A multidisciplinary approach for physical landscape analysis: scientific value and risk of degradation of outstanding landforms in the glacial plateau of the Loana Valley (Central-Western Italian Alps)

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Abstract: Landforms characterized by high scientific value (i.e. geomorphosites) might undergo modifications due to intrinsic and extrinsic factors (natural and human-induced processes). In the framework of geoheritage analyses, the assessment of the value (scientific or additional) of geomorphosites should be performed side by side with the analysis on the risk of degradation (fragility and vulnerability). A multidisciplinary method is proposed for the analysis of landforms that are potentially fragile but outstanding for their scientific value related to geological, geomorphological and ecological values. A geomorphological map was produced for the glacial plateaux of the Loana Valley (Central-Western Italian Alps), where an outstanding geomorphosite was detected: the Cortenuovo Calcareous Ridge. The site is herein analysed in terms of the representativeness of geological and (paleo)geomorphological features as well as for its support role to the ecosystem. For dissemination purposes, a simplified version of the geomorphological map (i.e., geomorphological box) was prepared for the site. Specific morphometric and dendrogeomorphological analyses were then performed to investigate more in detail the risk of degradation of the site. It resulted to be a spatially restricted hotspot of geodiversity, characterized by an average surface lowering rate (0.44 cm/y on average) comparable to that obtained in similar geomorphologic contexts in the Alpine environment. The obtained results testify a potential vulnerability to natural processes of this highly scientific valued site, which will surely benefit of a legal recognition as a component of geoheritage, with a specific regulation for its protection, that could prove to be strategic.

Key words: Physical landscape analysis, Geomorphological mapping, Dendrogeomorphology, Geoheritage, Loana Valley (Central-Western Italian Alps)

1. Introduction and aims

In the framework of physical landscape and geoheritage analyses in particular, different features of sites of geo(morpho)logical interest (i.e. *geosites* sensu WIMBLEDON, 1999) should be taken into account for assessing geosites values and needs for protection or valorisation. Recently published reviews (e.g. BRILHA, 2018) provide an overview on the most common and used attributes (i.e. scientific, additional and potential for use) for the quantitative assessment of geosites value. According to i) the specificity of each site (i.e. a value, scientific or additional, that may predominate over the other ones) and ii) the aim of the evaluation procedure (i.e. scientific research, conservation, valorisation), the key point is to identify the site peculiarity, i.e. the features that make the site a *uniquum* (*sensu* GARCÌA-ORTIZ *et alii*, 2014) at local, regional or international level (PANIZZA, 2001) and that could significantly influence the assessment procedure (BOLLATI *et alii*, 2014; SANTOS *et alii*, 2019). Some examples specifically regard the sites of geomorphological interest or *geomorphosites* (i.e. *sensu* PANIZZA, 2001), and a specific case is represented by *mountain geomorphosites* (*sensu* REYNARD & CORATZA, 2016). Geomorphosites have their own specificities (CORATZA & HOBLÈA, 2018; SANTOS *et alii*, 2019), among which dynamicity of the processes affecting them is scientifically and educationally relevant (PELFINI & BOLLATI, 2014; BOLLATI *et alii*, 2016; 2017a; DÌEZ-HERRERO *et alii*, 2018; PESCATORE *et alii*, 2019). Geomorphosites could be particularly fragile if they undergo degradation. In such cases, evaluation procedures should be combined with the analysis on the *risk to degradation* of geoheritage sites as suggested by GARCÌA-ORTIZ *et alii* (2014). These authors proposed a series of definitions deriving from an accurate review of the terms used in literature, as reported in Table 1. These definitions could be translated also in the representativeness of a geomorphosite as active or relict landform. Table 1 also shows the possible link between the features described by GARCÌA-ORTIZ *et alii* (2014) and the geomorphosite typologies proposed by REYNARD (2004), PELFINI & BOLLATI (2014), and BOLLATI *et alii* (2017a), considering the activity degree and typology of geomorphic processes. Despite the importance of such analyses, whereas papers focusing on geosites inventories and description, as well as on geotourism issues, are abundant in the framework of geoheritage researches, studies aimed at analysing geomorphosites values and their changes in relation to geomorphosites degradation are still few.

