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Luca CARTURAN [1,2*] & Norman GASPERINI [2]

GEOMORPHIC IMPRINT OF A SMALL GLACIER AND ITS RAPID VANISHING DURING 20th CENTURY: THE MARMOTTE GLACIER (ORTLES-CEVEDALE, ITALY)

Abstract: Carturan l. & Gasperini N., *Geomorphic imprint of a small glacier and its rapid vanishing during 20th century: the Marmotte Glacier (Ortles-Cevedale, Italy).* (IT ISSN 0391-9838, 2021).

This work presents a glaciological and geomorphological study carried out on an area of three square kilometers in the southern part of the Ortles-Cevedale Group. In this area, at the head of the Val di Peio (Province of Trento), a small glacier existed until the first half of the 20th century, named Marmotte Glacier. This study was aimed at defining the maximum extent of the glacier during the Little Ice Age (LIA), reconstructing its fluctuations in the last century, and providing a geomorphological context through the compilation of a detailed geomorphological map, at the scale of 1:2500.

A geomorphological survey was performed in the field, combining different survey techniques for establishing the transport history of glacigenic sediments and the relative age since deglaciation of rock surfaces. Historical glacier fluctuations have been reconstructed analysing historical sources, in particular old photos (aerial and oblique terrestrial photos) and glaciological observations started in the 1920s.

During the LIA, the glacier extent was 0.33 km^2, but already in the 1940s it was 40% smaller, and quickly become a glacieret by the end of the 1950s. In the following decades, the ice body went through a rapid fragmentation and completely vanished in the early 2000s. These results point to a high climatic sensitivity and high vulnerability for this small glacier, whose reconstructed equilibrium line altitude (ELA) matches very well with ELAs reconstructed for neighbouring glaciers in the LIA. This study provides evidence for significant marginal glaciation (i.e. the existence of very small glaciers and glacierets) during the LIA, in areas where geomorphological evidence is poorly expressed or even absent.

Key words: Very small glaciers, Glacial geomorphology, Glacier fluctuations, Little Ice Age, Italian Alps.

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Riassunto: Carturan l. & Gasperini N., *Evidenze geomorfologiche di un piccolo ghiacciaio e della sua rapida scomparsa nel corso del XX secolo: il Ghiacciaio delle Marmotte (Ortles-Cevedale, Italia).* (IT ISSN 0391-9838, 2021).

Questo lavoro presenta uno studio glaciologico e geomorfologico eseguito su un'area di tre chilometri quadrati del settore meridionale del gruppo Ortles-Cevedale. In quest'area, alla testata della Val di Peio (Provincia di Trento) esisteva un piccolo ghiacciaio, estinto nella seconda metà del ventesimo secolo, denominato Ghiacciaio delle Marmotte. Questo studio ha avuto come obbiettivi la ricostruzione della massima estensione del ghiacciaio durante la Piccola Età Glaciale (PEG), la ricostruzione delle sue variazioni nell'ultimo secolo, e la caratterizzazione del contesto geomorfologico tramite la realizzazione di una carta geomorfologica alla scala 1:2500.

È stato eseguito un rilevamento geomorfologico sul terreno, combinando diverse tecniche di studio finalizzate alla ricostruzione dei processi che hanno trasportato e messo in posto i depositi glaciali e alla determinazione dell'età relativa di deglaciazione delle superfici rocciose. Le variazioni storiche del ghiacciaio sono state ricostruite analizzando le fonti storiche disponibili, in particolare foto storiche (aeree e terrestri) e osservazioni glaciologiche a partire dagli anni '20 del secolo scorso.

Durante la PEG il ghiacciaio raggiungeva una superficie di 0,33 km^2, ma già negli anni 40 del '900 si era ridotto del 40% ed è rapidamente divenuto un glacionevato entro la fine degli anni '50. Nei decenni successivi il corpo glaciale residuo si è frammentato in più unità e si è estinto completamente all'inizio degli anni 2000. Questi risultati suggeriscono un'elevata sensibilità climatica e vulnerabilità per questo ghiacciaio, la cui linea di equilibrio (ELA) corrisponde molto bene con la ELA ricostruita recentemente per i ghiacciai vicini durante la PEG. Questo studio fornisce prove a supporto dell'esistenza di una significativa copertura glaciale marginale durante la PEG, costituita da piccoli ghiacciai e glacionevati, in aree dove le evidenze geomorfologiche sono assenti o scarsamente evidenti.

Termini chiave: Piccoli ghiacciai, Geomorfologia glaciale, Variazioni glaciali, Piccola Età Glaciale, Alpi Italiane.

INTRODUCTION

Glacier inventories compiled around the world show that 'very small glaciers', smaller than 0.5 km^2 (Fischer & *alii*, 2014), largely prevail in number and represent a significant fraction of the current total glacierised area in mid- to low-latitude mountain ranges (e.g. Pfeffer & *alii*, 2014). This must be valid also in the past, for example during the Little Ice Age (LIA). However, small ice bodies representing 'marginal' glaciation in the past often did not leave obvious geomorphological evidence. For this reason, mapping glacierets and very small glaciers that existed in the past can be extremely difficult and prone to large uncertainty; in some cases, it can be hard or even impossible to assess the mere existence of these perennial ice bodies in the past, in absence of other information.

Besides being intriguing for glaciologists, the reconstruction of small ice bodies and of their decay in the last centuries/decades, is of scientific and practical interest because it allows enhancing knowledge of processes governing glacier preservation and decay. In this way, the past behaviour of decaying/decayed small glaciers may serve as a benchmark for future projections, and may reveal the role of negative and positive feedbacks involved in glacier response and sensitivity to climatic changes (Huss & Fischer, 2016).

The history of recently-vanished small glaciers is also linked to the current transition from glacial to periglacial/paraglacial conditioning, and related landforms, observable in many areas that were covered by glaciers during the LIA. For example, reconstructing former glaciers and their decay may be useful for investigating the origin of some rock glaciers, or glacial-permafrost composite landforms, which often derive from vanished glaciers or have been interacting with them in the past (e.g. Seppi & *alii*, 2015; Capt & *alii*, 2016; Kellerer-Pirklbauer & Kaufmann, 2018).

Another reason for studying these vanished glaciers is to obtain geomorphological and environmental backgrounds for paleo-climatic and paleo-environmental investigations, aimed at the interpretation of climatic proxies. In some cases, the relationship between glaciers and climatic proxies is indirect and depends on a similar sensitivity to atmospheric variables, such as for tree rings (e.g. Watson & Luckman, 2004; Linderholm & *alii*, 2007; Cerrato & *alii*, 2020). In other cases, there is a direct influence of glaciers and glacigenic sediments on climatic proxies, such as for lake sediment sequences (e.g. van der Bilt & *alii*, 2015; Røthe & *alii*, 2018; Larsen & *alii*, 2020) sometimes in conjunction with permafrost related processes (e.g. Tolotti & *alii*, 2015).

This work presents a glaciological and geomorphological study in the area formerly occupied by the Marmotte Glacier, in the southern part of the Ortles-Cevedale Group. The study is aimed at i) defining the exact position of the front and the glacier extent at the LIA maximum, ii) reconstructing the fluctuations of the glacier from the end of the LIA to its complete extinction, and iii) drawing a detailed geomorphological map of the study area. This study was carried out by researchers from the University of Padua (TeSAF and Geosciences Departments), who cooperate with scientists from the Edmund Mach Foundation (Research Group Hydrobiology) involved in limnological investigations at the neighbouring Marmotte Lake (Giordani, 2020).

STUDY AREA

The area analysed in this work is located in the Southern part of the Ortles-Cevedale Group, and includes the site of the vanished Marmotte Glacier and its surroundings. The area is 3 km^2 wide, and the elevation ranges between 3330 m a.s.l. (Cima Marmotta) and 2700 m a.s.l., at the outlet of the Marmotte Lake (fig. 1).

The study area is located in the upper part of the Val de La Mare (a lateral of Val di Peio), in the Province of Trento, and is bordered on the north by the Val Martello, in the Province of Bolzano. The ridge that separates the two valleys is generally sharp, but becomes flatter and less defined at the site of the former Marmotte Glacier, corresponding to Passo Vedretta Alta / Hohenfernerjoch (3126 m a.s.l.).

The study area is characterised by rather flat terrain (slope < 10°), with the exception of the eastern part that is steeper, and of some rocky steps, the largest of which is located between the Marmotte Lake and the zone occupied by the glacier in the recent past. The entire area is exposed to the south and the orographic shadowing is insignificant.

The bedrock is almost entirely composed by chlorite-sericite mica schists (Peio-Campo Unit), with local quarzites and isolated andesitic veins (Martin & *alii*, 2009). The mica schists present a high variability in the content of iron, which is locally abundant and whose oxidation provides a dark-reddish colour to exposed bedrock and fresh debris.

Climatically, the area is close to the main so-called 'inner dry Alpine zone' (Frei & Schär, 1998), being characterised by the lowest precipitation in the entire European Alps (~500 mm y^{-1} at the floor of the Venosta Valley). Precipitation increases southward, however, reaching 900 mm y^{-1} in the valleys at the southern edge of the Ortles-Cevedale Group, while total precipitation of 1300-1500 mm y^{-1} has been estimated at 3000-3200 m a.s.l. in the upper Val de La Mare (Carturan & *alii*, 2012). The mean annual 0°C isotherm is located at ~2500 m a.s.l.

The investigated area is bordered by La Mare Glacier to the west, Forcola Glacier to the north-west, Vedretta Alta to the north-east, and Careser Glacier to the east. All these glaciers are shrinking fast, mainly due to the increasing temperature of the ablation season. Although long-term trends in total precipitation are not significant, the increasing temperature is leading to a decrease in the fraction of solid precipitation and in the length of the accumulation season (De Blasi, 2018; Carturan & *alii*, 2019).

According to recent investigations, permafrost is common in the study area, and in particular above 2900-3000 m a.s.l. (Carturan & *alii*, 2016). The alpine permafrost index map from Boeckli & *alii* (2012) confirms 'optimal conditions' for permafrost above 2900 m a.s.l. The occurrence of permafrost is also testified by several intact (*sensu* Barsch, 1996) rock glaciers, some of which are clearly active.

