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MARIA CRISTINA SALVATORE [1,2*], NICOLA BERTOCCHINI [1],
SIMONA GENNARO [1,2] & CARLO BARONI [1,2]

GEOMORPHOLOGICAL MAP OF VALNONTEY (GRAN PARADISO GROUP, WESTERN ALPS, ITALY)

ABSTRACT: SALVATORE M.C., BERTOCCHINI N., GENNARO S. & BARONI C., *Geomorphological map of Valnontey (Gran Paradiso Group, Western Alps, Italy).* (IT ISSN 0391-9838, 2021).

This paper describes the geomorphology of Valnontey (Valle d'Aosta, Graian Alps), located in the heart of the Gran Paradiso National Park in the Western Alps and illustrates the annexed geomorphological map at the scale of 1:15,000. Valnontey retains a relevant heritage of landforms linked to the Pleistocene and Holocene glacial activity, as evidenced by the characteristic Alpine morphology with its typical erosional landforms (U-shaped valleys, glacial cirques, horns, arêtes, trimlines) and well-preserved moraines. A complex system of moraines and glacial deposits outcropping outside the limit of the Little Ice Age (LIA) indicate a Lateglacial advance related to the Younger Dryas cold period (correlable to the Egesen *Auct.*). Valley and cirque glaciers are the most common and widespread glacier forms. Well-preserved LIA and present-day moraines testify recent glacier fluctuations at the valley head and at the highest elevation, where Valnontey still hosts glaciers that are among the widest and most impressive of the entire Gran Paradiso Group. The Valnontey glaciers have experienced an areal reduction of more than 50% since the LIA, and frontal retreat has further increased since the late 1920s, with a remarkable acceleration of contraction since the end of the 20th century. At present, the processes due to mass wasting, running water, periglacial and nival activities are playing a relevant role in sculpting the landscape. The geomorphological map was realized by using indirect survey techniques based on the photo-interpretative analysis of stereoscopic aerial photographs, digital orthophotos, LiDAR data, and long-lasting geomorphological field surveys. The structure of the legend follows the guidelines suggested by Campobasso & *alii* (2018). All the collected data were computerized and managed in a GIS environment, in order to build a geomorphological database containing morphogenesis, morphodynamic, morphotype, chronology (where possible), geological structure, and any additional information from other sources. This geomorphological map furnishes a significant tool for contributing to land management, geomorphological risk prevention, and geomorphosite valorization of this well-known and highly popular valley of the Gran Paradiso National Park.

KEY WORDS: Geomorphological mapping, Alpine geomorphology, Lateglacial, Holocene, Gran Paradiso Group.

RIASSUNTO: SALVATORE M.C., BERTOCCHINI N., GENNARO S. & BARONI C., *Carta geomorfologica della Valnontey (Gruppo del Gran Paradiso, Alpi Occidentali, Italia).* (IT ISSN 0391-9838, 2021).

Il presente lavoro descrive la geomorfologia della Valnontey (Valle d'Aosta, Alpi Graie), situata nelle Alpi Occidentali, nel cuore del Parco Nazionale del Gran Paradiso, e illustra la carta geomorfologica allegata alla scala di 1:15 000. La Valnontey conserva un rilevante patrimonio di forme legate all'attività glaciale del Pleistocene e dell'Olocene, testimoniato dalla caratteristica morfologia alpina con tipiche forme erosionali (valli a U, circhi glaciali, cime piramidali, *arête*, *trimline*) e morene ben conservate. Un complesso sistema di morene e depositi glaciali che affiora esternamente al limite della Piccola Età Glaciale (PEG) indica un'avanzata Tardoglaciale legata al periodo freddo dello *Younger Dryas* (correlabile all'Egesen *Auct.*, Baroni & *alii*, 2021). Alla testata della valle e alle quote più elevate, dove si annidano i ghiacciai (tra i più estesi e imponenti dell'intero Gruppo del Gran Paradiso) si trovano le morene della PEG e quelle attuali, che documentano le fluttuazioni glaciali più recenti. A partire dalla PEG, i ghiacciai della Valnontey hanno subito una riduzione areale di oltre il 50% e, a partire dalla fine degli anni '20 del XX secolo, il ritiro è progressivamente aumentato (con una marcata accelerazione nel corso degli ultimi 30 anni). Attualmente, i processi dovuti al *mass wasting* e all'azione delle acque superficiali, così come i processi periglaciali e nivali, giocano un ruolo rilevante nel modellamento del paesaggio. La carta geomorfologica è stata realizzata con tecniche di rilevamento indiretto,

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Authorship Statement - Project design by MCS and CB. NB and MCS conducted photointerpretation with the contribution of CB and SG. NB and MCS organized the database and processed the GIS data. CB conducted glacial-geological and geomorphological field surveys with the contribution of SG, NB and MCS. MCS prepared the first draft of the manuscript, while the final version was accomplished with the contribution of all authors.

Declaration of Competing Interest - The authors declare that they have no conflict of interest.

basate sull'analisi fotointerpretativa di aerofotografie stereoscopiche, ortofoto digitali e dati LiDAR, oltre che su rilevamenti geomorfologici e geologico glaciali. La struttura della legenda è organizzata secondo le linee guida suggerite da Campobasso & *alii* (2018). Tutti i dati raccolti sono stati informatizzati e gestiti in ambiente GIS, per costruire un database geomorfologico, che include dati morfometrici, morfogenetici, morfodinamici, morfocronologici (ove possibile), e strutturali, oltre a eventuali dati aggiuntivi. Questa carta geomorfologica fornisce uno strumento rilevante che può contribuire alla gestione del territorio, alla prevenzione del rischio geomorfologico e alla valorizzazione dei geomorfositi di questa nota e frequentata valle del Parco Nazionale del Gran Paradiso.

TERMINI CHIAVE: Cartografia geomorfologica, Geomorfologia Alpina, Olocene, Gran Paradiso, Alpi.

INTRODUCTION

The Gran Paradiso Group hosts the homonymous National Park (Parco Nazionale del Gran Paradiso, hereafter PNGP), the first Italian national park founded in 1922 (R.D.L. of 03/12/1922, n. 1584 in Gazz. Uff., 13/12/1922, n. 291 and then converted into Law 17/04/1925 n. 473 in Gazz. Uff., 05/05/1925, n. 104). Among one of the best-known natural parks in Italy and in the world, the PNGP is devoted to preserve national and international ecosystems for the present and future generations (IUCN & WCPA, 2017). Since 2014, the park has been included in the IUCN Green List, the list of a very small number of parks in the world (around 46 in 2019) chosen by the International Union for Conservation of Nature (IUCN & WCPA, 2017; IUCN Green List areas website). Although the Gran Paradiso Group preserves a relevant natural and cultural heritage, no geomorphological maps have yet been published and there is a strong need to produce a document for the entire massif, created with a new methodology and updatable in the Geographic Information System. Geomorphological maps are indeed crucial documents that synthetize landscape evolution by describing the origin and state of activity of landforms, and also by documenting the effects of past and ongoing climate changes on the natural environment. High mountain environment is exposed to the enhanced effects of climate warming, as the rate of warming is amplified with elevation, and the effect of elevation-dependent warming (EDW) accelerates the rate of change (ROC) in the complex and sensitive mountain system (Pepin & *alii*, 2015). Moreover, geomorphological maps are unique tools for land management and geomorphological risk prevention and also for geomorphosite valorization, whose relevance for the valorisation of natural and cultural heritage has recently been strongly confirmed (Reynard & Coratza, 2013).

In these perspectives, we implemented the geomorphological map of Valnontey, a wild valley located in the heart of the Gran Paradiso Group (Graian Alps, Western Alps) at a scale of 1:15,000.

