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GEOMORPHOLOGICAL MAP OF THE SAN PELLEGRINO PASS (DOLOMITES, NORTHEASTERN ITALY)

Abstract: Carton A., Abbà T., Bondesan A, Fontana A., Mozzi P., Surian N., Zanoner T., Breda A., Massironi M., Preto N. & Zampieri D., *Geomorphological map of the San Pellegrino Pass (Dolomites, Northeastern Italy).* (IT ISSN 0391-9838, 2021).

This paper discusses the geomorphological features of the northern slope of the San Pellegrino Pass (Autonomous Province of Trento, Northern Italy), located in a well-known area of the Dolomites between the San Pellegrino and the Biois valleys, and illustrates the annexed geomorphological map at a scale of 1:10,000. Geomorphological features are strongly influenced by the structural setting and range from ancient glacial and periglacial landforms to gravitational and karst morphologies. During the Last Glacial Maximum, a glacier from the west transfluenced through the pass. Numerous traces of subsequent events testify to the presence of independent glacial tongues flowing south-east, fed by glacial cirques occurring in the Costabella ridge. The chronological reconstruction suggests that almost all of the moraines generated by these glaciers can be attributed to the *Younger Dryas* (Egesen Stadial). A core drilled in Lèch de Campagnola (Campagnola Lake) provided two radiocarbon ages, the oldest dating back to 11,258-11,686 cal. yrs. BP. This indicates that since the very early Holocene environmental conditions had rapidly changed, and glacial processes in the area had concluded. The two ages represent the oldest Holocene radiocarbon dates in a sedimentary sequence of the Dolomites. There are also tongue-shaped rock glaciers, some of them very large in size; their aspect unequivocally indicates that they developed in a continuum from glacial to periglacial processes, evolving from debris-covered glaciers to ice-core rock glaciers.

The study enriches our knowledge of the geomorphology of a well-known sector of the eastern Dolomites, still lacking a systematic and detailed geomorphological survey. Moreover, considering the high tourist activity of the area, it also represents a tool to spread knowledge of the morphological evolution and the environmental problems through geotourist maps that can be derived from this geomorphological map. Finally, the availability of a large-scale geomorphological map can also contribute to the evaluation of geomorphological hazards for a safer use and management of the territory.

Key Words: Geomorphological map, Mountain geomorphology, Glacial and periglacial landforms, Late Glacial stadials, Rock glacier, Dolomites; Italy.

Riassunto: Carton A., Abbà T., Bondesan A., Fontana A., Mozzi P., Surian N., Zanoner T., Breda A., Massironi M., Preto N. & Zampieri D., *Carta geomorfologica del Passo di San Pellegrino (Dolomiti- Italia settentrionale).* (IT ISSN 0391-9838, 2021).

Questo lavoro descrive l'evoluzione geomorfologica del versante nord del Passo San Pellegrino (Provincia Autonoma di Trento, nord Italia), situato in una zona molto nota delle Dolomiti italiane, tra la Val San Pellegrino e quella del Biois. Lo studio si propone anche di illustrare l'annessa Carta geomorfologica alla scala 1:10 000. Il paesaggio è fortemente influenzato dall'assetto strutturale; sono presenti inoltre antiche morfologie glaciali e periglaciali, morfologie gravitative e carsiche. Durante l'Ultimo Massimo Glaciale, un ghiacciaio proveniente da ovest transfluiva attraverso il passo. Numerose tracce di eventi successivi testimoniano la presenza di lingue glaciali indipendenti che fluivano verso sud-est, alimentate da circhi scolpiti nel crinale della Costabella. Una ricostruzione cronologica suggerisce che quasi tutte le morene riferibili a questi ghiacciai possano essere attribuite allo *Younger Dryas* (*Egesen Stadial*). Un carotaggio, eseguito nel Lèch de Campagnola (Lago di Campagnola) ha fornito due datazioni ^{14}C; la più antica risale a 11 258-11 686 cal yrs BP. Ciò documenta che fin dall'inizio dell'Olocene, le condizioni ambientali erano rapidamente cambiate e la morfogenesi glaciale non era più attiva. Le due datazioni rappresentano le più antiche età ^{14}C oloceniche in una sequenza sedimentaria delle Dolomiti. Sono presenti anche *rock glacier*, alcuni molto estesi. La loro forma indica inequivocabilmente che si sono sviluppati in un *continuum* di processi da glaciale a periglaciale trasformandosi da *debris-covered glacier* a *rock glacier* a nucleo di ghiaccio.

Lo studio arricchisce le conoscenze sull'evoluzione geomorfologica di questo noto settore delle Dolomiti orientali, ancora privo di un sistematico e dettagliato rilievo geomorfologico. Inoltre, considerata l'elevata vocazione turistica dell'area, esso rappresenta uno strumento per far conoscere l'evoluzione morfologica e le problematiche ambientali anche attraverso mappe geoturistiche che possono essere realizzate sulla base della dettagliata carta geomorfologica realizzata. La disponibilità di una

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carta geomorfologica a grande scala può infine contribuire alla valutazione della pericolosità geomorfologica per una corretta gestione e una fruizione più sicura del territorio.

TERMINI CHIAVE: Cartografia geomorfologica, Geomorfologia alpina, Forme glaciali e periglaciali, Passo San Pellegrino, Rock glacier, Dolomiti, Italia.

INTRODUCTION

The Dolomites have been selected as a UNESCO World Heritage site because of both the extraordinary visibility of Permo-Triassic sedimentary formations as well as the spectacular geomorphology of the mountain environment (AA. VV., 2009; Panizza, 2009, 2011). Nonetheless, very few large-scale geomorphological maps describing this area have been published (e.g. Pellegrini, 2000; Del Longo & *alii*, 2001; Pasuto & *alii*, 2005; Panizza & *alii*, 2011; Coratza & *alii*, 2019). Here we describe the new map of the landforms and deposits in the area of San Pellegrino Pass, located south of the Marmolada Group, which is considered one of the most typical UNESCO Dolomitic sites.

From a methodological perspective, the map represents the application of detailed mapping in a high-mountain sector and it largely corresponds to the scope of geomorphological cartography of the on-going project for the new geological map of Italy (CARG Project - Geological Map of Italy at a 1:50,000 scale, ISPRA; Campobasso & *alii*, 2018). The choice to carry out a large-scale geomorphological mapping of this sector of the Dolomites was favoured by the evidence that a variety of morphogenetic phases, from the Last Glacial Maximum (LGM) to the present, are exceptionally represented. The complex interactions between ancient glacial and periglacial morphogenesis are particularly evident and testified by a series of well-preserved relict landforms.

STUDY AREA

The study area corresponds to the northern slope of the San Pellegrino Pass and belongs to Section 31 of the Unified International Orographic Subdivision of the Alpine System (SOIUSA - Suddivisione Orografica Internazionale Unificata del Sistema Alpino; Marazzi, 2005), at the boundary between the Provincia Autonoma di Trento and the Veneto Region. The pass separates the San Pellegrino Valley from the Biois Valley and lies on the divide between the Adige and Piave rivers. The San Pellegrino Valley is 11 km long down to the town of Moena (1170 m a.s.l.), where it merges with the Fassa Valley and the San Pellegrino Torrent joins the Avisio River. On the opposite side, the Biois Valley extends from the San Pellegrino Pass to Cencenighe Agordino (780 m a.s.l.), with a NW-SE direction; the Biois Torrent is a tributary of the Cordevole River.

The average altitude of the peaks is between 2500-2700 m a.s.l. and the maximum altitude is reached by Cima dell'Uomo (3003 m a.s.l.).

The area is characterised by the typical landscape of the Dolomites, with high and fairly vertical rock cliffs overlying vegetated slopes and alpine meadows (fig. 1). The elevation of the treeline is around 2200 m a.s.l. and the alpine grassland ends around 2700 m a.s.l. The investigated area extends for 25 km^2 with the western limit represented by the Pas da le Sele (Selle Pass) and the eastern limit corresponding to the Forca Rossa Pass. To the north it is delimited by the Costabella Group and to the south by the floor of the San Pellegrino Valley.

The upper part of the San Pellegrino Valley, near the pass, hosts beautifully preserved glacial, paraglacial, and gravitational landforms, especially on the northern slope, thanks to its wide and gentle morphology. The valley head partly corresponds to the northern flank of an anticline (geological profile A-A' in the attached geomorphological map) developed in the Permo-Triassic sedimentary succession; in the eastern sector, it corresponds to a series of thrusts (geological profile B-B' in the map).

The average annual precipitation recorded by the automatic weather station (AWS) located about 5 km to the south at Valles Pass (2020 m a.s.l.) in the period 1986-2018 was 1311 mm with a minimum of 955 mm (2005) and a maximum of 1846 mm (2008). Most of the precipitation is snow, with the snowpack remaining on the ground for up to 5-6 months. The mean annual air temperature (MAAT) of the 1991-2018 period was around 0.5 °C (Meteotrentino data archive). The value was calculated for a representative altitude of 2360 m a.s.l. (intermediate between the San Pellegrino Pass, 1918 m a.s.l., and the average elevation of the peaks of the Costabella Group, i.e. 2815 m a.s.l.), applying a standard vertical lapse rate of 0.65 °C/100 m (ICAO, 1993). The average annual temperature range is around 40 °C with lowest minimum values of -28 °C (1984) and a maximum of 26 °C (2018). The coldest month is January, while the hottest months are July and August. These temperature and precipitation values place the climate of the area in the "Dfc" class of Köppen (Köppen, 1931), i.e. "temperate-cold or boreal". The Meteotrentino data archive also shows that, from 1991 to 2018, the average annual temperature increased by 1.5 °C.