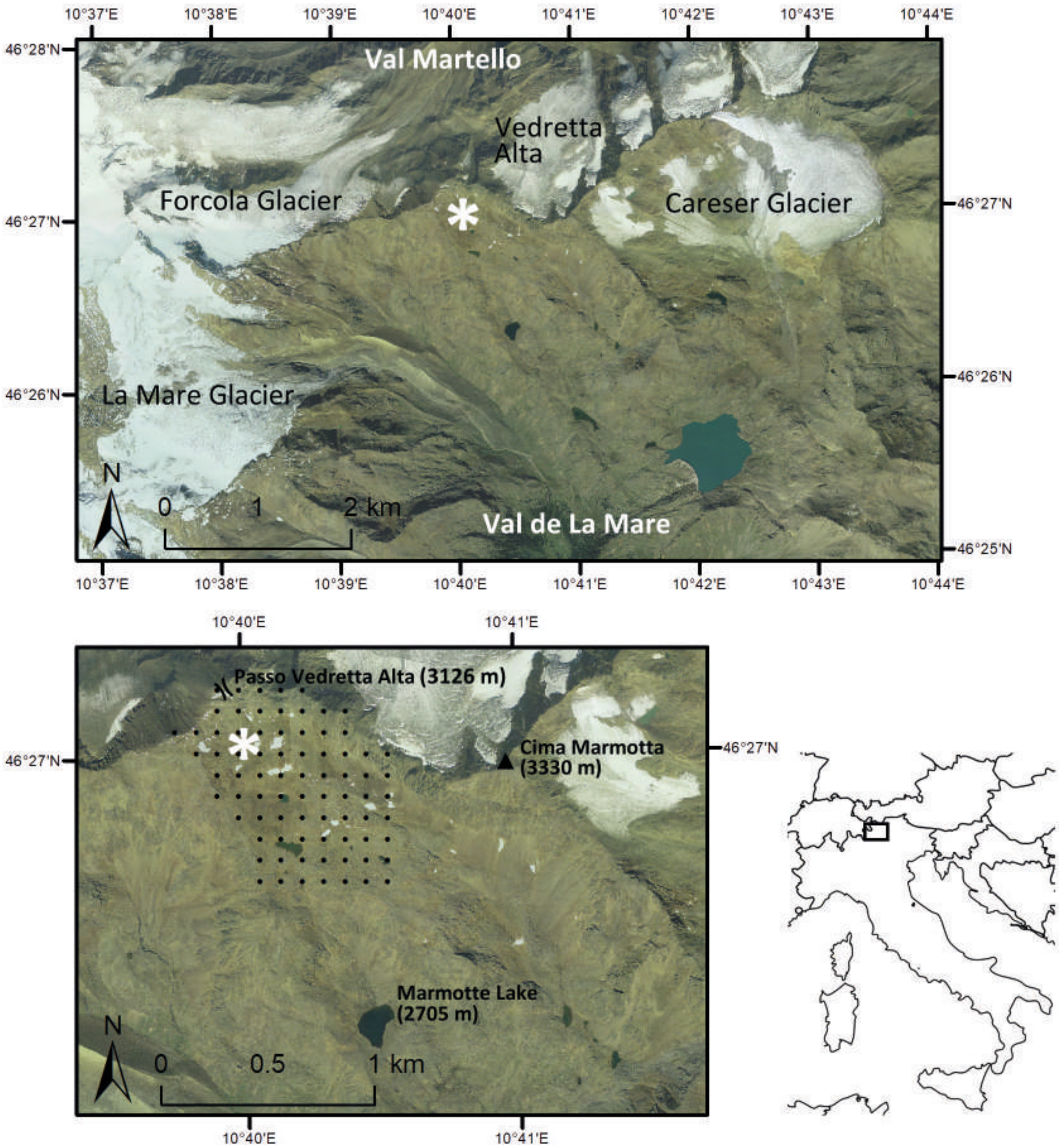

FIG. 1 - Geographic setting of the study area. The white asterisk marks the location of the vanished Marmotte Glacier and the black dots represent the 100 × 100 m grid used for detailed geomorphological observations, in the area covered by the geomorphological map (Immagine TerraItalyTM – © Blom CGR).

PREVIOUS INVESTIGATIONS

In comparison to neighbouring Careser and La Mare glaciers, which have been extensively studied and are subject to long-term mass balance monitoring (Carturan & *alii*, 2020; Baroni & *alii*, 2020a, 2020b), the Marmotte Glacier has received little attention by glaciologists and observers in the past. This is likely due to its smal size and remote location. The first systematic observations of the glacier date back to the 1920s (Desio, 1967). In this monograph of the Ortles-Cevedale Group, Desio lists the few authors that mentioned this small glacier before him: Payer (1869), Richter (1888) and Bonacossa (1915). These authors provided some hints on the glacier and estimated its geometric characteristics; unfortunately, these estimates do not agree with each other and leave uncertainty on the actual extent of the glacier at that time.

Periodic length change measurements and descriptions of the glacier have been published between 1925 and 1962 in the Bulletin of the Italian Glaciological Committee (CGI, 1914-1977). The glaciologists involved in these observations were A. Desio, C. Chiesa, B. Beccaria, L. Ziliani, R. Albertini, G. Vicenzi, and G. Zanon. The results of field campaigns document a sustained retreat of the glacier, with annual rates peaking at 49.5 m in 1961-62, and a significant thinning of the entire ice body. Measurements are however discontinuous and do not enable the construction of a complete glacier length change series.

In the first complete inventory of Italian glaciers (CGI-CNR, 1961) the Marmotte Glacier is reported as a small mountain glacier, 500 m long, 750 m wide, and with an area of 0.30 km^2. In the latest inventories, the glacier is classified as extinct (Salvatore & *alii*, 2015; Smiraglia & Diolaiuti, 2015).

The glacier was regularly reported in the topographic maps of this geographic area; however, its limits were imprecise, in particular at the lower edge (Desio, 1967). The first map with accurate limits is the 1963 map of the Italian Military Geographic Institute (sheet 'Monte Cevedale'), derived from aerial photos taken in 1959. The succeeding maps (Carta Tecnica Provinciale - CTP - various editions from 1980 to 2020) only report snowfields or irregular ice patches in the vanished glacier area.

Two geomorphological maps already exist for this study area. The first map is the result of a systematic geomorphological survey carried out in 1982 and 1983 by the National Group of Physical Geography and Geomorphology (GNGFG-CNR, 1986); it is drawn at the 1:15000 scale and comprises the entire upper Val de La Mare (35 km^2). The second map was surveyed at the 1:7500 scale and was mainly focused on the neighbouring La Mare Glacier (Delpero, 2009). Both maps were drawn at a scale that is too small for the aims of this work.

METHODS

Reconstruction of glacier fluctuations in the last century

A literature survey served to find all the available information regarding the fluctuations of the Marmotte Glacier. Information sources have been filtered to retain only the data functional to quantitative reconstructions. The collected data mainly consist of late-summer terrestrial photos (e.g. fig. 2) taken by observers and glaciologists (CGI, 1914-1977), aerial photos, and orthophotos (Table 1). These photos were used to draw outlines of the glacier in different years and to plot its evolution through time, starting from the front position in 1923 (Gasperini, 2021).

Glacier outlines were drawn in a GIS environment, using the ESRI ArcGIS v.10.7.1 Software, in the UTM-WGS84 coordinate system. The boundaries of the glacier (or snow/ice patches) were recognized from aerial photos and oblique terrestrial photos, with the help of hillshaded digital elevation models (DEMs) and of LANDSAT TM and SENTINEL-2 satellite images (Table 1). Orthophotos were ready to use, whereas aerial photos required orthorectification by means of the Agisoft Metashape Software.

Topographic maps were also considered for this work and have been scanned and georeferenced using the 2014 Lidar DEM as reference. However, topographic maps were not used for glacier reconstructions because they show i) unreliable glacier margins (e.g. the 1908 map of the Italian Military Geographic Institute at the 1:25000 scale, which reports glacier limits and surface topography with high approximation), ii) glacier margins hidden by snow cover (e.g. the 1972 map of the Italian Military Geographic Institute at the 1:25000 scale), and/or iii) irregular ice patches without distinction between ice, snow and firn. For this reason, we preferred to use terrestrial and aerial photos for quantitative reconstructions and topographic maps as a preliminary indication for glacier reconstruction.

Overall, the glacier or its remnants were mapped in nine different years, recognising glacier ice, snow and firn limits (when feasible) and mapping crevasses and crevasse traces. A specific analysis was done to map the snow cover during the summer season of 2017, which was selected for the good time coverage of SENTINEL-2 images. This analysis, combined with maps of late-summer snow patches in recent years, served to investigate the snow cover pattern, to recognize the dominant snow redistribution processes, and to highlight the areas subject to preferential erosion or deposition of snow.

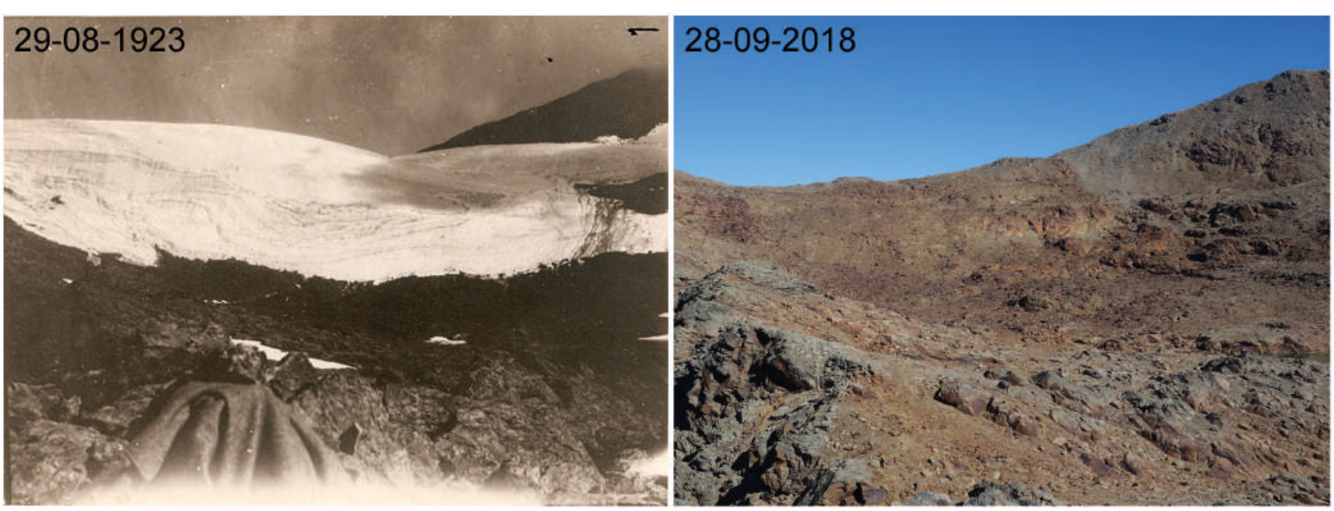

FIG. 2 - Late summer terrestrial photos of the Marmotte Glacier catchment, seen from Cima Nera (3037 m a.s.l.). The photo on the left was taken in late August 1923 (photo A. Desio, courtesy of Comitato Glaciologico Italiano), whereas the photo on the right was taken in late September 2018 (photo L. Carturan).

TABLE 1 - Types of photos, remote sensing images and DEMs used in this work, their sources and use.