THE STUDY AREA

Left tributary of the vast Cogne valley, Valnontey (fig. 1) shows a S-N orientation and develops for about 12 km from the village of Cogne in the north to the innermost and highest sector of the Gran Paradiso Group in the south, where the valley head reaches the highest altitudes. The valley spans in elevation from less than 1600 m on the lowest part of the valley floor to more than 3600 m, if we consider the

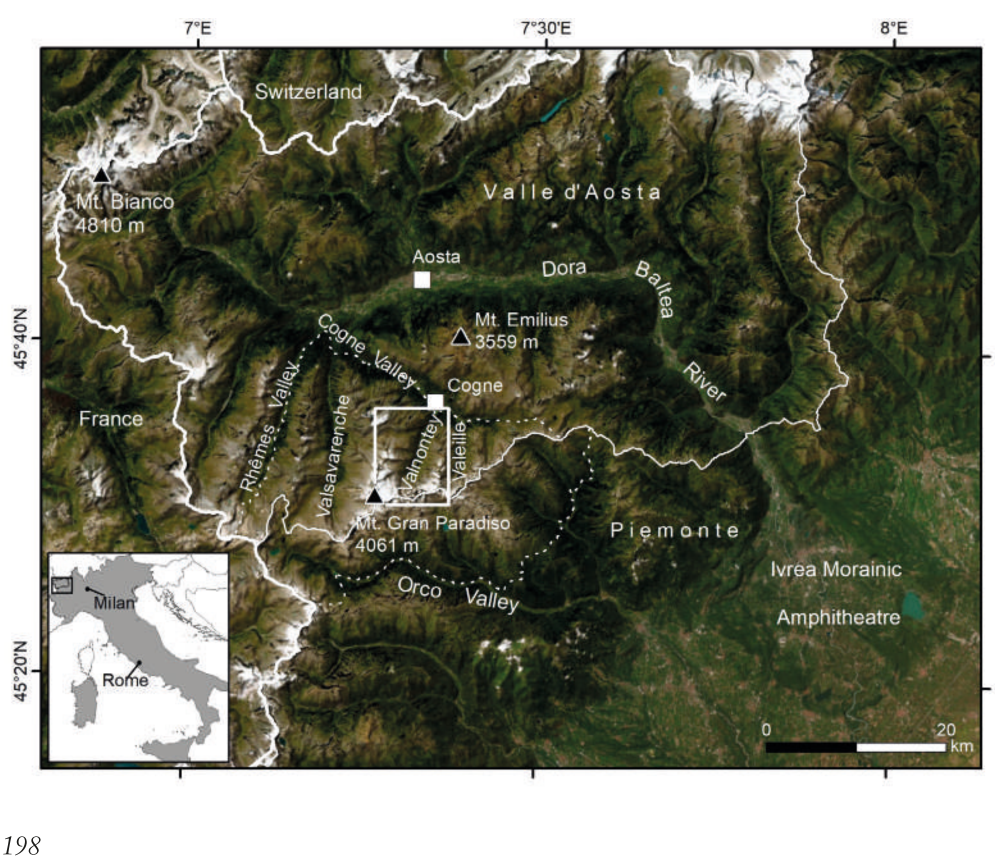

FIG. 1 - Location map of the study area (white rectangle). Dotted line indicate the Gran Paradiso National Park boundary. Base map source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.

peaks distributed on the main watershed, which reach the maximum height with Mt. Gran Paradiso (4061 m a.s.l.), the highest mountain of the entire massif.

Glaciers represent one of the most suggestive elements of the Valnontey landscape. A large part of the valley is affected by imposing glaciers, the most impressive of which is certainly the Tribolazione Glacier, the largest in the entire Gran Paradiso Group.

Climatic conditions of the area are strongly related to relief shape and geographic location; these factors can contribute to the development of microclimatic conditions (Garzena & *alii*, 2015; Poussin & *alii*, 2019). The average climatic conditions over the period 1980-2010, calculated based on the HISTALP dataset (Auer & *alii*, 2007) are shown in fig. 2. The average monthly rainfall shows two maxima, one in autumn and the other one – of minor entity – in spring/early summer. Indeed, the months characterized by an average precipitation (P) over the annual mean P in the 1980-2010 period were: AMJ (with a mean of 103 mm/month) and SON (with a mean of about 130 mm/month). Over the same period (1980-2010), the driest conditions, with a minimum of precipitations, can be detected during JA and D+-JFM(yr+1) (with a mean of 71 and 68 mm/month, respectively). On the basis of the HISTALP dataset (Auer & *alii*, 2007) and of the averages over the 1980-2010 period, the average temperature values computed for the Gran Paradiso Group range from about 10 °C during the summer (JJA) to about -5 °C during the winter (D+JF(yr+1)).

The temperature data (°C) of the period 10/2001-12/2022, obtained from a meteorological station located in Valnontey (45.5855 °N, 7.3371 °E, at 1682 m a.s.l.), are available online from the Functional Center (CF) of the Aosta Valley Region (https://presidi2.regione.vda.it/str_dataview, last access: 13/01/2023). The Valnontey records an average temperature (computed over the period 2002-2022) of 13 °C and -4 °C during summer (JJA) and winter (D+-JF(yr+1)), respectively.

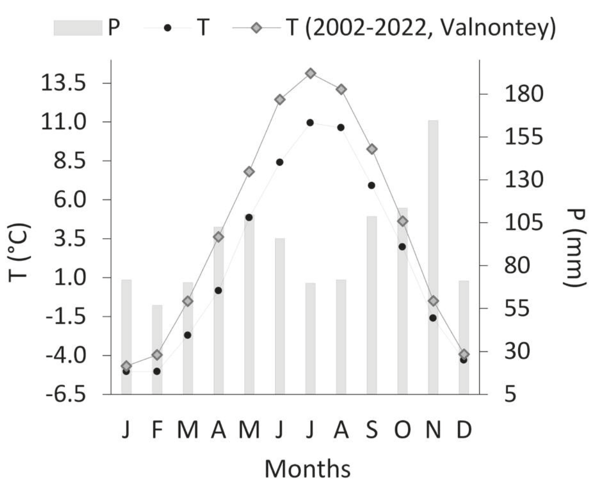

Fig. 2 - Climograph of the Gran Paradiso Group calculated on the basis of the HISTALP dataset (Auer & *alii*, 2007) over the period 1980-2010 (30 yrs). Grey diamonds represent the average temperature calculated between 2002 and 2022, considering data available online from the CF of the Aosta Valley Region (https://presidi2.regione.vda.it/str_dataview, last access: 13/01/2023). Temperatures (T in °C) are in the left y-axis and precipitations (P in mm) in the right y-axis.

Valnontey is inserted in the geological context of the Gran Paradiso Group, a large tectonic window overthrusted by different structural elements of the Piemont-Ligurian oceanic units in eclogitic facies, which include the Money Unit and the overlying Gran Paradiso Unit (Compagnoni & *alii*, 1974; Brouwer & *alii*, 2002; De Giusti & *alii*, 2003; Le Bayon & Ballèvre, 2006; Le Bayon & *alii*, 2006). The Money Unit, outcropping in the Valnontey and Valeille tectonic windows, is a Permo-Carboniferous mono-metamorphic complex consisting of a thick sequence of metamorphosed volcanic rocks and coarse-grained terrigenous rocks (Le Bayon & Ballèvre, 2006; Manzotti & *alii*, 2014, 2015a, b). The volcano-sedimentary sequence is intruded by a highly fractionated granitoid known as Erfaulet Granite, which is associated with aplitic and pegmatitic dykes. The boundary between the Erfaulet Granite and the units belonging to the Money complex was interpreted as a late Palaeozoic intrusive contact (Le Bayon & Ballèvre, 2004).

The Gran Paradiso Unit is spread over the entire study area. It consists mainly of gneiss-occhiadini derived from porphyritic metagranitoids of the Late Palaeozoic Age (Chessex & *alii*, 1964; Bertrand, 1968; Bertrand & *alii*, 2000), intruded into metasedimentary rocks (fine Gneiss). High-temperature relicts of regional pre-Alpine (Variscan) metamorphism, as well as evidence of contact metamorphism, were found in metasediments along intrusive contacts (Compagnoni & *alii*, 1974; Le Bayon & Ballèvre, 2006). The entire Variscan basement is covered by metasediments of the Permian-Liassic Age (Elter, 1960, 1972; Polino & Dal Piaz, 1978; Le Bayon & Ballèvre, 2006). The Piedmont-Ligurian Unit in Valnontey outcrops in the northern sector and is mainly represented by the classical ophiolitic triad consisting of prasinites, gabbros and serpentinites (Nebbia & *alii*, 2016; Piana & *alii*, 2017).

