The Last Glaciation in Valchiavenna (Italian Alps): maximum ice elevation data and recessional glacial deposits and landforms

Davide Tantardini[1], **Stefania Stevenazzi**[1] & **Tiziana Apuani**[1]

[1] Università degli Studi di Milano, Dipartimento di Scienze della Terra "A. Desio", Via L. Mangiagalli 34, 20133 Milano, MI, Italy.

DT, 0000-0003-3797-7619; SS, 0000-0003-2855-9829; TA, 0000-0002-0152-6704.

Ital. J. Geosci., Vol. 141, No. 2 (2022),
pp. 259-277, 9 figs., 2 tabs.,
https://doi.org/10.3301/IJG.2022.13.

Research article

Corresponding author e-mail:
davide.tantardini@unimi.it

Citation: Tantardini D., Stevenazzi S. & Apuani T. (2022) - The Last Glaciation in Valchiavenna (Italian Alps): maximum ice elevation data and recessional glacial deposits and landforms. Ital. J. Geosci., 141(2), 259-277, https://doi.org/10.3301/IJG.2022.13.

Associate Editor: Massimo Frezzotti

Submitted: 04 October 2021

Accepted: 11 April 2022

Published online: 26 April 2022

SUPPLEMENTARY MATERIAL is available at:
https://doi.org/10.3301/IJG.2022.13

SOCIETÀ GEOLOGICA ITALIANA
Fondata nel 1881 - Ente morale R. D. 17 ottobre 1885

ISPRA
Istituto Superiore per la Protezione e la Ricerca Ambientale

Sistema Nazionale per la Protezione dell'Ambiente

© Società Geologica Italiana, Roma 2022

ABSTRACT

This work presents the first extensive, 1:10,000-scale field survey data concerning glacial deposits and glacigenic landforms in the Valchiavenna territory, which has an area of 578 km^2. Valchiavenna is an inner Alpine valley in Northern Italy between the Lepontine and Western Rhaetian Alps.

A comprehensive 1:25,000 map of deposits and landforms from the last glaciation to the present is provided, describing i) glacial trimline evidence and associated features, such as moraine ridges, erratic boulders, ice-moulded bedrock surfaces and kame terraces; ii) glacial, ice-contact, lacustrine/peat and gravity-reworked till deposits; iii) other supraglacial, marginoglacial and subglacial landforms; and iv) erratics in glacial deposits. Establishing an absolute chronology of glacier dynamics was not the objective of this work. However, a relative chronology was inferred from sedimentological and geomorphological evidence: this allowed the description of the general behaviour of glaciers in the area during and after the Last Glacial Maximum (LGM).

The palaeogeography at the LGM and the palaeo-ice-flow pattern were reconstructed on the basis of field data; this data confirmed that the valleys were almost completely filled by glacier ice, covering about 88% of the study area, with only the most elevated ridges and a few nunataks emerging above the ice surface, and allowed the identification of different source areas for the erratics found on opposite sides of the main valley.

The observation of stratigraphical and geomorphological relationships between glacial deposits and landforms made it possible to propose a relative chronology of glacial advances and to outline the general glacial dynamics of the area. Both at the LGM and during the deglaciation after the LGM, the valley glacier inserted offshoots in tributary valleys, thus generally blocking the advance of local glaciers. With the gradual melting of the valley glacier during the deglaciation after the LGM, tributary glaciers could deposit tills on areas previously covered by valley glacier ice and at lower altitudes than the older lateral moraines. The main outcome of this work is a rich and homogeneous database of glacial deposits and glacigenic landforms that will be useful for further local and regional studies. It can guide the planning of geochronological dating and represents a fundamental step in the identification of glacial stadials and ice mass modelling. It can also support biogeography studies and the evaluation of the effects of climate change, slope dynamics modelling and hazard prediction.

KEY-WORDS: geomorphological mapping, trimline, LGM, glacial reconstruction, European Alps.

INTRODUCTION

Reconstructions of glacial advances are a fundamental step in understanding the palaeochronology, palaeoclimate and palaeogeography of glaciated regions (e.g., Lohse et al., 2011; Heyman et al., 2013; Baroni et al., 2021), as well as past glacier properties like the equilibrium-line altitude (ELA) position and the mass-balance ratio over time (e.g., Benn et al., 2005; Heyman et al., 2013; Baroni et al., 2021). The maximum ice elevation and retreat-advance glacial cycles affect the evolution of the stress state of mountains. They are also responsible for changes in hydrogeological features and surface temperature variations. Loading and unloading cycles are often suggested to be the predominant mechanism behind slope instability processes (Eberhardt et al., 2004; Holm et al., 2004). However, in addition to this debutressing effect, surface temperature variations control the chemical and mechanical weathering processes of the rock mass, and consequently, they modify rock mass properties and slope dynamics (e.g., Hormes et al., 2008; Sanhueza-Pino et al., 2011; Baroni et al., 2014; Nagelisen et al., 2015; Bajni et al., 2021; Sanz de Ojeda et al., 2021; Spreafico et al., 2021). It follows that glacier reconstruction plays a relevant role in driving slope dynamics reconstructions and thermal-hydro-mechanical stress-strain-time analyses (Baroni et al., 2014; Rootes & Clark, 2020; Morcioni et al., 2022).

Glacial advances are recognised by identifying trimlines and assessing their ice-marginal origin. This can be done best directly in the field, using either detailed geological and geomorphological mapping (e.g., Federici et al., 2017; Rettig et al., 2021), or remote sensing through aerial or satellite imagery (e.g., Glasser et al., 2008; Protin et al., 2019). Mapping can be aided by field and laboratory tests (e.g., Scapozza, 2015; Scotti et al., 2017), dendrochronological analyses (e.g., Ives, 1974; Longhi & Guglielmin, 2020) or historical and archaeological research (e.g., Zumbühl et al., 2008; Rootes & Clark, 2020). Without a radiocarbon chronology, the isotopic dating of cosmogenic radionuclides (e.g., ^{10}Be) can be used to assess the chronology of glacial dynamics, allowing the comparison of data from geographically distant and stratigraphically uncorrelatable locations (Ivy-Ochs et al., 2009; Scapozza et al., 2014; Ivy-Ochs, 2015; Federici et al., 2017; Monegato et al., 2017).

The aim of the present work is to provide a comprehensive map, based on field data, of glacial deposits and glacigenic landforms related to the Last Glaciation, the Late Glacial period and Holocene stadials up until the present, and a general reconstruction of the glacial dynamics of an inner Italian Alpine valley. The data presented were collected during detailed field surveys of Upper Pleistocene (Quaternary) deposits and geomorphological features. Establishing an absolute chronology of glacier dynamics was not the objective of this work; geochronological dating was not performed, but the detailed field observation of sedimentological and morphological features made it possible to propose relative chronologies. The investigated region covers the area of Valchiavenna (578 km^2), including San Giacomo Valley (N-S directed) and Bregaglia Valley (W-E directed).

The research contributes to knowledge concerning the glacier dynamics during and after the Last Glacial Maximum (LGM; Clark et al., 2009) in the Alps with detailed field data, which are summarised in the paper and additionally presented in the supplementary map at 1:25,000 scale. The database includes i) glacial trimline evidence and associated features, such as moraine ridges, erratic boulders, ice-moulded bedrock surfaces and kame terraces; ii) glacial, ice-contact, lacustrine/peat and gravity-reworked till deposits; iii) other supraglacial, marginoglacial and subglacial landforms; and iv) erratics in glacial deposits. Along with the description and interpretation of field data, this work can provide useful support for further local and regional studies in several geoscience fields, such as the use of geochronological dating to identify glacial stadials, biogeographical reconstruction, the evaluation of the effects of climate change, ice mass and slope dynamics modelling, and hazard prediction.

In the second chapter, we present an overview of state-of-the-art research on trimlines and glacial reconstruction. In the third chapter, we introduce the main geographical and geological characteristics of the study area, with a focus on previous Quaternary studies. In the fourth chapter, we describe the methodologies followed for geomorphological mapping and the reconstruction of glacial advances. In the fifth chapter, we present the results of the field survey and interpretations about ice-flow patterns, LGM palaeogeography and general glacial dynamics, and we compare the main results to previous LGM palaeogeographic reconstructions. In the sixth chapter critically summarises the main findings.

THE EXPRESSION AND INTERPRETATION OF TRIMLINES IN THE LITERATURE

Glaciers, ice caps and icefield reconstructions are based on the recognition of trimlines. A recent and thorough review of the glacial trimline concept was performed by Rootes & Clark (2020), who point out some current issues:

i. Glacial trimlines are not always related to the maximum ice elevation; they can also be related to the subglacial thermal regime. The knowledge of this issue has changed through time. In many studies, the assumption that the trimline, as the upper limit of glacial erosion, represents the maximum ice surface elevation reached by LGM glaciers on slopes has been repeatedly invalidated in various glaciated regions (e.g., Kleman, 1994; Kleman et al., 2010; Fabel et al., 2012; Ballantyne & Stone, 2015). In fact, the trimline is believed either to be an ice-marginal feature identifying an ice surface elevation or to mark the maximum elevation of the transition from temperate to cold based ice (Ballantyne, 2010; Couterrand, 2010, Fig. 1, p. 403). Ice marginal trimlines and thermal trimlines can coexist in the same ice mass (Rootes & Clark, 2020). Numerical models by Cohen et al. (2018) for the Rhine glacier (contiguous with the Valchiavenna region) showed that this valley glacier was temperate-based except in the most upstream portions of the valleys, where it was cold-based.
ii. Additionally, given the above, there is no clear definition of what a trimline is: a wide range of terms that refer to a variety of features is used, and there is no standard terminology or classification scheme. In this study, we use the definition proposed by Rootes & Clark (2020): 'Glacial trimlines are glacigenic features expressed as a break or transition in the vegetation, weathered material, erosion pattern, deposited material, or truncated slope landforms (e.g., talus cones, gullies) on the slopes of a glacierised or glaciated valley.'
iii. It is currently impossible to determine synchronicity between maximum trimlines. Dating methods can help, but at present the dates that they produce are not definitive because of the error ranges in the dating methods themselves. This synchronicity issue has to be taken into account, as it is a major assumption in glacial reconstructions (as in Kelly et al., 2004a). Rootes & Clark (2020) state that the main problem lies in identifying and mapping trimlines, which can be confused

with non-glacigenic landforms, especially in remotely sensed imagery, and they underline the importance of field surveys, geologic data and dating for the validation of trimlines.

Glacial trimlines can express themselves in a variety of modes (Rootes & Clark, 2020), such as through contrasts in glacial deposition or erosion, the discontinuities of slope process landforms and contrasts in surface aging, but some trimlines can be identified only by specific investigations, such as those devoted to defining exposure ages, weathering and geochemical features.

It follows that several methods to identify trimlines have been applied. Some authors, such as Florineth & Schlüchter (1998) and Kelly et al. (2004a), set the trimline at the upper limit of erosional morphologies on bedrock. Other authors (e.g., Ballantyne et al., 1998) indicated that the trimline coincides with the upper limit of the removal of weathered bedrock or debris by glaciers. Kelly et al. (2004a) also used till and indicator erratics, whereas Van der Beek & Bourbon (2008) relied on drumlin and lateral moraines. The trimline also separates glacier ice-scoured bedrock from bedrock that is not scoured and therefore is affected by periglacial processes and by chemical and biological weathering (Ballantyne et al., 1998; Ballantyne et al., 2008). At the trimline a convex or concave slope rupture can often be observed, depending on the geomechanical properties of the bedrock (Florineth & Schlüchter, 1998).

Alongside trimlines, glacial reconstructions also make use of ice-marginal features such as moraines and meltwater-related landforms: these landforms can help to identify glacial trimlines, but they are often directly used in reconstructions in the same way as glacial trimlines.

Since the 1980s, remote sensing observation-based methods have been used to link trimlines across distant areas through the observation of aerial photographs (Thorp, 1981, 1986, 1987) or satellite imagery (Knight et al., 1987; Glasser et al., 2008; Zasadni & Kłapyta, 2014; Blomdin et al., 2016). Additionally, cosmogenic nuclides have been used to estimate the exposure ages of weathering limits, polished rocks and erratics (e.g., Kelly et al., 2006; Ivy-Ochs et al., 2009; Ballantyne & Stone, 2015) and to aid in distinguishing between thermal and ice-marginal trimlines and in assessing trimline synchronicity.

Ice-marginal trimlines must be geometrically correlated to reconstruct the limits of glacial advances. Geographical information systems (GISs) and modelling techniques can be fundamental for investigating certain areas but can also lead to the inaccurate identification of trimlines, as highlighted by Rootes & Clark (2020).

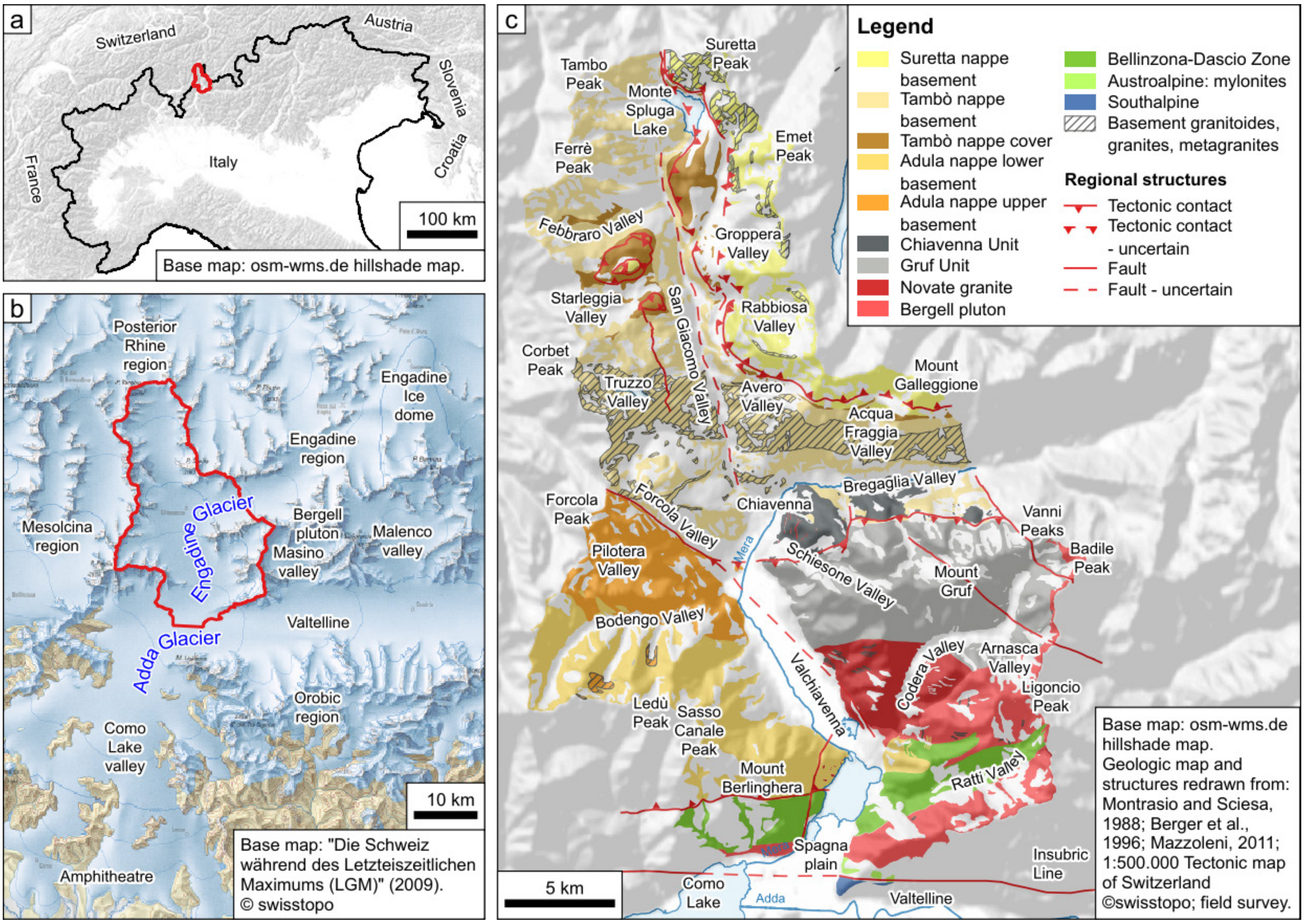


Fig. 1 - a) Location of Valchiavenna in the Alpine chain. b) Locations of the main ice bodies at the LGM (Bini et al., 2009). c) Geological map and main toponyms.