Several authors have studied this area, mainly from a geological point of view. The Quaternary deposits, and in some cases the connected landforms, have been synthetically mapped in several geological maps, but almost never described. Only a few works of physical geography dealt with the morphogenesis of this part of the San Pellegrino Valley. Geological and geomorphological knowledge is reported in Castiglioni (1926), Castiglioni & *alii* (1930), Vardabasso (1930, 1931a, 1931b), Bianchi Castiglioni (1960), Rossi (1962), G.B. Castiglioni (1964), Leonardi (1967), Rossi (1967), Leonardi & *alii* (1970), Rossi & *alii* (1977), Brondi & *alii* (1977), Carton & de' Luigi (1980), Mantovani (1987a, 1987b), Soldati (1988; 1989), Zanoner (2010, 2011), Provincia Autonoma di Trento (2017), and Abbà (2018). A detailed analysis of these studies is described in "Supplementary material".

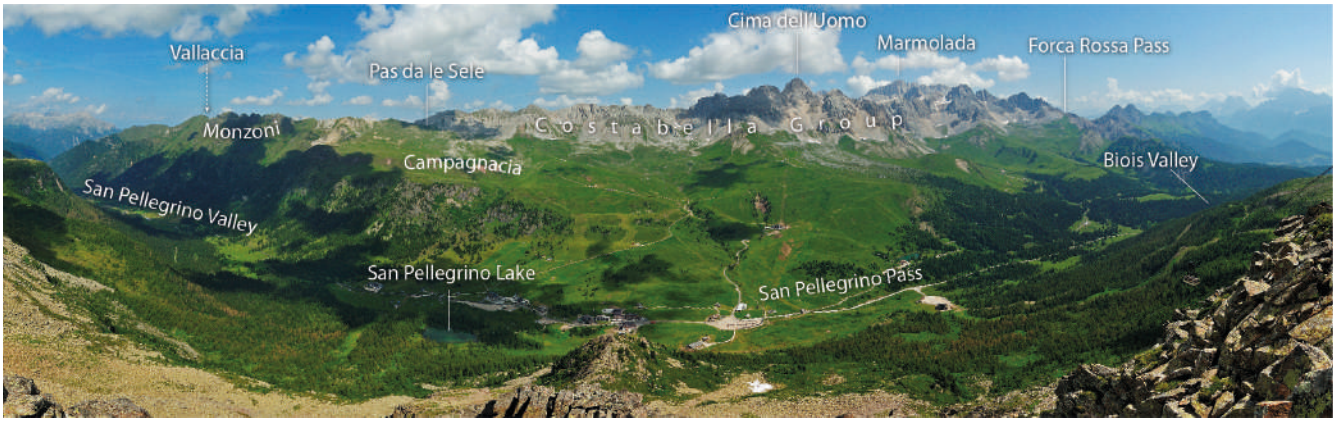

FIG. 1 - Overview of the study area corresponding to the south-facing slope of the San Pellegrino Pass, delimited to the north by the Costabella Group and to the south by the San Pellegrino Valley floor. The area is characterised by the typical landscape of the Dolomites, with high and fairly vertical rock cliffs overlying vegetated slopes and alpine meadows (photo M. Visintainer).

MATERIALS AND METHODS

The geomorphological map of the San Pellegrino Pass and its surroundings was created by integrating unpublished data from several geomorphological field campaigns carried out by the authors and from the fieldwork performed during the Geological Mapping course of the Bachelor's degree in Geological Sciences at the University of Padova (Italy).

Remote sensing included the interpretation of a LiDAR Digital Terrain Model (DTM) with a resolution of 1 m^2 from an original aerial LiDAR survey carried out in 2006 with ca. 5 points per square meter provided by the Autonomous Province of Trento; this proved to be particularly important for the accurate identification and mapping of geomorphological features. Moreover, relevant information has been obtained analysing hard-copy zenithal stereoscopic aerial photographs and digital orthophotos at scales ranging from 1:5000 to 1:10,000 (years: 1973, 2000, 2006, 2012 and 2014). All these indirect interpretations were subsequently checked through a geomorphological field survey carried out at scale of 1:10,000.

The topographical basis for the geomorphological map was the Technical Map of the Province of Trento at a scale of 1:10,000, Sections #28140 - Val S. Nicolò and #45020 - Passo di San Pellegrino.

The preparation 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 legend and symbols are similar to those already used in other large-scale geomorphological maps in the Dolomites (Del Longo & *alii*, 2001; Pasuto & *alii*, 2005; Panizza & *alii*, 2011; Coratza & *alii*, 2019) and more generally in alpine areas (Gruppo Nazionale Geografia Fisica e Geomorfologia, 1986; Baroni & Carton, 1996).

The landforms and associated deposits are depicted in various colours depending on the dominant geomorphic processes responsible for their development. Various symbols denote the geometry and nature of the features, whereas their activity or inactivity are indicated by, respectively, darker and lighter hues. A landform is considered active when its development is the result of an ongoing morphogenetic process driven by present-day morphoclimatic conditions; features resulting from processes no longer active in the current morphoclimatic framework are considered relict. The geological formations (Abbà & *alii*, 2018) have been grouped into five categories based on their response to modelling agents, according to the legend developed by Brancaccio & *alii* (1994) and Campobasso & *alii* (2018).

Structural features (thrusts, faults, folds, and bedding orientations) were mapped. These features were extracted from the recent geological map by Abbà & *alii* (2018) and were selected according to their importance and role with respect to the landforms.

Quaternary deposits are delineated in the geomorphological map on the basis of their morphogenetic agent. The dominant texture of each deposit is depicted symbolically. Morphogenesis refers to glacial, periglacial, cryogenic, nival, karst, and gravitational processes and to running waters.

In the area of Forca Rossa Pass and Lèch de Campagnola (Campagnola Lake) cores have been drilled by hand-augering with the use of an Eijkelkamp Edelman probe and a sampling gouge of 1 m in length. The cores have been described in terms of their lithological, sedimentological, and macropaleontological characteristics. Two samples of organic sediment from the base of core CAMP1 in Lèch de Campagnola (Campagnola Lake) have been radiocarbon-dated by the laboratory of Beta Analytic and their ages have been calibrated with the software Calib 8.2 (Stuiver & *alii*, 2021) using the curve IntCal20 (Reimer & *alii*, 2020).

The geological dataset was implemented within Esri ArcGIS 10.0 (https://www.esri.com/en-us/arcgis/about-arcgis/overview). The geometric primitives and alphanumeric attributes of interest for map generation were produced as a shape file in the Esri geodatabase, where a feature attribute table was developed to organise a set of attributes corresponding to the individual morphotypes and characterising the morphogenesis, morphodynamics, morphometry and, when available, the chronology of the erosional and depositional landforms. The layout map was exported into Adobe Illustrator (www.adobe.com/Illustrator) for the final layout of the geological map and cross-sections. The ArcGIS project uploaded into Adobe Illustrator loses all descriptive information; hence all the layers of the maps have been re-established as Adobe Illustrator layers. The LiDAR-DTM panoramic view, inserted within the map, has been produced using the ArcScene package of the ArcGIS 10.0 software.

GEOLOGICAL SETTING AND STRUCTURAL LANDFORMS

The lithological succession spans from the Lower Permian to the Middle Triassic, from the units of the Athesian Volcanic Group, at the base, to the Predazzo Intrusive Complex, which intruded through the pre-existing stratigraphic sequence. A succession of sedimentary, terrigenous, and carbonate units developed within this time interval.

The oldest units of the Athesian Volcanic Group crop out near the pass. The rounded relief of Campigol, carved by glaciers during the LGM at the south-eastern end of the study area, consists of rhyodacitic tuffs, lapilli, and ignimbrites (IGG) of the Gargazzone Formation. The rocks that form the right slope westwards of the pass belong to the same complex. The Member of San Pellegrino (LRE1) of the Regnana Formation consists of a poorly erodible andesitic dome controlled by some thrusts with an E-W trend, and together with the Ora Formation (ORA) it forms an imposing structural escarpment (fig. 2) at the base of Colifon up to Sas dal musc (Sas dal Mus).

The top of the San Pellegrino Member generates a large sub-horizontal structural surface at around 2220 m a.s.l. in Campagnola, which formed due to the complete erosion of the overlaying Val Gardena Sandstones. This surface features a small lake in a mild overdeepening hollow (Lèch de Campagnola).

The Val Gardena Sandstones (AVG) lie above the Athesian Volcanic Group, separated by an erosional unconformity surface (Massari & Neri, 1997) and they are much more degradable than the formations below. The AVG crops out quite widely north-east of the Colifon, where the gentle north-west dip (0 °-20°) generates slopes with different inclinations. The lower portion, mainly consisting of sandstones, produces escarpments and step-slopes; the upper portion of the same formation, mainly made up of siltstones more degradable than the underlying units, generates slightly inclined slopes. This morphology is particularly evident in the Campagnacia, (fig. 2) between 2230-2300 m a.s.l. along the contact with the San Pellegrino Member (LRE1) of the Athesian Volcanic Group.

The lithological succession continues upwards with the dolomitic marls, evaporites, and dark limestones of the *Bellerophon* Formation (BEL). These lithotypes host the greatest number of karst landforms, that are mostly located upstream of the Lach de le Poze (Pozze Lake) and southeast of the Cresta de le Sele (fig. 2). The structural features of this formation generate different landscapes. Slightly dipping steep slopes originate where the *Bellerophon* Formation is located on the northern limb of the Cima Bocche anticline with a north-western dip of few degrees (geological profile A-A' in the geomorpho-

FIG. 2 - Panoramic view of the right side of the San Pellegrino Valley, near the pass. The San Pellegrino Member (andesiti - LRE1) of the Regnana Fm. forms, together with the Ora Fm. (rhyolites - ORA), an imposing structural escarpment between the Colifon and the Sas dal musc. The lower portion of the Val Gardena Sandstones (AVG), mainly consisting of sandstones, produces escarpments and step-slopes (AVG^2); the upper portion of the same formation, mainly made up of siltstones, is more degradable than the underlying units and generates slightly inclined slopes (AVG^1). The *Bellerophon* Fm. (BEL) in turn originates slightly steep slopes in continuity with those characterising the underlying Val Gardena Sandstones (photo A. Carton).
rss = relict scree slope; aac = active avalanche cone

logical map and Abbà & *alii*, 2018), in continuity with those characterising the underlying Val Gardena Sandstones. An example of this morphology is documented in the upper part of the Campagnacia, south of the Pas da le Sele (Selle Pass) (fig. 2). In contrast, where the NE dip of the bedding increases, the heads of the layers generate elongated reliefs parallel to the slope strike, as in the Coste locality between 2310 m a.s.l. and 1850 m a.s.l. (the right side of Val Tegnousa). Further to the east, the intense deformation of the Permo-Triassic sedimentary succession, characterised by three S-vergent thrusts and folds, shortened the *Bellerophon* Formation and together with the overlying stratigraphic units generates a succession of reliefs (see geological profile B-B' in the map) as in Col de le Salae (fig. 8c), in Sasso Palazza and in Pizzo Forca (fig. 3).