Year	Type (author)	Source	Use
1923	Oblique terrestrial photo (A. Desio)	CGI archive	Reconstruction of the western frontal limit of the glacier
1939	Oblique terrestrial photo (A. Desio)	CGI archive	Reconstruction of the upper limit of the glacier
1945	Aerial photo	Italian Military Geographic Institute	Reconstruction of the glacier boundary
1959	Aerial photo	Italian Military Geographic Institute	Reconstruction of the glacier boundary
1983	Aerial photo	TEM1 - Regione Lombardia	Reconstruction of the glacier boundary
1994	Aerial photo	www.pcn.minambiente.it	Reconstruction of the glacier boundary
2003	Oblique terrestrial photos (L. Carturan)	unpublished photos	Reconstruction of the glacier boundary
2005	LiDAR DEM (2.5 × 2.5 m)	http://geokatalog.buergernetz.bz.it	Reconstruction of the glacier boundary, geomorphological mapping, georeferencing
2014	Aerial photo	siat.provincia.tn.it/	Reconstruction of the glacier boundary
2014	LiDAR DEM (0.5 × 0.5 m)	siat.provincia.tn.it/	Reconstruction of the glacier boundary, geomorphological mapping, georeferencing
2015	LANDSAT TM imagery	apps.sentinel-hub.com	Reconstruction of the glacier boundary
2017	Sentinel-2 imagery	apps.sentinel-hub.com	Snow cover analysis
2018	Sentinel-2 imagery	apps.sentinel-hub.com	Reconstruction of the glacier boundary
2020	Sentinel-2 imagery	apps.sentinel-hub.com	Reconstruction of the glacier boundary

Field surveys and geomorphological mapping

The fieldwork has been planned after a recognition of available information listed in the previous section, and of existing geomorphological maps. A preliminary version of the new geomorphological map was drawn in ArcGIS, with the aim of plotting landforms that were clearly visible in remote-sensing images (hillshaded DEMs and orthophotos). This preliminary mapping was intended as a mean for highlighting areas requiring specific fieldwork. However, since geomorphological evidences were really scarce and hardly recognizable in remotely-sensed images, we opted for a systematic field survey in the area formerly occupied by the glacier, with the help of a 100 × 100 m grid (see black dots in fig. 1). Detailed geomorphological observations were carried out at the vertices of this grid, whose position has been retrieved in the field by means of a portable GPS (horizontal accuracy ± 10 m).

Field observations regarded lithology, landform type (erosion/deposition), landform classification, geomorphological processes involved in landform formation and degradation, and morphodynamics. Additional observations concerned the occurrence and orientation of glacial striations over bedrock (measured with a compass), and sedimentological observations regarding the thickness of deposits (larger or smaller than 1 m), grain size, sorting and surface texture. Clast shape and roundness were determined by means of the C_{40} and RA indexes (Benn & Ballantyne, 1994). The C_{40} index expresses the percentage of clasts with c/a axial ratios less than – or equal to – 0.40, whereas the RA index expresses the percentage of angular and very angular clasts in the sample. These features and indexes where determined by means of visual observations in the field. Some subjectivity is inevitable with visual observations, however we decided to skip detailed field observations (e.g. by sieving, fabric analysis, single-clast measurements) or laboratory analyses, considering the aims of this work and logistic/time constraints.

Relative-age dating techniques were also employed, with the aim of detecting and mapping discontinuities in the degree of weathering of rock surfaces, to be used for mapping the LIA margin of the Marmotte Glacier. The intact rock strength (Matthews & Shakesby, 1984; Hubbard & Glasser, 2005) was measured using the Geohammer, produced by DRC S.r.l. (Ancona, Italy). Measurements were taken at the vertices of the 100 × 100 m grid, and along several transects crossing the LIA margins of the glacier, or better to say, their assumed position at the beginning of the fieldwork. Three series of five measurements (15 measurements in total) were taken at each point, discarding measurements that were clearly affected by irregularities in the substrate (cracks or quartz veins, for example). Each of the three series was entirely collected on bedrock surfaces or single blocks, in order to obtain separate series of measurements for bedrock and blocks, with the assumption that systematic differences exist between the two. Data processing, however, revealed that differences are negligible from a statistical point of view (Mann-Whitney test), and for this reason we averaged together all the 15 measurements at each sampled point. Geohammer measurements were taken over horizontal surfaces, keeping the instrument perpendicular to the surface. Instrument readings, that are rebound index (RI) values, have been used as they were, without using correlation curves (that would introduce approximations) to convert them to rock strength values.

Intact rock strength observations were complemented by surface roughness measurements, carried out at selected locations using the TECNIX PROFIL-N-30CM profilometer (Barton comb). The profilometer, which is 30 cm long and composed by 0.8 mm freely moving pins, was pressed against the rock surface and the profile transferred to paper in the field. The profiles have been taken only on bedrock surfaces, perpendicularly to the local slope direction (i.e. in a direction roughly perpendicular to the former ice flux), and they have been digitized in a Microsoft Excel spreadsheet. They have been converted to the roughness index 'A' (McCarroll & Nesje, 1996) using seven sampling distances, varying from 4 to 28 mm at 4 mm intervals.

Lichenometry was initially planned in conjunction with the described relative-age dating methods. Unfortunately, lichens are scarce in the majority of the study area, and thalli have irregular shape and tend to cluster along cracks and fissures of the bedrock. This is likely due to the high elevation of the site, and to the small size of the former glacier (i.e., the entire glacier vanished in a short period of time). For these reasons, we only used lichen cover visually estimated in percent units, as a characteristic for ranking each surveyed point in terms of surface weathering. We used three classes, spanning from 'absent weathering' (freshly exposed rock surface without lichens and signs of weathering) to 'intermediate weathering' (differential weathering visible, lichen cover < 50%, no soil patches) and finally 'high weathering' (rock surface exposed for a long time, lichen cover > 50%, clear signs of differential weathering such as prominent quartz veins, soil patches) (fig. 3). Measurements of the thickness of weathering rind were also planned, but were impossible to apply due to the schistosity of the rock.

Based on the collected evidences and field observations, a geomorphological map was created at the scale of 1:2500. The production of the geomorphological map followed the guidelines developed by the Geological Survey of Italy and by the AIGeo – the Italian Association of Physical Geography and Geomorphology (Gruppo Nazionale Geografia Fisica e Geomorfologia, 1986; Brancaccio & *alii*, 1994; Campobasso & *alii*, 2018). The map elements (points, lines, polygons) were firstly drawn in ArcGIS. Afterwards, the map has been edited in Adobe Photoshop Illustrator to obtain the final layout.

RESULTS

Snow cover analysis

In the area of the vanished Marmotte Glacier, the snow cover pattern during the ablation season is typical of high-altitude mountain regions above the tree line, where snow redistribution processes have high efficiency. In this geographic area, snow redistribution is mainly associated to strong north-westerly winds, leading to the formation of thick snow deposits in bedrock hollows and sharp slope changes downstream of rock steps, with preferential southern aspect. The location of thickest snow deposits is clearly visible in the second half of the summer season (fig. 4), when they survive longer to ablation compared to the surrounding terrain.

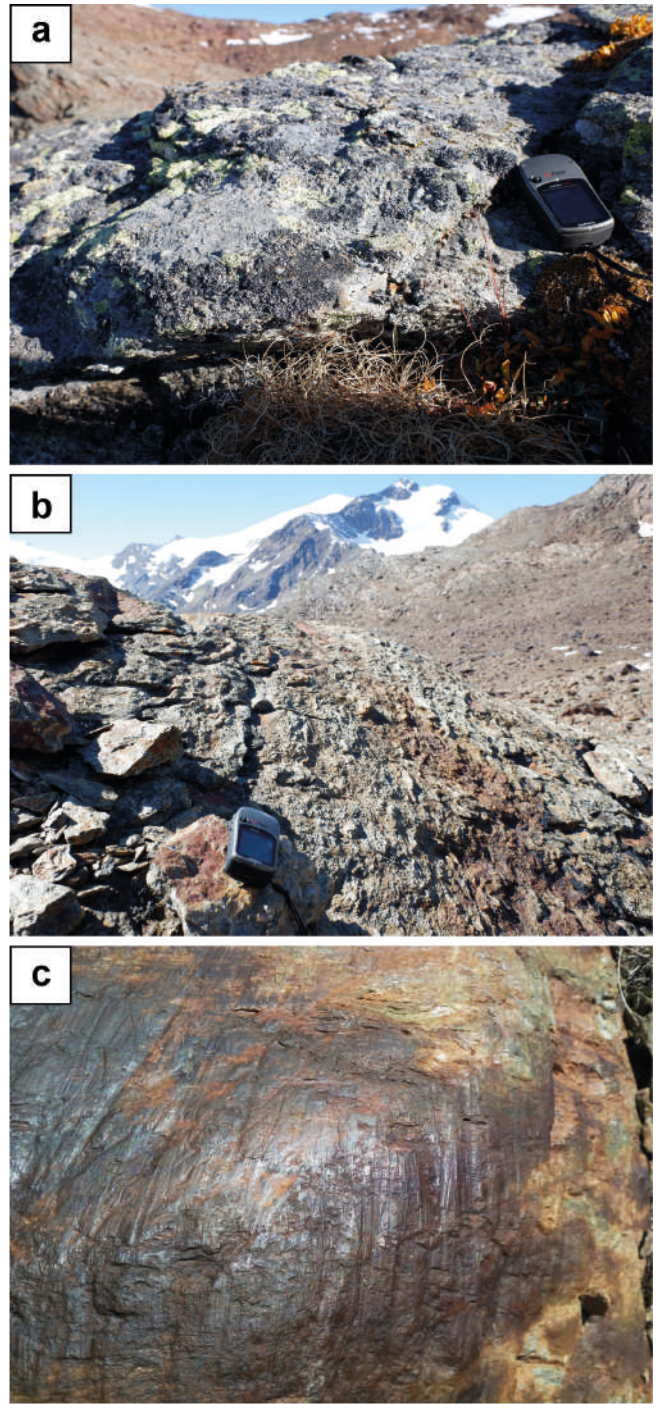

FIG. 3 - Examples of surface weathering: a) 'high' weathering of rock surface with lichen cover > 50%, prominent quartz veins, soil patches; b) 'intermediate' weathering with almost absent lichens but well visible differential weathering; c) 'absent' weathering for surfaces without lichens and differential weathering (in this case a freshly exposed rock surface with recent glacial striations).

