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Permafrost-based geomorphology of the Mt. Foscagno - Mt. Forcellina ridge (Adda – Inn River basins, Central Italian Alps)

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ABSTRACT
The permafrost-based geomorphological map of the Mt. Foscagno – Mt Forcellina ridge (Central Italian Alps) shows the distribution of permafrost probability (high, medium, low probability, and probable absence) obtained by the application of PERMACLIM (Guglielmin et al., 2003), a GIS-based model integrating *Digital Elevation Model* (DEM) topographic data and the *Climatic DataBase* (CDB) available from *Automatic Weather Stations* (AWS). In addition, the map provides information on the outcropping bedrock, the genesis and grain size of near-surface deposits, and geomorphological features with particular reference to periglacial and glacial landforms. Moreover, the map represents locations and values of ground measurements, *Bottom Temperature of winter Snow cover* (BTS) and *Vertical Electric Soundings* (VES), and the *Mean Annual Air Temperature* (MAAT; Guglielmin et al., 2003).

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1. Introduction

Geomorphological maps are irreplaceable tools for understanding the physical context of the Earth's surface: they provide a description of landforms identified with specific names and depicted with their correct shape or, where not allowed by the map scale, by appropriate symbols.

These maps should include information on the spatial properties of landforms, their origin, and evolution in connection with internal/external genetic agents and processes, also considering the effects of bedrock lithology/structure and near-surface deposits, their relative or absolute age, and the activity status of their genetic processes (Dramis et al., 2011).

According to the investigation purposes, geomorphological maps are produced at various scales; those of larger scale, from 1:10,000 upwards, developed primarily based on systematic field survey, are particularly useful as they represent the spatial-temporal distribution of potentially dangerous landforms and processes, in substantial detail.

Detailed geomorphological maps cover most the environments of the Earth's surface, including middle latitude high mountains where permafrost and related hazard conditions are often present (Dramis et al., 1995; Dramis and Guglielmin, 2008; Petroccia et al., 2020).

In high mountain periglacial environments, as in this study, it can be particularly useful to associate geomorphological data with the distribution of permafrost, primarily to assess the probability of triggering gravitational movements following permafrost warming and melting of buried ice (Haeberli and Beniston, 1998; Harris et al., 2001a, b). This topic has been discussed extensively within the *Permafrost and Climate in Europe* (PACE) Eu-Project with their proposal of legends and mapping examples (Harris et al., 2003), and in many subsequent papers (e.g. Boeckli et al., 2012; Wirz et al., 2016; Haeberli et al., 2017; Duvillard et al., 2021; Morino et al., 2021). However, despite the availability of several examples of small to medium scale cartographic representations of the probability of permafrost occurrence, few examples of large-scale geomorphological maps of mountain permafrost areas have been published to-date (e.g. Krainer et al., 2012; Müller et al., 2014; Kenner and Magnusson, 2017; Gachev, 2017).

This map focuses on landforms, the outcropping substrate, and near-surface deposits with probability zoning of permafrost occurrence. Considering the source data for production of this map is more than twenty years ago, the map can serve as a basis for comparison and investigating changes in the distribution of permafrost and its possible degradation, as a result

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of climate change. Such information is critical to determining potential hazard and risk.

2. The investigated area

The investigated area comprises the eastern and western slopes of the Mt. Foscagno (2892 m a.s.l.) – Mt. Corno (2986 m a.s.l.) – Mt. Forcellina (3087 m a.s.l.) ridge belonging to the Vallaccia Valley (Inn River basin) and the Foscagno Valley (Adda River basin), respectively (see main map). The lowest topographic point is in the Foscagno Valley (ca. 2320 m a.s.l.); the highest is Mt. Forcellina with a difference in altitude of ca. 767 m.