Basically, the current morphology of the Gran Paradiso landscape is the result of the glacial shaping that repeatedly occurred during the Pleistocene glacial periods and, in particular, during the Last Glacial Maximum (LGM), when large ice fields covered most of the Alpine chain (between about 26 and 19 ka; Ivy-Ochs & *alii*, 2008; Ivy-Ochs, 2015; Clark & *alii*, 2009; Gianotti & *alii*, 2015, and references therein). During the LGM, the imposing Dora Baltea Glacier, fed by the large ice fields flowing from the lateral valleys (Porter & Orombelli, 1982), occupied the entire valley floor of the Aosta Valley and reached the Canavese plain near Ivrea (Gianotti & *alii*, 2008, 2015). The past position of the great Dora Baltea Glacier is evinced by a vast and well-preserved complex morainic system, the so-called 'Ivrea Morainic Amphitheatre' (IMA), which is among the largest and best-preserved morainic amphitheatres in Italy (500 km^2), less extensive than only the Garda morain complex. Built by a number of major glaciations that occurred from the end of the Early Pleistocene to the Late Pleistocene, the IMA complex started to be deglaciated between 23.8 ± 1.7 ka and 20.1 ± 3.0 ka (Gianotti & *alii*, 2015). During the Lateglacial, the Dora Baltea Glacier completely retired upstream of the IMA and the large confluent glacial masses started to split into single minor glaciers, progressively retreating and advancing within their respective secondary valleys (Sacco, 1921; Gianotti & *alii*, 2015). The last significant glaciers advance in the Holocene dates back to the culmination of the Little Ice Age (LIA), during which glacier fronts reached their maximum Holocene extent (Orombelli, 2011; Vanuzzo, 2001). Glacial bodies are currently located mainly at the highest elevations of mountain ranges, often nested within glacial cirques crowning the valleys, while valley glaciers or composite valley glaciers are less frequent. The glacial imprint has now been reworked and in some cases even erased by numerous gravitational and fluvial processes occurring throughout the Valle d'Aosta region and, in particular, in the Gran Paradiso Group, both in the main and tributary valleys. The morphogenetic processes linked to the freeze/thaw cycles and to the permanence of snow on the ground are also relevant and widespread in all the territory, among which avalanches are the most impactful forms of nivation both for their high number of events and for the danger they pose to people and infrastructures (De Biagi & *alii*, 2012).

METHODS

The geomorphological map of Valnontey was realized using photointerpretation techniques integrated with newly and previously unpublished geomorphological and glacial geological field survey data. We carefully analysed stereoscopic aerial photographs taken in 1975, in paper format (23 × 23 cm) and in real colours, at a mean scale of 1:25,000, with a ground resolution of less than 1 m. Digital colour orthophotos at high geometric resolution (2006, 2015) and LiDAR data (2005, 2008) were used to improve photointerpretation. We collected Valnontey historical maps depicting glaciers dating back to the 18^{th} century as well as drawings (Baretti, 1875; Druetti, 1897; Peracchio in Porro, 1903), which provided a useful tool for reconstructing the position reached by glaciers during the Little Ice Age. A complete list of aerial and cartographic documents used as sources of data is reported in tab. 1.

The structure and the legend of the geomorphological map follow the criteria adopted by the Italian Geological Survey and by the Italian Association of Physical Geography and Geomorphology (Gruppo Nazionale Geografia Fisica e Geomorfologia, 1986; Brancaccio & *alii*, 1994; Campobasso & *alii*, 2018). The symbols are in accordance with those adopted for other large-scale geomorphological maps in alpine areas (Baroni & Carton, 1996; Panizza & *alii*, 2011; Coratza & *alii*, 2019; Carton & *alii*, 2021).

The various erosional and depositional landforms were depicted in different colours on the basis of their morphogenesis, while different symbols indicated features, geometry, and nature. Active and inactive landscape features were represented by darker and lighter tones, respectively.

The base for the geomorphological map was the Regional Technical Topographic Map at a scale of 1:10,000 produced by the Valle d'Aosta region, derived from the CGR 1991 aerophotographic coverage partially updated by the CGR IT2000 and the CGR 2003 flights (CTR-Carta Tecnica Regionale, Edition 2005, https://geoportale.regione.vda.it/download/ctr/, last accessed in Jan. 2023). As regards toponymy, the place names adopted in the CTR are different from those used in the IGM map: in our paper we refer to the toponomy of the Regional Technical Map with the exception of glaciers' name, which refer to the Inventory of Italian glaciers (CGI-CNR, 1961).

The geomorphological data derived from photointerpretation and field surveys were manually digitized and acquired in the vector domain (*.shp, point, line, polygon according to their geometry) by using the ESRI software Arcmap 10.2.2 and the open-source software Quantum GIS Desktop (coordinate system UTM-WGS84 - zone 32N). In order to create a geomorphological database, the alphanumeric attribute tables (dBase, *.dbf) associated with vector files were populated by inserting data related to morphogenesis, morphotypes, morphodynamics and, when available, chronology.

TABLE 1 - List of documents used as sources of data.

Survey year	Document	Contour interval (m)	Scale/pixel size (m)	Source
1885	F. 41 – Gran Paradiso, topographic map (paper map)	50	1:100,000/~9 × 9	IGM, Florence
1901	F. 41 – Gran Paradiso, topographic map (paper map)	50	1:100,000/~9 × 9	IGM, Florence
1931	Topographic map (raster format)	25	1:25,000/~2.5 × 2.5	IGM - Ministry of Environment and Protection of Land and Sea (WMS)
1952	Map (originally paper format)		1:100,000/~6 × 6	Vanni & *alii* (1953)
1975	Aerial photograph (paper format)	-	~1 × 1	CGR
2003	Technical Regional Topographic Maps (Raster and Vector, *.dxf)	10	1:10,000	Valle d'Aosta Region (Ed. 2005)
2005	DTM from LiDAR	-	0.5 × 0.5	Valle d'Aosta Region (bottom valleys)
2006	Digital colour orthophoto	-	0.5 × 0.5	Ministry of Environment and Protection of Land and Sea (WMS)
2008	DTM from LiDAR	-	2 × 2	Valle d'Aosta Region (high elevations)
2015	Digital colour orthophoto	-	0.2 × 0.2	Valle d'Aosta Region

FEATURES OF PRESENT-DAY GLACIATION AND HYDROGRAPHY

Valnontey hosts among the most impressive glaciers of the entire Gran Paradiso Group (fig. 3). The glaciers of this area can be classified as warm-temperate in terms of thermal regime; and as "local" or mountain glaciers considering their morphologies. In 2015, 15 glacial bodies (tab. 2, fig. 4) covering an area of more than 1130 ha (corresponding to about 32% of the entire glacierized area in the massif) nested at the head of the main valley, where the widest glaciers are located, and on the highest elevations of tributary valleys. The Inferno Nord and Tuf Settentrionale glaciers, still existing in 1957 (CGI-CNR, 1961), are now extinct.

The glaciers' mean orientation is towards the northern quadrants and their distribution is within an elevation range spanning from 2700 m to 3500 m. As concerns the Equilibrium Line Altitude (ELA), Baroni & *alii* (2021) reported a mean value for the Valnontey glaciers corresponding to 3171 ± 18 m (2006 CE) calculated with the AABR method, very similar to the massif average in the same year (3164 ± 13 m).

On the western slope, proceeding from north to south, the first glacier is the Rayes Noires glacier (120), hosted in the cirque that develops south of Colle Rayes Noires (3441 m a.s.l.). The small glacial body, indicated as glacieret in the CGI Inventory, now appears to be vanishing.

Further south, the Tuf Glacier (117) and the Lauson Glacier (116) are located at the head of the Vallon du Loson (Lauson). The former, nested in the glacial cirque developed between Point de l'Enfer (3393 m a.s.l.) and Point de Leviona (3419 m a.s.l.), is sub-elliptical in shape and is affected by widespread supraglacial debris cover. The Lauson Glacier, located in the Col de la Gran Serre cirque, shows the eastern frontal margin largely covered by supraglacial debris, which masks its effective extent at the frontal margin. The impressive and complex latero-frontal moraine system testifies to the past major extension of this glacier.

At the head of the homonymous tributary valley lies the Gran Val Glacier (115), a mountain glacier with an irregularly subquadrangular shape characterized by a long apron front. The glacier surface has no debris cover and is diffusely affected by transverse crevasses.

Further south, the Herbetét Glacier (114) is embedded within the glacial cirque depicted by the high rocky crests of the Grand Sertz and the Herbetét. Listed in the CGI inventory (CGI-CNR, 1961) as a glacieret, the small glacier has widespread debris cover that affects the frontal zone and most of the median portion.

Located in the south-western sector, the Dzasset Glacier (ID code113.0, named Tsasset on the map) is a simple basin valley glacier, extending for about 116 ha. The glacier's surface is free of supraglacial debris and extensively crevassed. At the highest elevations of the accumulation basin the glacier retains windscoops and avalanche cones, the latter significantly contributing to its feeding.

The widest glacial body of the entire valley is the Tribolazione Glacier, which extends for more than 500 ha. The head of this wide compound valley glacier is delimited by a rocky crest, which reaches its highest elevation at the Gran Paradiso (4061 m a.s.l.). Most of the glacier's surface is deeply affected by crevasses and seracs, the latter well evident near the frontal margin and in correspondence to the structurally-controlled bedrock-slope breaks. The glacial ice flows are divided into three main branches defining an articulated

TABLE 2 - Valnontey glaciers in 2015. The names and identification codes (code.sub-code) of each glacier follow the criteria adopted by Salvatore & *alii* (2015), according to the Italian Glaciers Inventory (CGI-CNR, 1961). For the location, see fig. 4 and the geomorphological map.