On the other hand, traditional geological and geomorphological methods have been proved to be largely accurate and meaningful in assigning landforms to specific glacial advances or stadials (Ivy-Ochs et al., 2009).

CHARACTERISTICS OF THE STUDY AREA

Geographical and geological outline

Valchiavenna is an Alpine valley that separates the Lepontine and Rhaetian Alps; it runs along the Italian-Swiss national border and covers 578 km^2 (Fig. 1). It is formed by two narrow northern valleys, the tributary San Giacomo Valley, which comes from the NNW, and Bregaglia Valley, which continues from the Swiss Engadine region in the NE, that join near Chiavenna to form the wider southern N-S main valley. Throughout these valleys, there are suspended valleys and cirques and narrow tributary valleys. The Mera River flows southward through Bregaglia Valley and Valchiavenna; it flows into Lake Como near the intersection of the Valtelline and the Adda River (the main tributary of Lake Como).

The Valchiavenna region is characterised by a complex geology (Fig. 1c). For a general overview see Montrasio & Sciesa, 1988 and Sciesa, 1991; Marquer et al., 1994; Stucki et al., 2003; Engi et al., 2004; Berger et al., 2005; Ciancaleoni & Marquer, 2006; Nagel, 2008; Galli et al., 2013 and the references therein. Located north of the Insubric Line, the outcropping bedrock belongs to the Pennidic domain; it was built up by sub-horizontal Mesoalpine gneissic bodies (basements of the Adula, Tambo and Suretta nappes) and separated by their permo-mesozoic metasedimentary cover units. Starting from the upper units in the north, the Tambo and Suretta basements are mostly made up of paragneisses (with some orthogneisses), and they also contain intrusive rocks, the Truzzo metagranites and the Roffna rhyolites, respectively. The Starlera nappe, the unit covering the Suretta and Tambo nappe, is composed of marbles, dolomites, breccias and green Spluga quartzites. The Adula nappe consists of orthogneisses and migmatites, and it is covered by the Misox Zone Unit, which outcrops mostly in Swiss territory. Northward, the nappes gently dip ENE, whereas southward, the same units are folded, tilted up and verticalised. South-east of Chiavenna, the mafic Chiavenna Unit and the migmatitic gneisses of the Gruf Unit outcrop; they were tilted during the oligocenic periadriatic intrusions of the Bergell Pluton (granodioritic and tonalitic) and Novate Granite (two-mica granite), which outcrop in the SE part of the study area. In the southernmost part of the study area (Root Zone), high-grade metamorphic rocks (Bellinzona-Dascio Zone) of the Austroalpine and Southalpine units outcrop in a thin E-W belt.

During the Pleistocene, the Quaternary geology of Valchiavenna and the surrounding region was characterised by the Alpine glaciations. The main valley glacier in Valchiavenna was the Engadine glacier, originating ENE near the Swiss Engadine glacial dome (Florineth, 1998; Florineth & Schlüchter, 2000; Bini et al., 2009; Fig. 1b). It ran through the entire valley from N to S, receiving various tributary glaciers (e.g., the San Giacomo glacier); at Spagna Plain, it joined the bigger Adda glacier coming from Valtelline, and the two flowed into Lake Como, joining to form a single trunk glacier. Downstream from Lake Como, the Adda glacier created a three-lobe morainic amphitheatre.

This dynamic occurred various times during the Pleistocene, resulting in the deposition of various synthems, each related to a glacial episode, with the last synthem being the Cantù Synthem, whose deposits can be found from the amphitheatre to the highest valley heads. The age of this last glacial episode is corroborated by geochronometric calculations (e.g., Bini, 1997; Comerci et al., 2007; Scapozza et al., 2014 and the references therein; Bernoulli et al., 2018 and the references therein).

Previous data and knowledge from near the study area

A regional-scale palaeogeographic reconstruction of glaciers all over Switzerland and its neighbouring territories was performed by Bini et al. (2009); from now on, this reconstruction is referred to as the Swiss LGM reconstruction. However, the Swiss LGM reconstruction in Valchiavenna was performed through the interpolation of trimline evidence that was mainly external to the valley itself.

At that time, studies about glacial sediments and geomorphological features in Valchiavenna were scarce and scattered, consisting mainly of some unpublished works based on field surveys, conducted or supervised by the same author, focused on the Montespluga area, Rabbiosa Valley and Starleggia Valley in the northern part of the study area and on Codera Valley in the southern part of the study area. These works described glacial deposits' characteristics, identified some glacial landforms, especially moraines and erratics, and drew simple maps of the surveyed areas. North-east of Valchiavenna, in the upper Bregaglia Valley and mainly in the Engadine region, Florineth (1998) reconstructed the geometry of the LGM ice surface and the glacier flowlines in its accumulation area, collecting data from previous works, carrying out ad-hoc field surveys and identifying trimlines, nunataks, erratic boulders and glacial striae. South-west of Valchiavenna, Maggi (1992) described the glacial landforms and the Quaternary geology in the upper Lake Como area, identifying the valley glacier deposits, describing erratic lithologies and hypothesising about the glacial dynamics in that area.

Most of the unpublished data used for the Swiss LGM reconstruction were revised, integrated and included in the Italian National Geological Map Sheets and corresponding notes covering Valtelline, the Lake Como valley and most of the amphitheatre area: Sheet 024 – Bormio (Montrasio et al., 2012), Sheet 058 – Monte Adamello (Brack et al., 2008), Sheet 041 – Ponte di Legno (Chiesa et al., 2012), Sheet 057 – Malonno (Gosso et al., 2011), Sheet 056 – Sondrio (Boriani & Bini, 2012), Sheet 076 – Lecco (Gaetani et al., 2012), Sheet 075 –Como (Michetti et al., 2013), Sheet 096 – Seregno (Bini et al., 2014) and Sheet 097 – Vimercate (Bersezio et al., 2014). These works map glacial deposits and landforms in a wide territory, describing the Quaternary units and the glacial dynamics in the area, but they do not cover the Valchiavenna territory. As for the Italian side, field data concerning the glacial deposits and landforms of the Swiss territory were revised and integrated, and they are currently included in the Geological Atlas of Switzerland 1:25,000 (GeoCover, https://map.geo.admin.ch/).

Recently, a few studies have focused on glacial geomorphology in Valchiavenna. They concern the glacial dynamics in San Giacomo Valley (Tantardini et al., 2013), the Quaternary geology and geomorphology of the lower part of Valchiavenna (Tantardini, 2016) and descriptions of Quaternary deposits (Tantardini et al., 2016).

MATERIALS AND METHODS

During the decade from 1990–2000, the researchers of the *Dipartimento di Scienze della Terra 'A. Desio' – Università degli Studi di Milano* (Dept. of Earth Sciences 'A. Desio' of the University of Milan) carried out field geomorphological surveys in quite small areas, which were scattered and distant from each other, mostly in San Giacomo Valley. These unpublished data, available to the authors, have been revised, homogenised and integrated by the authors during an extended field survey carried out from 2009 to 2015 (see Acknowledgements) through collaboration with the Mountain Community of Valchiavenna, and they constitute an original contribution to this work.

From the geological/geomorphological field survey and mapping of significant features (e.g., glacial deposits and landforms, trimline evidence, local and erratic lithologies), a reconstruction of the LGM glaciated area was proposed. A relative chronology was inferred from sedimentological and geomorphological evidence: this made it possible to describe the general behaviour of glaciers in the area during and after the LGM.

Lastly, we compared the reconstructed palaeogeography of the glaciated area at the LGM with the small-scale LGM reconstruction of the Swiss Alps (Bini et al., 2009) to highlight similarities and differences.

Field survey and geomorphological mapping

Between 2009 and 2015, Valchiavenna was the object of an extensive geomorphological and Quaternary geology field survey carried out by the research group (see Acknowledgements) supervised by the authors. Trimline data, related to both valley and local glaciers, were collected. The field survey, aimed at mapping Quaternary deposits and landforms, was carried out at a 1:10,000 scale. More than 85% of the whole territory was covered by direct field survey, while less accessible areas were covered through panoramic observation and remote sensing (aerial imagery analysis). The topographic 1:10,000-scale Technical Map of the Lombardy Region (http://www.geoportale.regione.lombardia.it/) was used as a baseline map for field surveys. The collected data were merged in a unique database through GIS software and georeferenced using the UTM projection, Zone 32 N, datum WGS 1984 (E.P.S.G. code 32632).

During the field work, glacial trimline evidence and associated features, such as moraine ridges, erratic boulders, ice-moulded bedrock surfaces and kame terraces, were mapped, and the sedimentological, petrographical and stratigraphical features of glacial, fluvial and lacustrine/peat deposits were identified and described. The lithologies of erratics in glacial deposits (tills) were described and mapped to reconstruct ice flow directions in the valleys.

A 1:25,000-scale map of Quaternary glacial deposits and landforms in Valchiavenna is provided as supplementary material, and it contains the field data this paper refers to. Stratigraphic data from two borehole logs with depths of 250 m and 100 m located in Chiavenna and Spagna Plain were used to evaluate the depth of the sedimentary infill at the bottom of the valley (data provided by local public administrations; Tantardini, 2016), whereas in Bregaglia Valley, it was inferred from unpublished borehole logs (Pigazzi et al., 2022 - A.M.AL.PI.18 project).

Reconstruction of glaciers' geometry: from field evidence to correlations and cross sections

In this work, the positions of glacial trimlines on slopes were defined using both geomorphological and sedimentological evidence, following the criteria proposed in the literature (see chapter 2): erosional steps, truncated spurs, moraines, aligned and significant erratics and the stratigraphy of glacial deposits. We followed the nomenclature and classification scheme proposed as standard by Rootes & Clark (2020).

Following the cartographic approach (Pearce et al., 2017), trimlines that identify glacial advances were correlated with each other on the basis of their geometry and mutual positions to reconstruct glacial advance limits. In this paper, we refer to a generic glacial advance limit to indicate the position in the territory where a glacier once stopped its advance and left sedimentary and/or geomorphologic evidence. Figure 2 shows a generic example of the correlation of trimlines (Rootes & Clark, 2020); several photos representing various field evidence are shown in the supplementary map.

The recognised glacial advance limits made it possible to reconstruct both the palaeogeography and the glacial dynamics in Valchiavenna, from the LGM to the present. Being aware of the synchronicity issue discussed by Rootes & Clark (2020), in our reconstruction we assumed that the erosional trimlines at the highest elevations were formed by the LGM icefield, as in Kelly et al. (2004a).

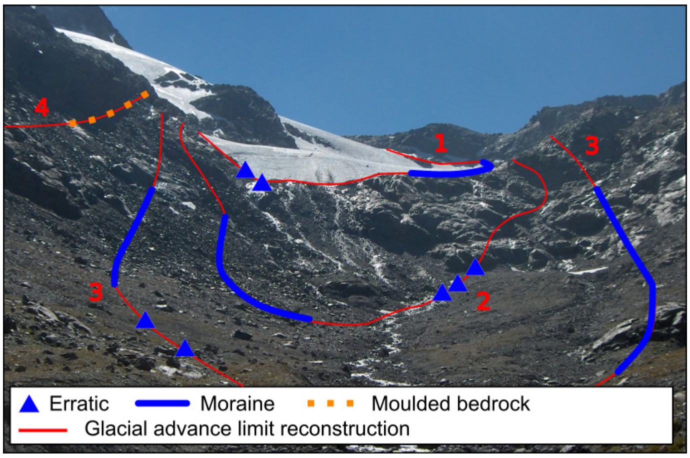


Fig. 2 - Example of the correlation of trimlines (*sensu* Rootes & Clark, 2020) that can be identified thanks to erosional and depositional features. Photo: Ferrè glacier, NE San Giacomo Valley, 2011.

The trimlines and ice-marginal features present in Valchiavenna can be quite far away from each other, and, in areas with intense slope dynamics, there are distances up to some kilometres without evidence. Therefore, while the geometry of glacial advance limits in some areas can be easily inferred based on near and clear evidence, in other areas with less or more distant evidence, this geometry is reconstructed with a good degree of reliability, and in other areas, it can only be hypothesised due to very distant evidence. This was taken into account in the interpretation of evidence: for LGM trimlines, we reconstructed the maximum advance limit, highlighting various degrees of reliability (i.e., with evidence, reconstructed, hypothesised). For all the other glacial advances, we only drew limits where there was clear evidence, without identifying stadials from the LGM to the present. Except for the LGM trimline, only a relative chronological significance was attributed to trimlines or to glacial advance limits reconstructed from trimlines.