The area has an average annual air temperature ranging between 0 and – 4.5 °C, depending on the elevation. From the data available in the 1891-1990 interval (Ceriani and Carelli, 1999), the average annual rainfall ranges between 850 and 900 mm/y mainly in the form of snow, although rainfall events, sometimes extreme, are frequent in the summer months. The Livigno – St. Rocco meteorological station (located at 1865 m a.s.l., 7 km northwest of the La Foppa glacial cirque) reports a *Mean Annual Air Temperature* (MAAT) of 2.88 °C and a mean annual rainfall of 779 mm/yr. (peaking in late spring-early summer) from 1972 to 1992. According to Belloni et al. (1993), the elevation of the isothermal lines of 2°C and -1°C is 2465 and 2630 m a.s.l., respectively. Snow thickness ranges between 120 and 340 cm, with its maximum from February to March. The La Foppa – Vallaccia snow-meteorological station, located at 2665 m a.s.l., installed by Regione Lombardia and fully operational since September 1993, recorded a -0.648 °C MAAT and an average 41 cm/month snowfall from October 1993 to March 1994, and a maximum snow cover thickness of 252 cm, in March – April 1994. The annual rainfall was 985 mm, distributed over 122 days.

The vegetation cover in the lower part of the investigated ridge consists of Alpine meadow with a smaller portion of Alpine shrub (Pirola, 1959). In the upper part, there are patches of pioneer vegetation (*Oxyrietum digynae*) on bare ground (Cannone, 1998, 1999).

From a geological point of view, the area belongs to the Upper Austroalpine domain (Guglielmin, 1989; Notarpietro, 1990), locally characterized by two metamorphic complexes: a medium-high grade *paragneiss with andalusite complex*, consisting mainly of paragneiss and orthogneiss composed of andalusite, staurolite, and garnets, and a medium-low grade, *micaschist paragneiss complex*, composed of micaschists and phyllads. The first complex prevails above 2800 m a.s.l., the second is dominant at lower elevations. A small acidic intrusive mass, consisting of a small granitic-granodioritic pluton of late Hercinyan age, is present at the top of Mt. Forcellina. In most of the area, the bedrock underlays thick detrital mantles of different grain size and texture, produced by weathering, gravitative, glacial, and fluvial processes.

The geomorphological evolution of the study area during the Late Glacial is quite well known (Calderoni et al. 1993; Calderoni et al., 1998; Guglielmin 1994; Guglielmin, 1997; Guglielmin et al. 2001). At that time, the mapped area was entirely subject to glaciation. A short hanging valley, headed by a vast glacial cirque, was present on the northern slope of the investigated ridge, another imposing cirque was occupied by a glacier on the northern slope of Mt. Forcellina. The occurrence of three different glacial advances is testified by a sequence of moraine ridges (Calderoni et al., 1998).

Because of the rapid glacial recession during the Holocene and the masking effect of mass wasting and periglacial processes, a reliable record of the maximum extent of glaciers is lacking. In the Forcellina and La Foppa cirques, there are glacial deposits and moraine ridges of Holocene age, likely related to a glacial re-advance around 5000 y BP (Bonani et al., 1994; Longhi & Guglielmin, 2020). The glacial sediments are shapeless and almost entirely covered by slope debris (Dramis et al., 1997). A small glacier was still present in 1932 between 2650 m and 2800 m a.s.l. on the northern slope of Mt. Forcellina (Nangeroni, 1932).

The action of the periglacial processes caused the formation of numerous rock glaciers in the investigated area. Based on the presence/absence of vegetation and geomorphological features indicative of movement, we have divided them into active and inactive. The largest active is the Foscagno rock glacier (Fig. 1), developed between 2450 and 2730 m a.s.l. in the Mt. Forcellina cirque (Calderoni et al., 1993). The only available surface movement data are referred to La Foppa I rock glacier between 1992 and 2002, when the movement ranged between 5 and 35 cm/year (Cannone & Gerdol, 2003).

Other periglacial landforms, widespread in the study area, are solifluction lobes, patterned ground (stone circles, sorted soil stripes, sorted polygons ranging in diameter from 30 to 100 cm), and ploughing blocks. Stone-banked solifluction (Ballantyne, 2018) lobes cover a large part of the La Foppa crest. At the foot of Mt. Corno peak, there are other two active rock glaciers (Calderoni et al., 1993).