Another scarcely studied aspect is the *ecological support role* (Supplementary File A) of landforms, especially as part of the scientific value of geomorphosites (BOLLATI *et alii*, 2015): endemisms, in fact, may be due to particular geo(morpho)logical conditions, as well as arboreal vegetation may suffer and record the geomorphic dynamic processes impacting on it, as dendrogeomorphological analyses demonstrate (PELFINI *et alii*, 2010; BOLLATI *et alii*, 2018a).

The evaluation of the degradation rates of geomorphosites approached through multidisciplinary methodologies, also including the biotic components of the ecosystems, represent a very recent topic, useful for defining the best management practices towards geoconservation or promotion of geoheritage sites (BOLLATI *et alii*, 2018a).

The approach proposed in the present paper consists of a sequence of steps: i) geomorphological mapping of a geoheritage-significant area; ii) analysis of the scientific value of outstanding landforms in relation with the biotic component of the ecosystem; (iii), individuation of the most fragile one by means of dendrogeomorphological analyses; (iv) elaboration of simplified versions of the geomorphological map accompanying the results (i.e. geomorphological boxes, BOLLATI *et alii*, 2017b and reference therein). This research method is contextualized in Figure 2, reporting a sketch of the relations existing between the different branches of geoheritage researches in literature.

The selected area is the upper portion of the Loana Valley (Central-Western Italian Alps; Fig. 1a), where a glacial plateau characterizes the boundary with the Val Grande National Park (VGNP). In this area, and in the downstream region, different geomorphosites are present, which have already undergone a quantitative evaluation procedure by BOLLATI *et alii* (2017b), as components of the geoheritage. Anyway, official recognition has not yet been applied to all of them as described in the following paragraph. The Cortenuovo Calcareous Ridge, according to previous studies (e.g., BOLLATI et al., 2017b), obtained the highest results and it was selected with the aims of: i) characterizing it from a morphometric point of view in relation with the other geological elements in the area; ii) calculating the risk of degradation by means of a technique based on the biotic elements of the landscape (i.e., dendrogeomorphological analysis on roots exposure).

1.1. Current state of geosites inventories in the Loana Valley

The area represents a noteworthy place where geomorphology and geology interface significantly. Besides geomorphological features, geological elements are relevant too (i.e. *representativeness of geological processes,* Supplementary File A). The importance of the area for crustal dynamics and metamorphic processes (i.e. *geohistorical importance,* Supplementary File A) has been recognized by several authors since long time ago (REINHARD, 1966; KRUHL & VOLL, 1976; ALTENBERGER *et alii*, 1987; SCHMID *et alii*, 1987). For example, REINHARD (1966) identified, in a 5.5 km transect along the valley, from S to N, an evident metamorphic gradient from the greenschist to the upper amphibolite and granulite facies. KRUHL & VOLL (1976) underlined how these associations of rocks differ from those of the neighbouring areas (i.e. *rarity*; Supplementary File A). Moreover, ALTENBERGER *et alii* (1987), after discussing on the P-T path relative to the mylonitization along the Insubric Line and the possible kinematic movements, evaluated "*the southern margin of the Central Alps between Loana and Ossola valley as an excellent example of the interaction between a continuous deformation and a temperature increase and subsequent decrease*". More recently, STECK *et alii* (2013) indicated how the Loana Valley constitutes a representative section through the Paleozoic basement and its sedimentary cover of the Canavese Zone (see details in the geological setting, par. 2.1).