Strong winds remove snow systematically from convex areas, which lack snow cover for most of the year. These areas clearly stand out as bare rock surfaces at the end of the accumulation season (fig. 4) and in the first part of the

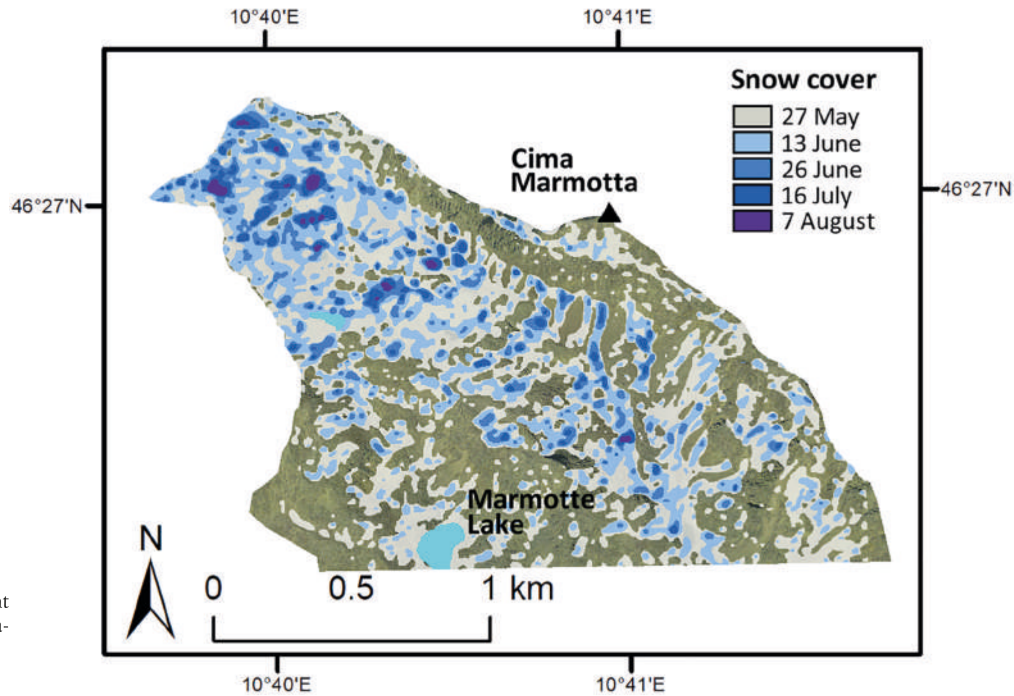

FIG. 4 - Snow cover in five different dates during the 2017 ablation season.

ablation season. Among them, we highlight the convex areas in the rounded crest zone at the top of the former Marmotte Glacier, which generally have low (if any) snow accumulation in the cold season, when snow is dry and readily removed by wind. Based on authors' observations and measurements on other glaciers of the Ortles-Cevedale Group, these areas require wet snow in the warm season to achieve significant accumulation and to preserve a durable snow cover.

The steep rock walls along the eastern hedge of the study area release avalanches that accumulate at their foot. However, due to the small extent of rock walls, avalanches play a minor role in redistributing snow, compared to wind action. The thickest and longer-lasting avalanche deposits are observed outside the area of the vanished glacier, and in particular at the foot of Cima Marmotta, where perennial snowfields exist (please see the attached geomorphological map).

Geomorphology

The main geomorphological features are described in this section and illustrated using photos taken from the viewpoints displayed in fig. 5. Figures 6 and 7 illustrate the periglacial and glacial landforms, respectively. Each photo in the figs. 5, 6 and 7 includes the corresponding viewpoint reported in fig. 5a.

From a geomorphological point of view (please refer to the attached geomorphological map at the 1:2500 scale), the study area is dominated by rock outcrops that prevail in areal extent (41%), followed by glacial deposits (27%) and gravitational deposits (debris cones and scree slopes, 18%). The rock outcrops are widespread in the entire study area and in particular over steep slopes and where glacial erosion prevailed in the past. Where the slope exceeds 40-45°, rocky outcrops are shaped as crests and erosional scarps. Outcrops in less steep areas are instead rounded, with a clear glacial imprint. Rocky crest lines can be distinguished into sharp and rounded crests. A rounded crest exists at the head of the vanished Marmotte Glacier, with clear transfluence saddles (fig. 5b), while sharp crests prevail on the eastern edge of the study area. These sharp crests can be classified as arêtes, deriving from the action of adjacent cirque glaciers that cause backwall recession, with a pyramidal peak (Cima Marmotta) in the middle, which can be classified as a 'horn'.

Between the summit plateau (above 3000 m), which during the LIA was partly glaciated, and the Marmotte lake (at 2700 m), there is a glacial valley step. Another step with similar origin is located to the west of the LIA glacier, and is characterized by the presence of three transfluence saddles. This steep glacial valley step is currently evolving into a degradational scarp, under the influence of gravitational processes (rock falls) and physical degradation processes (cryoclastism).

Slopes between 20° and 40° characterize the gravitational deposits (talus cones and scree slopes). They are characterized by an increasing grain size towards the lower part, where boulders prevail. These deposits are composed by clasts that are typically angular or very angular. In some cases, the lower edge of talus cones and scree slopes is in connection with the rooting zone of a rock glacier (fig. 6a). Small debris flow channels and deposits can be observed locally at the surface of gravitational deposits, especially in areas of concentrated flow, such as at the top of talus cones.

The glacial deposits are generally sparse, discontinuous and shallow, with sub-meter thickness. Thicker glacial deposits exist only in the lower part of the area occupied by the

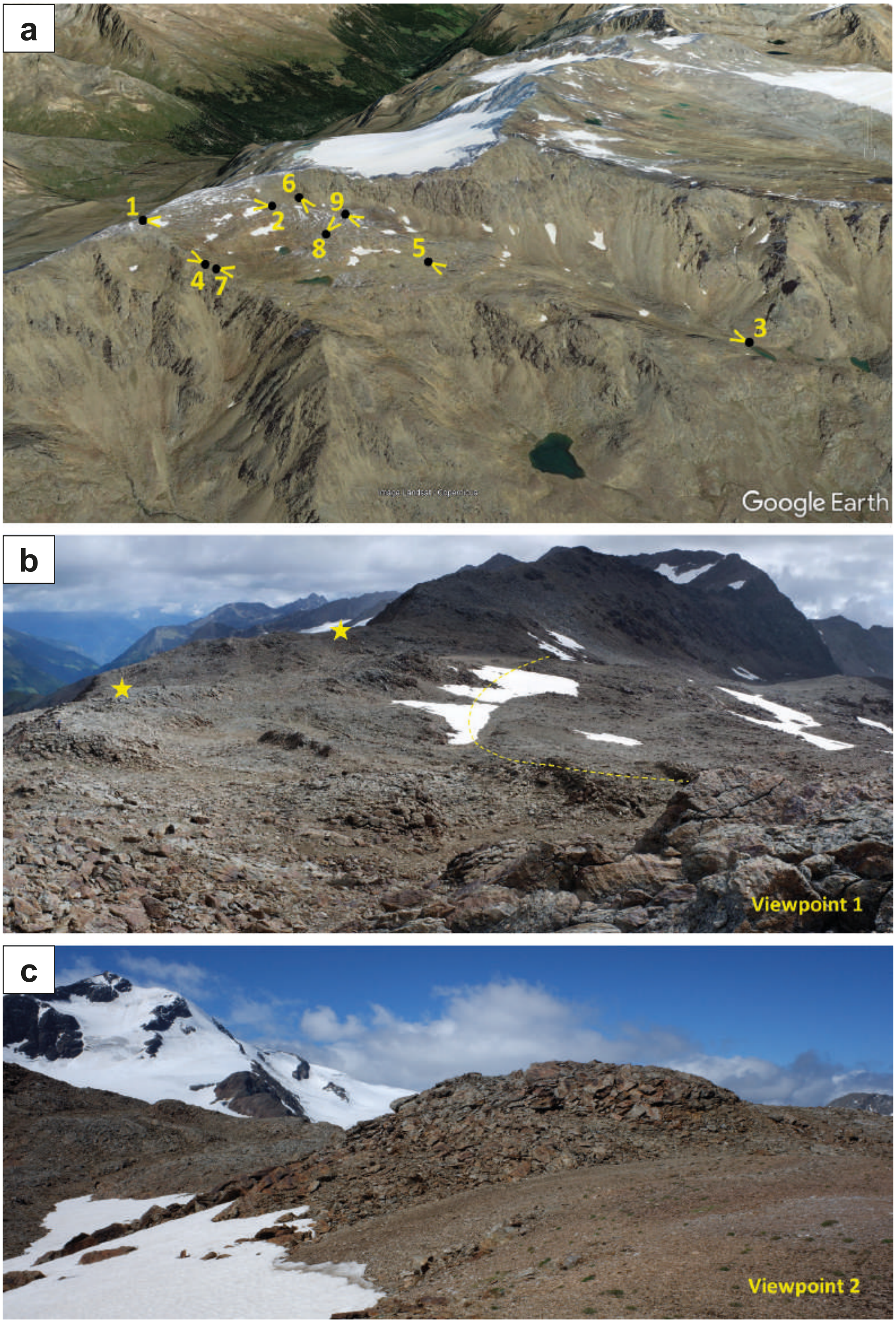

FIG. 5 - a) 3D view of the study area taken from Google Earth, with numbered viewpoints of photos shown in figs. 5, 6 and 7. b) The rounded and highly weathered crest in the upper accumulation zone of the vanished Marmotte Glacier; the yellow dashed line indicates the upper limit of the area with glacial striations, the two yellow stars indicate transfluence saddles. c) Highly weathered *roche moutonnée* in the upper part of the vanished Marmotte Glacier.

glacier during the LIA and in the surroundings of the Marmotte Lake. The thickest glacial deposits in the LIA zone can be classified as lodgement till (fig. 7a), characterized by elongated, faceted and striated clasts, partially immersed in a matrix-supporting diamicton, and aligned with glacier flow direction. Small fluted moraines can be observed in this zone, more obvious in aerial photos than in the field.

Field surveys confirm the first direct observations in the 19^{th} and 20^{th} centuries, describing a single accumulation area feeding two different ablation tongues. The area occupied by the western tongue lacks lateral and frontal moraines, and presents a sparse, unweathered glacial deposit (fig. 7b), lying over a much weathered bedrock. Supraglacial debris supply was probably absent or negligible