To understand the relationship between the main glacial tongue (the Engadine glacier) and the tributary glaciers (e.g., the San Giacomo glacier) present in Valchiavenna at the LGM, four glaciers' cross sections have been reconstructed. The reconstruction is based on topographical profiles from the Lombardy Region 5 m cell DTM (http://www.geoportale.regione.lombardia.it/, open data published under CC-BY 4.0 licence - https://creativecommons.org/licenses/by/4.0/legalcode) and information from borehole logs. The geometry of the ice surface was reconstructed by considering the maximum ice elevation on the slope. The presence of medial moraines was hypothesised, as these moraines are a common feature when there is contact between two or more glacier tongues downstream from a ridge or nunatak (Evans, 2013).

RESULTS AND INTERPRETATION

Glacial deposits in Valchiavenna

Glacial deposits in Valchiavenna are mostly made up of ablation till and lodgement till, and they include matrix-supported diamicton, which is slightly overconsolidated. Tills crop out throughout the entire territory and are discontinuously present on all the slopes, having been completely denudated in areas that are very steep or have intense slope dynamics. Tills are also present in all the tributary valley bottoms, while the main Valchiavenna bottom is covered by postglacial fluvial deposits.

Tills are thicker at lower altitudes and on low-angle slopes, and thinner at high altitudes and on high-angle slopes. The till thickness grows towards the south and downstream. The lodgement till gently covers the slopes and is usually some metres thick (up to about 20 m) where the slope dip is lower, and it presents itself as a cover moraine that is usually some decimetres thick in cirques or where the slope dip is higher. The ablation till usually covers the lodgement till with variable thicknesses (from some decimetres to a few metres). It forms several lateral and terminal moraines on slopes and most valley bottoms, and scarce hummocky moraines are present only in a few high-altitude valley bottoms or upland areas. These landforms are usually small, up to a few metres high and some decametres long. For some examples, see the photos in the supplementary map.

Clasts in tills are mostly paragneisses, orthogneisses, granites and granodiorites, and quartzites. Micaschists, blue metapelites and mafics (peridotites, serpentinites, amphibolites, gabbros) are also present. Rare grey-yellowish marbles and light green quartzites ('Spluga quartzites') are present; they come from the metasedimentary Penninic nappe covers.

The tills have an erosional unconformity surface as their lower bounding surface; only the contact with the bedrock was observed. Tills can either outcrop directly on the topographic surface or be in contact through an erosional surface with postglacial deposits. Where visible, the upper boundary surface does not always show a well-preserved morphology due to earth slides or soil creep.

The field survey shows that the glacial deposits present in Valchiavenna have ages ranging from the Upper Pleistocene to the Holocene to the present. The glacial deposits belong to the last glaciation and to Late Glacial advances, i.e., Cantù Synthem (also identified in nearby areas: Boriani & Bini, 2012; Gaetani et al., 2012; Michetti et al., 2013), and even to Little Ice Age (LIA) advances (Po Supersynthem).

It has been recognised that glacial deposits and landforms in Valchiavenna span from the LGM to the present, but no attribution has been given to distinguish post-LGM recessionary phases and Late Glacial and LIA advances and recessions. Without robust dating and field tests, such an attribution would have been in the form of an interpretation based on comparisons and analogies with surrounding areas (e.g., Böhlert et al., 2011; Scotti et al., 2017; Longhi & Guglielmin, 2020, 2021; Scapozza et al., 2021) and not on field data; to date, there is little field data from the study area (Scapozza et al., 2021).

Lithologies of erratics and ice flow

Field data on the lithologies of erratics in tills (Fig. 3, Tab. 1) show the following, from north to south:

i. In San Giacomo Valley, the till always contains lithologies from all the geologic units outcropping in this territory, without relevant differences on the opposite slopes of the valley.
ii. In Bregaglia Valley, on both slopes, there are some erratic clasts that clearly come from the Swiss Engadine region, i.e., Bergell granodiorites/granitoids.
iii. In the main valley (south of Chiavenna), there are distinct erratic lithologies on the two opposite main slopes. On the western slope, there are Truzzo metagranites, marble, limestones and Spluga quartzites: their source rocks outcrop in San Giacomo Valley. On the eastern slope there are Bergell clasts (granites, granodiorites/tonalites) and mafic rocks from the Chiavenna Unit: the source areas for these lithologies are in the Swiss territory and Bregaglia Valley.
iv. On the Valchiavenna–Valtelline watershed, the erratic lithologies are composed of Bergell clasts and mafic rocks, like those on the eastern Valchiavenna slope. However, the geometry of the glacial landforms shows that the source areas are different on the two sides of the watershed: on the Valchiavenna side, the source areas are Bregaglia Valley and the Swiss territory, while on the Valtelline side, Bergell clasts come from Masino Valley

Table 1 - Erratic lithologies found in tills. For evidence positions, see Fig. 3. Data sources: a) Tantardini (2016); b) this work; c) Maggi (1992). Coordinates are in UTM Zone 32 N, WGS 1984 (E.P.S.G. code 32632).

ID in Fig. 3	Local toponym	Coordinates (m)		Outcropping bedrock unit (lithology)	Erratics lithology	Source
		X	Y			
A	Suretta Peak	527211	5148783	Suretta nappe basement, Roffna metarhyolites (metarhyolites)	Starlera nappe marble	b
B	Andossi	527230	5145211	Starlera nappe (marbles and dolomites)	Orthogneisses, paragneisses, micaschists	b
C	Pian dei Cavalli	524030	5141080	Tambo nappe cover (marbles, micaschists, quartzites)	Paragneisses	b
D	Alpe Boggi	525200	5139018	Tambo nappe cover (marbles, micaschists, quartzites)	Paragneisses	b
E	Crespallo	530050	5133278	Tambo nappe, Truzzo metagranite (granite and metagranite)	Spluga quartzites	b
F	San Bernardo	526855	5132745	Tambo nappe, Truzzo metagranite (granite and metagranite)	Paragneisses	b
G	Slope N of Villa di Chiavenna	538593	5132203	Tambo nappe, Truzzo metagranite (granite and metagranite)	Bergell granodiorites / quartz diorites	a, b
H	Savogno	533867	5131876	Tambo nappe, Truzzo metagranite (granite and metagranite)	Rare blue metapelites	a
I	N of Prosto	531358	5131232	Tambo nappe basement (Ms-Chl paragneisses, schists, micaschists, locally amphibolitic gneisses)	Rare mafic rocks (amphibolites)	a
J	Bette	529301	5130379	Tambo nappe basement (Ms-Chl paragneisses, schists, micaschists, locally amphibolitic gneisses)	Truzzo metagranites, mafic rocks (amphibolites)	a
K	Slope S of Villa di Chiavenna	539780	5129799	Tambo nappe basement (micaschists and paragneisses)	Bergell granites / granodiorites / quartz diorites, rare blue metapelites, very rare mafic rocks and paragneisses	a
L	N of Menarola	526519	5128649	Tambo nappe basement (granodioritic augen orthogneisses)	Rare amphibolites and very rare Spluga quartzites, Starlera nappe dolomites and marbles	a, b
M	SE of Chiavenna	533414	5128186	Chiavenna Unit (ultramafites, metagabbros)	Granites / granodiorites	a
N	S of Menarola	525981	5126494	Adula nappe, basement (granodioritic augen gneisses, flaser, locally migmatitic)	Truzzo metagranites	a
O	SE of Prata Camportaccio	531886	5126495	Gruf Unit (migmatitic gneisses)	Bergell granites / granodiorites	a
P	Donadivo	527360	5125750	Adula nappe, basement (granodioritic augen gneisses, flaser, locally migmatitic)	Truzzo metagranites, paragneisses, Spluga quartzites	a
Q	W of Samolaco	528230	5121436	Adula nappe, Paglia Schlingencomplex (migmatitic gneisses)	Starlera nappe marbles	a
R	E of Codera	536989	5121409	Novate Granite (two-mica leucogranite)	Bergell granodiorites and tonalites, quartzdiorites	a
S	Avert Manco	526567	5121041	Adula nappe, Paglia Schlingencomplex (migmatitic gneisses)	Truzzo metagranites	a
T	W of Casenda	529297	5119714	Adula nappe, Paglia Schlingencomplex (migmatitic gneisses)	Paragneisses	a
U	E of Verceia	536160	5116455	Bellinzona-Dascio Zone (migmatitic gneisses)	Bergell granites /granodiorites, paragneisses, Novate granites	a
V	N of Bugiallo	530466	5115661	Bellinzona-Dascio Zone (migmatitic gneisses with amphibolite lenses)	Truzzo metagranites and Spluga quartzites	a, c
W	Bugiallo	530816	5114662	Bellinzona-Dascio Zone (migmatitic gneisses with amphibolite lenses)	Truzzo metagranites	a, c
X	La Piazza and nearby slopes	535310	5112694	Tonale series (gneissic insubric mylonites)	Mafic rocks (amphibolites, serpentine), Bergell granites /granodiorites	a, b
Y	Valchiavenna / Valtelline watershed	534552	5112611	Tonale series (gneissic insubric mylonites)	Mafic rocks (amphibolites, serpentines), scarce Bergell granites /granodiorites	a, b
Z	Vercana	525315	5111794	Morbegno gneisses (Bt-gneisses, micaschist, phyllonites)	Bergell granites /granodiorites	c

(the Bergell pluton outcropping in both the Italian and Swiss drainage basins) and mafic rocks come from Malenco Valley.

Given the above, during the last glaciation, Valchiavenna was filled by a glacier that was made up of two distinct tongues: one from San Giacomo Valley and one from Bregaglia Valley. These two bodies joined at Chiavenna, but still kept their respective identities. Figure 3 schematically shows the source areas of erratic lithologies, their flow paths and their places of deposition. These erratic lithologies were found at various altitudes on the slopes, showing no variation in the deposition of glacial deposits over time in Valchiavenna. Maggi (1992) reports a few Bergell granite erratics at 400 m a.s.l. just SW of the studied area (Z in Tab. 1 and Fig. 3). Since there is no evidence of sudden changes in glacial dynamics during the deglaciation, it can be inferred that the distinction between the two glacier bodies was maintained both at the LGM and during an advanced deglaciation. The evidence found by Maggi (1992) suggests that during an advanced stage of the deglaciation, either i) the San Giacomo glacier did not reach those areas, probably being progressively thinned by the greater Engadine glacier that, in this way, could deposit its till and erratics on the western slope of the valley (more probable), or ii) the entire Engadine glacier did not reach these areas, so the erratics came from Masino Valley and were deposited by the Adda glacier (less probable).

Valchiavenna glaciers at the LGM

Based on trimline evidence (Tab. 2), it was possible to reconstruct the extent of the glaciated area at the LGM for both the valley glaciers and local glaciers (Fig. 4). Figure 4 shows that at the LGM, almost all of the Valchiavenna territory was glaciated. The glaciers at the LGM covered about 512 km^2 out of the 578 km^2 study area (88.6% of the whole territory).

We identified 25 trimlines related to valley glaciers and 32 related to local glaciers. Forty-eight out of 57 trimlines are due to a contrast in glacial erosion and 33 are due to a contrast in glacial deposition; some of the trimlines belong to both categories. We observed that the discontinuities of slope process landforms and weathering contrast discontinuities are, when present, associated with erosional features. Only 7 out of 25 valley glacier trimlines are visible due to a contrast in glacial erosion: this occurs in the upper San Giacomo Valley and at two other sites that present very steep slopes, while till and erratics are present in all the other cases.

As outlined in this work and in the Swiss LGM reconstruction, Valchiavenna at the LGM was occupied by a valley glacier. In particular, it was filled by two glacial bodies – the Engadine and San Giacomo glaciers – as confirmed by the evidence of the erratic clasts described above. The Engadine tongue originated at the Engadine dome, which was located outside of Valchiavenna towards the east (Florineth,

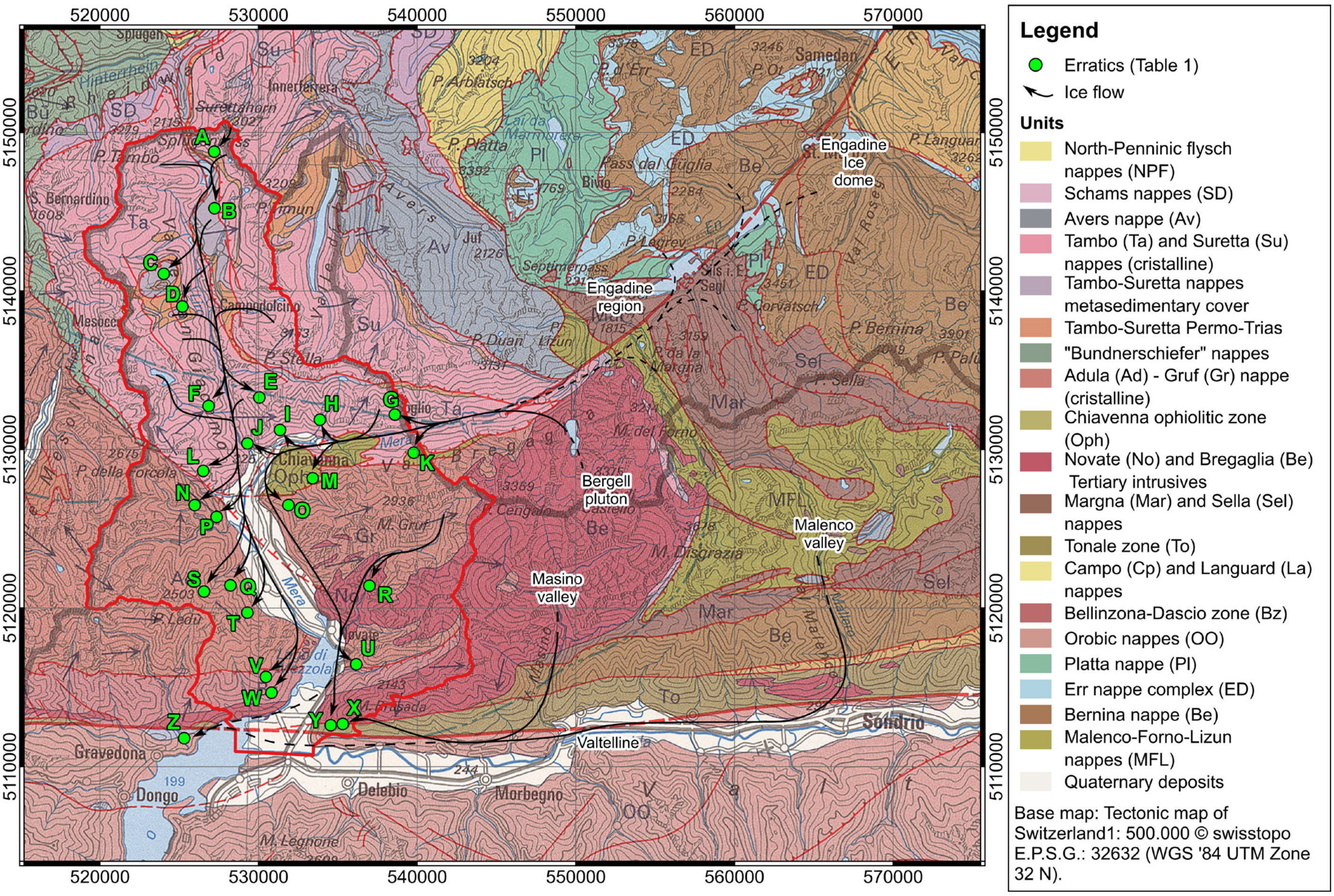


Fig. 3 - Erratic clasts found in till and their positions. Arrows go from the general source areas of erratic clasts to the positions where erratic clasts where found. Refer to Tab. 1 for the complete list of erratic (A–Z) characteristics and referred sources. Dashed lines indicate an uncertain flow path.

