the Ciardoney Glacier. Photo taken in September 2007 from the Ciardoney Glacier (about 3040 m a.s.l.), view looking SW (photo by G. Mortara). (c) Large rock fall along the North-East wall of the Grande Uja di Ciardoney. Dashed yellow line indicates the rock fall scar. Photo taken on June 13, 2016, from the Ciardoney Glacier (about 2900 m a.s.l.), view looking SW (photo by SMI).

In consideration of the specific needs of applied studies, and of the peculiarities of glaciated and recently deglaciated areas, the map was made at a detail scale and updated with the latest good quality aerial imagery available for the study area. The multitemporal analysis, covering a range of more than 30 years, allowed to recognize a large number of slope instability events (over 1400 starting points), which provided additional information on the degree of activity of the geomorphological elements represented in the maps. This information is particularly crucial for high mountain areas, where geomorphological processes are very active, especially under present climate change. The main drawback of our work is that it lacks a systematic check with field data. This means, in particular, that the quality of the map is tightly related to the quality of the imagery that has been used. This issue is particularly relevant for mapping the starting points of natural instability processes, while the use of multi-temporal images allowed to minimize the problems of misinterpretation of geomorphological features, that may be encountered when using a single flight.

The use of GIS tools makes it possible to statistically analyze the geomorphological composition of the area of interest, to compare and combine the geomorphological information with other types of geographical data. Moreover, in a GIS environment, the information can be easily updated and implemented. This last point is crucial for fast evolving areas, like the glaciated and recently deglaciated ones. In conclusion, glacier shrinkage, permafrost degradation, and snow cover reduction are dramatically changing the alpine landscape and geomechanical properties of rocks, debris, and ice, generating new hazards and modifying the spatio-temporal distribution of already existing ones. For this reason, hazard assessment in high mountains has to be frequently reviewed, based on updated information on the geological and geomorphological setting, and on on-going geomorphological dynamics. The methodology that we propose in this work for the upper Orco Valley aims to meet these needs and to contribute to a new, dynamic approach to hazard assessment in mountain areas, which takes into account geomorphological dynamics activated by climate change.

Software

The geomorphological maps were created using Esri ArcGIS® 10.4, while the maps of the instability events were created using QuantumGIS 2.14.3. The final layout was made with Adobe® Illustrator® CS5. Photos were managed and compiled using Adobe® Photoshop® CS2.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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