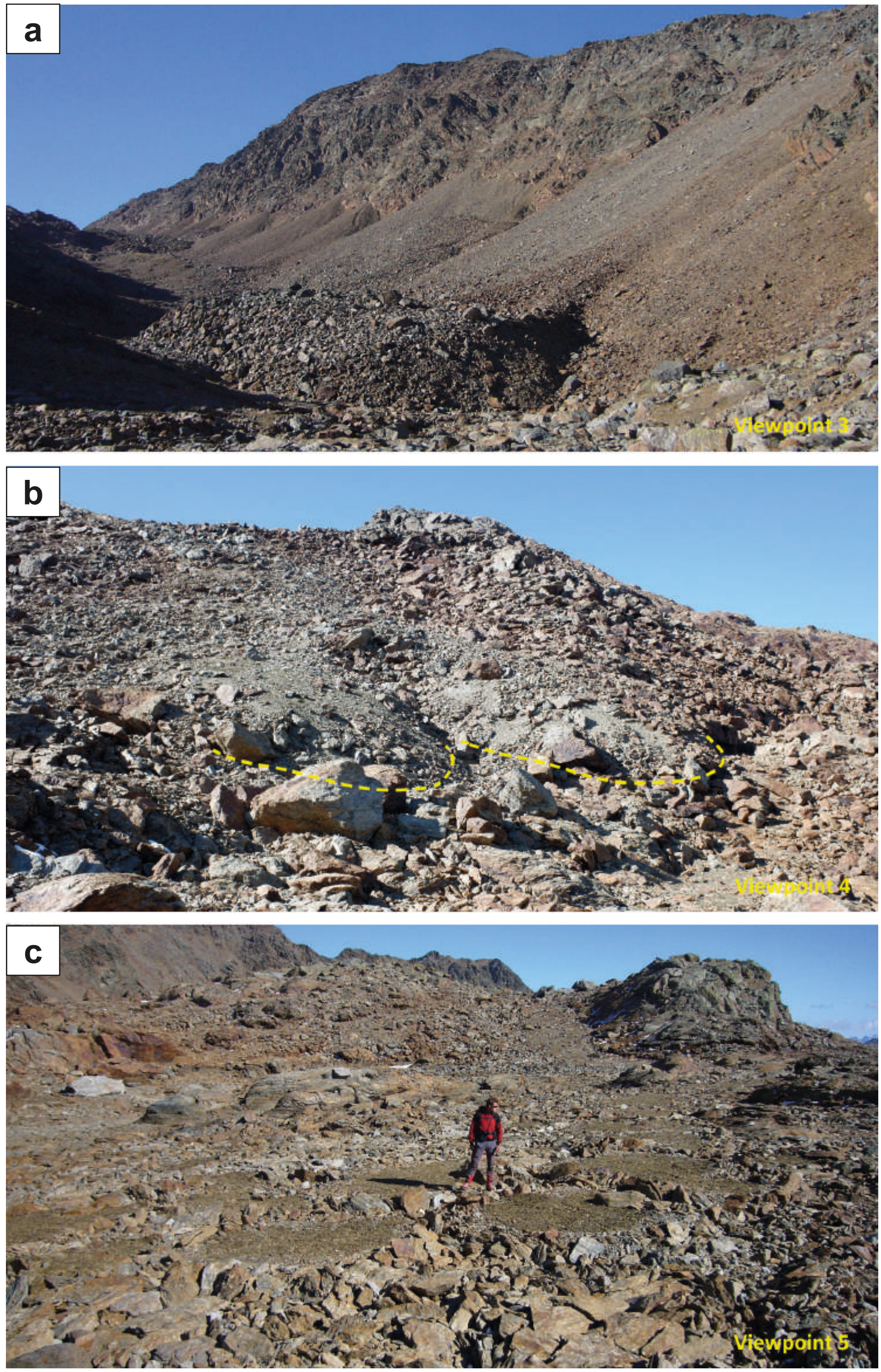

FIG. 6 - Periglacial landforms in the study area: a) an intact rock glacier whose rooting zone is in contact with talus cones, b) two gelifluction lobes, and c) sorted polygons. These landforms are almost inexistent in the area of the vanished Marmotte Glacier.

in this zone, whose accumulation area had the shape of a small ice cap (fig. 2, Desio, 1967). The largest part of debris was likely entrained at the glacier bed in this zone of the glacier.

The eastern portion of the glacier was completely different, because it was bounded at east by steep slopes that release debris and snow avalanches. In this area, glacial deposits are several meters thick and organized into lateral and frontal moraines (fig. 7c). Clasts display increasing elongation and angularity towards the frontal zone, especially in the orographic left. In the former ablation area, glacial deposits are much less consolidated compared to the accumulation area and to the western part of the glacier. Clasts are not faceted or striated, and the deposit can be classified as

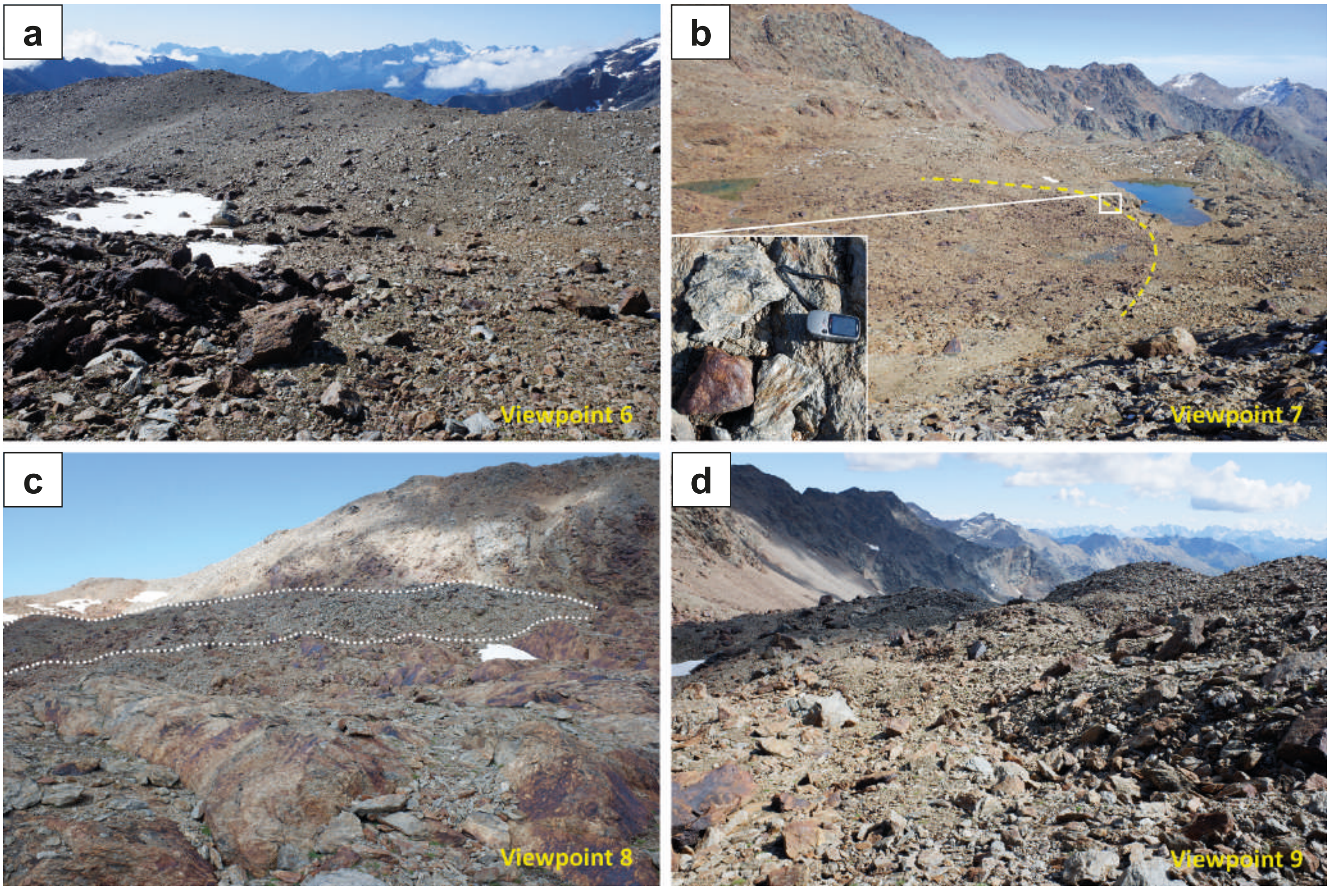

FIG. 7 - Glacial landforms in the area of the vanished Marmotte Glacier: a) lodgement till and small fluted moraines at the top of the eastern lobe, b) sparse glacial deposit left by the western lobe, c) lateral moraine at the hedge of the eastern lobe, and d) hollows and bumps on the surface of the glacial deposit left by the eastern lobe. The inset photo in b) shows the weathering difference coupled to a different oxidation between LIA sparse deposits (sub-angular reddish clast) and older deposits (very angular greyish clasts) at the frontal hedge of the western lobe, shown by a dashed yellow line.

supra-glacial melt out till. Locally, the glacial deposits show evident hollows and bumps (fig. 7d), which may suggest the presence of a dead-ice body buried under thick debris. These observations suggest the existence of a debris-covered glacier tongue in the past, confirmed by field observations of glaciologists between the 1920s and the 1960s.

Much older lateral moraines where deposited in the area of the Marmotte Lake, at the southern edge of the study area. These moraines are clearly visible and well preserved, and have a discontinuous cover of herbaceous plants. The lichen cover is widespread and glacial striations are well preserved only over surfaces exposed by recent erosion.

Small glacial contact deposits were found at the edge of the LIA glacier, characterized by the presence of sorted sediments, from gravels to silts with a prevalence of sands, locally bedded. These deposits take the shape of kame terraces along the orographic right edge of the former glacier, and of very small alluvial plains at the former front, filling small depressions in the bedrock with sub-horizontal layering.

Periglacial landforms are common in the study area. Rock glaciers are the most evident and large landforms of this type. Based on their surface characteristics and elevation (above 2800 m), these landforms are expected to be intact (active or inactive, certainly not relict). Their surface is noticeably convex, with steep frontal slopes and without vegetation cover (fig. 6a); two of them are certainly active because they show clear displacement in recent multi-temporal hillshaded DEMS, with rates exceeding locally 0.7 m y^{-1}. Their origin is periglacial, i.e. they are 'talus' rock glaciers fed by frost-shattered rock fragments (Barsch, 1996) with the exception of a 'debris' rock glacier which deformed the frontal moraines built by the eastern lobe of the Marmotte Glacier.

In the study area there are also some solifluction lobes, which given their altitude can probably be attributed to gelifluction dynamics. Most of the lobes deform gravitational deposits (example in fig. 6b), with the exception of few lobes located close to the Marmotte Lake, which deform glacial deposits. Patterned grounds, and in particular sorted polygons, are commonly found just outside and downstream of the LIA area, at an altitude around 3000 m. The diameter of these landforms average one metre, but can locally exceed two metres (fig. 6c). They are typically clustered in semi-flat areas with fines (sands-silt). Another type of patterned ground consists of horizontal surfaces with selected coarse material (mainly juxtaposed pebbles and cobbles) with a total absence of fines at the surface, located into small depressions that were dry during field visits, but are probably water-logged during the snow melt season. This type of patterned ground probably results from cryogenic sorting phenomena.

Small lakes and ponds characterize the study area, and tend to increase their size towards lower elevation. The largest one is the Marmotte Lake, with a maximum length of 203 m, a width of 136 m and a maximum depth of 6.5 m. The lakeshores almost totally lack fines. Even the lake bed (with the exception of the Marmotte Lake), at least near the shore, is composed of coarse debris. This likely depends on the low solid transport of tributaries and/or cryogenic sorting processes.

Fluvial landforms have small relevance in the study area. The small streams are mainly fed by snowmelt (and ice melt in the past) and for most of the year they have a low discharge and frequently disappear under coarse debris. The tributary of the Marmotte Lake, fed by the glacier in the past, created a small alluvial plain upstream of the lake, resulting from the coalescence of three alluvial fans. The apex of fans is slightly steeper and made up of coarser debris, with scarce vegetation cover. It is possible that these fans have been partly fed by small debris flows.

Overall, the landforms mapped in the study area are all actively evolving. The main exception is represented by glacial landforms, due to the complete disappearance of glaciers. Glacial landforms are locally evolving under the effect of running water (rill erosion on the outer side of moraines and glacial contact deposits) or periglacial processes (small rock glacier developed from frontal moraines).