Table 2 - Trimline evidence used in this work. Data sources:
a) Tantardini, 2016; b) this work; c) Maggi, 1992. Coordinates are in UTM Zone 32 N, WGS 1984 (E.P.S.G. code 32632).

ID in Fig. 4	Local toponym	Coordinates (m)		Elevation (m a.s.l.)	Evidence	Source
		X	Y			
01	Mount Cardine	525673	5146744	2320	Slope gradient change, ice-scoured rocks	b
02	Camosciè Peak N slope	525354	5134921	2153	Last till (moraine)	b
03	Bianco Peak - Dei Rossi Peak	520169	5144054	2950	Ice-scoured rocks	b
04	Mount Baldiscio N slope	519717	5142143	2460	Ice-scoured rocks	b
05	SE ridge of Montagna Peak	522236	5138668	2400	Slope gradient change, last till	b
06	Ridge between Motto Alto and Rosso Peak	524122	5138191	2213	Slope gradient change, last till	b
07	Il Pizzetto	525699	5130647	2060	Last till	b
08	Slope between Alpigia Pass and Camosciè Peak	524751	5134754	2310	Slope gradient change, ice-scoured rocks	b
09	Casa Peak	526173	5149118	2320	Slope gradient change, ice-scoured rocks	b
10	Caurghetta Valley	526927	5148996	2320	Slope gradient change, ice-scoured rocks	b
11	Nero Lake	528071	5147648	2320	Slope gradient change	b
12	Emet Lake	529037	5147370	2320	Slope gradient change, ice-scoured rocks	b
13	Sterla Valley	529239	5144304	2250	Slope gradient change, ice-scoured rocks	b
14	Fortezza divide	529059	5140275	2220	Slope gradient change	b
15	Crespallo	530138	5133379	2080	Last erratics, last till	b
16	Alpe Pescedo	529737	5117125	1685	Last till (moraine)	a, c
17	Mount Berlinghera, NE slope	530630	5117827	1690	Slope gradient change, ice-scoured rocks	a
18	Basello della Costa, SW of Alpe Gigiai	527619	5116874	1690	Last erratics, last till	a
19	Corna di Garzone Peak	535030	5127116	2170	Last erratics, last till	a
20	E ridge, Corna di Garzone Peak	535042	5126897	2195	Last erratics	a
21	S slope of Mount Galleggione	538081	5133638	2255	Last erratics, last till	b
22	N of Vallon Peak	541061	5127801	2250	Slope gradient change	a
23	Avert Manco	526229	5120873	1757	Last erratics	a
24	Avert Campo	527687	5120004	1750	Last till	a
25	E ridge of Mount Brusada	537554	5114089	1805	Slope gradient change, last till	b
26	Ridge of Mount Borlasca	525825	5122468	1790	Last till	a
27	Mount Frasnedo	539370	5117778	1840	Last till (moraine)	a
28	Ridge of Mount Cucco	524084	5122198	1850	Last till	a
29	Il Mottone	523841	5125424	1890	Slope gradient change, last till	a
30	Ridge of Avert Cima	524434	5127906	1970	Last erratics, last till	a
31	Piangesca, basin of Acqua Fraggia Lake	534388	5134310	2145	Slope gradient change, last till (moraines)	a
32	Carmezzano	532934	5133860	2130	last erratics	a
33	Piazza Peak	522181	5125497	2140	Ice-scoured rocks	a
34	Settagiolo Dentro Peak	520302	5124687	2370	Ice-scoured rocks	a
35	E of Avert Pregassone	524152	5128151	1960	Ice-scoured rocks	a
36	Avert Fugiana	523081	5128819	2290	Slope gradient change, ice-scoured rocks	a
37	Piodella Peak	522145	5127130	2360	Ice-scoured rocks	a
38	Spondone Valley	522112	5121389	2000	Decolorated ice-scoured rocks	a
39	S dell'Oro Peaks	542351	5121960	2150	Slope gradient change, ice-scoured rocks	a
40	Vanni Pass	542564	5127912	2520	Slope gradient change, ice-scoured rocks	a
41	Teggiola Valley	542691	5127679	2500	Ice-scoured rocks	a
42	NW ridge of Altare Peak	543720	5127531	2690	Slope gradient change, ice-scoured rocks	a
43	Trubinasca glacier cirque, Badile Peak	544354	5126528	2750	Slope gradient change, decolorated ice-scoured rocks	a
44	Caser Valley	536124	5123880	1950	Last erratics, last till	a
45	Caser Valley, E slope	537249	5124712	1950	Last erratics, last till	a
46	W cirque of Sasso Manduino Peak	539514	5119535	2170	Decolorated ice-scoured rocks	a
47	SW slope of Bresciadega Peak	539909	5121071	2300	Decolorated ice-scoured rocks	a
48	Codogno Valley	539454	5115022	2110	Last till (moraine)	a
49	Ligoncio Peak, S slope	542221	5120582	2875	Decolorated ice-scoured rocks	a
50	Gaiazzo Peaks	541061	5120608	2835	Decolorated ice-scoured rocks	a
51	Bonazzola Peak	541637	5120599	2830	Decolorated ice-scoured rocks	a
52	Malvedello Peak	541958	5115627	2500	Decolorated ice-scoured rocks	a
53	Alpe Primalpia II	542632	5116488	2400	Decolorated ice-scoured rocks	a
54	On the slope above Alpe Camera	541096	5118206	1990	Last erratics, last till (moraine)	a
55	Motto Rotondo	524037	5120450	2350	Slope gradient change, decolorated ice-scoured rocks	a
56	Ladrogno Valley	539909	5119833	1960	Slope gradient change, decolorated ice-scoured rocks	a

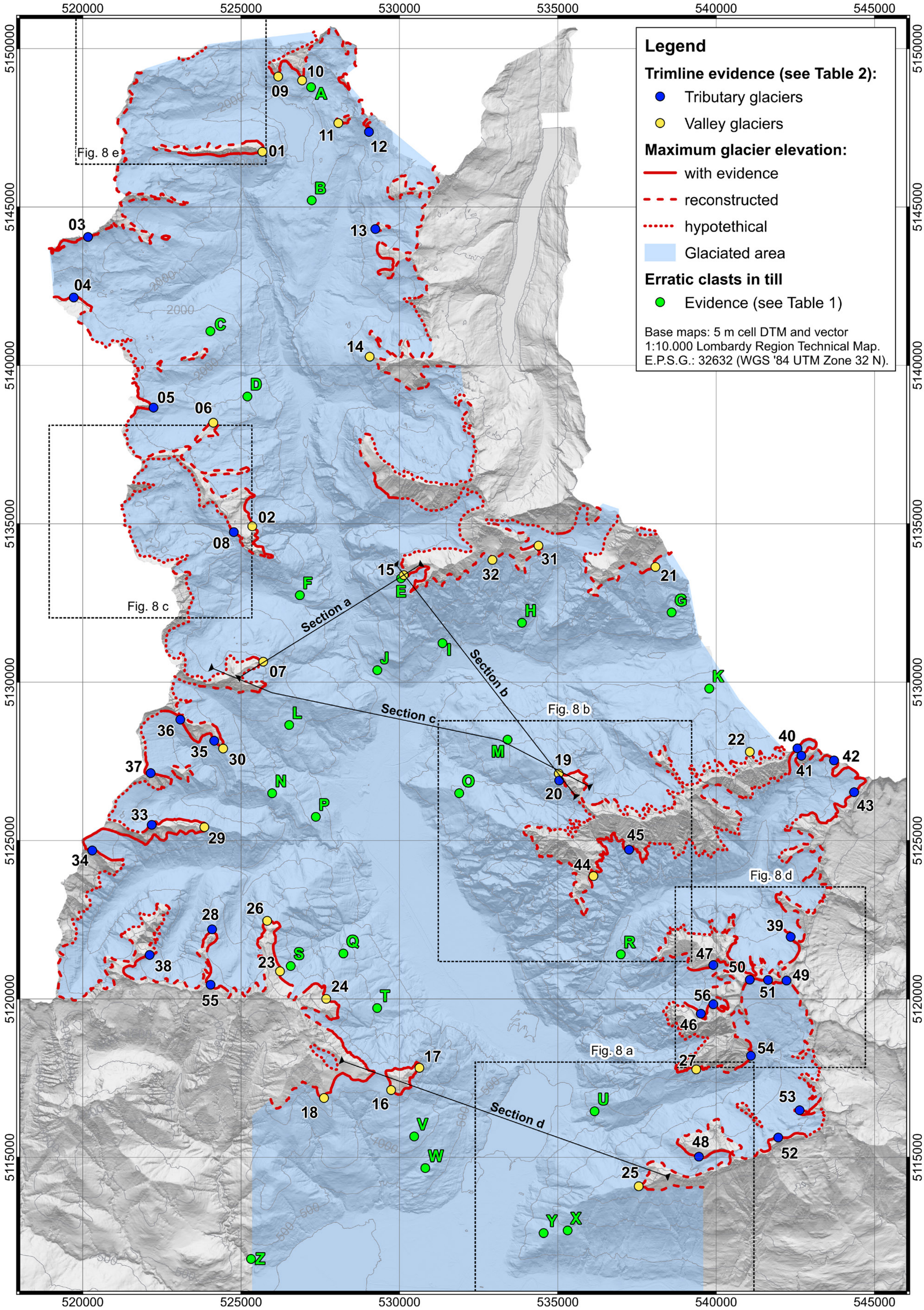


Fig. 4 - Reconstruction of the glaciated area at the LGM in Valchiavenna based on the identified geomorphological and sedimentological evidence. Numbers refer to the evidence IDs and related features in Tab. 2. Letters refer to the erratic lithologies in Tab. 1. The section traces correspond to the cross sections in Fig. 5.

1998), and entered Valchiavenna by flowing through Bregaglia Valley; it reached the Adda glacier (which occupied Valtelline) near the upper Lake Como region. The tributary San Giacomo glacier tongue originated in the homonymous valley and flowed southward and joined the Engadine glacier near the town of Chiavenna.

During the field survey in Valchiavenna, no evidence was found of older glaciations' deposits. The trimlines indicate that the accumulation zone of the glaciers almost reached the watershed ridge tip, with only the most elevated ridges and a few nunataks emerging above the ice surface.

The accumulation area of the San Giacomo glacier was located in the northern part of the valley, and some of the tributaries of this glacier had points of contact with Rhine catchment glaciers. According to the field data and the following reconstructions, glaciers belonging to the Rhine catchment touched glaciers belonging to the Po catchment at some mountain passes, but low ice thicknesses, hardly a few tens of metres, did not permit the glaciers to flow freely across the pass. In the southern part of San Giacomo Valley, the glacier was in the ablation zone: here, the trimline is marked by sedimentary evidence (IDs 02, 07 and 15 in Tab. 2 and Fig. 4; photo E in the supplementary map). Refer to Tantardini et al. (2013) for a more detailed description of the San Giacomo glacier geometry at the LGM.

According to Florineth (1998) the Engadine glacier came from a glacial dome located in the Engadine region (Switzerland), which reached an altitude of about 3000 m a.s.l., with ice thicknesses of about 1200 m. We found that near the Italian-Swiss national border, the altitude of the Engadine glacier had decreased down to 2250 m a.s.l., following the topography of the valley bottom, as confirmed by two trimlines (IDs 21 and 22 in Tab. 2 and Fig. 4; photo O in the supplementary map) located at the same altitude on opposite sides of Bregaglia Valley.

In the Italian part of Bregaglia Valley, the diffuse sedimentary evidence (till, erratics, moraines) corresponding to the maximum glacier altitude shows that the Engadine glacier was in the ablation zone. Several small tributary glaciers were present in the suspended cirques of the southern slope of Bregaglia Valley, whereas on the northern slope, there was only one tributary glacier, the Acqua Fraggia glacier. Although it was not possible to identify its local trimline, the presence of outcropping rock smoothed by ice at the NE pass (near Galleggione Peak) on both sides of the watershed indicates that from this pass, the Acqua Fraggia glacier flowed in both the Po River and Rhine catchments.