Glacier name	CGI code.sub-code	WGI code	Area (ha)	Group
Pêne Blanche (o di Patrì Superiore)	108.0	IT4L01512018	27.6	Gran Paradiso - Rocciaviva
Valletta	106.0	IT4L01512017	19.7	Gran Paradiso - Rocciaviva
Patrì Inferiore	107.0	IT4L01501107	8.6	Gran Paradiso - Rocciaviva
Coupè di Money	109.0	IT4L01512019	145.9	Gran Paradiso - Rocciaviva
Money	110.0	IT4L01512020	124.1	Gran Paradiso - Rocciaviva
Grand Croux	111.0	IT4L01512021	91.8	Gran Paradiso - Rocciaviva
Grand Croux Orientale	111.1	-	16.8	Gran Paradiso - Rocciaviva
Grand Croux Sud-Occidentale	111a.0	IT4L01512041	5.1	Gran Paradiso - Rocciaviva
Tribolazione	112.0	IT4L01512022	512.1	Gran Paradiso - Rocciaviva
Dzasset	113.0	IT4L01512023	116.6	Gran Paradiso - Rocciaviva
Herbetét	114.0	IT4L01512025	4.5	Gran Paradiso - Rocciaviva
Gran Val	115.0	IT4L01512026	31.6	Grivola Gran Serra
Lauson o del Gran Sertz	116.0	IT4L01512027	21.6	Grivola Gran Serra
Tuf Meridionale	117.0	IT4L01512028	11.1	Grivola Gran Serra
Inferno Nord	118.0	IT4L01512029	-	Grivola Gran Serra
Tuf Settentrionale	119.0	-	-	Grivola Gran Serra
Rayes Noires o della Rossa	120.0	IT4L01512030	2.5	Grivola Gran Serra

FIG. 3 - The valley head of Valnontey. The Grand Croux Glacier on the left, the Tribolazione Glacier in the center (photo N. Bertocchini, June 2018).

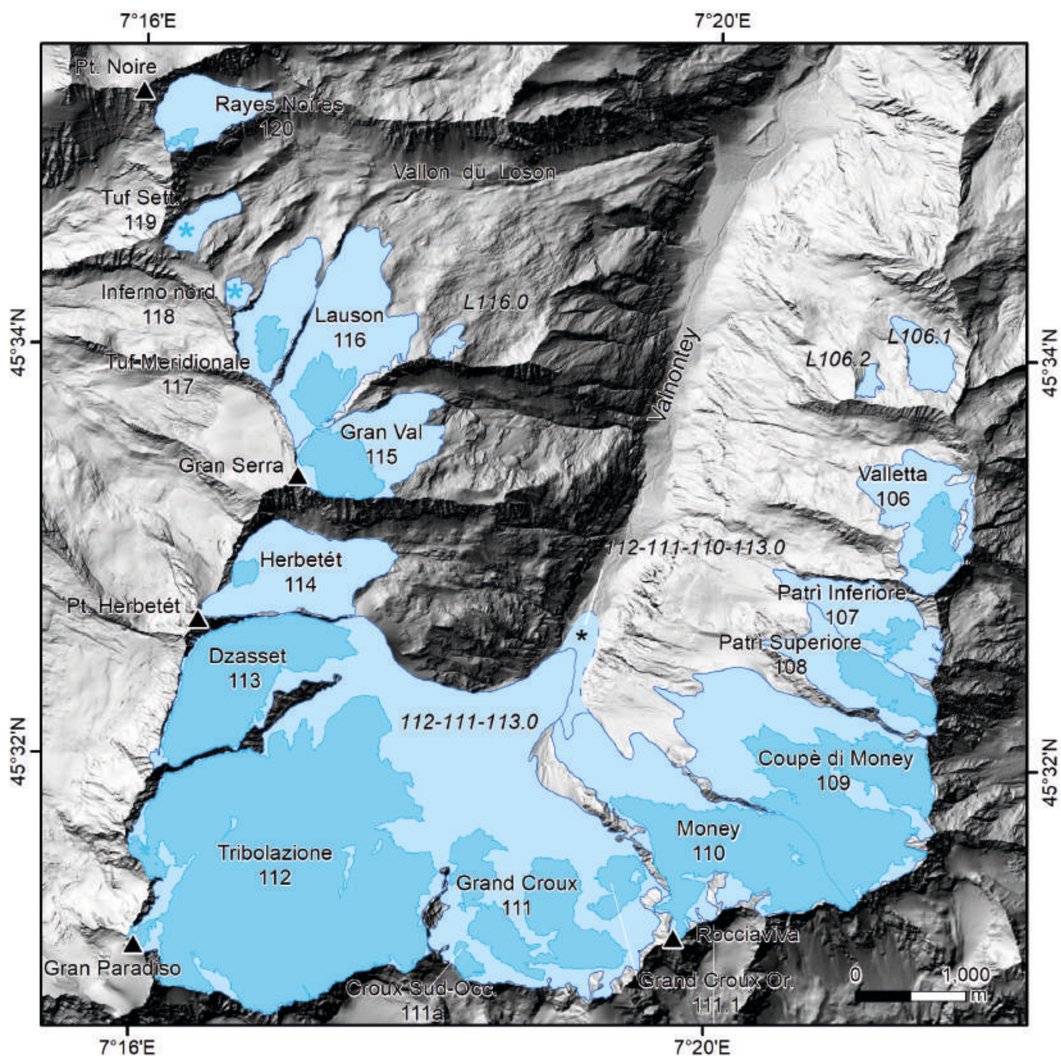

FIG. 4 - Valnontey glaciers during 2015 (dark cyano) and the Little Ice Age (light cyano). Numbers in italics refer to codes attributed to glaciers coalescing during the LIA or, if preceded by the letter L, existing only during the LIA. The asterisk on the front of the composite glacier indicates the position reached by the front during the LIA according to Sacco's reconstruction. In this work, the position of the front we reconstructed on the basis of geomorphological evidence is more rearward and the Money Glacier is separated from the Tribolazione Glacier. Cyano stars indicate extinct glaciers with respect to 1957.

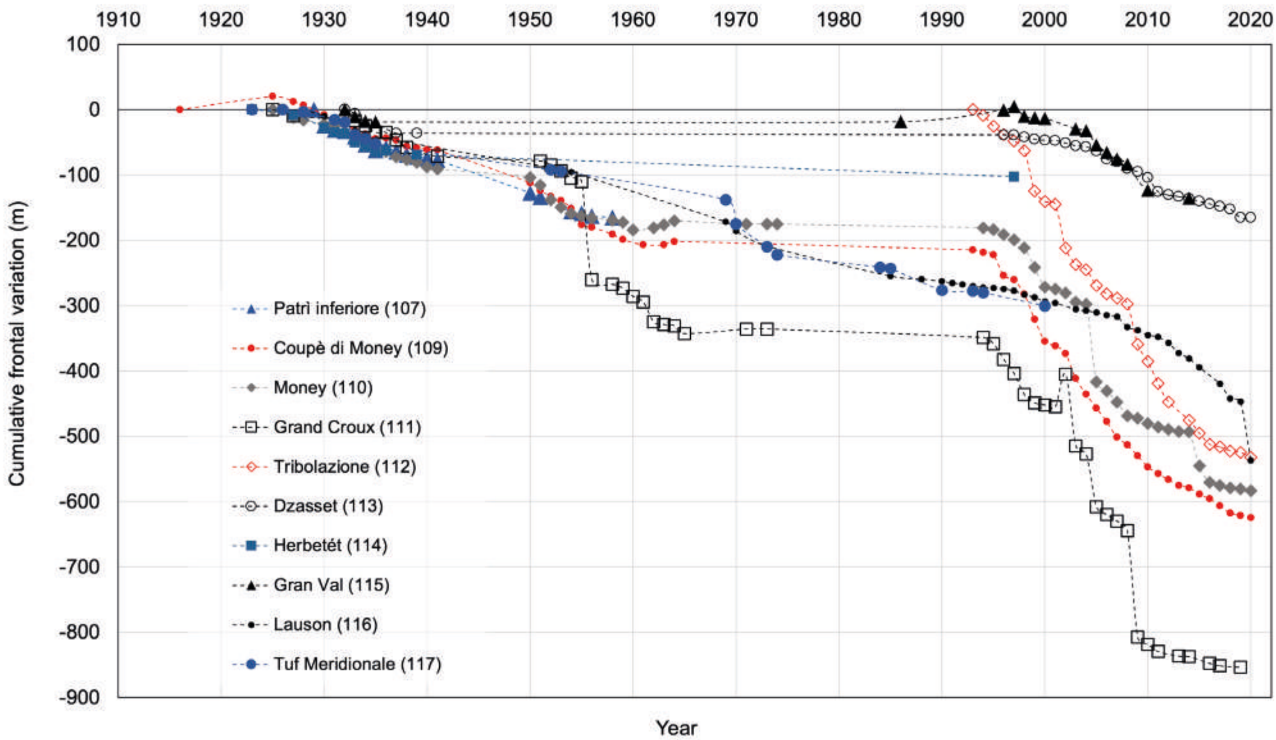

FIG. 5 - T-D curves of Valnontey glaciers. Dashed line indicates unlikely or no data on frontal variations.

frontal margin that alternates between sectors with ice cliffs and others with ice aprons. Supraglacial streams are widespread, in particular on the northern frontal margin, where numerous glacier mouths feed proglacial streams.