The significant increase in the northward inclination of the terrigenous carbonate units of the lower Triassic means that the Werfen Formation is well-exposed, generating multicoloured rocky ridges. These are particularly evident at the base of the crests of the Costabella Group, e.g. south of Cima de Campagnacia, at L'Om picol (fig. 4) and Pizzo Forca (fig. 3). The subdivision into several members with alternating carbonate (limestone, marly and silty limestone) and siliciclastic (siltstone and fine sandstone) lithologies creates local morphoselection phenomena. For this reason, in the geomorphological map the Werfen Formation is divided into three groups with different geomorphic (rheological) behaviours. Due to the similarity in the geomorphic behaviour, the underlying *Bellerophon* Formation and the overlying Richthofen Conglomerate, consisting of conglomerate and sandstone derived from erosion of the Werfen Formation and emerging in a small strip near Forca Rossa Pass, are included in one of the three above-mentioned categories. At the contact between the metamorphic aureole and the plutonic rocks of the Predazzo Intrusive Complex, the contact metamorphism turned the sedimentary lithologies of the Werfen Formation into hornfels that are much more resistant to erosion, as can be found at Pas da le Sele (Selle Pass) (fig. 5) and along the Cresta de le Sele (fig. 2)

The Anisian succession continues with nodular grey silty limestones (Morbiac Limestone) and massive white limestones (Contrin Formation). Above this in the western part of the area, a succession of thin bedded limestone crops out (Livinallongo Formation). These sedimentary rocks are continuously present at the foot of the Costabella Group (fig. 4).

The Costabella Group is articulated by the presence of glacial cirques carved on its flanks. The bedding generally maintains a northern dip, but where the erosion surfaces correspond to fracture planes, or clinoforms, along which the dikes were injected, strike slopes are generated (fig. 6). Numerous examples of this morphology, which also gives the ridges a jagged pattern, are present near the ridge from Cima de Costabela to Ponta de le Valate.

Finally, along the entire Costabella Group, many dikes and sills of the Predazzo Intrusive Complex are present, injected into fractures or along bedding planes. They are more erodible than limestones, forming magnificent examples of morphoselection, such as trenches or corridors (fig. 7). Their presence greatly influences the morphology of the ridge and the slopes: corresponding to these, saddles are formed or gullies begin, as for example in the stretch between Cima de Costabela and Ponta de le Valate. They behave differently in those cases where they are injected into equally resistant rocks, such as near L'Om picol, where no morphoselection is evident between the dikes and the members of the Werfen Formation (Siusi, Oolite a gasteropodi and Campil members).

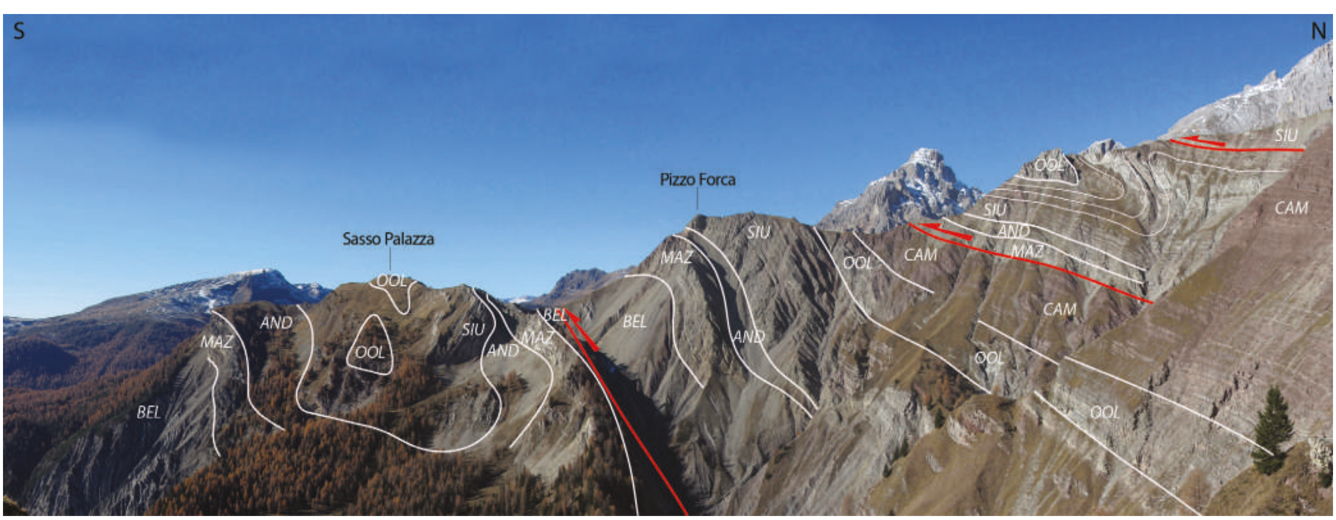

FIG. 3 - Panoramic view of the eastern part of the study area: the intense deformation of the Permo-Triassic sedimentary succession, characterised by three S-vergent thrusts and folds, shortens the *Bellerophon* Fm. and generates, together with the overlying stratigraphic units, a succession of reliefs as in Sasso Palazza, and in Pizzo Forca (after Abbà & *alii*, 2019).
CAM = Campil Member (Werfen Fm.); OOL = Oolite a Gasteropodi Member (Werfen Fm.); SIU = Siusi Member (Werfen Fm.); AND = Andraz Member (Werfen Fm.); MAZ = Mazzin Member (Werfen Fm.); BEL = *Bellerophon* Fm.

FIG. 4 - Panoramic view of the Costabella Group. The increase in the northward inclination of the Lower Triassic terrigenous carbonate units means that the Werfen Fm. (WF) is largely well-exposed at the foot of the Costabella chain, generating multicoloured rocky ridges as L'Om picol. The Anisian succession (CON, LIV) contributes to complete the slopes that end in correspondence with the Sciliar Fm. (SCI). A large sill of the Predazzo Intrusive Complex, injected along a bedding surface, is clearly visible (s) (photo A. Carton).
SCI = Sciliar Fm.; LIV = Livinallongo Fm.; s = sill of the Predazzo Intrusive Complex; CON = Contrin Fm.; WF = Werfen Fm.; CAM = Campil Member (Werfen Fm.); OOL = Oolite a Gasteropodi Member (Werfen Fm.); SIU = Siusi Member (Werfen Fm.).

FIG. 5 - Cresta de le Sele. Corresponding to the aureole of the metamorphic contact with the plutonic rocks of the Predazzo Intrusive Complex, the metamorphism has made some members of the Werfen Fm. very resistant to erosion (photo A. Carton).
SCI = Sciliar Fm.; LIV = Livinallongo Fm.; s = sill of the Predazzo Intrusive Complex; CON = Contrin Fm.; CAM = Campil Member (Werfen Fm.); OOL = Oolite a Gasteropodi Member (Werfen Fm.); SIU = Siusi Member (Werfen Fm.).

FIG. 6 - The crests of the Costabella Group between Cima de Costabela and El Ciastel de Costabela (see location in fig. 8b). The saw-toothed ridge is due to the preferential erosion of the dikes of the Predazzo Intrusive Complex (d) injected into obliquely oriented fractures in the Sciliar Fm. In a) the detail of the dikes injected into the less erodible Sciliar Fm. can be seen (photo A. Carton).
SCI = Sciliar Fm.; d = dike of the Predazzo Intrusive Complex; LIV = Livinallongo Fm.; s = sill of the Predazzo Intrusive Complex; CON = Contrin Fm.; mr = morain ridge.

FIG. 7 - Costabella Group. Along the entire ridge, many dikes and sills of the Predazzo Intrusive Complex injected into fractures or bedding planes of the Sciliar Fm. are present. They are more erodible than limestones and form trenches and gullies. In the picture, a stretch of path built during the First World War (aided path - Klettersteig - Alta Via Bepi Zac) is carved along a dike. The apexes of some talus cones are also generated in correspondence with the dikes. It is evident that large blocks of Sciliar Fm. are detached from dikes, feeding the underlying scree slope and morainic ridge (photo A. Carton).
SCI = Sciliar Fm.; d = dike of the Predazzo Intrusive Complex; tca = talus cone apex.