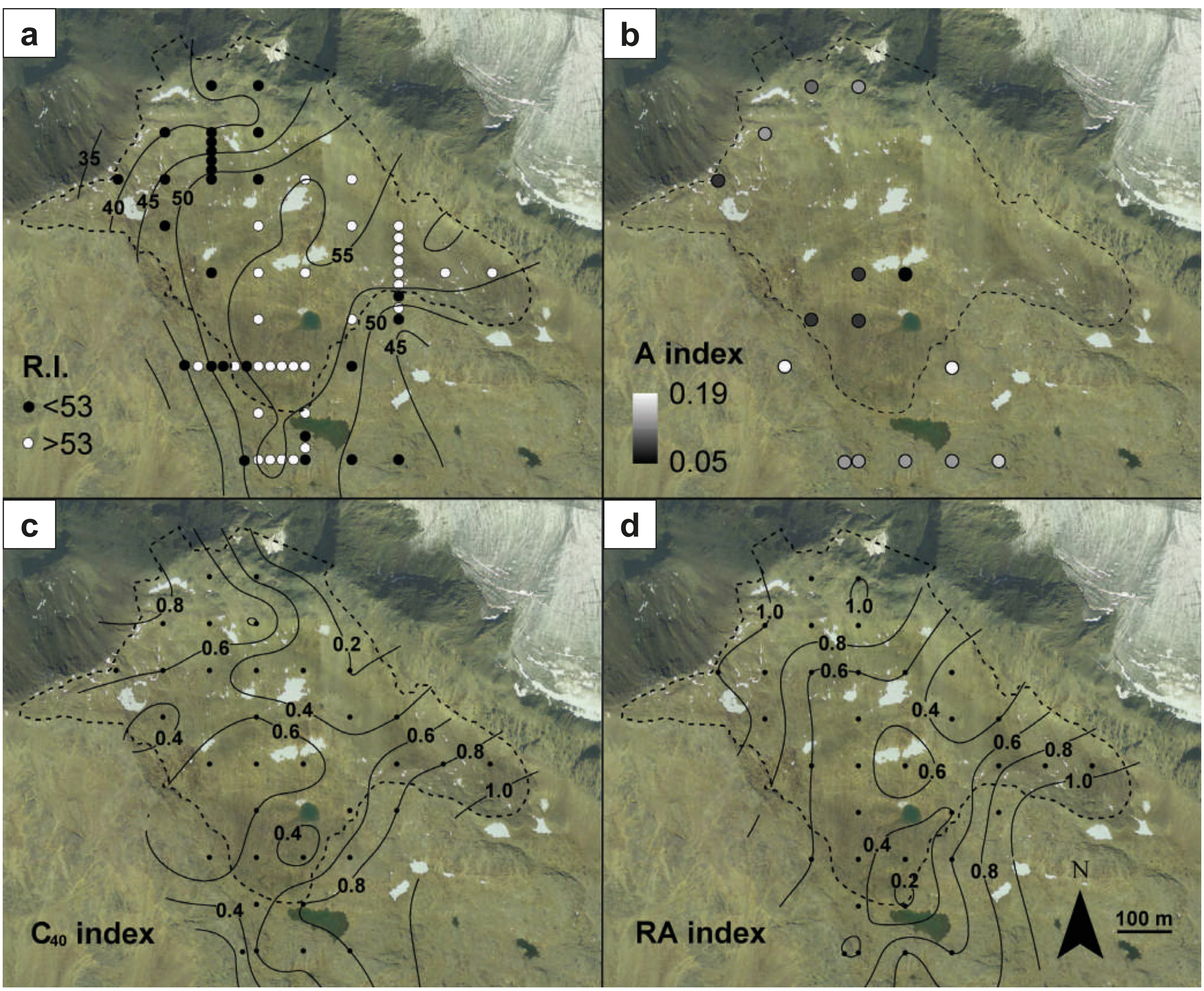

FIG. 8 - Spatial variability of a) intact rock strength (rebound index R.I.), b) surface roughness (A index, 4 mm interval), c) clast shape (C_{40} index), and d) clast roundness (RA index). The dashed line represents the reconstructed LIA limits of the Marmotte Glacier. The dots represent sites surveyed in the filed for each variable.

Surface weathering of rocks and clasts

The degree of weathering of rock surfaces and the presence of glacial striations is highly variable in space. At the head of the catchment, rock outcrops are highly weathered (fig. 5c) and without striations, whereas in the remaining area occupied by the glacier in the recent past they are clearly less weathered and present striations. The latest are not deep, nor widespread, and tend to cluster on top of bedrock outcrops (fig. 3c). There is a clear transition between weathered bedrock and striated bedrock at the top of the vanished glacier, shown with a dashed yellow line in fig. 5b. Glacial striations are absent or poorly preserved outside the recently deglaciated area, because rock surfaces have been affected by differential weathering (fig. 3b). The highest degree of weathering, with almost complete lichen cover, protruding quartz veins and soil/vegetation patches, was detected on top of rocky humps that are free from snow for most of the year and likely deglaciated for millennia.

The surface weathering of clasts is normally similar to that of rock outcrops at the same location. However, just above the small lake visible in fig. 7b, there is a strong weathering difference coupled to a different oxidation between (younger) unweathered clasts deposited over (older) weathered bedrock and deposits.

Spatial variability of intact rock strength and surface roughness

The intact rock strength measurements highlight a zone with RI values above 50-55, in the middle and lower portions of the vanished glacier (fig. 8a). Lower values have been found on the rounded crest zone at the top of the vanished glacier, and outside its lower edges. Steep gradients in intact rock strength appear moving from the central area (where it is rather uniform) towards the crest and the edges. A threshold value of RI equal to 53 separates rather well the terrain formerly occupied by the glacier (dashed line in fig. 8) from the terrain outside it. The rounded crest zone, with its weak rock strength, is a clear exception to this rule, even though it was certainly covered by the glacier during the LIA and was still partially glacierized in 1945 (fig. 11).

Measurements of the roughness index 'A' confirm the results of intact rock strength measurements. The lowest roughness was measured in the central zone, which is characterized by high RI values (fig. 8b). In the area outside the LIA glacier the surface roughness is larger, with peak values over highly weathered rock humps. In the rounded crest zone, the surface roughness is rather high and comparable to the terrain outside the LIA glacier at lower elevations.

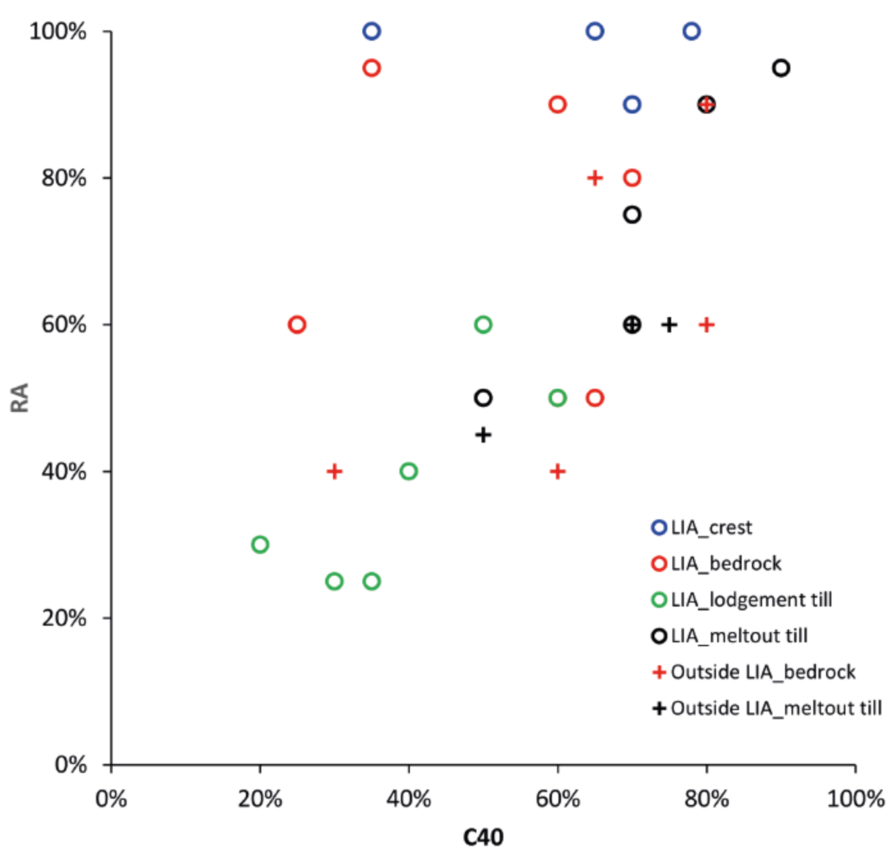

FIG. 9 - (Color online) Clast shape (C_{40}) vs. roundness (RA) at 28 sites surveyed in the field, corresponding to the points shown in figs. 8c and 8d.

Spatial variability of clast shape and roundness

The co-variance of clast shape and roundness, expressed by the two indexes C_{40} and RA, respectively, is analysed in fig. 9. This scatterplot shows the combinations of C_{40} and RA for each of the 28 sites investigated, and should serve to identify and/or highlight clusters of samples or to trace the progressive effect of transport and weathering (Benn & Ballantyne, 1994). The data recorded in our study provide a (positive) correlation coefficient of 0.56, significant at the 0.001 level, with few outliers. Within-group correlation is significant for the 'LIA-meltout till' group ($r = 0.93$, $p < 0.05$) and nearly significant for the 'LIA-lodgement till' group ($r = 0.80$, $p = 0.059$). The scatterplot clearly shows higher rounding and presence of blocks (*sensu* Benn & Ballantyne, 1994, i.e. clasts with high c/a axial ratio) for the lodgement till, compared to the meltout till that has a higher percentage of angular and elongate clasts (low c/a axial ratio). Bedrock areas have pockets of debris in small depressions, with no apparent co-variance between clast shape and roundness; this could derive from the different processes responsible for the deposition of clasts in areas of preferential (glacial) erosion.

The spatial variability of clast shape and roundness reflects quite well the observed variability in intact rock strength and roughness (fig. 8). The central zone with higher RI and lower roughness corresponds to higher clast rounding and presence of blocks (figs. 8c, 8d). A clear gradient towards more angular and elongate clasts is observable towards southeast and northwest. The two frontal lobes of the vanished glacier present a remarkable dichotomy, with a prevalence of angular and elongated clasts in the eastern lobe, and a prevalence of rounded and blocky clasts in the western lobe. This evidence suggests different sediment entrainment and transport mechanisms, as well as different glacier mass balance dynamics, for the two lobes. In detail, the eastern lobe was affected by avalanches and rock falls, leading to the accumulation of 'passively transported' (*sensu* Boulton, 1978) debris at the surface, whereas the western lobe was mainly fed by snowfalls and wind-drifted snow, with 'actively transported' debris at the glacier bed (Benn & Evans, 2010).

LIA glacier extent and ice flow

Based on the information collected and results described in the previous sections, it was possible to outline with reasonable accuracy (maximum error of 20 m) the extent of the glacier during its maximum Holocene expansion (fig. 10a), when it reached an area of 0.33 km^2. Based on ^{14}C dating at the neighbouring La Mare Glacier, we can preliminarily date this expansion to the LIA maximum, around 1600 AD (Carturan & *alii*, 2014; Carturan, 2016).

On the eastern sector, the lateral and frontal moraines provide clear constraints for mapping the ablation area, whereas the upper limit is a little more difficult to map because it is partly hidden by scree slopes and because there are no clearly visible trimlines. Consequently, the upper limit in this zone was traced considering the slope change at the foot of rock walls, checking also old photos.