The ^{14}C dating of paleosoils buried by rock glaciers indicate Holocene calibrated ages with La Foppa I range between 773 and 1025 AD and La Foppa II between 3948 and 3652 BC in the La Foppa cirque, while 391-102 AD for the Foscagno rock glacier (Calderoni et al., 1993). Moreover, the buried relict glacier ice found in the Foscagno active rock glaciers indicate a calibrated age between AD 765 and 1260 (Guglielmin et al., 2004; Stenni et al., 2007). Subsequently, during the Little Ice Age, a small glacier reformed in

Figure 1. View of the front of the Foscagno Rock Glacier, one of the largest and more intensively studied rock glaciers in Europe. In the background the Forcellina Peak (photo M. Guglielmin).

the Foscagno Valley, between 2650 and 2800 m a.s.l. on the northern slope of Mt. Forcellina (Guglielmin et al., 2001) and lasted until 1932.

3. Evidence of permafrost in the study area

Various investigation methods, such as *Bottom Temperature of winter Snow cover* (BTS) measurements, geophysical soundings, and temperature measurements of spring waters, have been applied in the past to identify the presence of permafrost in the study area (Guglielmin & Tellini, 1993, 1994; Guglielmin et al., 1994; Dramis et al., 1997; Guglielmin, 1997; Harris et al., 2001a, b; Guglielmin et al., 2001).

Remote sensing techniques for permafrost mapping have demonstrated good results in the Foscagno Valley and La Foppa cirque, as shown by the comparison between the resulting permafrost distribution obtained through a supervised classification of multispectral Landsat TM images and permafrost areas identified by BTS and VES (Antoninetti et al., 1993a, b).

The BTS method, proposed by Haeberli (1973), is based on the principle that snow cover, if sufficiently thick, acts as a thermal insulator preventing solar radiation from reaching the ground surface. In this case, ground temperatures are primarily controlled by the ground heat flux, which is, in turn, influenced by the heat stored during summer and by the occurrence and depth of a permafrost table.

Guglielmin and Tellini (1993, 1994) performed 180 BTS measurements (129 of which fall within the mapped area) over and around the Foscagno rock glacier (Mt. Forcellina cirque) and the La Foppa I, II and III rock glaciers (La Foppa cirque) at distances variable between 20 and 50 m. The obtained BTS values indicate the presence of permafrost in both areas, with representative temperature values lower than -3 °C (Haeberli, 1973).

In addition, more than 30 *Vertical Electric Soundings* (VES) were carried out to detect the thickness of the active layer and, where possible, also the thickness of permafrost buried ice (Guglielmin, 1997). In the investigated rock glaciers, the thickness of the active layer, where present, ranged from 0.8 to 5 m, with a mean value of 1.8 m. The mean thickness of permafrost was 12 m, but in many cases, we could not reach its base because of the insufficient length of soundings. In the inactive rock glaciers, relict permafrost cores were found at a mean depth of 22 m.

The temperatures of spring waters from the active rock glaciers were always lower than or equal to 1.7 ° C, while those from the inactive range from 2 to 4 °C, as is the case for other springs in the mapped area. According to Evin (1984), temperatures lower than 2 °C may be indicators of permafrost occurrence in the feeding catchment.

In 1998, during the PACE European Project (Harris et al., 2001a, b), a 24 m deep borehole was drilled in the frontal part of the Foscagno rock glacier at 2510 m a.s.l. In this borehole, after a 2.3 m thick active layer, there is a 14.5 m permafrost layer composed of 5.35 m of massive relict glacial ice overlying a frozen diamicton with segregated ice lenses and pore ice (Guglielmin et al., 2001).

4. Distribution of permafrost

The distribution of permafrost in the study area was obtained by applying PERMACLIM (Guglielmin et al., 2003), a GIS-based model integrating *Digital Elevation Model* (DEM) topographic data and the *Climatic DataBase* (CDB) available from the closest and available Automatic Weather Stations (AWS) around the study area, between 1000 and 2300 m a.s.l.: Passo Bernina and Poschiavo in Switzerland, Fusine, Premadio, Livigno and Cancano in Italy (see Guglielmin et al., 2003 for details). The model calculates the *Mean Annual Ground Surface Temperature* (MAGST) for each cell of the DEM, including the snow buffering effect according to heat conduction theory, which uses both the CDB and field measurements of snow thermal characteristics. The MAGST map distinguishes permafrost distribution as absent, probable, or present, with values higher than 0 °C, ranging from 0 to -2 °C and lower than -2 °C, respectively.