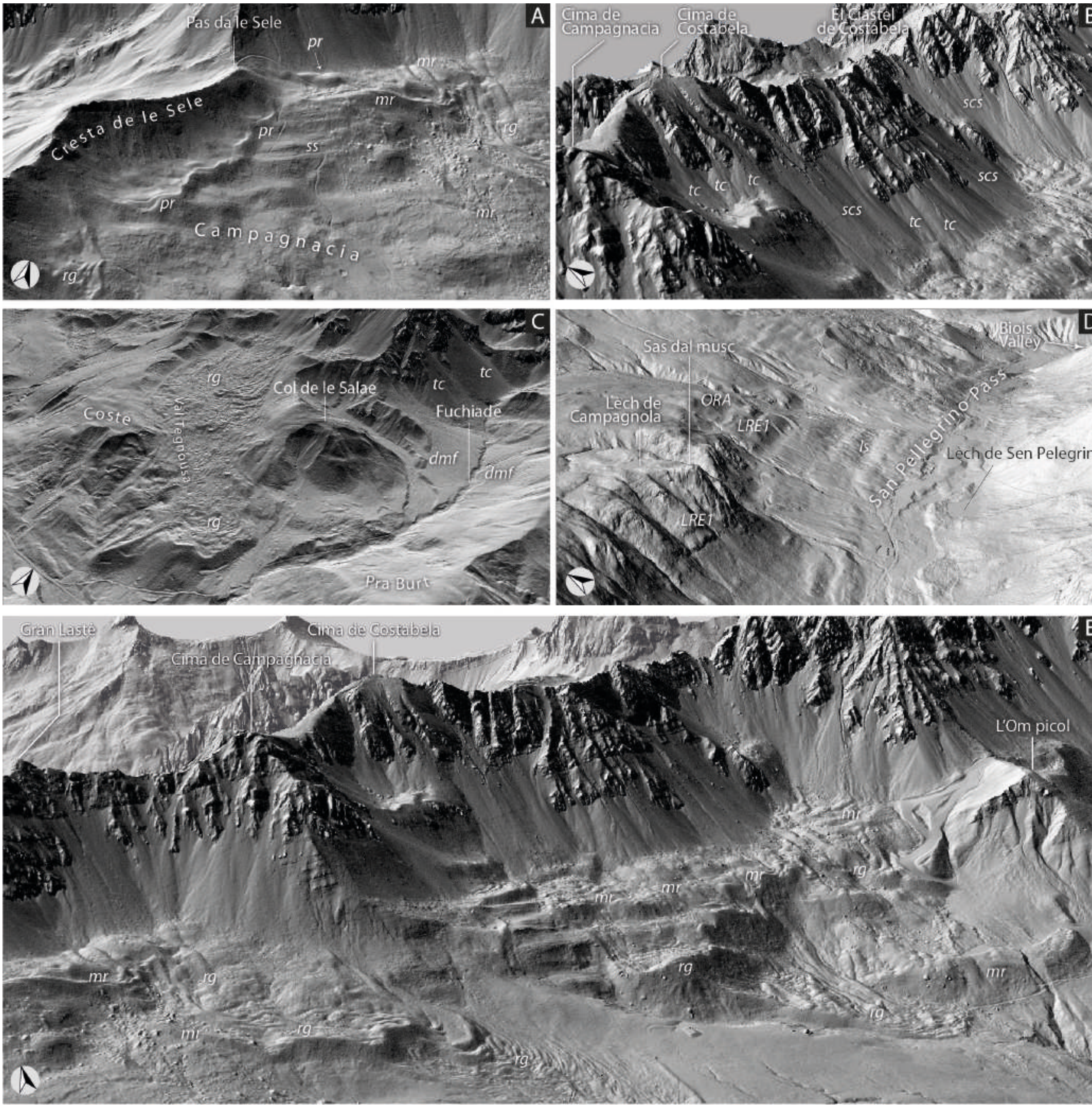

FIG. 8 - LiDAR images of the most common morphologies of the study area. a) Protalus rampart (pr), morain ridge (mr), rock glacier (rg) and structural steps (ss) (Lastè system in the morphological sketch annexed to the geomorphological map) on the southern and south-eastern side of Pas da le Sele (Selle Pass). b) Scree slopes (scs), and talus cones (tc), related to cryogenic processes acting on densely fractured and stratified rocks, continuously border the base of the Costabella Group and represent a main and characteristic dolomitic landscape; the complex system of late glacial moraines and the upper parts of rock glaciers, evolved from glacial deposit, extend at the foot of the rocky walls. c) The spectacular rock glacier of Val Tegnousa is visible in the centre of the image, bordered in its upper part by lateral moraines. In the terminal sector it widens and generates a wide steep front that stops at an altitude of 1810 m a.s.l. On the right is the Fuchiade basin, mainly occupied by a large talus cone, scree slopes and a mud flow fan. d) Overview of the San Pellegrino Pass. In the foreground, on the left, the San Pellegrino Member (andesiti) of the Regnana Fm. (LRE1) forms, together with the Ora Fm. (rhyolites - ORA), an imposing structural escarpment. The linear features (lf), visible to the left of the pass, can be attributed to the specific bedrock characteristics (see the critical analysis in 7.1.1 Last Glacial Maximum). e) Scree slopes, talus and talus cones, moraine ridges and rock glaciers border the base of the Costabella Group. It is evident how all the rock glaciers evolved from glacial deposits; some developed within perimeters previously occupied by glaciers, while others exceeded the position reached by the glacial fronts, breaking the frontal moraines.

GLACIAL LANDFORMS AND DEPOSITS

Last Glacial Maximum (LGM)

It is widely accepted that during the LGM the San Pellegrino Pass was a transfluence saddle of a glacier coming from the Fassa Valley, as shown by the presence of erratic boulders of rocks of the Avisio catchment in the upper Biois Valley (Castiglioni, 1926). Thus, the oldest traces left by glaciers can be attributed to the LGM. Nevertheless, a straightforward differentiation of LGM glacial deposits from Lateglacial ones is often difficult. The only clue that allows us to univocally attribute a glacial deposit to the LGM is the presence of monzonite and monzogabbro pebbles (Predazzo Intrusive Complex), which document transfluence. These were found in some glacial deposits immediately north of the pass during excavations connected with the construction of departure stations for two ski lifts.

The extensive till that lies in Pian de la Roda, Ciamp dal Pec and Majarè (south and south-west in the geomorphological map) occupies a position compatible with an LGM glacial lodgement till, but appears also in continuity with Lateglacial deposits. On the hydrographic left of the San Pellegrino Valley, Lateglacial deposits seem to overlap with those related to the LGM, corresponding to some west-facing moraines of clear southern origin (Bocche chain). One of these ridges supports the Lèch de Sen Pelegrin (San Pellegrino Lake - fig. 9).

In the morphological sketch at a scale of 1:80,000 by Castiglioni (1926), some short and straight moraine ridges were mapped near the pass, parallel to each other, which were also re-proposed in Bianchi Castiglioni (1960), Rossi (1962) and Mantovani (1987b). These were interpreted by some authors as segments of left lateral moraines referable to the transfluent LGM glacier, deposited during subsequent thinning phases. The LiDAR DTM (fig. 8d and DTM in the geomorphological map) also highlights this series of longitudinal small ridges west of the Rio de Tomasc. However, these forms are not considered moraines in our study, as the till is supported by elongated rock cores. These linear features are thus to be attributed to the specific bedrock characteristics, in a phenomenon of geomorphological convergence often found in glacial environments, as already highlighted by various authors (e.g. Stewart & *alii*, 1990; Bini & *alii*, 1992).

Significant LGM erosional glacial landforms are limited to some rounded reliefs immediately east of the pass at Campigol and Col de Mez, and rocky surfaces modelled by glacial erosion at Burt and Malga de Col de Mez. In the low-relief area of Campagnola the glacial erosion carved a small overdeepening hollow on the porphyritic rocks, which is presently occupied by the Lèch de Campagnola (Campagnola Lake).

Lateglacial

Lateglacial till is present on the wide slope of the Campagnacia, between the Costabella chain and the San Pellegrino Pass. The numerous moraine ridges are often interrupted, close to each other, not always of clear origin, and in some cases poorly preserved. This makes their attribution to the specific traditional Lateglacial stadials extremely difficult (Penk & Brückner, 1909). Furthermore, numerous rock glaciers evolved from glacial deposits, modifying their original morphology (figs. 8e, 10). The ridge of Costabella Group is carved by several cirques and, at its foot, presents some well-preserved frontal and lateral moraines. These landforms allow us to identify five cirques/set of cirques that fed and hosted local independent glaciers, separated by low rocky ridges (see the morphological sketch in the geomorphological map for location): 1) immediately east of the Pas da le Sele (Selle Pass) at the foot of the Gran Lastè

FIG. 9 - Lèch de Sen Pelegrin (San Pellegrino Lake), dammed by a frontal moraine, related to the Lateglacial, of a glacier coming from the Bocche chain (Col Margherita). The semi-circular shape of the conifers in front of and on the sides of the lake exactly defines the geometry of the moraine ridge (photo A. Carton).

FIG. 10 - Overview of the complex intertwining of glacial and periglacial landforms at the foot of the Costabella chain. Numerous rock glaciers have developed overprinting on former glacial bodies, modifying their original morphology. It is evident that numerous moraine ridges are close to each other, often interrupted, discontinuous, and in some cases poorly preserved (photo A. Carton).
mr = morain ridge; rdg = rock glacier deposit.

(hereafter referred to as the Lastè glacier); 2) in the large enclosure between Cima de Campagnacia and Ponta de le Valate at the foot of Cima de Costabela (Costabella glacier); 3) below Cima dell'Uomo, between Ponta de le Valate and Sass da la Tascia (Tegnousa glacier); 4) in the articulated basin between Ponte Ciadine and Sass de Valfreida (Le Pale glacier); and 5) in the valley south-west of Monte la Banca (Valfredda glacier).

Fairly well-preserved frontal moraines are located at the foot of the Costabella Group. They exclusively consist of debris belonging to the local sedimentary rocks and abundant fragments of subvolcanic rocks from dikes and sills of the magmatic complex of Predazzo. The glacial deposits of Gran Lastè, and in part of Costabella and Valfredda, can be classified as massive clastic-supported diamicton (DMC), while in the other areas, massive matrix-supported diamicton (DMM) is most common.

The abundance of large blocks in the DMC is probably due to dikes and sills, which led to the splitting of the massive limestone and dolostone of the Sciliar Formation into large blocks. In contrast, the glacial deposits of Valfredda derive almost exclusively from tectonically-fractured rocks of the Sciliar Formation.

The highest frontal moraines of the Lastè glacier are well-preserved and stand at around 2430 m a.s.l.; in the nearby Costabella glacier (below Cima de Campagnacia - El Ciastel de Costabela) a series of short discontinuous frontal moraine ridges, grouped together, are present at around 2360 m a.s.l.; in the Tegnousa glacier under Ponta de le Valate another moraine lies at an altitude of 2410 m a.s.l.; in Valfredda, frontal moraines lie at 2360 m a.s.l.; at the Le Pale glacier, extensive debris slopes cover most of the morainic banks and only one short segment crops out at an altitude of 2400 m a.s.l., south-east of the Palon de Jigole (see the DEM in the geomorphological map for location).