The upper part of the accumulation area covered almost entirely the rounded summit ridge, showing transfluences towards NE and NW (arrows in fig. 10a). Old photos from the 1920s and 1930s were very useful in this case to confirm the interpretation of field observations, which is rather difficult because in this area the bedrock shows a clear glacial imprint but also a high degree of weathering (figs. 5b, 5c). Old photos clearly show that this area was shaped as a small icecap, and that trasfluences were actively draining crevassed glacier ice.

The middle and lower part of the glacier were simpler to outline, based on the surface weathering of deposits and bedrock. The weathering difference is rather easy to see in the field and orthophotos, because it is frequently coupled to a different oxidation of the iron minerals composing the rocks, making the LIA area more 'reddish-brown' compared to the external area (inset in fig. 7b).

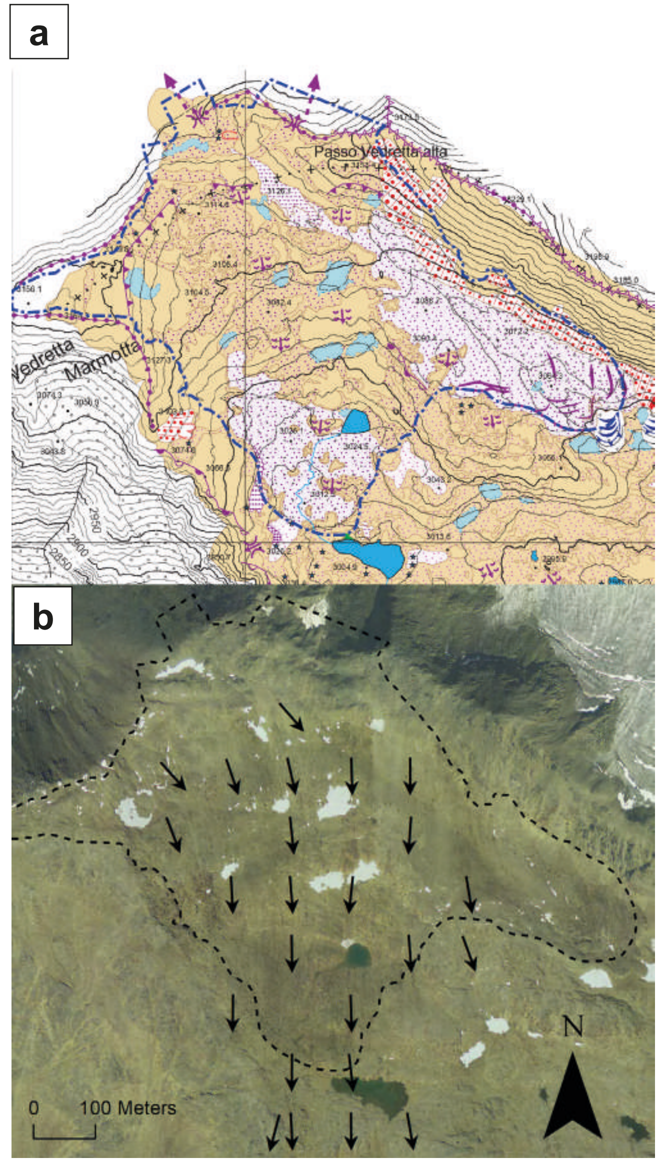

FIG. 10 - Excerpt of the geomorphological map showing a) the reconstructed LIA glacier boundary (blue line) and b) arrows showing the reconstructed ice flow direction indicated by glacial striations.

The orientation of glacial striations suggests that the ice flow was southwards, with almost parallel flow lines. The ice flow direction during the LIA was unchanged compared to older periods (fig. 10b).

Reconstructed glacier fluctuations in the last century

The collected data show that the Marmotte Glacier went through a rapid and almost continuous decay in the last century, persisted since the 1920s without significant interruptions until extinction. Already in 1945, the glacier was 40% smaller compared to the LIA maximum extent (fig. 11). The western front was 200 m upslope of the LIA outer position and 60 m upslope of the 1923 position. The eastern front was covered by debris and the clean-ice limit was 210 m upslope of the LIA frontal moraines. The transfluences in the upper part, still connected to the main glacier body in the 1920s-1930s photos, look clearly disconnected in the 1945 aerial photos, which show the glacier almost devoid of residual snow (AAR = 0.02), with firn cover only on the upper third. This portion of the glacier was the only one preserving few open crevasses (fig. 11), indicating residual ice flow.

Between 1945 and 1959, the glacier thinned considerably, as suggested by new bedrock outcrops. The upper margin retreated much more rapidly than the lower one, which is the only part of the glacier covered by snow and firn at the end of the 1950s. These observations, together with the irregular shape of the ice body, the lack of accumulation area, and the lack of open crevasses (only crevasse traces are visible in the 1959 aerial photo), suggest that in the period between 1945 and 1959 the glacier was clearly out of balance with climatic conditions. In this period, it went from active retreat (shrinking of the lower margin and increase of the mean elevation) to stationary thinning and gradually transformed into a residual ice patch.

In spite of conditions generally favourable for Alpine glaciers between the 1960s and early 1980s (e.g. the neighbouring La Mare Glacier advanced 320 m in this period, Carturan & *alii*, 2014), the residual ice patch continued its fragmentation and by 1983 it was spread into seven remnants and other smaller snowfields. A further reduction of remnants occurred by 1994, ending with their almost complete vanishing in the warm summer of 2003. The very

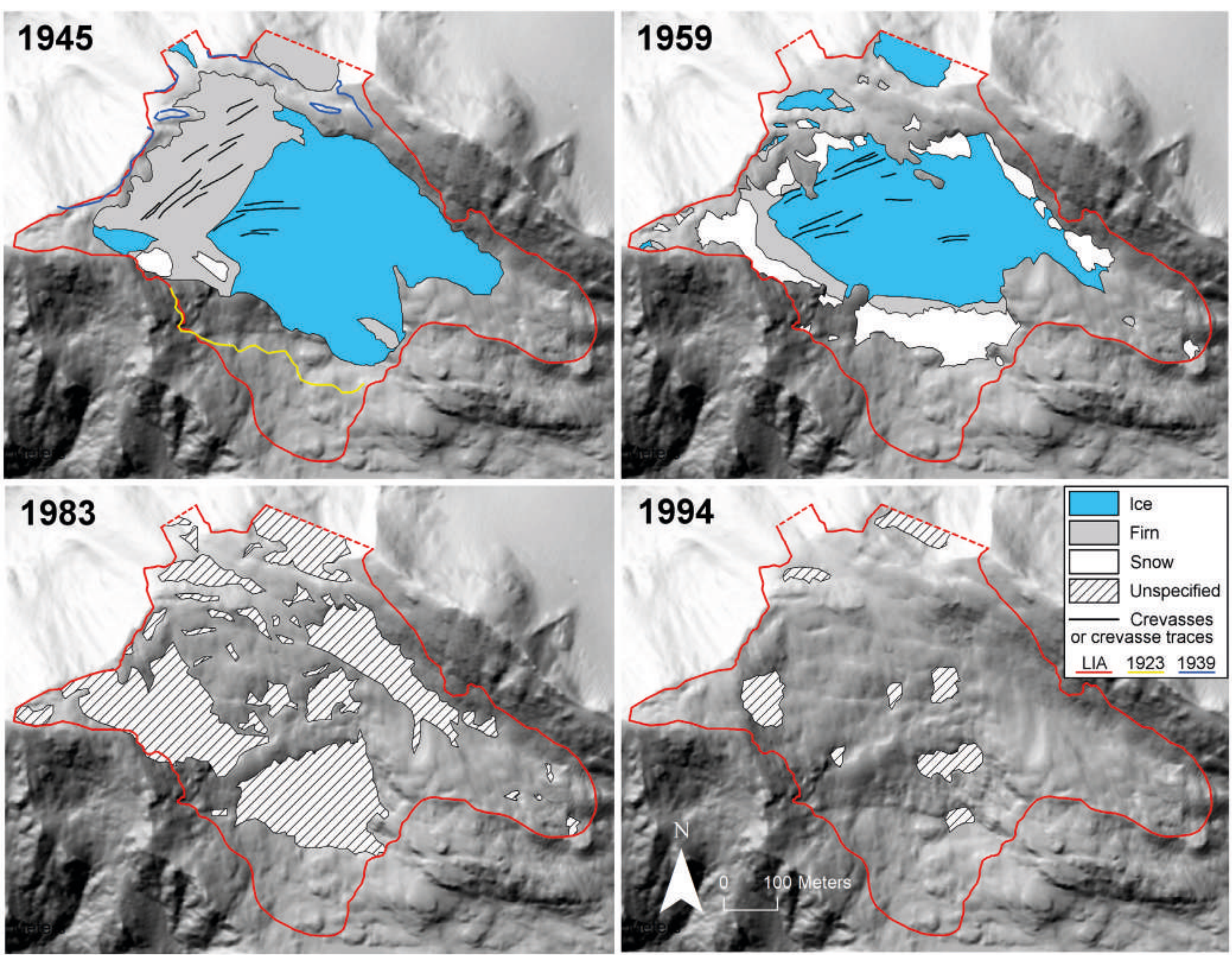

FIG. 11 - (Color online) Reconstructed extent of the Marmotte Glacier in different periods during the 20th century.