Despite the simplified relationships between latent heat and heat flux, the PERMACLIM data, averaged over the period 1978–1994, fit well with the geophysical and borehole data (Guglielmin et al., 1994; Guglielmin, 1997; Guglielmin et al., 2001) as well as with the BTS measurements (Guglielmin and Tellini, 1993, 1994; Guglielmin, 1997). For all 26 points, where other methods detected permafrost occurrence, the model predicted probable permafrost.

We also compared permafrost occurrence obtained with PERMACLIM (Guglielmin et al., 2003) with the distribution proposed by Boeckly et al. (2012), as shown in Table 1. The latter appears to overestimate the permafrost distribution, considering the available BTS and VES measurements.

5. The permafrost-based geomorphological map

For the construction of the permafrost-based geomorphological map of the Mt. Foscagno – Mt. Forcellina ridge, we used data available from literature (Calderoni et al., 1993; Guglielmin and Tellini, 1994), including those provided by a detailed field survey (Calderoni et al., 1998). For the general layout of the cartographic design, we used air photo interpretation (Lombardy Region, 1981, scale 1:10,000) and OpenStreetMap images.

The map highlights the relationship between bedrock lithology, near-surface deposits granulometry, geomorphological features, ground measurements, and permafrost occurrence probability classes.

In particular: (1) the intrusive/metamorphic lithological units of the outcropping bedrock, and deeply weathered rock were distinguished by different shades into *massive rock*, *foliated rock*, *cataclasite and mylonite*, and *deeply weathered material*; (2) the near-surface deposits with a thickness higher than 2 m were distinguished by granulometry into *boulders*, *gravel* and *pebbles* or *sand*, providing an idea of the possible ice content, and mapped with different coloured shades according to their genetic agent (Panizza, 1972; Brancaccio et al., 1994); the slope deposits were distinguished into active and inactive; (3) also the mapped landforms were genetically distinguished using differently coloured symbols, inactive and active rock glaciers were distinguished with a label. Particular attention has been paid to landforms generated by periglacial processes and possible indicators of permafrost presence, such as rock glaciers and stone-banked solifluction lobes.

We upgraded the three classes of permafrost probability (absent, probable, present) of the PERMACLIM model (Guglielmin et al., 2003) to four classes (high, medium, low probable occurrence, and probable absence) considering the characteristics of the outcropping materials (Tab. 2). Table 2 shows different properties of the deposits, such as grain size, type, thermal properties and therefore the permafrost probability. Indeed, boulders, independent of their origin

Table 1. Comparison between our new permafrost probability classes (lower panel), PERMACLIM (Guglielmin et al., 2003) and Boeckly et al., 2012. The new classification underestimates permafrost distribution compared to PERMACLIM model, on which it is based. Boeckly et al., 2012 classification overestimates permafrost distribution compared to PERMACLIM (Guglielmin et al., 2003).

Source	Classes	Area (km^2)	Area (%)
Boeckly et al., 2012	Probably + certain	3.760	75.35
	Less probable	0.928	18.60
	Absent	0.302	6.05
PERMACLIM (Guglielmin et al., 2003)	High probability	1.777	35.61
	Low probability	2.472	49.54
	Absent	0.740	14.83
New permafrost classes	High probability	0.223	4.47
	Medium probability	1.464	29.34
	Low probability	1.169	23.43
	Absent	2.133	42.75

Table 2. Factors that modify thermal properties and permafrost probabilities for different deposit types (upper panel) according their granulometry, their structure (i.e. slope deposits generally clast supported vs. glacial deposits matrix supported) and their weathering profile (soil) that in general is more developed in inactive deposits and even more in glacial inactive matrix supported deposits. Analogously in the bottom panel the effect of the bedrock has been weighed according to their structure and composition.