The south-eastern sector of the valley head is occupied by two extensive mountain glaciers, whose flows are separated by a well-defined ice divide: the Coupè di Money (CGI code 109.0) and Money (CGI code 110.0). The glaciers' surface is extensively affected by crevasses and seracs, while the supraglacial debris affects only part of the south-western front.

Located in the southern portion of the valley, the Grand Croux Glacier is currently fragmented into four distinct glacial bodies. At the highest altitudes, a small unit extends in the shadow of the head of Grand Croux (approx. 3440 m a.s.l.). Sacco (1922) named it the "Testa del Grand Croux" Glacier, while a more recent work (Salvatore & *alii*, 2015) – adapting to the nomenclature of the CGI Inventory – referred to it as the southwestern Grand Croux Glacier (Code 111a, tab. 1). This small glacial body flowed from an altitude of 3300 m to 3000 m and, since the 1930s, it has been hanging over the underlying main body of the Grand Croux Glacier. Fed by an effluence from the nearby Tribolazione Glacier until 2003 (Armando & *alii*, 2004), the progressive shrinkage and contraction of the Grand Croux Glacier has led to the separation of part of the eastern sector (Grand Croux orientale) during the 1950s and successively to the fragmentation of the main glacial body into two distinct units, connected only in a limited portion of the accumulation basin.

At the foot of the western slope of Pène Blanche Sud (3579 m a.s.l.) is located the Patrì Glacier, consisting of a southern portion stretching towards the valley floor, which is called the Pêne Blanche Glacier or Patrì Superiore (108), and of a northern portion, the Patrì Inferiore Glacier (107). In connection until the early 2000s, the two glacial bodies are now completely separate. The surface of the Pêne Blanche Glacier is mostly free of debris and characterised by extensive crevassed areas, while that of the Patrì Inferiore presents a considerable covering of supraglacial debris. Finally, placed along the slopes of the rugged rocky ridge between a well defined pyramidal peak (3417 m a.s.l.) and Point de Valletta Nort (3315 m a.s.l.), the Valletta Glacier (106) is a cirque glacier of reduced size, with widespread crevasses scattered over its entire surface. Numerous supraglacial streams affect the terminal area and contribute to feeding a small lake adjoining the frontal margin.

Snow detachments and collapses from glaciers' ice cliffs are frequently reported in glaciological campaigns, most notably that of the upper Patrì Glacier in 1934 (CGI-CNR, 1935) and the frequent events affecting the Money and Coupè di Money glaciers (e.g., 1930, 1931, 1939) and the Tribolazione Glacier front both in historical times (e.g., 1933, 1955) and more recently in 2009 (CGI-CNR 1928-1977; Baroni & *alii*, 2010). The instabilities affecting the glaciers are also related to glacial outburst events such as the one occurred on August 14, 2016 on the eastern portion of the Grand Croux Glacier, which required interventions for hazard mitigation in the following years (Baroni & *alii*, 2017, 2018).

TABLE 3 - Temporal lengths of the front variation measurement series and extent of frontal variation for the Valnontey glaciers.

Glacier name (code)	Observation period	Length (yr)	Validate observation	Variation (m)
Patrì Inferiore (107)	1929-1958	30	18	-165.3
Coupè di Money (109)	1916-2020	105	55	-624.5
Money (110)	1925-2020	96	58	-583.7
Grand Croux (111)	1925-2019	95	47	-853.5
Tribolazione (112)	1993-2020	28	26	-532.5
Dzasset (113)	1932-2020	89	28	-165.5
Herbetét (114)	1923-1997	75	10	-103.0
Gran Val (115)	1932-2014	83	17	-135.5
Lauson (116)	1928-2020	93	42	-537.1
Tuf Meridionale (117)	1923-2000	78	19	-300.5

TABLE 4 - Area (in ha) of Valnontey glaciers during the LIA. Numbers in italics refer to codes attributed to glaciers coalescing during the LIA or, if preceded by the letter L, existing only during the LIA. The asterisk indicates coalescent glaciers during the LIA, according to Sacco's reconstruction.

Glacier name (code)	Area (ha)
Tuf Settentrionale (119)	16.4
Gran Val (115)	87.0
Lauson o Gran Sertz (116)	126.0
Tuf Meridionale (117)	56.5
Coupè di Money (109)	272.7
Valletta (106)	80.9
Pêne Blanche (o Patrì Superiore) (108)	72.8
Patrì Inferiore (107)	66.4
(L106)	22.8
Herbetét (114)	98.9
(L116)	6.1
Inferno Nord (118)	5.0
(L106)	4.5
Money (110)	216.3
Tribolazione-Grand Croux-Dzasset (*112-1-3*)	1204.3
Tribolazione-Grand Croux-Money-Dzasset (*112-1-0-3*)*	1438.4

The snapshot of glaciers in 2015 shows glaciers that during the 20th century progressively reduced in size and/ or fragmented into smaller bodies. Some glaciers that existed in 1957 (CGI-CNR, 1961) are extinct, such as those to the north of Pointe de l'Enfer. A picture of more recent glacier fluctuations is provided by the time-distance curves (fig. 5) collected during the CGI annual glaciological survey (GFDQ 1928-2020, http:// www.glaciologia.it/en/i-ghiacciai-italiani/le-campagne-glaciologiche/) since the end of the 19th century (CGI, 1928-1977, 1978-2018; Baroni & *alii*, 2019, 2020a, 2020b). Among the glaciers hosted in Valnontey, 10 glacial bodies started to be monitored in the first decades of the 1900s and are still annually measured nowadays except for the Patrì Inferiore and the Tuf Meridionale glaciers, the measurements of which date back to the end of the 1990s. T-D curves evidence periods with no survey data, ever since around the 2000s. However, datasets have been continuous for many glaciers and recorded glacier fluctuations over the past 20 years. The Lauson, Grand Croux, Money and Coupè di Money glaciers retain the highest number of validated observations (42, 47, 58 and 55 observations, respectively) with measurement coverage of more than 90 years (tab. 3). The cumulative front variation curves depict a progressive retreat with a clearly stronger increase, in particular starting from the end of the 90s, interrupted by short periods of stasis or re-advance (fig. 5). In 2002 the Grand Croux Glacier exhibited an unexpected positive peak, which could be attributed to a collapse of the terminal part of the frontal zone that slid 50 m downstream, although it remained connected to the feeding zone (Armando & *alii*, 2003).

Considering the glaciers that are still being measured, the retreat ranges from about 165 m (Dzaset Glacier, 1933-2020) to over 600 m (Coupè di Money Glacier, 1925-2020). Remarkable is the Tribolazione Glacier, which has suffered a withdrawal of more than 540 m in less than 30 years.

Landscape analysis and historical cartography allowed to reconstruct glacier outlines during the LIA (fig. 4). Valnontey hosted 16 glacial bodies covering an area of about 2380 ha (tab. 4). The maximum position reached by the valley-head glacier is open to two different reconstructions (fig. 4), the former based on landscape analysis and the latter on historical literature (Sacco, 1921). Geomorphological evidence depicts two valley glaciers (Dzasset-Tribolazione-Grand Crux Glacier and Money Glacier) with distinct non-coalescent glacial tongues, descending into the valley floor to the elevation of about 1985 m and 2200 m, respectively. On the contrary, Sacco (1922) described Grand Croux and neighbouring glaciers as confluent into a single tongue, reaching an elevation of about 1900 m in the mid-19th century.