Due to this relevant geohistorical importance, geosites should be recognized in the area. Geosites inventories (national, regional or local) in the Italian territory are continuously updated and revised. According to the last check (July 2019), geosites belonging to the Loana hydrographic basin are reported in the following inventories:

i the ISPRA *Italian National Geosites Inventory* (http://sgi.isprambiente.it/geositiweb/Default.aspx). It includes: i) the *Alpe Scaredi* area (including the Marble Lake), that corresponds to the glacial transfluence saddle and the neighbour areas, ii) the (*Pozzo Vecchio) Loana Waterfall* located at the confluence between the Loana Stream and the Eastern Melezzo;

ii the *Geoportale of Regione Piemonte Inventory* includes only the *Pozzo Vecchio Loana Waterfall*

iii the *SVGP Geosite List* (http://www.sesiavalgrandegeopark.it/geositi.html) does not include any geosite located in the Loana hydrographic basin.

In the upper portion of the Loana Valley, from the VGNP Northern border as far as the *Nucleo Alpino La Cascina*, 13 *potential geomorphosites* (*sensu* BRILHA, 2018) were detected and evaluated by BOLLATI *et alii* (2017b) and 9 of them were considered *effective geomorphosites* (*sensu* BRILHA, 2018), according to the quantitative comparison with a legally recognized geosite included both in the National and Regional Inventory of geosites and located in the same municipality (i.e. *Pozzo Vecchio Loana Waterfall*). 2 geotrails for the exploration of relevant geological features characterizing the Loana Valley have been recently equipped by the Malesco Municipality with illustrative panels at selected locations (i.e. geostops).

In the Supplementary File A, the list of parameters used by the BOLLATI *et alii* (2017b) and the formulas applied to calculate the *Global Value* and the *Potential for use* of these potential geomorphosites and of the related geotrails are reported.

As resulted from the evaluation procedure, the most valued geomorphosite of the area is the *Cortenuovo Calcareous Ridge* (i.e. CCR in the present research and G11 in BOLLATI *et alii*, 2017b, Fig. 1c), not yet included in legally-recognized geosite inventories. In Figure 3 the CCR assessment results are put in comparison with the *Pozzo Vecchio Loana Waterfall.*

CCR is constituted by a series of whale back reliefs, surrounded by V-shaped valleys that are structurally controlled and testifying to an intense interplay between bedrock lithology (i.e. carbonates), regional tectonic structures (mainly SW-NE oriented) and Pleistocene glacial erosion. Such kind of reliefs were shaped at first by glaciers and later by the action of water and gravity on a bedrock dissected as a consequence of the intense fracturing. Due to bedrock lithology and structures, the glacial erosional action on carbonates and phyllonites increases the geodiversity of landforms (*representativeness of (paleo)geomorphological processes* and *geodiversity*, Tab. 2), particularly easy to detect, also due to the different colour of the rocks and to the, up to now, preserved features (i.e. *integrity*, Tab. 2).

On the CCR upper surface, thanks to the presence of a thin soil layer, arboreal vegetation is present (mainly *Larix Decidua* Mill.), with a particular concentration with respect to the surroundings areas. *Aquilegia alpina* L. was surveyed and *Dryas octopetala* L. is reported (PNVG, 2006) as typical flora related to carbonate bedrock. This testifies the *ecological support role* (Tab. 2) of the bedrock and the potential role of CCR landforms as a support to the biological elements of the ecosystem. More in detail, the *Dryas octopetala* L. could behave like an engineering species (EICHEL *et alii*, 2016), providing a stabilizing function on slopes. *Aquilegia alpina* L. is a rare species, reported in the *Direttiva Habitat* (Attachment IV; https://eur-lex.europa.eu/legal-content/IT/TXT/?uri=LEGISSUM:l28076), and totally protected. Since the areal distribution of *Aquilegia alpina* L. along the Alps is fragmentary, the presence at CCR is particularly relevant.