At Chiavenna, the Engadine glacier flowing from the ENE and the San Giacomo glacier flowing from the NNW joined and formed a single glacier, which flowed southwards through lower Valchiavenna. Considering the differences in elevations and volumes between the two glaciers, the name 'Engadine glacier' is used to refer to the valley glacier flowing in lower Valchiavenna, which was composed of the two glacier tongues. Thus, at the LGM, the lower Valchiavenna was filled by a valley glacier made up of a main Engadine tongue and a minor San Giacomo tongue. Despite the difference between their volumes (Fig. 5), the two glacier tongues maintained their respective identities, as confirmed by the petrography of tills on the opposite slopes of lower Valchiavenna (Tab. 1, Fig. 3). Trimline evidence on the opposite

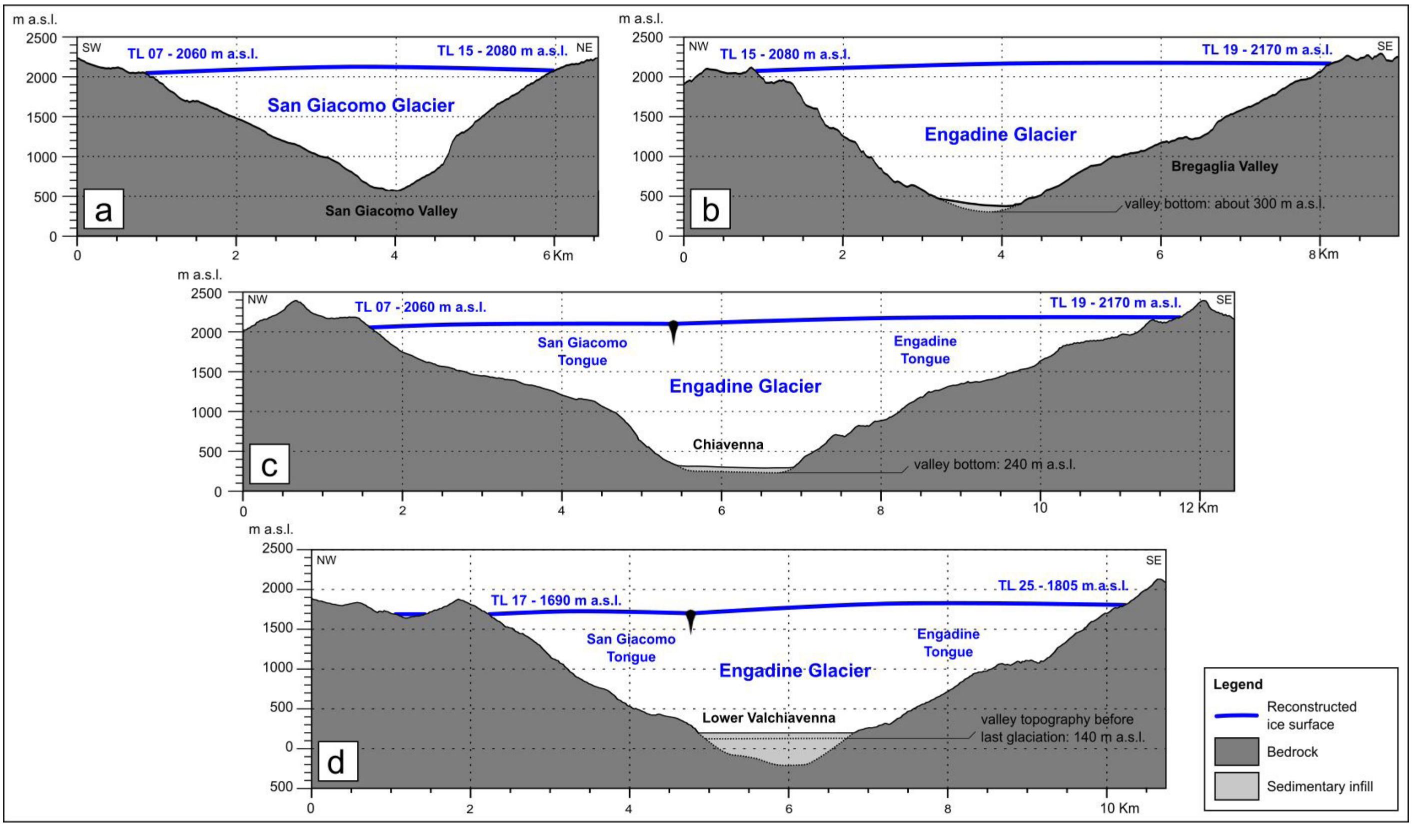


Fig. 5 - Schematic cross sections of the San Giacomo and Engadine glaciers throughout Valchiavenna. 'TL' indicates the ID numbers of the trimline evidence in Tab. 2 and Fig. 4.

slopes of the valley shows that the San Giacomo tongue flowed throughout southern Valchiavenna at slightly lower altitudes than the Engadine tongue (Fig. 5). Thus, the Engadine glacier had a difference in altitude of nearly 110 m from one side to the other, with the eastern side being at higher altitudes. The reconstructions in Figure 5 show the following: i) the San Giacomo glacier north of Chiavenna reached a thickness of about 1550 m and a flow section of about 4.08 km^2; ii) the Engadine glacier just NE of Chiavenna was about 1800 m thick or a little more (the sedimentary infill thickness is uncertain) and had a flow section of about 7.44 km^2; iii) around the junction at Chiavenna, the glacier thickness was about 1800–1970 m, considering that the city of Chiavenna is located at about 300 m a.s.l., with a valley infill a few decametres thick; and iv) the thickness of the glacier body near the Valchiavenna–Valtelline junction was about 1550–1665 m, with a flow section of about 8.25 km^2, considering that the present valley bottom is at 200 m a.s.l., whereas prior to the deposition of post-glaciation sediments, the valley bottom was at about 140 m a.s.l., where an abrupt change in sedimentation occurs.

The morphological and sedimentary features of the trimline evidence present in the watershed areas of the tributary valleys originate from the valley glacier rather than the local glaciers. As an example, it is possible to infer that the Engadine glacier inserted lateral tongues into its tributary valleys, such as the Bodengo (photo H in the supplementary map), Codera and Ratti valleys. Local glaciers, whose presence is inferred by glacial sediments and landforms (e.g., on the Mount Gruf north slope, in Forcola Valley, on the Sasso Canale Peak east slope), were trapped in their original cirques and in the heads of their respective valleys. Their accumulation basins were most likely in direct contact with the Engadine glacier body.

Glacial advances after the LGM

Following the same procedure used to correlate LGM trimline evidence, glacial advance limits were reconstructed for the glacial advances that occurred after the LGM. In this way, a relative chronology of events is established even in the absence of absolute dating: the behaviour of the glaciers and interactions among them are inferred, even though these events cannot be specifically attributed to the last glaciation recession or to a definite Late Glacial stadial.

Figure 6 shows a map of the glacial advance limits, incorporating previously published data for San Giacomo Valley (Tantardini et al., 2013) and extending the reconstruction to the remaining part of Valchiavenna catchment (Italian part of Bregaglia Valley and the southern main valley).

The glacial advance limits were generally reconstructed over relatively short distances for the following reasons: i) the intense slope dynamics have erased the sedimentary evidence of the various glacial advances through territory denudation; ii) the glacial dynamics caused the glacier to express more evident variations of the glacial mass volume in its front zone than in its marginal or lateral zones; and iii) the field evidence is often located on slopes a few kilometres distant from each other, especially for valley glaciers.

Nonetheless, the general framework outlined for San Giacomo Valley (Tantardini et al., 2013) is also found to be valid for the Italian part of Bregaglia Valley and lower Valchiavenna. At the maximum of the last glaciation expansion, lateral glaciers could have been trapped within their own valleys by the bigger mass of the valley glacier. Field evidence indicates that even after the LGM, the valley glaciers inserted lateral tongues into the tributary valleys, just as the Engadine glacier did. In this way, tributary glaciers were generally trapped within their own valleys, and they could only advance at times when the valley glacier had melted. Examples of this behaviour can be found in Forcola Valley and Schiesone Valley. In these two areas, one can clearly observe how the glacial advance limits of the valley glacier and those of the tributary glaciers overwrite each other depending on the relative movement (advance/withdrawal) of the ice masses (Fig. 7a, b).

With the gradual melting of the valley glacier, the tributary glaciers could deposit till and erratics and form moraines on slope and valley bottom areas previously covered by the valley glacier ice and at lower altitudes than the valley glacier's older lateral moraines, which remain on higher parts of the slopes. Examples of glaciers expressing this behaviour are the Quadro glacier (Starleggia Valley), Fortezza glacier (Groppera Valley), Acqua Fraggia glacier and Codera glacier (in the homonymous valleys; Fig. 7c–f). The landforms previously deposited by the valley glacier were destroyed during the advance of local glaciers, which deposited their sediments above the older sediments or replaced the previous sediments.

Discussion of this work and other studies in the Alpine region

The current knowledge on Alpine glaciers is the result of decades of work: in the beginning, extensive geomorphological field surveys were performed, progressively updated and integrated through detailed field surveys and modern techniques (e.g., geochronological dating and aerial or remote sensing surveys). The work of Penck & Brückner (1909) is a milestone. The Alpine area was the object of several field surveys through time, and a great amount of field data was produced and summarised using geological and palaeogeographical maps (e.g., Jäckli 1962, 1970 for Switzerland and Venzo, 1946, 1965 for the Lake Como and Lake Garda amphitheatres, respectively).

More recent works located in regions around Valchiavenna, such as Florineth (1998) and Kelly et al. (2004), gave an updated reconstruction of the geometry of glaciers at the LGM using previous field data (mostly from Jäckli, 1962, 1970) and carried out focused field surveys in order to acquire data to resolve particular issues. Even the palaeogeographic Swiss LGM reconstruction is a clear example of this accumulation of data through time.

With respect to these more well-known areas, Valchiavenna remained less studied. Other areas across the Alpine arc were in the same situation and were also only investigated in recent times. As an example, following a detailed field survey spanning two decades combined with the ^{14}C dating of glacial deposits, Federici et al. (2017) described and chronostratigraphically constrained a glacial deposit sequence spanning from the LGM to the LIA in the Maritime Alps. On the opposite side of the Alpine arc, Rettig et al. (2021) reconstructed the LGM and Late Glacial palaeoglaciers of a small valley in the Carnic Alps, using GIS modelling and a three-year field and remote sensing (LIDAR) survey.

The extensive and detailed field survey conducted in Valchiavenna in recent years made it possible to reconstruct

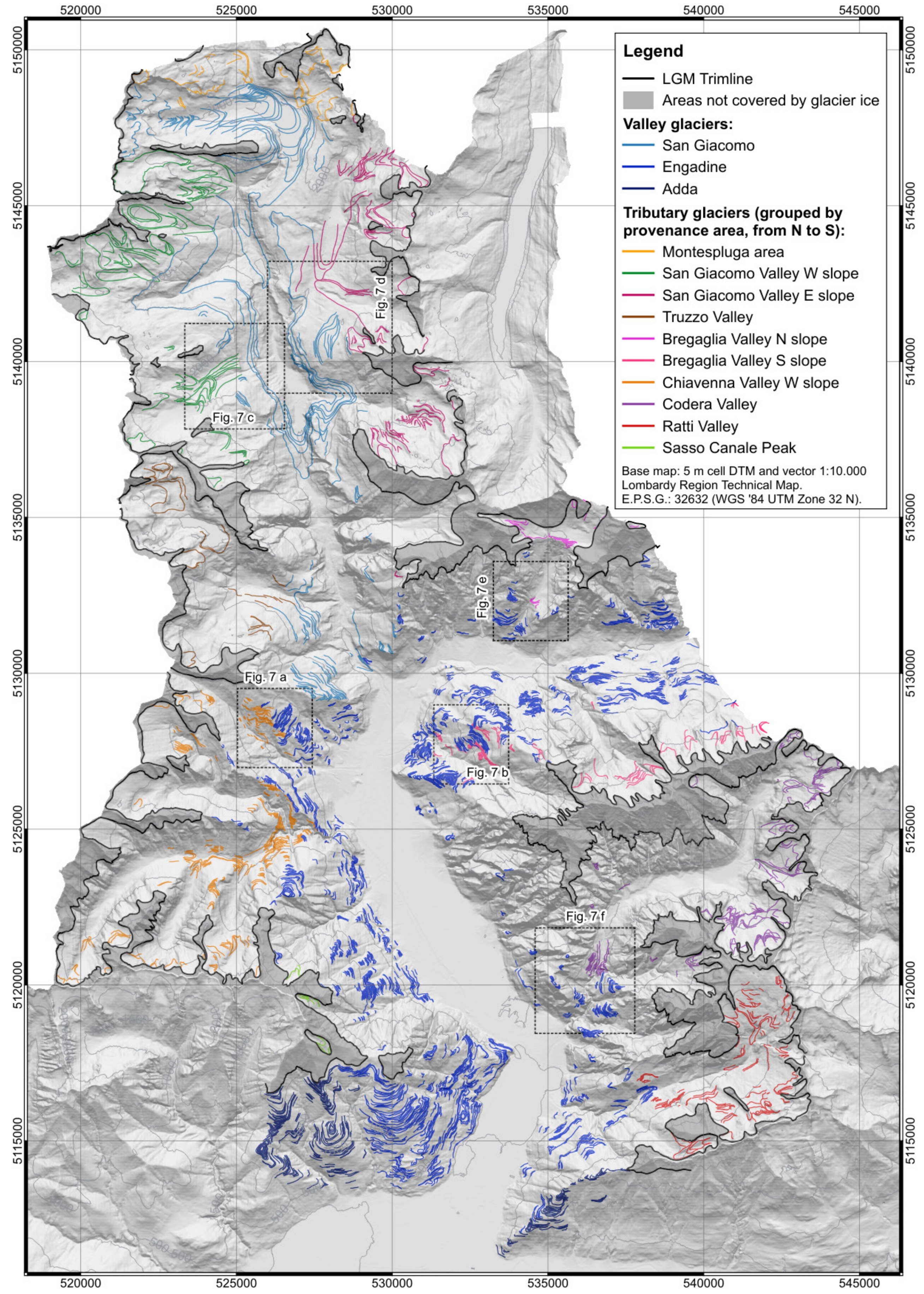


Fig. 6 - Map of glacial advance limits. Data for San Giacomo Valley come from Tantardini et al. (2013). Glaciers are grouped by valley or area of provenance. A wider version of Fig. 6 is provided as supplementary material.