The data presented in this work are referred to the first hypothesis, which reconstructs a huge composite valley glacier (Dzasset-Tribolazione-Grand Crux Glacier) covering more than 1430 ha, corresponding to ca. 60% of the entire glacierized area in Valnontey during the LIA. The more easterly Money and Coupè di Money glaciers occupied a wide portion of the valley head and reached a frontal margin elevation of about 2370 m and 2190 m, respectively. Since the LIA, the Valnontey glaciers have undergone a marked reduction and contraction, which has led to a decrease in their number and extent, with a reduction of more than 50% over the last 160 years and a retreat of fronts of even more than 2000 m for the main glaciers (tab. 3).

As concerns the hydrographic network, Valnontey is furrowed for its entire length by the homonymous stream, fed mainly by the melted waters of the Tribolazione and Grand Croux glaciers. The Valnontey River catchment basin covers an area of about 60 km² and has an average altitude of 2713 m above sea level. In general, all the glaciers present in the valley contribute to feeding with their meltwater numerous minor streams descending from the lateral valleys and forming a dense hydrographic network.

GLACIAL LANDFORMS AND DEPOSITS

The Valnontey landscape retains remarkable traces of the Pleistocene glaciation testified by a typical alpine morphology with well-preserved erosional and depositional landforms like U-shaped valleys, roches moutonnées, cirques, horns, trimlines as well as glacial deposits and well-preserved moraines.

Erosional landforms

The main valley is characterized by a spectacular U-shaped transversal profile: the steep walls of glacial trough, inherited from the past glaciation, stretch for more than 9 km, and glacial shoulders are preserved along both sides at an elevation between 2200 and 2400 m (about 400-500 m above the valley floor). Several lateral tributary valleys overlook the main valley through a suspended threshold of hanging valleys. Glacial valley steps are found along the longitudinal profile of the main valley, in particular in the recently deglaciated area of the headwater sector, whose development is often related to a structural control.

Several glacial cirques occur at the highest sectors of the valleys, many of which are still occupied by glaciers or by glacierets and snowfields like those on the western slope of Valnontey hosting the Tuf Glacier and the Lauson Glacier, which perfectly preserve their characteristic bowl-like shape open at the lower end.

Sharp rocky crest-lines, horns and trimlines frame and characterize the uppermost sector of the study area in contrast with the smoothed landscape and rounded rocky crest lines that have been moulded by glacial erosion.

The *roches moutonnées* are widespread throughout the entire valley and well-preserved especially at higher altitudes, as in the proglacial area of the Tribolazione, Grand Croux and Money glaciers. Glacial striae all over the valley are well-developed on the *roches moutonnées* outcropping where deglaciation has occurred more recently; instead, these features are faint and less evident in areas deglaciated since the Lateglacial.

Trimlines are well defined by contrast in colour on the bedrock as a result of different weathering degree above and below upper erosional limits. Trimlines are well evident on the highest crest of the valley head and on the steep slope bordering the Comba de La Valletta and Comba Couteléina valleys (on the right-hand side of Valnontey), and they provide constraints on both the vertical and horizontal position of the glaciers during the LIA and the LGM. Sharp rocky crest-lines characterize throughout its length the main watershed of Valnontey, whose continuity is interrupted by transfluence saddles and short portions where rounded rocky crest-lines resulting from past glacial erosion are present.

Constructional landforms and deposits

Valnontey preserves relevant evidences of glacier activity with widespread constructional landforms consisting of glacial tills, lateral and terminal moraines, as well as of scattered glacial drift and erratic boulders. Moraines are widespread and often well-preserved in the entire study area, documenting Holocene and Lateglacial glacier advance and retreat phases.

Lateglacial moraines can be found locally throughout the valleys at low elevation close to the floor of the main valley and/or at higher elevations on the shoulders of Valnontey (fig. 6).

Lateglacial moraines are less common and only partially preserved compared to the Holocene moraines. Lateral moraines are generally better preserved, because they have not been obliterated by successive advances, as recorded in other parts of the Alpine chain (e.g., Cavallin & *alii*, 1997). In addition to the topographic context and compared to the more recent Holocene deposits, Lateglacial moraines show a higher degree of oxidation and weathering of boulders, a more extensive lichen cover and the development of soil on the top. In general, these features are more stabilized with less steep sides and are widely colonized by vegetation, with grass at the higher elevations and trees at the lower ones. Lateglacial lateral moraines are found on the right side of Valnontey in the Comba Coutelèina valley and on the so called Alpe Money (to the south-west of Money stream), where well-preserved lateral moraines outline the past Patrì and Coupè di Money glaciers. On the left side of the valley, beautiful examples of the Lateglacial advance are provided by the moraines of the main and secondary valleys of Grand Loson. Finally, relevant to the reconstruction of the glacial history of Valnontey is the presence of two segments of Lateglacial lateral moraines on the valley floor, near the village of Valnontey. Indeed, during the Lateglacial Valnontey was occupied by several glacial bodies, one of which is among the largest of the entire Gran Paradiso Group. The valley head hosted a vast valley glacier, the frontal margin of which is well depicted by lateral moraines deposited in proximity of Valnontey village at about 1680 m a.s.l.; a second relevant glacier occupied the Vallon du Loson but did not reach the main tongue of the valley glacier (Baroni & *alii*, 2021). ^{10}Be exposure dates from erratic boulders located on top of significant moraines chronologically constrain the last Late-

FIG. 6 - Lateglacial moraines on right slope of Vallon du Loson, at an elevation of about 2630-2640 m. In the background, glacial cirques of the eastern side of Valnontey. Note the rock glacier of the Grandzetta valley in the left cirque (photo N. Bertocchini, June 2018).

FIG. 7 - Little Ice Age latero-frontal moraines in proglacial areas of Grand Croux and Money glaciers (in the background) and Coupè di Money (on the left) (photo C. Baroni, July 1993).

glacial glacier advance phase to the Egesen stadial, as a result of climatic deterioration at around 12.9 +/- 11.7 ka (Baroni & *alii*, 2021). In fact, the Egesen (13.5-11.7 ka) is expressed in many sites by complex series of moraines which, in some cases, well testify also a multiple response to the latest Pleistocene climatic deterioration stage, as testified in several places across the Alps (e.g., Moran & *alii*, 2016; Baroni & *alii*, 2017).

Holocene deposits are widespread in all the areas overlooking the present-day glaciers and at middle-high elevation (fig. 7). Well-preserved moraines depict the maximum Holocene advance during the LIA, whose culmination in the Gran Paradiso Group dates back to ca. 1820-1850 (Beschel, 1958; Zienert, 1965; Vanuzzo & Pelfini, 1999; Vanuzzo, 2001; Lucchesi & *alii*, 2014).

LIA moraines and deposits consist mainly of a massive matrix-supported diamicton (Dmm) characterised by a silty matrix and subangular to sub-rounded clasts; differently from Lateglacial deposits, the soils are poorly developed and less than 20 cm thick (Baroni & *alii*, 2021).

The LIA lateral moraines show the characteristic sharp and well-shaped profile with steep and poorly vegetated flanks; the terminal moraines are generally less preserved since they are frequently remoulded by fluvio-glacial streams. As recognised for other areas in the Italian Alps (e.g., Chiarle & *alii*, 2007; Mortara & Chiarle, 2005; Zanoner & *alii*, 2017), the poorly consolidated LIA moraines are frequently affected by mass wasting processes, in particular by debris flow events.

Among the best examples of LIA moraine complexes, worthy of note are those facing the Tribolazione and the Grand Croux glaciers, which reach the lowest altitudes of Holocene glacial deposits in the valley (2000 m a.s.l.) and are among the longest and imposing morains in Valnontey.

The majestic glaciers located at the head of the valley during the late 1800s aroused the interest of enthusiasts of the natural phenomena of that time. Sacco (1922) describes the activity of Abbot Chamonin, who carved a sign (A.D. 1817) above a large angular boulder located less than a kilometre from Erfaulets Bridge, which had apparently been reached by the then united glaciers in 1817. In 1866, Abbot Carrel and Captain D'Albertis carved another sign on a rocky slope with the inscription 'Glacier-1866', marking the position reached by the glacier in that year.

Within the LIA limit, numerous other moraines underline phases of retreat and advancement that occurred after the maximum Holocene expansion. Fluted moraines, about one-meter high and from tens to hundreds of meters long, related to Holocenic sub-glacial deposits, characterize the proglacial area of the Tuf, Lauson and Herbetét glaciers. Finally, most present-day glaciers are characterized by the presence of supraglacial debris covering the lower part of the ablation zone, which continuously expands on account of the increased contraction and mass loss of the glacier.