A second series of frontal moraines, or short pieces of them, is located at a slightly lower elevation, downstream from the previous ones: for the Costabella glacier at an altitude of 2240 m, in Le Pale at 2270 m, in Tegnousa at 2300 m, and in Valfredda at 2270 m a.s.l. The remaining moraines, preserved for short tracts, represent the remains of lateral and latero-frontal moraines. Some of these may have particular significance. For example, the highest altitude (MELM - Maximum Elevation of Lateral Moraines; Lichtnecker, 1938) reached by the left lateral moraine of the Tegnousa glacier (2250 m a.s.l.) ends close to a rocky outcrop that does not, by itself, represent a constraint to glacial sedimentation. It can be used to calculate the Equilibrium Line Altitude (ELA) of this glacier, which was later occupied by a great rock glacier. The same can be said for a stretch of the right lateral moraine of the Lastè glacier located south-east of Pas da le Sele (Selle Pass). Although partially covered by a landslide, it appears to end around 2400-2410 m a.s.l., suggesting a possible check-point for the ELA calculation of that glacier. Finally, a series of short stretches of probable latero-frontal moraines could indicate a series of steps reached by some glacial fronts.

The frontal moraines at the highest altitudes occur in two well-defined altimetric levels – the higher one between 2430 and 2360 m a.s.l. (average 2392 m a.s.l.), the lower one between 2300 and 2240 m a.s.l. (average 2270 m a.s.l.) (fig. 11) – such that two glacial phases for their emergence can be inferred. The slight decrease in altitude of the Costabella glacier frontal moraines in both levels can be attributed to the "form factor" of the glacial cirque, which is significantly larger than the others. In all other cases, there are no significant correspondences in altitude between the morainic ridge belonging to various glaciers.

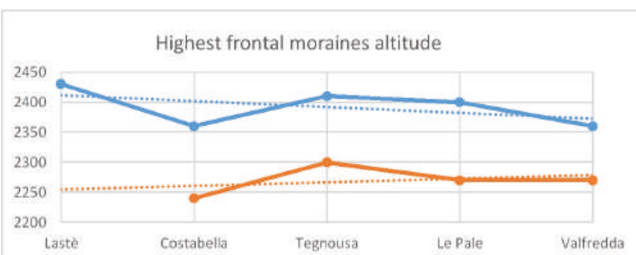

Fig. 11 - Highest-altitude frontal moraines located in two well-defined altimetric levels – the higher one between 2430 and 2360 m a.s.l. (average 2392 m), the lower one between 2300 and 2240 m a.s.l. (average 2270 m).

Chronological reconstruction of Lateglacial stadials

Some authors proposed a chronology of glacial deposits in this area (Castiglioni, 1926; Bianchi Castiglioni, 1960); the most recent attribution (Castiglioni, 1964) assigned the moraines close to Costabella Group to the Daun stadial, and those near San Pellegrino Pass to the Gschnitz stadial. In the same paper, a significant number of moraines, situated between these two stages, are considered not easily attributable to one of the two stages or referable to "supernumerary stages".

In order to chronologically attribute the paleo-glaciers and their respective deposits to a specific Lateglacial stadial, several techniques are available (Pellittero & *alii*, 2015) and they all essentially involve calculating the ELA (Equilibrium Line Altitude) and comparing it with LIA (Little Ice Age) or current ELAs (Ivy-Ochs S. & *alii*, 2008). Nevertheless, in the Dolomites these techniques have not yet been systematically applied, perhaps due to objective difficulties of their application, except in Valparola (Ghinoi & Soldati, 2017) and in the Altipiani Ampezzani (Masini, 1998).

In a geochronological approach, it is possible to infer the absolute ages of the glacial deposits and landforms through radiocarbon dating carried out on organic samples representative of sediments that are older, younger, or synchronous to the glacial deposits. It is also possible to attribute absolute dates by means of the exposure age technique, which has come into use quite recently. This technique has been applied in several areas of the Alps (Baroni & *alii*, 2017; 2021), but it should be notes that it gives significant information on non-carbonate rocks, while on dolostone and limestone lithologies it presents some significant uncertainties (Alfimov & Ivy-Ochs, 2009; Baroni & *alii*, 2018). Furthermore, the confidence intervals in this type of dating can be comparable to the length of Lateglacial stadials (from ±740 to ±1030 yrs: Moran & *alii*, 2016), thus sometimes not resolving to which stadial the dated material belongs.

In the centre of the Lèch de Campagnola (Campagnola Lake - fig. 12) a core was drilled in 2011 below 1.2 m of water, and it sampled 2.55 m of slightly organic silts with rare plant debris that were resting over bare grey sandy silts with centimetric pebbles of rhyolite. The core stopped at 3.05 m because of the presence of large pebbles or bedrock (fig. 13). Two samples of organic sediment were collected at 2.55 and 2.05 m and radiocarbon-dated, generating ages of 9970 ± 40 (11,258-11,686 cal. yrs. BP) and 9400 ± 40 (10,510-10,731 cal. yrs. BP), respectively. The geochronological information testifies that a sharp change in the sedimentology of the depression occurred since the passage from *Younger Dryas* to Holocene, indicating a dramatic change in the environmental and geomorphological processes going on in the catchment area. At the moment, this is the oldest radiocarbon date available for a Holocene sedimentary sequence in the Dolomites; it testifies to an important earliest-Holocene biomass production and suggests that glacial conditions were by then already concluded.

To calculate the ELA of paleo-glaciers, it is possible to use methods that are based exclusively on the position of the glacial landforms, and altitude in particular (MELM - Maximum Elevation of Lateral Moraines; CFA - Cirque Floor Altitudes; HM - Hypsometric Maxima), as well as methods that also require reconstructing the geometry of the paleo-glacier surface (THAR - Toe to Headwall Altitude Ratio; AAR - Accumulation Area Ratio; MGE - Median Glacier Elevation; AABR - Accumulation Area Balance Ratio). In particular, the latter technique is not applicable in the study area because there is insufficient evidence of the glaciers' boundaries to trace the surfaces of paleo-glaciers with an acceptable degree of reliability. In fact, there are no traces of trim lines, of frontal moraines (except for those located at the highest altitudes), or of continuous lateral moraines that connect with the topography (the altimetry) of the reconstructed glacial tongues.

Another problem of not negligible importance is estimating the value of the LIA and current ELAs to compare with the reconstructed Lateglacial ELAs. This aspect, for the Dolomites, has been extensively discussed by Ghinoi & Soldati (2017), who highlight how the previous authors have often used "current ELA" with different values, and suggest using the ELA of the LIA as a reference (Ivy-Ochs et al., 2008). This latter is considered to be the maximum advancement of Holocene glaciers in most of the catchment areas of the Alps and its ELA determination is more reliable than the "current" ELA (Gross & *alii*, 1977).

FIG. 12 - Lèch de Campagnola (Campagnola Lake), located just above the vertical cliffs of the rhyolitic San Pellegrino Member of the Regnana Fm. (photo A. Carton).

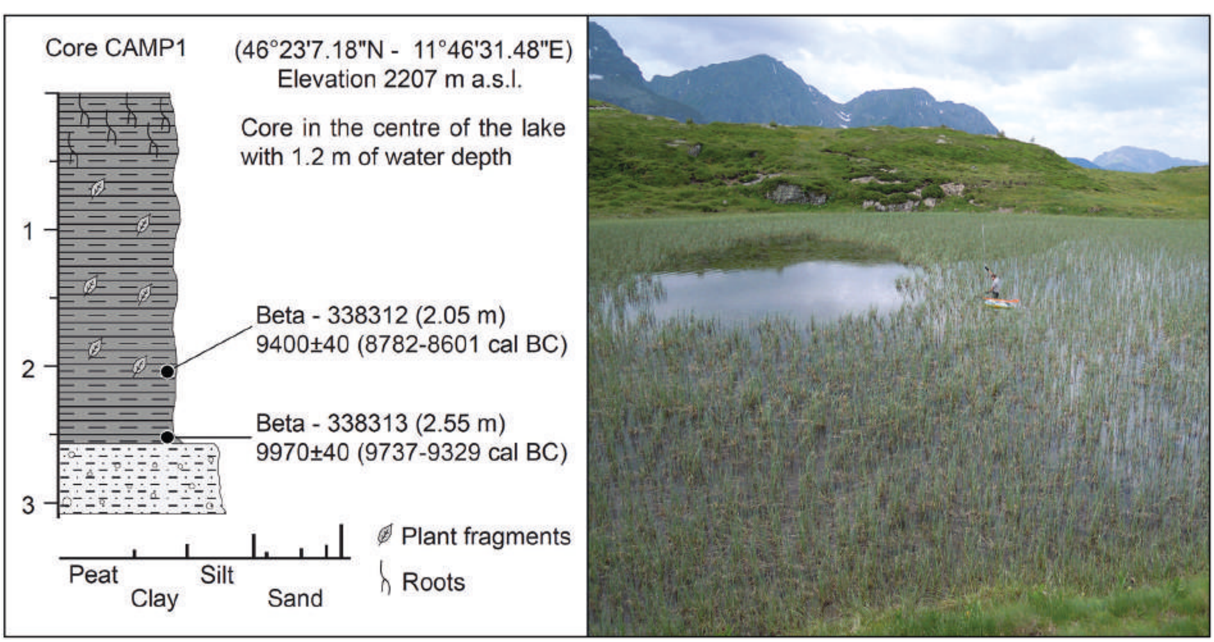

FIG. 13 - Lèch de Campagnola (Campagnola Lake); on the bottom a 3.05 m drilling was carried out below 1.2 m of water and it sampled 2.55 m of slightly organic silts with rare plant debris that were resting on bare grey sandy silts with centimetric pebbles of rhyolite. The core stopped at 3.05 m because of the presence of large pebbles of the bedrock (photo A. Carton).