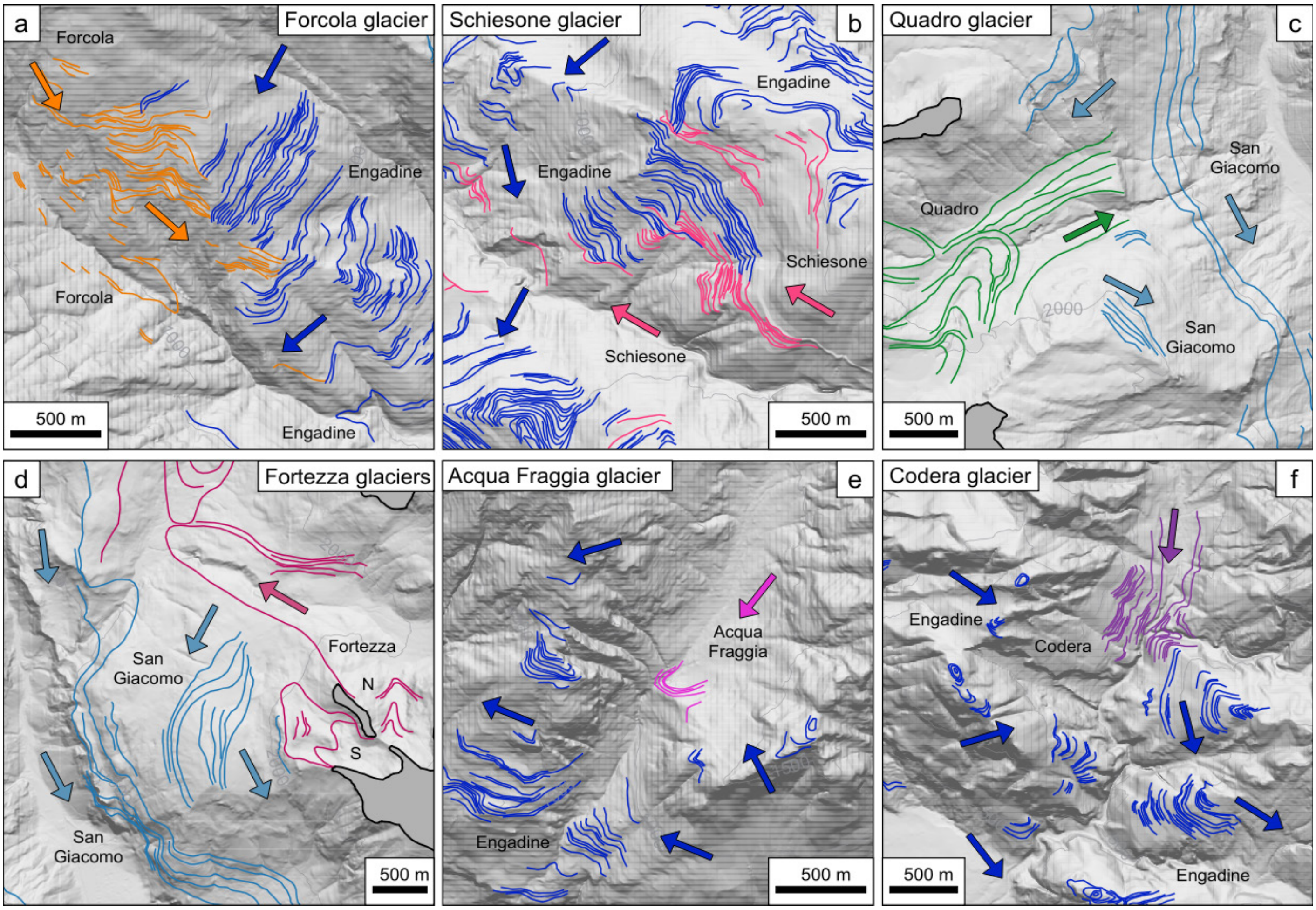


Fig. 7 - Examples of interactions between a valley glacier and local glaciers. The arrows indicate the direction of ice flow at different periods. a, b) Forcola and Schiesone tributary glaciers advance when the Engadine valley glacier melts down, and its deposits and morphologies are destroyed by the advancing local glaciers. On the opposite side, the Engadine glacier destroys local glacier landforms when it grows in volume and advances. c, d, e, f) Examples of local glaciers that flow into their valleys, depositing till and building morphologies on the valley bottom, when the advanced melting of the valley glacier occurs. Previously, the valley glacier occupied these same tributary valleys.

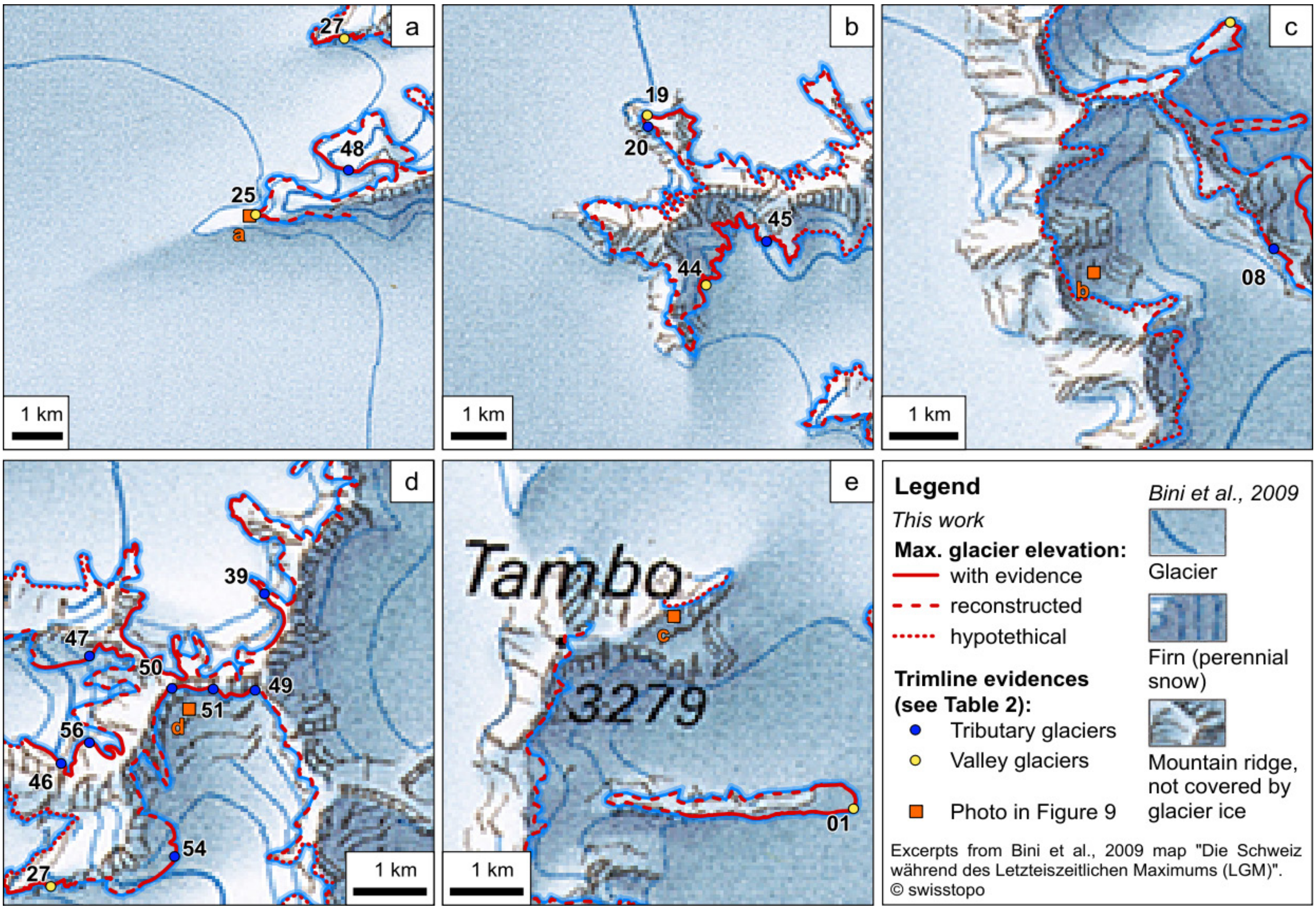
LGM palaeogeography and a relative chronology for glacial advances. Although a thorough chronostratigraphic reconstruction of glacial advances has not been performed, a comparison of the reconstructed LGM palaeogeography with existing LGM palaeogeographies can be attempted; the Swiss LGM reconstruction was chosen for this comparison, as it is the most updated reconstruction.

The greater detail of the data in this work makes it possible to better define the geometry of the glaciers at the LGM with respect to previous works: some differences with the Swiss LGM reconstruction are apparent, in the context of generally good agreement between the two works given the difference in scale. These differences are related to the different elevations of the San Giacomo and Engadine glaciers on the opposite slopes of Valchiavenna, the presence of contacts among the Po River and Rhine Basin glaciers and the presence of local glaciers in some cirques. Some examples are shown in Figure 8.

Near the Valtelline watershed ridge (Fig. 8a), in the Swiss LGM reconstruction, the valley glacier reaches about 1600 m, which is about 200 m lower than the observed trimline at 1805 m a.s.l. (ID 25 in Fig. 4, Tab. 2) that is expressed by a slope gradient change and the presence of tills (Fig. 9a). Even on the ridges SE of Chiavenna (Fig. 8b), the trimline is about 200 m higher than in the Swiss LGM reconstruction (ID 19 in Fig. 4 and Tab. 2), and it can be identified by its erratics and tills.

The Swiss LGM reconstruction indicates that some cirques did not hold local LGM glaciers, but the presence of glacial deposits and large-scale erosion landforms on rock outcrops inside these cirques contradict this hypothesis. For example, for the western slope of Truzzo Valley (Corbet Peak ridge), the Swiss LGM reconstruction maps outcropping rocks (Fig. 8c), but there are glacial deposits in the field that indicate the past presence of local glaciers in the cirques at the foot of the watershed ridge (Fig. 9b). The same can be found for the cirques of the upper Ratti Valley and middle Codera Valley (Fig. 8d): the Ratti glacier in the Swiss LGM reconstruction occupies only the western portion of the cirque, whereas observed glacial features indicate that the whole cirque was occupied by the glacier, both at the LGM and after (Fig. 9d; photo V in the supplementary map).

According to the Swiss LGM reconstruction, Tambo Peak at the head of San Giacomo Valley was not covered by glaciers, but



Excerpts from Bini et al., 2009 map "Die Schweiz während des Letzteiszeitlichen Maximums (LGM)". © swisstopo

Fig. 8 - Comparison between the Swiss LGM reconstruction palaeogeographic map (Bini et al., 2009) and the trimline reconstruction and field evidence of this work. a) Valchiavenna-Valtelline watershed: the trimline was recognised due to the presence of till deposits and a slope change (Fig. 9a). b) Eastern Valchiavenna side. c) Truzzo Valley (valleys of Corbet Peak ridge): the Swiss LGM reconstruction indicates that at the LGM, most of the watershed ridge slope was not covered by glaciers or firn. On the contrary, in this area, till deposited by a local glacier coming from the SE cirque of the peak south of Corbet Peak is present (Fig. 9b). d) Ratti glacier (S Ligoncio Peak cirque) filled the head of the valley, almost reaching the mountain ridge, all over the cirque, not just in some portions as the Swiss LGM reconstruction claims (Fig. 9d). N Ligoncio Peak cirque: in this cirque, the local glaciers are slightly wider than they are in the Swiss LGM reconstruction. e) At the LGM, Tambo Peak was almost entirely covered by local glaciers (Fig. 9c) connected to other glaciers in the Swiss territory through a pass; only Tambo Peak and the minor peak on its eastern side on the same ridge were not covered by glacier ice.

only by firn. On the contrary, moraines and tills (Fig.s 8e and 9c) prove the presence of local glaciers that almost entirely covered its SE slopes and touched, along the current watershed ridge, local glaciers on the NW Swiss slopes. This discrepancy between the present work (i.e., local glaciers extending almost to the summits or ridges) and the Swiss LGM reconstruction (i.e., glaciers that do not completely cover the higher parts of the slopes) is mainly due to the lack of direct field data for the Swiss LGM reconstruction, and this discrepancy also occurs for other peaks, e.g., Galleggione Peak, Suretta Peak, Emet Peak, Forcola Peak, Ledù Peak ridge and Ligoncio-Badile-Vanni Peaks ridge.

CONCLUSIONS

The field work carried out in Valchiavenna allowed us to study in a comprehensive way a wide territory with old, scarce and scattered previous work. The data were collected using a 1:10,000 scale, and a 1:25,000-scale map of Upper Pleistocene glacial sediments and landforms was drawn. Field data on the maximum ice elevation were used to reconstruct an LGM palaeogeographic map, while data on erratics made it possible to identify the palaeo-flow directions. Detailed field observations of the sedimentological and morphological relationships between glacial deposits and landforms made it possible to establish relative chronologies and to outline the general glacial dynamics of the area.

The palaeogeographic reconstruction of the glaciated area at the LGM made it possible to confirm with field evidence that valleys were almost completely filled by glacier ice at the LGM, covering about 88% of the study area, with only the most elevated ridges and peaks emerging above the ice surface. The glaciers reached slightly different elevations on the opposite slopes of the main valley, with ice thicknesses up to 1800–1970 m near Chiavenna. In Valchiavenna, the Engadine glacier was composed of two distinct glacial bodies, a bigger glacier coming from Switzerland, through Bregaglia Valley, and a smaller glacier from San Giacomo Valley. As shown by the different erratic lithologies on the two sides of the valley, this configuration lasted at least until an advanced stage of the last glaciation retreat.

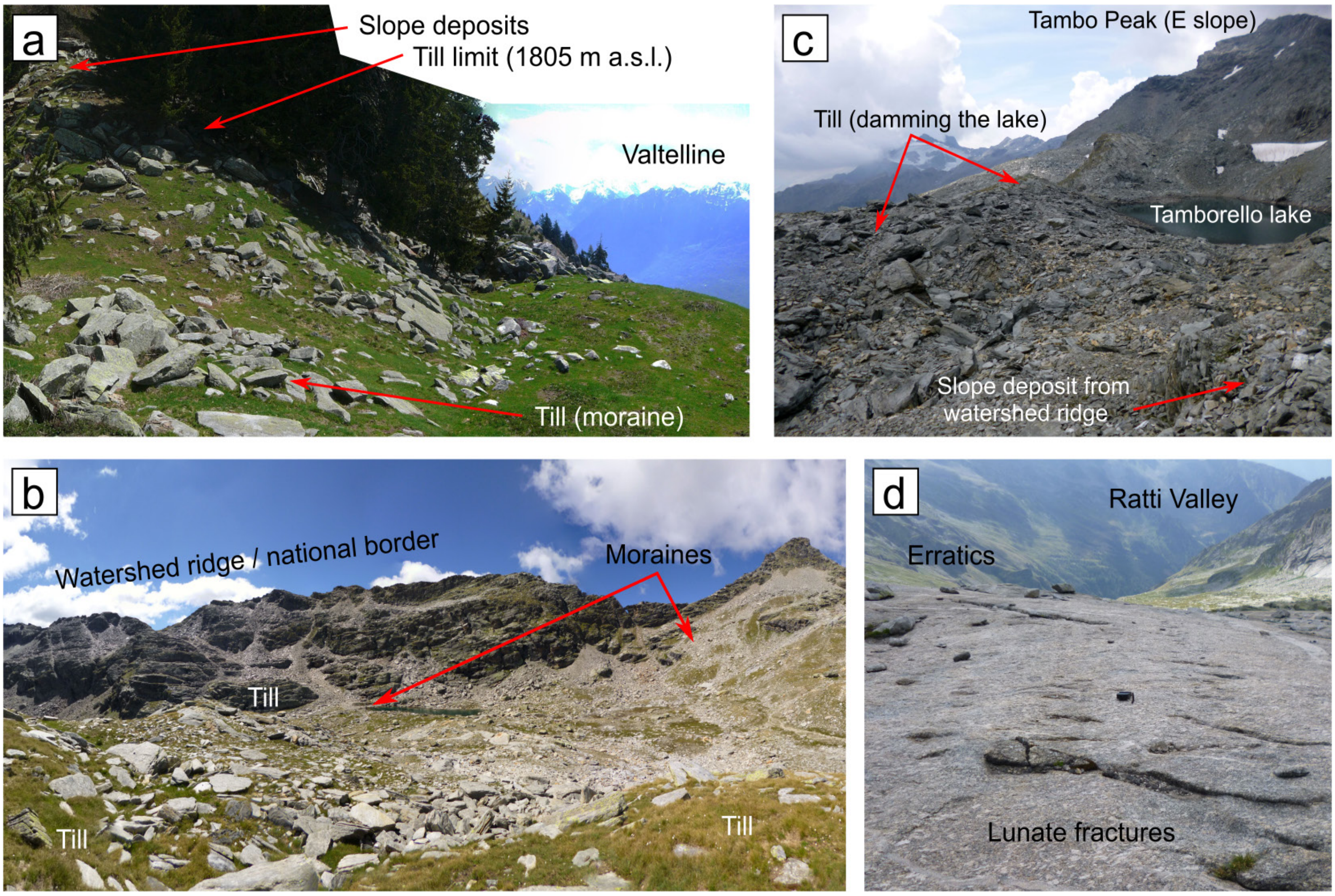


Fig. 9 - Field evidence: a) Trimline (ID 25) on the Valtelline–Valchiavenna watershed ridge; b) Moraines and till in a cirque south of Corbet Peak; c) Till deposited by Tambo Peak local glaciers a few hundred metres from the watershed ridge / national border (located just to the right of Lake Tamborello); d) Erratics and lunate fractures in the Ligoncio Peak cirque, at the northernmost head of Ratti Valley.