CRYOGENIC AND NIVAL LANDFORMS AND DEPOSITS

Evidences of cryogenic and nival processes are testified throughout Valnontey, especially at the highest altitudes where temperature and precipitation conditions favour their development and permanence. Among the most evocative landforms are numerous rock glaciers located within glacial cirques or at the slope toes at higher altitudes. Most of the 30 mapped rock glaciers originated from Holocene glacial deposits and developed within perimeters previously occupied by LIA glaciers (glacier-derived rock glaciers). The most common morphology is tongue-shaped or complex, with a very broad root zone and a tongue-shaped snout. Only a few rock glaciers, smaller in size, originate from debris slopes. In both cases, the surface consists of coarse grained debris with well-developed longitudinal and transversal ridges and furrows, while the front slope shows a steep gradient. As regards altitude distribution, the rock glaciers of Valnontey are mainly located between 2800 m and 3200 m, and subordinately between 2400 m and 2800 m. Most of the rock glaciers can be considered inactive, especially the larger ones, which fall within the lower altitude belt cited before (fig. 8).

Among the most evident and extensive in the entire area is the rock glacier located in the cirque at the head of Grandzetta Valley (n. 26 in fig. 8), which covers an area of approximately 0.55 km^2 and stretches over 1 km in length between 2750 m and 2400 m in elevation, ending with a steep front. Other significant rock glaciers between less than 0.6 ha and 6 ha in size, are hosted on the right side of Vallon du Loson in the glacial cirques and at the slope toe at higher elevation. In some cases, more than one phase of activation of the rock glacier is recognised, with evidence of portions that are overextended on relatively older bodies, such as for example the rock glacier north of Pointe de l'Enfer and south of Pointe Feniliaz (n. 10-12 and 25-26 in fig. 8, repectively).

Avalanche channels are widespread throughout the study area and affect, in particular, the cliff faces at higher elevations, which are incised by deep gullies generally averaging about 100 m in length. However, avalanche channels are recognized also at lower elevations along glacial shoulders and across a few talus slopes. Avalanche deposits are common and clearly visible in the upper basin of glaciers, where they can significantly contribute to their feeding. The occurrence of avalanches is clear even at the lowest elevations where they are evidenced by avalanche paths. These latter are so frequent that they prevent the establishment of tree cover. As a matter of fact, if present vegetation growing on avalanche paths consists mainly of alders (*Alnus viridis*) and subordinately of rhododendrons, at the edges of the paths tall trees (larix, stone pine, and fir) often show clear impact scars or appear with completely or partially broken crowns and/or branches (candelabra tree shape, sensu Stoffel & Bollschweiler, 2008).

On the northeast slope of Mont Herban is preserved the most impressive avalanche path linked to an extreme event occurred on 15 December 2008. The avalanche, induced by extreme snow and meteoreologic conditions and exceeding the extent reported by the regional avalanche registries, affected an area of about 44 hectares and is still clearly visible nowadays because of vegetation removal along the slope (more than 5,000 trees including larches and spruces: (Debernardi & *alii*, 2022).

Blockfields (*felsenmeer*) and blocksheets (*sensu* Baroni, 1987) occupy relatively large areas located along the main watershed and at higher elevations, where the freeze-thaw activity is most effective in fragmenting exposed rock *in situ*. The mobilization of coarse rock debris along the slope originates linear deposits with downslope alignment, which define well-evident block streams.

Gelifluction lobes, ranging from 10 m to more than 300 m in length, are widespread on the eastern slope of Mont Herban, where occurrence is favored by the presence of schist bedrock that is highly affected by frost shattering and that provides a significant amount of fine material resulting from the weathering of phyllosilicates.

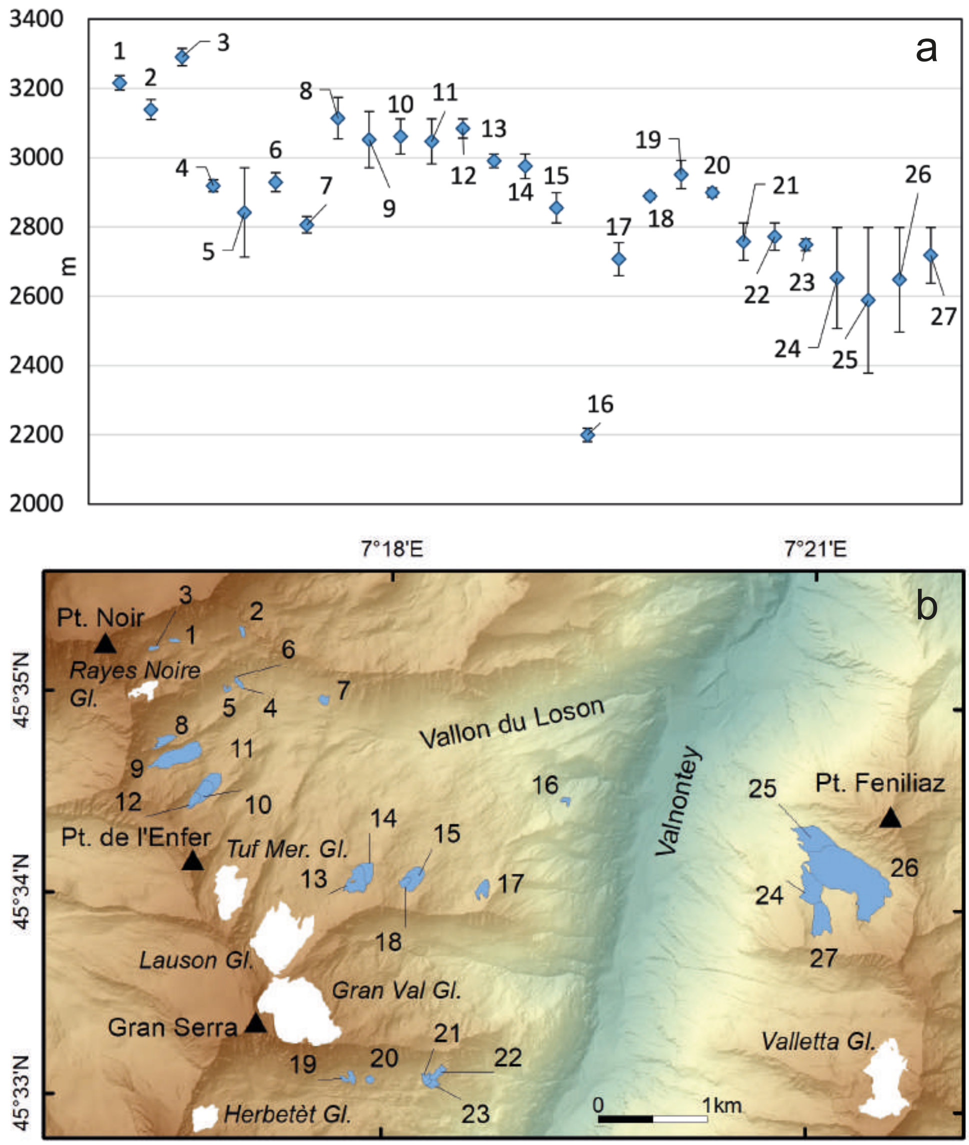

FIG. 8 - (a) Rock glacier distribution with respect to elevation in Valnontey. The caps at the end of the vertical bars indicate the minimum and maximum elevations; (b) Spatial distribution of Valnontey's rock glacier. In white, glaciers existing in 2015.

LANDFORMS AND DEPOSITS DUE TO GRAVITY

Gravitational landforms and deposits are among the most recurring features in Valnontey, favored by high relief energy, by the fracture system affecting the substrate, and by the frost action facilitating the production of debris (fig. 9).

Gravitational deposits are present throughout Valnontey, in particular in areas deglaciated since the Lateglacial. Scree and debris cones, widespread at the foot of rocky walls, smooth the junction between glacially eroded slopes and valley floor deposits and are frequently affected by channels and lobes of debris flow.

Landslides are widespread over the entire investigated area and assume a relevant role in the landscape evolution. The rock-falls are very common and represent about 95% of the landslides that have been mapped. We identified over 100 fall landslide bodies affecting areas ranging from 1 to more than 100 ha, and over 400 ha smaller in size, the latter evidenced by large single blocks located both along slopes and in valley bottoms. The glacial trough is likewise affected by a rotational landslide located a few hundred meters northeast of Pont des Erfaulets village and of two extensive complex landslides north of the village of Valnontey. The former, located on the right slope and the larger in size (about 41 ha), shows morphological evidence of a combination of both fall and rotational movement, while the latter, located on the opposite slope, extends for about 36 ha and shows peculiar characteristics of rotational sliding but also a component attributable to deep slope movements. Finally, we report on the NE slope of Mont Herban, in the Bois de Robat location, an extensive landslide body interpreted as a rock avalanche considering the large volumes of fragmented rock involved and the rock mass features.