A further difficulty in using the current ELA for chronological estimates of the glacial deposits in this area is that the largest present glacier in the Dolomites, the nearby Marmolada glacier, has climatic and non-orographic snow conditions that limit the significance of its data. Moreover, since the second part of the 20th century, the conditions of the Marmolada glacier have been altered for a long time in the accumulation/ablation relationships by summer skiing activities (Carton & Varotto, 2011). The nearby Uomo glacier, now extinct, was for a long time a debris-covered glacier and therefore cannot be used to derive comparison parameters (Seppi & *alii*, 2015).

We attempted to estimate the Lateglacial ELAs in the study area using the Marinelli (1928) method, later confirmed by Louis (1954-1955). This method consists in computing the average value between the maximum altitude of the rock ridges that delimit the glacial catchment and the altitude of the reconstructed glacier's front. It does not substantially contrast with the principles on which the Kurowski method (1891) is based; it rather represents a somewhat coarse simplification but, however, it has the advantage of being easily applicable also to those glaciers of which only the elevation of the front and the contour of the feeding basin can be reconstructed, as in the study case.

The calculated paleo-ELA values are reported in table 1 and were compared with a "potential" value of ELA-LIA of around 2800 m a.s.l., assessed for the Dolomitic area in accordance with a critical analysis by Ghinoi & Soldati (2017).

A test of the reliability of the paleo-ELAs deriving from this calculation is possible for the Lastè glacier. Here the glacial tongue with the front at 2150 m a.s.l. (Lastè 3 of table 1) provided a paleo-ELA at an altitude of 2425 m, confirmed by the upstream contact with the bedrock (MELM) of a related right lateral moraine (Lastè lat. of table 1) at around 2410 m a.s.l. Therefore, it is likely that the altitudes obtained from the paleo-ELA calculations are quite reliable within the limits of the method.

The ELA depression versus LIA ELA of the five basins present in the study area are represented in fig. 14. Almost all moraines have an altitude ranging between -450 and -180 m below 2800 m a.s.l. (potential value of ELA-LIA). A comparison of this topographic interval with the values indicated in Ivy-Ochs & *alii* (2008) and the chronology proposed by those authors indicates a likelihood that all these moraines and related deposits were formed during the Egesen stadial. In particular, the two series of frontal moraines located at the highest altitude, which are the best preserved forms of the whole examined territory, can be attributed to the last phases of the Younger Dryas.

This chronological attribution is also reflected in the morphological features of the deposits of this time interval as described in Ivy-Ochs & *alii* (2008) and defined as follows: "*Series of morphologically fresh moraines, often well preserved, distinguishable in two and sometimes three distinct groups, often rich in large blocks and boulders. Presence of rocky glaciers developed widely during the Egesen stadial, advancing into areas which became ice free after the Egesen maximum advance*".

Considering the low elevation of the frontal portion of the glacial tongue of Tegnousa (suggested by the lateral moraine "Tegnousa lat." of table 1 but now completely obliterated by the large rock glacier) and the glacial tongue of Valfredda (lateral-frontal moraine "Valfredda 8" of table 1), we hypothesise that these glacial landforms belong to an older stadial.

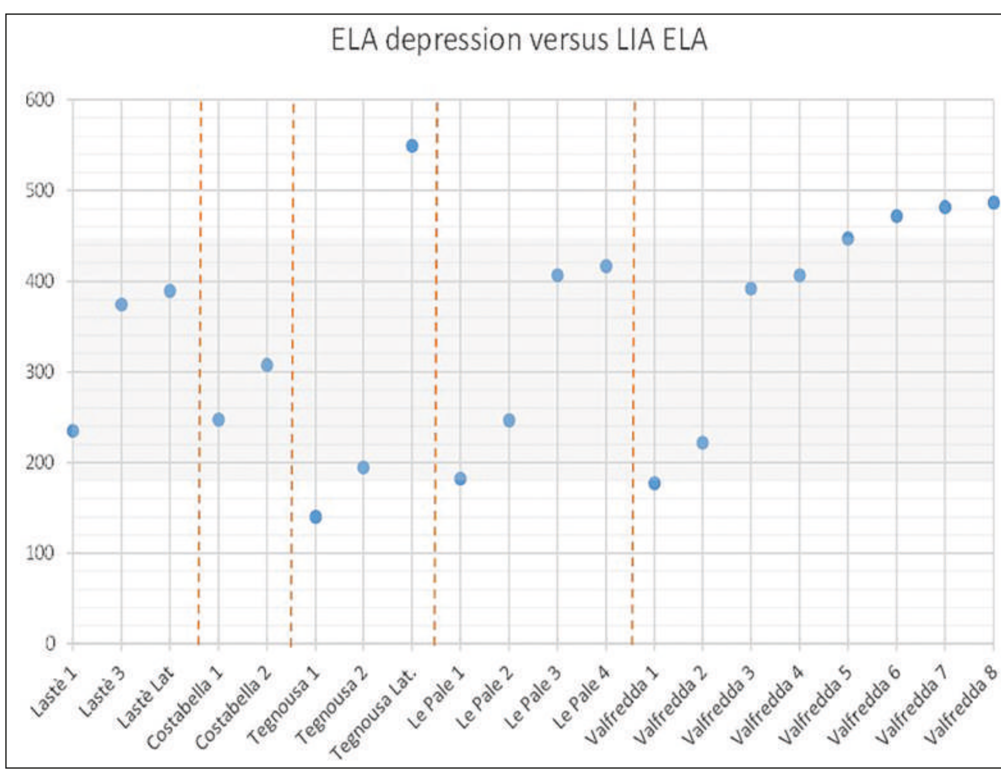

FIG. 14 - ELA depression versus LIA ELA. Gray band = ELA depression versus LIA ELA altitude range considered for stadial Egesen (Younger Dryas cold phase) according to Ivy-Ochs & *alii* (2008). Blue dots indicate the ELA depression versus ELA LIA in the five basins presented in the study.
ELA depression versus ELA LIA: difference in m.

TABLE 1 - Calculated paleo-ELA values. Numbers indicate the altitude in m a.s.l. Numbers in brackets indicate the probable altitude of the ice front interpolating the curvature of the short stretches of lateral-frontal moraines up to the valley centre.
ELA depression versus ELA LIA: difference in m.

		Lastè	Costabella	Tegnousa	Le Pale	Valfredda
Peaks maximum altitude average		2699	2744	2910	2835	2885
Frontal moraine	1	2430	2360	2410	2400	2360
ELA	1	2565	2552	2660	2618	2663
ELA dep. versus ELA LIA	1	*235*	*248*	*140*	*182*	*177*
Frontal moraine	2		2240	2300	2270	2270
ELA	2		2492	2605	2553	2578
ELA dep. versus ELA LIA	2		*308*	*195*	*247*	*222*
Lateral-frontal moraine	3	2150			1950	1970 (1930)
ELA	3	2425			2393	2408
ELA dep. versus ELA LIA	3	*375*			*407*	*392*
Lateral-frontal moraine	4				1930	1950 (1900)
ELA	4				2383	2393
ELA dep. versus ELA LIA	4				*417*	*407*
Lateral-frontal moraine	5					1840 (1820)
ELA	5					2353
ELA dep. versus ELA LIA	5					*447*
Lateral-frontal moraine	6					1800 (1770)
ELA	6					2328
ELA dep. versus ELA LIA	6					*472*
Lateral-frontal moraine	7					1800 (1750)
ELA	7					2318
ELA dep. versus ELA LIA	7					*482*
Lateral-frontal moraine	8					1750 (1740)
ELA	8					2313
ELA dep. versus ELA LIA	8					*487*
Lateral morain		2410		2250		
ELA		2410		2250		
ELA dep. versus ELA LIA		*390*		*550*		

PERIGLACIAL LANDFORMS AND DEPOSITS

Cryogenic and nivation landforms.

The most common landforms relative to the periglacial environment are rock glaciers (Baroni & *alii*, 2004; Seppi & *alii*, 2010; 2011; 2019) of complex genesis. Six of them occur in the area, some rather unique in the south-eastern Alps for their size, such as the one located in the Tegnousa Valley, which extends for a length of 2200 m (Seppi & *alii*, 2012).

They are of high interest as they represent the effects of past climate changes, which have modulated the interaction between glacial and periglacial processes (Haeberli, 2000; Harris & Murton, 2005; Keiler & *alii,* 2010; Waller & *alii*, 2012), similar to those currently occurring in high-altitude mountain areas (Seppi & *alii*, 2015, Jones & *alii*, 2019). This is the set of geomorphological processes termed "paraglacial" according to the concept of Church & Ryder (1972), which describes the rapid readjustment of glacial environments to new conditions.

All the rock glaciers in the study area evolved from glacial deposits; some developed within perimeters previously occupied by glaciers, while others exceed the position reached by the glacial fronts, breaking the frontal moraines. They can all be classified as relict rock glaciers (Frauenfeder & Kääb, 2000; Frauenfelder & *alii*, 2001), tongue shape, complex, with surface morphology characterised by ridges, grooves, and hollows, often disposed in a concentric pattern.

The spatial relationship between these forms and the Lateglacial till and glacial landforms suggests that they most probably were ice-cored rock glaciers deriving from former glaciers (cf. Berthling, 2011).

According to many authors (Potter, 1972; Whalley & Martin, 1992; 1994; Humlum 1996; Ackert, 1998; Clark & *alii*, 1998) this kind of rock glacier may also develop through a continuum of processes from glacial to periglacial transforming a debris-covered glacier into a rock glacier. The formation of ice-cored rock glaciers in similar environments has already been described by Krainer & Mostler (2000a, b, 2001), Krainer & *alii* (2002), and Seppi & *alii* (2015).