		Lithology			
		Slope active	*Slope Inactive*	*Glacial*	*Bedrock*
Deposit granulometry	*Boulders*	5	5	5	
	Gravel and pebbles	4	3	2	
	Gravel and pebbles/ sand	3	2	1	
Bedrock thermal conductivity	*High*				4
	Medium				3
	Low				2

Table 3. Model used to improve the permafrost probability classes obtained by PERMACLIM considering the different weights of deposits and bedrock types (Table 2).

		PERMACLIM (Guglielmin et al., 2003)		
		High	*Low*	*Absent*
Classes from Tab. 2	*5*	High	Medium	Low
	4	High	Medium	Absent
	3	Medium	Low	Absent
	2	Low	Absent	Absent
	1	Low	Absent	Absent

and degree of weathering, strongly favour the Balch effect (Balch, 1990). The ground temperature normally decreases due to the replacement of warm air with cold air within the larger and interconnected voids of the boulder material. Therefore, they are assigned the highest probability classification (a 'weight' of 5). On the other hand, when deposits are less coarse as for gravel and pebble or gravel-sand, the voids are smaller, and the air flow is much less relevant, the 'weights' from 4 to 1 reflect the structure of the deposits and the occurrence of soil (organic material with low thermal conductivity). Regarding the different bedrock types, we classified the different lithologies on the base of their thermal conductivity (estimated according to their structure and composition). For example, we classified as moderate thermal conductivity ('weight' of 4) the massive granitic rock occurring on the Mt. Forcellina and some related dikes, while we considered as relatively low conductivity ('weight' of 2) mylonite and deeply weathered rocks. We validated the four classes through the VES and BTS measurements carried out in the area (Guglielmin and Tellini, 1993: Guglielmin et al., 1994; Guglielmin, 1997; Calderoni et al., 1998). We also examined the effect of weathering profiles (soils) in decreasing the thermal conductivity of the outcropping materials due to their higher organic matter and clay content. Therefore, where soils are better developed, the permafrost probability decreases. The four classes derive from combining the PERMACLIM probability classes of permafrost occurrence with the Table 2 characteristics (Tab. 3). The permafrost distribution classes are distinguished on the map by pale blue gradations, superimposed on the topographic map, forming a background for the geomorphological data distinguished from the geo-lithological basis, traditionally used in Italy for detailed geomorphological maps (Panizza, 1972; Brancaccio et al., 1994). The black point symbols indicate the positions and values of the BTS and VES measurements made in the area. Furthermore, we represented the MAAT recorded in the 1978-1994 interval.

6. Conclusions

The geomophological map of the Mt. Foscagno ridge provides a detailed representation of landforms, near-surface deposits, and outcropping bedrock units in a high-elevation sector of the Italian Central Alps. In addition to these elements, the map shows the potential distribution of permafrost (high, medium, low probable occurrence, and probable absence) based on the PERMACLIM model (Guglielmin et al., 2003) and the thermal characteristics of the outcropping materials. The four classes were validated through VES and BTS measurements. Considering that the data used for the construction of the map is more than twenty years old, this map could constitute a basis for comparison, to investigate the changes in the distribution of permafrost and its possible degradation as a consequence of the climatic changes in progress, also taking into account the situations of hazard and risk that could be associated with them. A new geomorphological research campaign in the area, including a systematic update of the BTS and VES data, could be meaningful in this regard.

Software

The map has been drawn using the software QGIS (v. Desktop 3.10.3 A Coruña with GRASS 7.8.2).

Geolocation information

The study area is located at the watershed between Adda and Inn River, near Foscagno Pass, in the Central Alps (northern Italy). The area is placed between 5149256 N – 590782 E and 5146674 N – 592704 E, Coordinate System: WGS 1984 / UTM Zone 32 N.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement (DAS)

The data that supports the findings of this study are freely available within the article or from the corresponding author, [MB], upon reasonable request. Furthermore, the Digital Elevation Model of the sector is provided by the Geoportale of Regione Lombardia (https://www.geoportale.regione.lombardia.it/).

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