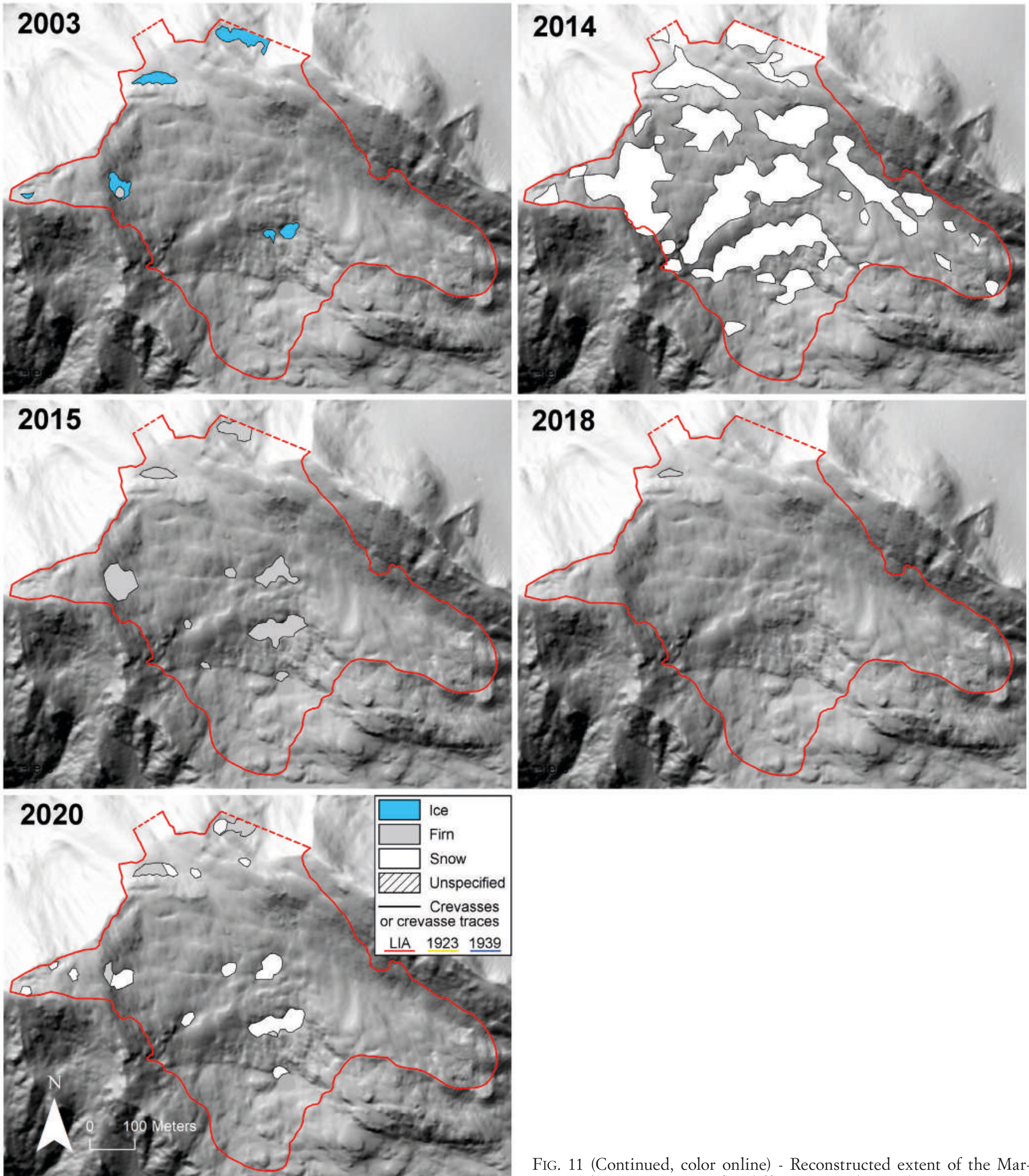

FIG. 11 (Continued, color online) - Reconstructed extent of the Marmotte Glacier remnants in five different years during the 21st century.

small patches left in 2003, composed of old glacier ice, melted completely in 2007.

In the last 20 years, there has been a high interannual variability of conditions, with few years leading to the formation of new snowfields and glacierets, followed by warm and/or dry years leading to their rapid melt. After the last cycle of formation (in 2013 and 2014) and almost complete melt (by 2018), new small glacierets have been observed in the last three years, with a small inter-annual variability in their size (fig. 11).

DISCUSSION

The reconstruction of the maximum extent of the Marmotte Glacier during the LIA, and of successive variations, was made difficult by the scarcity of lateral and frontal moraines. Combining geomorphological, sedimentological and relative-age dating observations at a 100 × 100 m grid of survey points, enabled highlighting the subtle differences, especially in the surface weathering of clasts and exposed bedrock, useful to distinguish between the LIA and Lateglacial areas (Baroni & *alii*, 2017, 2021). We point out, however, that weathering and relative-age evidence can be confusing if taken in isolation. For example, there are areas with high RI values downstream of the LIA glacier front, in a zone of high snow accumulation (figs. 4, 8a), and the RI is rather low in the rounded crest zone at the top of the vanished glacier (discussed below).

The 'grid strategy' helped to cover systematically the study area with detailed observations, not limited to the grid vertices but performed also moving from one point to the next. Clearly, this strategy takes a long time and is probably not applicable to larger study areas, unless the grid size is adequately widened to decrease the density of points.

The procedures used to determine the weathering of rocks and clasts gave satisfactory results. Thanks to the high number and redundancy of the measurements, Schmidt hammer samplings provided results with high statistical significance, in spite of the high schistosity of the rock.

The rounded crest zone in the upper part of the catchment is of particular interest and posed some interpretation difficulties. There is evidence that this zone was glaciated during the LIA, as suggested by photos taken between the 1920s and 1940s. In particular, the persistence of ice cover in the 1945 aerial photo is significant because the 1940s have been characterized by rapid glacier shrinking in the Alps (WGMS, 2021). Multi-year imbalance conditions can be inferred by the small extent of the firn area in 1945, and by the detachment of transluences still joined to the glacier in the 1920s-1930s, confirmed by glaciological reports (CGI, 1914-1977).

The rock outcrops in the rounded crest zone, in spite of the recent glaciation, are highly weathered and fragmented, with very low hardness and total absence of glacial striations, despite having the typical shape of *roches moutonnées* (fig. 5c). They look very different from the rock outcrops in the middle and lower part of the LIA glacier, which show clear evidence of recent subglacial erosion.

It can be assumed that this portion of the LIA glacier had insufficient basal ice flow to 'reset' the surface weathering of the bedrock, due to the low ice thickness in association to the low topographic gradient. The inferred low ice thickness is based on the fact that this area is convex and particularly exposed to wind erosion, as confirmed by the snow-cover analysis in 2017 (fig. 4), snow cover conditions visible in old photos (e.g. fig. 21 in Andreatta, 1954), and its rapid deglaciation in the first half of the 20th century (fig. 11). It is possible that this area of the glacier, shallow and with small snow accumulation, was polythermal and/or cold-based, and therefore dynamically different from the rest of the glacier (Benn & Evans, 2010). Based on these hypotheses, basal sliding should have been negligible, or non-existent, preserving the weathering status of underlying rocks. The latter probably remained exposed for most of the Holocene, before the LIA, and the bumps, which show the largest weathering, tend to be free from snow even during winter. This means that they are exposed to severe temperature changes, which favour surface weathering and fragmentation.

The glacial deposit of the eastern tongue of the glacier suggest the interaction between glacial and periglacial/paraglacial processes. One hundred meters upstream of frontal moraines we found surface outcrops of ice among blocks. The high probability of permafrost in this zone (Boekli & *alii*, 2012), and the lack of banding, lead us to assume that this ice is formed by regelation of meltwater at the bottom of the snowpack, under freezing temperature. Nevertheless, it cannot be excluded that a glacier ice core persists underneath the thick debris mantle, whose surface is irregular, locally unstable and with hollows that may suggest ongoing melt at depth.

The occurrence of permafrost is revealed by the presence of several rock glaciers in the study area, even at low altitude. One of them deformed the frontal deposits of the eastern lobe of the glacier. It is not clear whether this rock glacier is still active because multitemporal DEMs do not show clear displacement recently, however its surface morphology, steepness and grain size of the front, and spring temperature (stable at 0.1°C), strongly suggest that it is intact.

The reconstructed maximum extent of the glacier during the LIA (0.33 km^2) and minimum elevation (3005 m a.s.l.) match rather well with estimations made by Payer (1869), who reported a surface of 0.31 km^2 and a minimum elevation of 3018 m a.s.l.. Richter (1888) reported a surface of 0.57 km^2 and a minimum elevation of 3204 m a.s.l., which looking significantly overestimated. On the other hand, the 2984 m a.s.l. minimum elevation in 1925 reported by Desio (1927) looks underestimated, because it would imply a front about 200 m down valley from our reconstructed LIA maximum advance, which is not supported by geomorphological evidences.

Compared to previous geomorphological maps (GNGFG-CNR, 1986; Delpero, 2009), the higher spatial resolution of surveys and larger scale of the map produced in this study enabled retrieving and mapping smaller geomorphological evidences, and more subtle differences in surface weathering. Our results better constrain the outer margins of the LIA glacier, and in particular they reveal a smaller extent of the glacier during the Olocene, with the lower margin about 500 m upstream of previous estimations. In addition, the collected evidences clearly highlight a peculiar dynamic behaviour of the different portions of this glacier, previously unrecognized.

The results of this study indicate that the Marmotte Glacier had a high climatic sensitivity. Some of its characteristics are typical of the most 'vulnerable' glaciers (Carturan & *alii*, 2020): low elevation range, low slope, southern exposure, little or no avalanche feeding and topographic shadowing, and negligible debris cover. Recent investigations on the behaviour of very small glaciers have highlighted a high variability in their response to past and current climatic fluctuations, due to the important role of local microclimatic and topographic effects (e.g. Kuhn, 1995; DeBeer & Sharp, 2009; Huss & Fisher, 2016). Their response is often modulated by feedbacks related to debris cover, avalanche activity and increasing topographic shadowing over retreating glacier surfaces (e.g. De Marco & *alii*, 2020; Colucci & *alii*, 2021). The Marmotte Glacier did not benefit from these (negative) feedbacks during deglaciation, and therefore its rapid vanishing is not surprising.

The reconstruction of the surface topography of the LIA glacier would have been highly subjective and prone to excessive approximation, considering its shape and the lack of topographic constrains. For this reason, we estimated the LIA ELA using simple methods, such as the maximum elevation of lateral moraines, and the terminus-to-head altitude ratio (Benn & *alii*, 2005). The two methods provided almost identical ELAs at 3085 and 3086 m a.s.l. respectively. Given the low elevation range between the front, at 3007 m, and the top of the glacier, at 3165 m, this estimate is assumed quite reliable.

The resulting ELA is 35 m higher than the ELA reconstructed for the neighbouring La Mare Glacier (3050 m) and 60 m higher than estimated for the Careser Glacier (3025 m) by Baroni & *alii*, (2017). The small positive deviation is fully consistent with the smaller glacier size (leading to a lower 'cooling effect', Carturan & *alii*, 2015), the southern exposure, and the low snow accumulation in the upper accumulation area, exposed to wind erosion.

CONCLUDING REMARKS

In this study, we have reconstructed the maximum extent of the Marmotte Glacier during the LIA and its fluctuations in the last century, dating its transition from a glacier to a glacieret between the 1940s and the 1950s, its fragmentation into separate patches between the 1960s and the 1980s, and its rapid extinction afterwards.

These results derive from detailed fieldwork, aimed at the creation of a large-scale geomorphological map, the characterization of the transport history of glacigenic sediments, and the relative-age dating of rocks and clasts, to be used in conjunction with documentary data for glacier reconstructions.

The field observations and measurements have benefitted from the adoption of a predefined scheme of survey points, arranged on a 100 × 100 m grid to avoid subjectivity, and from the combination of different techniques. This last point is very important because if these techniques had been taken in isolation, they would have led to misleading results and interpretations.

Overall, the research has provided useful evidence for the ongoing limnological studies at the Marmotte lake (Giordani, 2020), whose tributary drained the melt water from the vanished glacier. In particular, the interpretation of lake sediments will benefit from the reconstructed LIA geometry of the glacier and the dating of its complete vanishing. The presence and distribution of permafrost in the study area, its interaction with the vanished glacier, and the absolute dating of the maximum glacier advance during the LIA, are other aspects that require further investigation for the interpretation of the limnological proxies.

Even though very small glaciers and glacierets left poorly expressed geomorphological evidences, not comparable to larger glaciers, they represented a significant portion of the worldwide glaciated area in the past. Therefore, the methodology and results of this study have significant implications for the study and modelling of climate-related glacier change, considering the highly specific and extremely variable climatic response of very small glaciers, and the limited knowledge of their past distribution and extent.

SUPPLEMENTARY MATERIAL

Supplementary materials associated with this article can be found in the online version, at http://gfdq.glaciologia.it/044_2_03_2021/ These data include the "Geomorphological map of the vanished Marmotte Glacier Area (Ortles-Cevedale - Italy)" at the scale of 1:2500.

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