The westernmost rock glacier (Lastè) has a length of about 850 m, extending within the limits of the pre-existing glacier and ending just upstream of the left lateral-frontal moraine; those of Costabella are smaller. They interrupt, flank, and overlap the system of frontal moraines located at the highest altitudes. The spectacular Val Tegnousa rock glacier (figs. 8c, 15) is bordered in the upper part by lateral moraines; in the terminal sector it widens, generating a wide steep front that stops at an altitude of 1810 m and displays a topographic gradient of 55%. Almost all previous authors have interpreted it as a frontal moraine of an ancient glacier of the Gschnitz stadial (Castiglioni, 1964). However, the presence of many ridges, grooves, and close hollows, as well as the morphological and geometric characteristics of the front, support its interpretation as a rock glacier. Its morphological features allow us to distinguish and map different phases in its formation and they are separated in the map.

The easternmost rock glacier, located near Forca Rossa Pass (fig. 16), is still well-preserved and shows geometric characteristics compatible with an ancient debris-covered glacier that evolved into a rock glacier. The rock glacier tongue, in its progress, broke through the central part of a group of frontal moraines (Valfredda 1 in table 1). Most likely part of the glacier had been covered by debris, possibly by landslides which, with their thick cover deposits, contributed to ice preservation. This hypothesis is supported by the marked instability of the rock wall immediately above the rock glacier, still documented today by a recent landslide. Due to its spectacular morphology and "didactic exemplarity" (Carton, 2021), this rock glacier has been included in the list of geosites of the Veneto Region (GV038 - Regional Atlas of Geosites).

The morphological situation described thus far indicates that rock glaciers already developed during the Younger Dryas, sometimes advancing in areas that became ice-free right after the Egesen maximum advance (Ivy-Ocs & *alii*, 2008). They indicate the presence of permafrost at that time starting from 1800 m a.s.l., almost in agreement with 2000-1900 m a.s.l. reported by other authors (Kerschner, 1978; Sailer and Kerschner, 1999; Frauenfelder & *alii*, 2001). Following the model already proposed by Ivy-Ocs & *alii* (2008), it is likely that rock glacier activity continued throughout the later part of the *Younger Dryas*, considering its development and extension.

Periglacial conditions are also responsible for the production of large amounts of frost-shattering debris, which has been shaped in the form of protalus ramparts, debris cones, and scree slopes. The few protalus ramparts recognised in the area are mainly located south of Pas da le Sele (Selle Pass) (fig. 17) or within some glacial cirques. They are generally relict and only the one located south of the Picol Lastè still seems to be active. The "festooned" protalus rampart south of the Pas da le Sele (Selle Pass) suggests a transition towards landforms more similar to rock glaciers.

Fig. 15 - The spectacular Val Tegnousa rock glacier extending for a length of about 2300 m (photo M. Visintainer).

Gravity-induced slope landforms and processes

Gravitational landforms and processes are the most recurrent geomorphological features along the steep rock walls. Gravitational processes have produced scree slopes, talus, and talus cones, essentially related to cryogenic processes acting on densely fractured and stratified rocks. Active gravitational deposits continuously border the base of the Costabella Group and represent a characteristic dolomitic landscape.

Most of the debris cones and scree slopes have been intensely modelled by debris flows, which have created large accumulation lobes (fig. 18). Presently, linear erosional processes seem to prevail over depositional processes, with the formation and marked deepening of the channels. This trend is testified by the rapid growth of vegetation cover on many debris cones and by the opening of deep incisions and channels in them.

Numerous degradational scarps are carved into the bedrock or in detrital deposits. A rockfall with large boulders is located SW of Monte la Banca (already mentioned in the discussion on the genesis of the Forca Rossa rock glacier), and another just SE of Pas da le Sele (Selle Pass). This latter is represented in the geomorphological map as an inactive rock fall but, considering the significant distance from the originating slope (over 1000 m) and the dis-

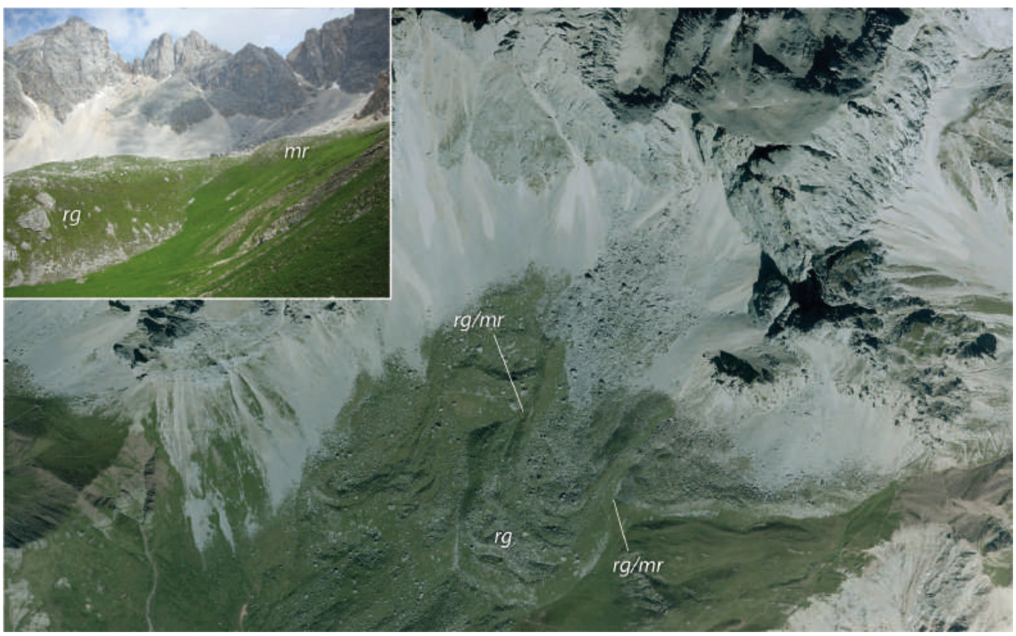

FIG. 16 - The Forca Rossa rock glacier. The rock glacier tongue is characterised by ridges, grooves and hollows, laying in concentric pattern. The rock glacier's tongue in its progress has broken through the central part of a group of frontal moraines. (Orthophoto 20 cm [2018] AGEA - all rights reserved). a) Detail of the relationship between rock glacier and moraine ridge.
rg = rock glacier; rg/mr = relationships between rock glacier and moraines.

FIG. 17 - Relict protalus ramparts, located south of Pas de le Sele (photo A. Carton).

FIG. 18 - Talus cone and debris-flow/mud-flow fan on the eastern slopes of Sas da la Tascia. Most of the debris cones and scree slopes have been intensely modelled by debris flows. Presently, linear erosional processes seem to prevail over depositional processes (photo M. Visintainer).

persion of the related blocks and debris, it is possible that this deposit was related to a supraglacial landslide. This genetic interpretation is justified by the fact that the deposit is distributed for about 800 m, on a gently inclined surface (15%) and a few hundred meters from the rocky walls that fed it. Probably the presence of a glacier on which the original collapse settled allowed the distribution of the debris away from the walls (fig. 19).

The sector overlooking San Pellegrino Pass along its western stretch is comprised of relict scree slopes, with some minor talus cones at the feet of the main impluvium. The debris accumulation is fed by the overhanging volcanic cliff.

In the area of the Lach de le Poze (Pozze Lake), where the slope is steeper, some rotational landslides created very well-defined scarps at their crown with gravitational trenches on the back, and may be related to a complex and probably deep movement of the slope. Small incisions on the slope create receding degradation escarpments with small rockfalls and prevailing runoff features on the erosional surface.

Landforms and deposits due to running waters

Fluvial landforms are quite scarce in the study area. Valleys of various shapes (V-shaped, through-shaped and flat-bottomed), more or less deep, mostly depending on the characteristics of the bedrock in which they are cut, occur over the whole area. They often highlight the different erodibility of the various rocks as in the above-mentioned case of the Rio de Tomasc at the contact between the Val Gardena Sandstones and porphyritic rocks.

Limited fluvial deposits with a grain-size from boulder to sand are found in the main valley immediately west of the San Pellegrino Pass. A fluvial erosion scarp is located east of the pass, corresponding to the main stream, in the middle valley of Fuchiade and in the lower Valfredda Valley (north of Pian dei Cros). East of the pass some alluvial fans, oriented towards the Biois Valley, overlap the LGM till. Colluvial fans are generated at the mouth of minor valleys or short incisions and gullies. Colluvial deposits mainly accumulated inside topographic depressions as well, where running waters are conveyed together with their fine load.

Large surfaces modelled by sheet and rill erosion are evident in the Campagnacia area and immediately north of the San Pellegrino Pass at the Martinet locality.

A cemented stream deposit crops out between San Pellegrino Pass and the Lach de le Poze (Pozze Lake), along the road to Falcade (fig. 20). It is a well-cemented conglomerate consisting of pebbles from the formations cropping out in the area; an outcrop near the lake shows pebbles essentially belonging to the *Bellerophon* Formation and the Werfen Formation. The deposit is well-cemented with a silty matrix, and is locally covered by glacial deposits. Previous authors (Bianchi, 1960; Leonardi, 1967) hypothesised that it is an interglacial conglomerate. These conglomerates have never been studied in detail, but on the basis of similar situations found in Val di Fassa, near Moena and along the SS 48 between Soraga and Vigo, it is believed that the cementation is instead related to the gypsum of the *Bellerophon* Formation, always present upstream or in the vicinity.

In the study area, three lakes of different origin are present. The Lèch de Sen Pelegrin (San Pellegrino Lake - 1890 m a.s.l.), near the pass, is of glacial origin and it is dammed by a well-preserved frontal moraine (fig. 9) of a glacier coming from the Bocche chain (Col Margherita) on the southern side from the San Pellegrino Pass. The lake level changes seasonally at the upstream end, depending

FIG. 19 - Extensive landslide deposit located south-east of Pas da le Sele. It can be considered a supraglacial landslide due to the significant distance from the originating slope (over 1000 m) and the dispersion of the related blocks and debris. On the left is visible the Lateglacial lateral moraine of the Lastè glacier (Lastè Lat. in fig. 14 and table 1) (photo A. Carton).
ld = landslide deposit; lm = Lateglacial lateral moraine.