Erratics found on the eastern slope of southern Valchiavenna came even from distant source areas in the Engadine and Valtelline regions due to the Engadine and Adda glaciers, respectively.

During the last glaciation, the valley glacier inserted offshoots in tributary valleys, thus generally blocking the advances of local glaciers, which could advance only when a sufficient withdrawal (melting) of the valley glacier occurred. At the moment, with the data that are available, it is impossible to ascertain if those advances occurred during the last glaciation retreat or during a Late Glacial stadial advance: this evidence may simply be related to the identification of the local icefield network, due to the decrease in the volume of the valley glaciers. With the gradual melting of the valley glacier, tributary glaciers could deposit tills in areas previously covered by valley glacier ice and at lower elevations than the valley glacier's older lateral moraines, which remain on higher parts of the slopes.

Although a thorough chronostratigraphic attribution of glacial deposits and glacigenic landforms using dating methods is missing, this work provides a rich and homogeneous database that will be useful for further local and regional studies. It can guide the planning of geochronological dating, and it represents a fundamental step in the identification of glacial stadials and ice mass modelling. It can also support biogeography studies and the evaluation of the effects of climate change, slope dynamics modelling and hazard prediction.

ELECTRONIC SUPPLEMENTARY MATERIAL

This article contains electronic supplementary material which is available to authorised users.

ACKNOWLEDGEMENTS

This study was financially supported by the 'Comunità Montana di Valchiavenna' in the framework of the collaboration agreements with the 'Stazione Valchiavenna per lo Studio dell'Ambiente Alpino' (Chiavenna Research Centre for the Study of the Alpine Environment in Valchiavenna) of the Department of Earth Sciences 'A. Desio' at the University of Milan. Additionally, this study was supported by the European Regional Development Fund under the Interreg V-A Italy-Switzerland Cooperation Program, A.M.AL. PI.18 'Alpi in Movimento, Movimento nelle Alpi. Piuro 1618-2018' (ID 594274).

Field survey activities were carried out by D. Tantardini (Ph.D. scholarship, 2012–2015), E. De Finis (research grant, 2009–2011), M. Baldini, P. Biraghi, A. Pedroncelli, N. Riganti, S. Stevenazzi, D. Tantardini and P. Taglieri (graduation thesis), under the supervision of Prof. T. Apuani and Prof. A. Bini. S. Stevenazzi is currently affiliated with the Dipartimento di Ingegneria Civile, Edile e Ambientale of the Università degli Studi di Napoli "Federico II".

The 1:10,000-scale Technical Map and the DTM of the Lombardy Region are published under CC-BY 4.0 licence (http://www.geoportale.regione.lombardia.it/); the Swiss Federal Office of Topography swisstopo enables free use for its basic geodata (https://www.swisstopo.admin.ch/en/swisstopo/free-geodata.html).

We acknowledge Prof. C. Scapozza and the two anonymous reviewers for their careful reviews and thoughtful comments. Thanks are also due to the editorial board.

We also thank L. Zuccoli for information on the studies near Valchiavenna carried out by Prof. A. Bini and other collaborators, and we give a special and heartfelt thanks to Prof. A. Bini †.

REFERENCES

Bajni G., Camera C., Brenning A. & Apuani T. (2021) - Rock mass geomechanical properties to improve rockfall susceptibility assessment: A case study in Valchiavenna (SO). IOP Conference Series. Earth and Environmental Science, 833(1), IOP Publishing, https://doi.org/10.1088/1755-1315/833/1/012180.

Ballantyne C.K., Stone J.O., McCarroll D. & Nesje A. (1998) - The last ice sheet in North-West Scotland: reconstructions and implications. Quaternary Science Reviews, 17, 1149-1184, https://doi.org/10.1016/S0277-3791(98)00003-1.

Ballantyne C.K., Stone J.O. & McCarroll D. (2008) - Dimensions and chronology of the last ice sheet in Western Ireland. Quaternary Science Reviews, 27, 185-200, https://doi.org/10.1016/j.quascirev.2007.10.019.

Ballantyne C.K. (2010) - Extent and deglacial chronology of the last British–Irish Ice Sheet: implications of exposure dating using cosmogenic isotopes. Journal of Quaternary Science, 25(4), 515-534, https://doi.org/10.1002/jqs.1310.

Ballantyne C.K. & Stone J.O. (2015) - Trimlines, blockfields and the vertical extent of the last ice sheet in southern Ireland. Boreas, 44(2), 277-287, https://doi.org/10.1111/bor.12109.

Baroni C., Martino S., Salvatore M.C., Scarascia Mugnozza G. & Schilirò L. (2014) - Thermomechanical stress–strain numerical modelling of deglaciation since the Last Glacial Maximum in the Adamello Group (Rhaetian Alps, Italy). Geomorphology, 226, 278-299, https://doi.org/10.1016/j.geomorph.2014.08.013.

Baroni C., Gennaro S., Salvatore M.C., Ivy-Ochs S., Christl M., Cerrato R. & Orombelli G. (2021) - Last Lateglacial glacier advance in the Gran Paradiso Group reveals relatively drier climatic conditions established in the Western Alps since at least the Younger Dryas. Quaternary Science Reviews, 255, 106815, https://doi.org/10.1016/j.quascirev.2021.106815.

Benn D.I., Owen L.A., Osmaston H.A., Seltzer G.O., Porter S.C. & Mark B. (2005) - Reconstruction of equilibrium-line altitudes for tropical and sub-tropical glaciers. Quaternary International, 138-139, 8-21, https://doi.org/10.1016/j.quaint.2005.02.003.

Berger A., Mercolli I. & Engi M. (2005) - The central Lepontine Alps: Notes accompanying the tectonic and petrographic map sheet Sopra Ceneri (1:100.000). Schweizerische Mineralogische und Petrographische Mitteilungen, 85, 109-146.

Bernoulli D., Ambrosi C., Scapozza C., Castelletti C. & Wiedenmayer F. (2017) - Foglio 1373 Mendrisio (parte Est) con parte Ovest del foglio Como - Atlante geologico della Svizzera 1:25.000, Carta 152. Ufficio federale di topografia swisstopo, Wabern.

Bernoulli D., Ambrosi C., Scapozza C., Stockar R., Schenker F.L., Gaggero L., Antognini M. & Bronzini S. (2018) - Foglio 1373 Mendrisio (parte Est) con parte Ovest del foglio Como. Ufficio federale di topografia swisstopo, Wabern.

Bersezio R., Bini A., Gelati R., Ferliga C., Rigamonti I. & Strini A., (2014) - Note Illustrative della Carta Geologica d'Italia alla scala 1:50.000, F. 097 Vimercate, 296 pp., Regione Lombardia.

Bini A. (1997) - Stratigraphy, chronology and palaeogeography of Quaternary deposits of the area between the Ticino and Olona rivers (Italy-Switzerland). Geologia Insubrica, 2(2), 21-46.

Bini A., Buoncristiani J.-F., Coutterand S., Felber M., Florineth D., Graf H.R., Keller O., Kelly M.A., Schlüchter C., Schoeneich P. & Ellwanger D. (2009) - Die Schweiz während des letzteiszeitlichen Maximums (LGM). Bundesamt für Landestopografie swisstopo.

Bini A., Sciunnach D., Bersezio R., Scardia G. & Tomasi F. (2014) - Note Illustrative della Carta Geologica d'Italia alla scala 1:50.000, F. 096 Seregno, 192 pp., regione Lombardia.

Blomdin R., Heyman J., Stroeven A.P., Hättestrand C., Harbor J.M., Gribenski N., Jansson K.N., Petrakov D.A., Ivanov M.N., Alexander O., Rudoy A.N. & Walther M. (2016) - Glacial geomorphology of the Altai and Western Sayan Mountains, Central Asia. Journal of Maps, 12(1), 123-136, https://doi.org/10.1080/17445647.2014.992177.

Böhlert R., Egli M., Maisch M., Brandová D., Ivy-Ochs S., Kubik P.W. & Haeberli W. (2011) - Application of a combination of dating techniques to reconstruct the Lateglacial and early Holocene landscape history of the Albula region (eastern Switzerland). Geomorphology, 127(1), 1-13, https://doi.org/10.1016/j.geomorph.2010.10.034.

Boriani A. & Bini A. (2012) - Note Illustrative della Carta Geologica d'Italia alla scala 1:50.000, F. 056 Sondrio, 113 pp., Regione Lombardia.

Brack P., Dal Piaz G.V., Baroni C., Carton A., Nardin M., Pellegrini G.B. & Pennacchioni G. (2008) - Note Illustrative della Carta Geologica d'Italia alla scala 1:50.000, F. 058 Monte Adamello, 144 pp., Provincia Autonoma di Trento.

Chiesa S., Micheli P., Cariboni M., Tognini P., Motta D., Longhin M., Zambotti G., Marcato E., Ferrario A. & Ferliga C. (2012) - Note Illustrative della Carta Geologica d'Italia alla scala 1:50.000, F. 041 Ponte di Legno, 156 pp., Regione Lombardia.

Ciancaleoni L. & Marquer D. (2006) - Syn-extension leucogranite deformation during convergence in the Eastern Central Alps: example of the Novate intrusion. Terra Nova, 18, 170-180, http://dx.doi.org/10.1111/j.1365-3121.2006.00677.x.

Clark P.U., Dyke A.S., Shakun J.D., Carlson A.E., Clark J., Wohlfarth B., Mitrovica J.X., Hostetler S.W. & McCabe A.M. (2009) - The Last Glacial Maximum. Science, 325(5941), 710-714, https://doi.org/10.1126/science.1172873.

Cohen D., Gillet-Chaulet F., Haeberli W., Machguth H. & Fischer U.H. (2018) - Numerical reconstructions of the flow and basal conditions of the Rhine glacier, European Central Alps, at the Last Glacial Maximum. The Cryosphere, 12(8), 2515-2544, https://doi.org/10.5194/tc-12-2515-2018.

Comerci V., Capelletti S., Michetti A.M., Rossi S., Serva L. & Vittori E. (2007) - Land subsidence and Late Glacial environmental evolution of the Como urban area (Northern Italy). Quaternary International, 173-174, 67-86, https://doi.org/10.1016/j.quaint.2007.06.014.

Cossart E., Braucher R., Fort M., Bourlès D.L. & Carcaillet J. (2008) - Slope instability in relation to glacial debuttressing in alpine areas (Upper Durance catchment, southeastern France): Evidence from field data and 10Be cosmic ray exposure ages. Geomorphology, 95(1), 3-26, https://doi.org/10.1016/j.geomorph.2006.12.022.

Coutterand S. (2010) - Étude géomophologique des flux glaciaires dans les Alpes nord-occidentales au Pléistocène récent. Du maximum de la dernière glaciation aux premières étapes de la déglaciation. Ph.D. thesis, Université de Savoie, 472 pp.

Eberhardt E., Stead D. & Coggan J.S. (2004) - Numerical analysis of initiation and progressive failure in natural rock slopes—the 1991 Randa rockslide. International Journal of Rock Mechanics and Mining Sciences, 41(1), 69-87, https://doi.org/10.1016/S1365-1609(03)00076-5.

Engi M., Bousquet R., Berger A., Oberhansli R., Goffè B., Gosso G., Spalla M.I., Zucali M., Schuster R., Koller F., Hoeck V., Hoinkes G. & Handy M.R. (2004) - Explanatory notes to the map: metamorphic structures of the Alps. In: Metamorphic structures of the Alps. Mitt. Österr. Miner. Ges., 149, 115-226.

Evans D.J.A. (2013) - Moraine forms and genesis. Elsevier, Encyclopedia of Quaternary Science, Second Edition, 1, 769-779.

Fabel D., Ballantyne C.K. & Xu S. (2012) - Trimlines, blockfields, mountain-top erratics and the vertical dimensions of the last British-Irish Ice Sheet in NW Scotland. Quaternary Science Reviews, 55, 91-102, https://doi.org/10.1016/j.quascirev.2012.09.002.

Federici P.R., Ribolini A. & Spagnolo M. (2017) - Glacial history of the Maritime Alps from the Last Glacial Maximum to the Little Ice Age. In: Quaternary Glaciation in the Mediterranean Mountains. Hughes P.D. & Woodward J.C. (Eds.), Geological Society of London, 137-159.

Florineth D. (1998) - Surface geometry of the Last Glacial Maximum (LGM) in the southeastern Swiss Alps (Graubünden) and its palaeoclimatological significance. Eiszeitalter und Gegenwart, 48, 23-37.

Florineth D. & Schlüchter C. (1998) - Reconstructing the Last Glacial Maximum (LGM) ice surface geometry and flowlines in the Central Swiss Alps. Eclogae Geologicae Helvetiae, 91(3), 391-407, http://dx.doi.org/10.1007/s00015-004-1109-6.

Florineth D. & Schlüchter C. (2000) - Alpine avidence for atmospheric circulation patterns in Europe during the Last Glacial Maximum. Quaternary Research, 54, 295-308, https://doi.org/10.1006/qres.2000.2169.

Gaetani M., Sciunnach D., Bini A. & Rossi S. (2012) - Note Illustrative della Carta Geologica d'Italia alla scala 1:50.000, F. 076 Lecco, 216 pp., Regione Lombardia.

Galli A., Le Bayon B., Schmidt M.W., Burg J.-P. & Reusser E. (2013) - Tectonometamorphic history of the Gruf complex (Central Alps): exhumation of a granulite–migmatite complex with the Bergell pluton. Swiss Journal of Geosciences, 106, 33-62, https://doi.org/10.1007/s00015-013-0120-1.