Deep-seated gravitational slope deformations (DSGSDs) are a common type of large slope instability in Valnontey. Among the 5 DSGSDs identified, the two most relevant

FIG. 9 - Debris cone and scree slope, and degradational scarp on the left slope on the glacial trough (on the right). Note the well-developed recent alluvial deposits on the valley floor (photo N. Bertocchini, June 2018).

in size develop on schist bedrock. The former is located on the NE slope of Mont Herban (Inventory of Instability ID 30747, https://mappe.partout.it/pub/geodissesti/, last access January 4, 2023), and extends for more than 145 ha including the entire catchment area of the Buthier stream; the latter affects the left slope of the Vallon du Loson and extends for about 50 ha. Other smaller DSGDSs are located on both sides of the glacial trough north of the Herbetét stream (about 34 ha), on the eastern slope of Tramouail (20 ha), and at Grandzetta Valley (11 ha, Inventory of Instability ID 29919, https://mappe.partout.it/pub/geodissesti/, last access January 24, 2023).

LANDFORMS AND DEPOSITS DUE TO RUNNING WATER (PARTLY FLUVIOGLACIAL)

Erosional and depositional processes due to surface water runoff are quite diffused in the area and play a major role in the post-glacial shaping of Valnontey. The present-day hydrographic network is remoulding a morphology inherited from past glacial processes, by eroding Pleistocenic and Holocenic glacial deposits and moraine, and is depositing significant sedimentary bodies, which nowadays partially conceal the original U-shaped profile of the glacial trough.

The main valley floor and the vast plain of Pré de Saint Ours (Prati di Sant'Orso), which is part of a wider fluvio-glacial fan, are filled with fluvio-glacial deposits, mainly consisting of gravels and pebbles (fig. 10). Traces of paleochannels and overflow channels are still clearly recognized along the portion closest to the outlet of Valnontey and on the alluvial deposits of the valley floor, respectively. Palustrine deposits have settled on the inner edge of the alluvial deposits in the locality of Praz Soppia, south of the Valnontey village which, owing to their considerable naturalistic value, are included among the sites of Community importance for Aosta Valley, according to the EEC Directive 43/92.

A series of well-developed alluvial fans are located in the main valley at the junction between the valley floor and the glacial trough slopes. The distal portion of these sedimentary bodies appears in places complexly interdigitated with the alluvial deposits of the main Holocenic river, although in other cases it is clearly affected by fluvial erosion scarps. The texture of the alluvial fans generally consists of sorted rounded pebbly gravels with cobbles and boulders, locally containing debris flow deposits. Noteworthy is the large complex alluvial fan on which the Valnontey settlement stands, formed by an inactive telescopic-like alluvial fan on which an active fan fed by debris flow and avalanche events is superimposed. Alluvial fans also accumulate at the mouth of tributary valleys (e.g., Vallon du Loson) and at higher elevation on the right glacial shoulder, where the proglacial streams transporting power decrease (e.g., Pêne Blanc Glacier).

Common throughout the study area, debris flows are among the most vigorous processes that contribute to the shaping of the present-day landscape and are, together with avalanches, among the most significant drivers of geomorphological hazards in the area. Occurring at both high and low elevations, debris flows affect both bedrock and Quaternary deposits. We identified more than 300 debris flow channels, whose detachment zone originates at elevations spanning from 3463 m to about 1700 m. Most of the debris flows develop at the higher elevations, where they affect the lateral moraines of the LIA, scree slopes, and debris cones, owing to the large quantities of unconsolidated and mostly unvegetated sediments available. However, a significant number of debris flow channels and lobes reach the main valley floor, where they contribute to the development of composite fans.

FIG. 10 - In the foreground, the village of Cogne built on terraced fluvio-glacial deposits on which trace paleochannels are visible. On the right, evidence of the huge avalanche occurred in December 2008 on the eastern slope of Mont Herban, highlighted by the absence of tree cover. In the background, glaciers at the head of Valnontey. The view is from the north (photo N. Bertocchini, June 2018).

FINAL CONSIDERATIONS

The geomorphological map of Valnontey reveals a complex geomorphological history, characterised by the transition from a glacial to a non-glacial state. The post-LGM deglaciation and the accelerated glacier retreat since the Little Ice Age have led to a rapid transition, especially at high altitudes, from a glacial to a paraglacial environment (*sensu* Ballantyne, 2002), favouring slope denudation conditions.

During the Pleistocene, the Gran Paradiso Group and most of the Valle d'Aosta region were occupied by large icefields forming a complex glacial system of confluent glaciers feeding the huge Dora Baltea glacier. This large piedmont glacier built up the Ivrea Morainic Amphitheatre (IMA), after multiple Pleistocene glacial cycles (Gianotti & *alii*, 2008, 2015). Following the post-LGM deglaciation, the Dora Baltea glacier gradually retreated and, in the study area, broke up into smaller glaciers that nestled within the confluent valleys. During the Lateglacial, the Valnontey glaciers experienced advancing and retreating phases testified by a complex system of moraines and glacial deposits outcropping outside the limit of LIA moraines. Newly obtained ^{10}Be exposure ages indicate that the pre-LIA glacier advance in the Gran Paradiso Group occurred between 13-11 ka (Baroni & *alii*, 2021), and can be correlated to the regional Egesen stadial *Auct.* (Favilli & *alii*, 2009; Ivy-Ochs, 2015; Baroni & *alii*, 2017).

During the Holocene, the last major advance recognized in Valnontey is ascribed to the LIA and can be dated back to the last advance phase of the 19th century (Vannuzzo, 2001; Orombelli, 2011; Lucchesi & *alii*, 2014).

Since the LIA, the Valnontey glaciers have experienced a relevant contraction, which has led to a decrease in their number and extent, with an areal reduction of more than 50% over the last 160 years and a retreat of fronts of even more than 2000 m for the main glaciers.

At present, glacial morphogenesis does not significantly contribute to the landscape evolution of Valnontey, except for pro-glacial areas where recessional moraines and deposits are relevant features. Gravity, running water, and nival and cryonival processes are currently the most relevant geomorphic agents contributing to landscape sculpting. Landforms of gravitational origin affect about 14% of the entire valley area, of which more than 61% are active processes. Most of the landforms due to fluvial and fluvio-glacial processes are active, and among these the most widespread are those due to debris flow processes, which mostly affect Holocene moraines, scree, and debris cones. Finally, cryogenic and nival landforms contribute to the current landscape evolution diffusely affecting the area at the highest elevation but frequently extending to the valley floor through avalanche tracks and channels.

Mountain regions are very sensitive to climate change (Beniston, 2003, 2005), with amplified effects at higher altitudes known as "elevation-dependent warming" (EDW; Pepin & *alii*, 2015).

Climate warming, particularly significant across the Alps since the end of the LIA (around 1850 A.D.), has increased during the last century (IPCC, 2007, 2013; Brunetti & *alii*, 2009; Büntgen & *alii*, 2011). In the European Alps, the clearest evidence of ongoing temperature rise is testified by pronounced glacier retreat, which experienced an unprecedented decline during the early 21st century (Zemp & *alii*, 2015; Sommer & *alii*, 2020). The Gran Paradiso glaciers have reduced their area by more than 80% compared to the LIA: since the maximum Holocene expansion, Valnontey glaciers have shown a significant decrease in both glacier number and extent with accelerated shrinkage in the last 20 years.

As a response of the high mountain environment to climate warming, we observe a relevant increase in landscape disturbance and in magnitude and frequency of slope instabilities (Savi & *alii*, 2021; Ding & *alii*, 2021, and reference therein) induced by the rapid change of the cryosphere (Huss & Hock, 2018).

In this context, updated geomorphological mapping has proven to be a valuable tool to identify areas exposed to geomorphological hazards and to contribute to mitigating the risk. The scenarios projected by the IPCC (2007, 2013) of a progressive expected rise in global temperatures in the next years highlight a future in which climate change and its effects on the natural and anthropic environment will increasingly play a leading role. Glaciers, already in a state of strong imbalance with the current climate context, will experience further shrinkage, with increasing consequences on the local economy and on the geomorphological susceptibility and hazard of the alpine environment, which will face a continuous evolution, opening more and more new spaces to the paraglacial environment.

SUPPLEMENTARY MATERIAL

The "Geomorphological map of the Valnontey (Gran Paradiso Group, Western Alps, Italy)", at the scale of 1:15,000, associated to this article can be found in the online version at http://gfdq.glaciologia.it/044_2_07_2021

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