FIG. 20 - Cemented stream deposit between San Pellegrino Pass and the Lach de le Poze (Pozze Lake) along the road that descends to the village of Falcade. It is a well-cemented conglomerate consisting of pebbles from the stratigraphic units cropping out in the area; the pebbles essentially belong to the *Bellerophon* Fm. and Werfen Fm. The deposit is well-cemented with a silty matrix (photo A. Carton).

on the water supply, which is mainly linked to snow melt. During late-summer low-stand, a significant part of the lake turns into a palustrine environment. The second lake, Lach de le Poze (Pozze Lake - 1913 m a.s.l.) is located on the left valley side immediately east of the San Pellegrino Pass (fig. 15). It lies on the *Bellerophon* Formation and has a karst origin. Marinelli (1904) suggested that the depression was generated by subsidence related to sub-surface gypsum dissolution. However, it cannot be excluded that the depression that hosts the lake is the result of the coalescence of several dolines, very frequent in the area. The third lake, Lèch de Campagnola (Campagnola Lake - figs. 12, 19), is located just north of Sas dal musc (2220 m a.s.l.). It is rather small in size (ca. 0.5 ha) and it lies on a gentle overdeepening hollow in a structural surface in the San Pellegrino Member of the Regnana Formation (Athesian Volcanic Group).

Karst landforms

Karst phenomena are locally present on limestone and gypsum-rich bedrock, where the *Bellerophon* Formation crops out, especially near the Lach de le Poze (Pozze Lake). Here, in a fairly limited area, there are numerous dolines, generally of small dimensions (5-10 m in diameter and 1-2 m deep) and of regular shape. Some are coalescent and merge together. Some of the dolines are developed on glacial deposits, reproducing at the surface the dissolution phenomena of the underlying substrate. On limestone surfaces, rill karren and small alveolar cavities (alveolisation) are quite often found.

The karst dissolution and reprecipitation of carbonate-rich waters is likely also related to the occurrence of the cemented deposits that characterise some peculiar areas. This situation probably favoured the formation of the conglomerate deposits cropping out along the road, east of the San Pellegrino Pass, where the *Bellerophon* Formation seems to be at a shallow depth.

Man-made landforms

The primary man-made landscape modifications are presently related to tourist activities. The economic interest in the San Pellegrino Pass dates back to the 1920s, when the first ski lift was built by the manager of one of the hotels (Gorfer, 1975). In the 1980s, the Col Margherita cable car was built, with cabins that were avant-garde at the time, designed by renowned Italian designer Pininfarina. The numerous hotels and the continuously growing number of ski lifts increased the anthropogenic pressure in both winter and summer. The area of the San Pellegrino Pass is part of the Trevalli ski area (Falcade-San Pellegrino, Moena-Lusia-Bellamonte) and makes an excellent winter sports resort.

The largest number of ski slopes is located on the northern side of the pass; in general, the ski slopes have not caused evident modifications to the natural morphology, apart from some slope cuts or depression filling. In summer, the grazing of livestock is still widespread.

The territory underwent heavy anthropogenic modifications in the period from 1915-18 during the First World War (fig. 21). The Austrian front developed on the rocky ridge between Pas da le Sele (Selle Pass) and Cima de Campagnacia; the Italian one between Cima de Campagnacia and Ponte Ciadine.

The top of the Costabella Group crest, between Picol Lastè and Cima dell'Uomo, is entirely crossed by trenches and tunnels dug into the rock, which have contributed to its degradation and to the production of debris conveyed to the scree slopes. Natural morphoselection processes between sills and dikes of the Predazzo Intrusive Complex intruded into the Sciliar Formation were used as walkways and trenches (fig. 7). An aided path (Klettersteig) allows hikers to cross the entire ridge (Alta Via Bepi Zac) with panoramic views on the study area. Other traces (trenches and bomb craters) are present in the Campagnacia up to the Pas da le Sele (Selle Pass), where there was a defensive wall blocking the passage to the neighbouring Val dei Monzoni.

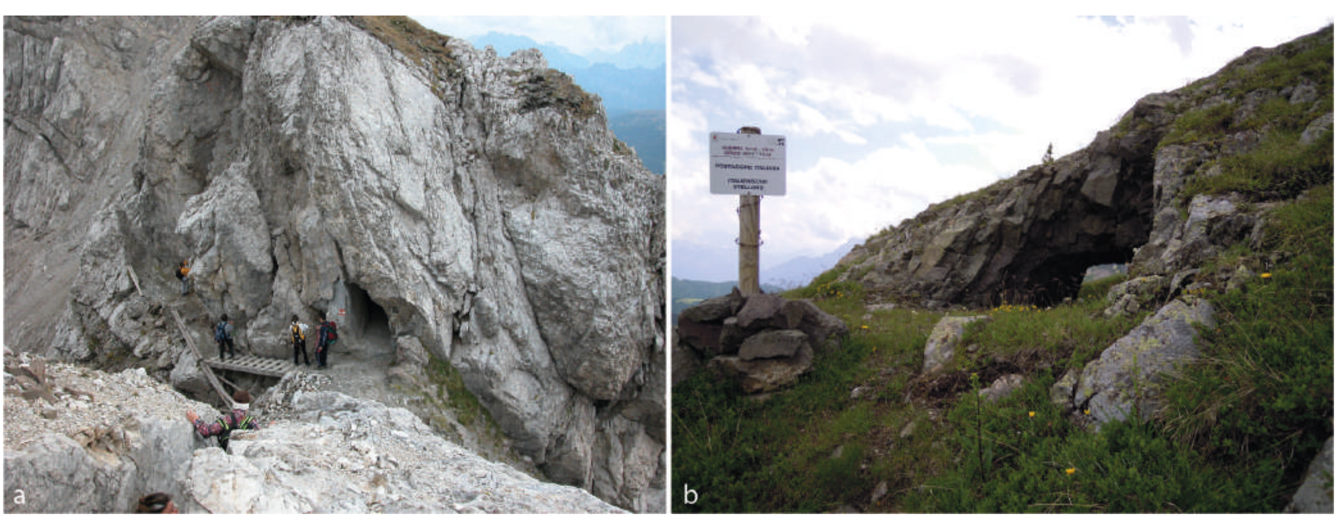

FIG. 21 - The territory underwent heavy anthropogenic changes in the period from 1915-18 during the First World War. a) aided path (Klettersteig - Alta Via Bepi Zac). The ridge, between Picol Lastè and Cima dell'Uomo, is crossed by trenches and tunnels dug into the rock. b) other military positions are present in the Campagnacia up to the Pas da le Sele (Selle Pass) (photo A. Carton).

CONCLUSIONS

The San Pellegrino Pass, at the southern margin of the Marmolada Group, constitutes one of the most typical UNESCO Dolomitic landscapes. Its peculiar geomorphological features, strongly influenced by the structural setting, vary from ancient glacial and periglacial landscape features to gravitational and karstic landforms.

This research enabled a detailed analysis and cartographic representation of the geomorphological features on the northern slope of the San Pellegrino Pass and the reconstruction of their evolution. Landforms have been mapped in the attached geomorphological map at the scale of 1:10,000.

The extremely detailed geomorphological survey of this high mountain area made use of high-resolution LiDAR cover and aerial/satellite images, and from several extensive summer field surveys.

The landscape was mainly shaped by glacial and periglacial processes. During the LGM, a glacier from the west transfluenced through the pass. Some strips of glacial deposits and some erosional landforms still remain from this episode. Although discontinuous, numerous traces of subsequent events persist, testifying to the presence of independent glacial tongues that flowed toward the southeast and were fed by cirques present along the ridge of the Costabella Group.

A simple chronological reconstruction suggests that almost all the moraines (multiple moraine ridges) referable to these glaciers can be attributed to the *Younger Dryas* (Egesen Stadial). Within this stage, using ELAs computation, two-three phases have been recognised, as documented in other sectors of the Alps. The highest frontal moraines are located between 2430 and 2360 m a.s.l., while the lower ones outcrop between 2300 and 2240 m a.s.l.

Two radiocarbon dates from a core drilled in the Lèch de Campagnola (Campagnola Lake) have been obtained. The oldest, dated to 11,258-11,686 cal BP, documented that, since the very early Holocene, environmental conditions had rapidly changed, and glacial processes in the area were concluded. These are the oldest Holocene radiocarbon dates in a sedimentary sequence of the Dolomites.

All rock glaciers have a tongue-shaped morphology. They developed on a continuum from glacial to periglacial processes through a transformation of debris-covered glaciers to ice-cored rock glaciers. Therefore, their genesis chronologically follows the extinction of the glaciers, and their activity seems to have endured throughout the final part of the *Younger Dryas*. Since the very early Holocene, the morphodynamical setting of the study area shifted from prevalent cryogenic processes to gravitational processes and widespread activity of running waters.

Karst forms develop on the gypsum-rich *Bellerophon* Formation, mainly as small solution dolines and alluvial dolines.

Although the area have been of interest since prehistoric times, anthropogenic landforms are at present linked to ski resorts and mountain tracks. Furthermore, trenches, military outposts, and many other well-preserved relics of the First World War are still present and visited by tourists.

The geomorphological study carried out has several purposes. Firstly, it enriches our knowledge of the geomorphology of a well-known sector of the eastern Dolomites very close to UNESCO System 2 "Marmolada" (one among the nine systems of the Dolomites according to the UNESCO World Heritage list; https://www.dolomitiunesco.it/en/), where nevertheless a detailed cartographic survey was lacking.

Secondly, considering the high tourist activity of the area, it represents a tool for sharing knowledge on the evolution and environmental problems through geotouristic maps that can be made on the basis of our detailed geomorphological map.

Furthermore, the availability of a large-scale geomorphological map can also contribute to the evaluation of present and future geomorphological hazards, for safer use by tourists and for possible future geological surveys according to the National Geological Cartography guidelines.

SUPPLEMENTARY MATERIAL

Supplementary materials associated with this article can be found in the online version, at http://gfdq.glaciologia.it/044_2_01_2021/ These data include the "Geomorphological map of the San Pellegrino Pass (Dolomites, Northeastern Italy)" at the scale of: 1:10,000.

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