Glasser N.F., Jansson K.N., Harrison S. & Kleman J. (2008) - The glacial geomorphology and Pleistocene history of South America between 38°S and 56°S. Quaternary Science Reviews, 27(3), 365-390, https://doi.org/10.1016/j.quascirev.2007.11.011.

Gosso G., Spalla M. I., Siletto G. B., Berra F., Bini A. & Forcella F. (2012) - Note Illustrative della Carta Geologica d'Italia alla scala 1:50.000, F. 057 Malonno, 220 pp., Regione Lombardia.

Heyman B.M., Heyman J., Fickert T. & Harbor J.M. (2013) - Paleo-climate of the central European uplands during the last glacial maximum based on glacier mass-balance modeling. Quaternary Research, 79(1), 49-54, https://doi.org/10.1016/j.yqres.2012.09.005.

Holm K., Bovis M. & Jakob M. (2004) - The landslide response of alpine basins to post-Little Ice Age glacial thinning and retreat in southwestern British Columbia. Geomorphology, 57(3), 201-216. https://doi.org/10.1016/S0169-555X(03)00103-X.

Hormes A., Ivy-Ochs S., Kubik P.W., Ferreli L. & Maria Michetti A. (2008) - ^{10}Be exposure ages of a rock avalanche and a late glacial moraine in Alta Valtellina, Italian Alps. Quaternary International, 190(1), 136-145, https://doi.org/10.1016/j.quaint.2007.06.036.

Ives J. (1974) - Biological refugia and the nunatak hypothesis., Arctic Alpine Environ., 605-636.

Ivy-Ochs S., Kerschner H., Maisch M., Christl M., Kubik P.W. & Schlüchter C. (2009) - Latest Pleistocene and Holocene glacier variations in the European Alps. Quaternary Science Reviews, 28, 2137-2149, https://doi.org/10.1016/j.quascirev.2009.03.009.

Ivy-Ochs S. (2015) - Glacier variations in the European Alps at the end of the last glaciation. Cuadernos de Investigación Geográfica, 41(2), 295-315, http://dx.doi.org/10.18172/cig.2750.

Jäckli H. (1962) - Die Vergletscherung der Schweiz im Würmmaximum. Eclogae Geologicae Helvetiae, 55(2), 285-294.

Jäckli H. (1970) - Die Schweiz zur letzten Eiszeit - La Suisse durant la dernière période glaciaire. Eidg. Landestopographie, Wabern-Bern.

Kelly M.A., Buoncristiani J.-F. & Schlüchter C. (2004a) - A reconstruction of the last glacial maximum (LGM) ice-surface geometry in the western Swiss Alps and contiguous Alpine regions in Italy and France. Eclogae Geologicae Helvetiae, 97, 57-75, https://doi.org/10.1007/s00015-004-1109-6.

Kelly M.A., Kubik P.W., von Blackenburg F. & Schlüchter C. (2004b) - Surface exposure dating of the Great Aletsch Glacier Egesen moraine system, western Swiss Alps, using the cosmogenic nuclide ^{10}Be. Journal of Quaternary Science, 19(5), https://doi.org/10.1002/jqs.854.

Kelly M.A., Ivy-Ochs S., Kubik P.W., von Blackenburg F. & Schlüchter C. (2006) - Chronology of deglaciation based on ^{10}Be dates of glacial erosional features in the Grimsel Pass region, central Swiss Alps. Boreas, 35, 634-643, https://doi.org/10.1111/j.1502-3885.2006.tb01169.x.

Kleman J. (1994) - Preservation of landforms under ice sheets and ice caps. Geomorphology, 9(1), 19-32, https://doi.org/10.1016/0169-555X(94)90028-0.

Kleman J., Jansson K., Angelis H.D., Stroeven A.P., Hättestrand C., Alm G. & Glasser N. (2010) - North American Ice Sheet build-up during the last glacial cycle, 115-21 kyr. Quaternary Science Reviews, 29(17-18), 2036-2051, 10.1016/j.quascirev.2010.04.021.

Knight, P., Weaver, R., Sugden, D. (1987) - Technical note. Using LANDSAT MSS data for measuring ice sheet retreat. Int. J. Remote Sens. 8(7), 1069-1074.

Lohse K., Nicholls J.A. & Stone G.N. (2011) - Inferring the colonization of a mountain range—refugia vs. nunatak survival in high alpine ground beetles. Molecular Ecology, 20(2), 394-408, https://doi.org/10.1111/j.1365-294X.2010.04929.x.

Longhi A. & Guglielmin M. (2020) - Reconstruction of the glacial history after the Last Glacial Maximum in the Italian Central Alps using Schmidt's hammer R-values and crystallinity ratio indices of soils. Quaternary International, 558, 19-27, https://doi.org/10.1016/j.quaint.2020.08.045.

Longhi A. & Guglielmin M. (2021) - The glacial history since the Last Glacial Maximum in the Forni Valley (Italian Central Alps). Reconstruction based on Schmidt's Hammer R-values and crystallinity ratio indices of soils. Geomorphology, 387, 107765, https://doi.org/10.1016/j.geomorph.2021.107765.

Maggi V. (1992) - Geologia del Quaternario del Monte Berlinghera e del Pizzo Sasso Canale. Il Quaternario, 5(2), 235-250.

Marquer D., Baudin T., Peucat J.-J. & Persoz F. (1994) - Rb-Sr mica ages in the Alpine shear zones of the Truzzo granite: timing of the Tertiary alpine P-T-deformations in the Tambo nappe (Central Alps, Switzerland). Eclogae Geologicae Helvetiae, 87(1), 225-239.

Michetti A.M., Livio F., Pasquaré F.A., Vezzoli L., Bini A., Bernoulli D. & Sciunnach D. (2013) - Note Illustrative della Carta Geologica d'Italia alla scala 1:50.000, F. 075 Como, 206 pp., Università degli Studi dell'Insubria e Servizio Geologico Svizzero.

Monegato G., Scardia G., Hajdas I., Rizzini F. & Piccin A. (2017) - The Alpine LGM in the boreal ice-sheets game. Scientific Reports, 7(1), 2078, https://doi.org/10.1038/s41598-017-02148-7.

Montrasio A., Berra F., Cariboni M., Ceriani M., Deichmann N., Ferliga C., Gregnanin A., Guerra F., Guglielmin M., Jadoul F., Longhin M., Mai, V., Mazzoccola D., Sciesa E. & Zappone A. (2012) - Note Illustrative della Carta Geologica d'Italia alla scala 1:50.000, F. 024 Bormio, 152 pp., Regione Lombardia.

Montrasio A. & Sciesa E. (1988) - Carta geologica della valle Spluga e aree adiacenti. Profilo Crosta Profonda 88 02, CNR. Dipartimento Scienze della Terra, Università degli Studi di Milano, Milano.

Morcioni, A., Apuani, T. & Cecinato, F. (2022) - The Role of Temperature in the Stress–Strain Evolution of Alpine Rock-Slopes: Thermo-Mechanical Modelling of the Cimaganda Rockslide. Rock Mechanics and Rock Engineering (2022), https://doi.org/10.1007/s00603-022-02786-y.

Nagel T.J. (2008) - Tertiary subduction, collision and exhumation recorded in the Adula nappe, Central Alps. Geological Society, London, Special Publications, 298(1), 365-392, http://dx.doi.org/10.1144/SP298.17.

Nagelisen J., Moore J.R., Vockenhuber C. & Ivy-Ochs S. (2015) - Post-glacial rock avalanches in the Obersee Valley, Glarner Alps, Switzerland. Geomorphology, 238, 94-111, https://doi.org/10.1016/j.geomorph.2015.02.031.

Pearce D.M., Ely J.C., Barr I.D. & Boston C.M. (2017) - Glacier reconstruction. In: Geomorphological Techniques. British Society for Geomorphology, 1-16 pp.

Penck A. & Brückner E. (1901/1909) - Die Alpen im Eiszeitalter. 3 Vols. Tauchnitz, Leipzig, 1199 p.

Pigazzi E., Bersezio R., Morcioni A., Tantardini D. & Apuani T. (2022) - Geology of the area of the Piuro 1618 event (Val Bregaglia, Italian Central Alps): the setting of a catastrophic historical landslide. Journal of Maps, 1-10, https://doi.org/10.1080/17445647.2022.2057878.

Protin M., Schimmelpfennig I., Mugnier J.-L., Ravanel L., Le Roy M., Deline P., Favier V., Buoncristiani J.-F., Aumaître G., Bourlès D.L. & Keddadouche K. (2019) - Climatic reconstruction for the Younger Dryas/Early Holocene transition and the Little Ice Age based on paleo-extents of Argentière glacier (French Alps). Quaternary Science Reviews, 221, 105863, https://doi.org/10.1016/j.quascirev.2019.105863.

Rettig L., Monegato G., Mozzi P., Žebre M., Casetta L., Fernetti M. & Colucci R. (2021) - The Pleistocene evolution and reconstruction of LGM and Lateglacial paleoglaciers of the Silisia Valley and Mont Raut (Carnic Prealps, NE Italy). Alpine and Mediterranean Quaternary, 34(2), 277-290, https://doi.org/10.26382/AMQ.2021.17.

Rootes C.M. & Clark C.D. (2020) - Glacial trimlines to identify former ice margins and subglacial thermal boundaries: A review and classification scheme for trimline expression. Earth-Science Reviews, 210, 103355, https://doi.org/10.1016/j.earscirev.2020.103355.

Sanhueza-Pino K., Korup O., Hetzel R., Munack H., Weidinger J.T., Dunning S., Ormukov C. & Kubik P.W. (2011) - Glacial advances constrained by 10Be exposure dating of bedrock landslides, Kyrgyz Tien Shan. Quaternary Research, 76(3), 295-304. https://doi.org/10.1016/j.yqres.2011.06.013.

Sanz de Ojeda P., Sanz Pérez E., Galindo R. & Sanz Riaguas C. (2021) - Retrospective Modeling of a Large Paleo-Landslide Related to Deglaciation in the Sierra de Urbión, Cordillera Ibérica, Spain. Applied Sciences, 11(9), 4277, https://doi.org/10.3390/app11094277.

Sciesa E. (1991) - Geologia delle Alpi Centrali lungo la traversa Colico-Passo dello Spluga (Provincie di Sondrio e Como). Il naturalista Valtellinese: Atti del Museo civico di Storia Naturale di Morbegno, 2, 23-34.

Scapozza C., Castelletti C., Soma L., Dall'Agnolo S. & Ambrosi C. (2014) - Timing of LGM and deglaciation in the Southern Swiss Alps. Géomorphologie : relief, processus, environnement, 20(4), 307-322.

Scapozza C. (2015) - Evolution des glaciers et du pergélisol depuis le dernier maximum glaciaire dans la région du mont Gelé-Mont Fort (Alpes Valaisannes, Suisse): chronologie, modalités de la dernière déglaciation et datations des âges d'exposition à l'aide du marteau de Schmidt. Quaternaire. Revue de l'Association française pour l'étude du Quaternaire, 26(2), 141-173, https://doi.org/10.4000/quaternaire.7250

Scapozza C., Del Siro C., Lambiel C. & Ambrosi C. (2021) - Schmidt hammer exposure-age dating of periglacial and glacial landforms in the Southern Swiss Alps based on R-value calibration using historical data. Geographica Helvetica, 76(4), 401-423, https://doi.org/10.5194/gh-76-401-2021.

Scotti R., Brardinoni F., Crosta G.B., Cola G. & Mair V. (2017) - Time constraints for post-LGM landscape response to deglaciation in Val Viola, Central Italian Alps. Quaternary Science Reviews, 177, 10-33. https://doi.org/10.1016/j.quascirev.2017.10.011.

Spreafico M.C., Sternai P. & Agliardi F. (2021) - Paraglacial rock-slope deformations: sudden or delayed response? Insights from an integrated numerical modelling approach. Landslides, 18(4), 1311-1326, https://doi.org/10.1007/s10346-020-01560-x.

Stucki A., Rubatto D. & Trommsdorf V. (2003) - Mesozoic ophiolite relics in the Southern Steep Belt of the Central Alps. Schweizerische Mineralogische und Petrographische Mitteilungen, 83, 285-299.

Tantardini D., Riganti N., Taglieri P., De Finis E. & Bini A. (2013) - Glacier dynamics in San Giacomo Valley (Central Alps, Sondrio, Italy). Alpine and Mediterranean Quaternary, 26(1), 77-94.

Tantardini D. (2016) - Geologia del Quaternario e geomorfologia della Bassa Valchiavenna. Ph.D. thesis, Università degli Studi di Milano, Milano, 249 pp.

Tantardini D., Apuani T. & Bini A. (2016) - Quaternary deposits of the Chiavenna Valley: detailed description and outcrop map. Geologia Insubrica, 12(1), 179-187.

Thorp, P. (1981) - A trimline method for defining the upper limit of Loch Lomond Advance glaciers: examples from the Loch Leven and Glen Coe areas. Scott. J. Geol., 17(1), 49-64.

Thorp, P.W. (1986) - A mountain icefield of Loch Lomond Stadial age, western Grampians, Scotland. Boreas, 15(1), 83-97.

Thorp, P.W. (1987) - Late Devensian ice sheet in the western Grampians, Scotland. J. Quat. Sci., 2(2), 103-112.

Van der Beek P. & Bourbon P. (2008) - A quantification of the glacial imprint on relief development in the French western Alps. Geomorphology, 97(1-2) Special Issue: "Glacial landscape evolution: implications for glacial processes, patterns and reconstructions", 52-72, https://doi.org/10.1016/j.geomorph.2007.02.038.

Venzo S. (1946) - Rilevamento geomorfologico della Brianza orientale e del Bergamasco sudoccidentale, con particolare riguardo al flysch e all'apparato morenico dell'Adda di Lecco. Bollettino della Società Geologica Italiana, 65(1), 57-68.

Venzo S. (1965) - Rilevamento geologico dell'anfiteatro morenico frontale del Garda dal Chiese all'Adige. Mem. Soc. It. Sc. Nat. Mus. Civ. Storia Nat. Milano, 14, 1-82.

Zasadni J. & Kłapyta P. (2014) - The Tatra Mountains during the Last Glacial Maximum. Journal of Maps, 10(3), 440-456, https://doi.org/10.1080/17445647.2014.885854.

Zumbühl H.J., Steiner D. & Nussbaumer S.U. (2008) - 19th century glacier representations and fluctuations in the central and western European Alps: An interdisciplinary approach. Global and Planetary Change, 60(1), 42-57, https://doi.org/10.1016/j.gloplacha.2006.08.005.