The historical use of georesources (i.e. *cultural value* in Tab. 2) in the Loana Valley is relevant too. Besides the more famous "*Pietra laugera*" or *"Pietra ollare*" (CAVALLO, 2017), mainly used for jars, pots and pipes, carbonate outcrops in the valley were quarried in the past to produce lime. Old lime kilns, located in the valley bottom, have been recently restored and constitute a geoarcheosite (i.e. *Le Fornaci della calce*, BOLLATI *et alii*, 2017b). The possibility of experimenting lime production is periodically proposed to both mountain hikers and school groups.

Considering sources other than the geosites inventories, it is quite interesting that the analysed site is indicated as a Natural Monument (“Limestone outcrop”) in a map addressed to excursionists (Geo4Map, 2018). Natural Monuments are surveyed, for this kind of maps, by the volunteers of the Italian Alpine Club.

2. *Study area*

The CCR extends at an altitude between 1,680 and 1,750 m (a.s.l.) within the glacial plateau of the Loana Valley, in the Western Italian Alps (Verbano - Cusio - Ossola Province). The head of the valley is one of the main entrance to the territory of the Val Grande National Park (Fig. 1a), and the area is also part of the Sesia Val Grande Geopark (Fig. 1a), recognized in 2013 by the UNESCO Global Geoparks Network for its outstanding value in terms of geology (SVGP, 2013). The Loana Valley is N-S oriented and its hydrographic basin covers an area of about 27 km^2. The Loana stream flows from S towards N, being a tributary of the Eastern Melezzo that drains the Vigezzo Valley and flows, toward East, into the Maggiore Lake, in the Swiss territory.

2.1 Geological setting

The Loana Valley is located in the Western Alps sector, an area extensively studied for the reconstruction of the Alpine nappe tectonics (e.g. STAMPFLI *et alii*, 2002; STECK, 2008; STECK *et alii*, 2013). The valley lies along the boundary between the Austroalpine, to the NW, and the South Alpine domains, to the SE, which are separated by the *Canavese Line* (*sensu* SCHMID *et alii*, 1987; STECK, 2008; STECK *et alii*, 2013).

The Austroalpine domain represents a composite unit of the Adriatic continental crust (FESTA *et alii*, 2020). As recently reviewed by MANZOTTI *et alii* (2014), it presents a complex history. According to the Authors, the Austroalpine nappes show a polyphase deformation history (HP/LT; mainly blue-schist to eclogite facies conditions; FESTA *et alii*, 2020) related to specific Alpine orogeny phases (Late Cretaceous-Early Tertiary). The Sesia Zone, in particular, underwent subduction, high-pressure metamorphism, extrusion and accretion to the Adriatic margin with the genesis of a mylonite zone (STECK *et alii*; 2013). In the studied area the Sesia Zone crops out in the NW sector of the Loana Valley (SL in Fig. 1c): its northern contact against the Monte Rosa Nappe is characterized by a belt of migmatites, whereas its southern edge has been named Loana line by BURRI *et alii* (2005).

The South-Alpine Domain constitutes the northern border of the Adriatic plate (STAMPFLI *et alii*, 2002) and it is characterized by a S-vergent structure (LAUBSCHER, 1985). The SA consists of a pre-Alpine metamorphic basement and its sedimentary cover, only locally experiencing localised Alpine deformation and related metamorphism. As reviewed by STECK *et alii* (2013), it is subdivided into the *Strona-Ceneri Zone*, outcropping to the south-east of the study area and not described in the present study, and the *Ivrea-Verbano Zone* and the *Canavese Zone*, interesting the study area.

The *Ivrea-Verbano Zone* (IVZ), outcropping in the south-eastern portion of the study area (SA in Fig. 1c), represents a polyciclic lower crust basement, showing an overprint by a granulite facies (HT/LP) metamorphism dated back to Permian (290 Ma; STECK *et alii,* 2013 and reference therein). The metamorphic grade in the IVZ increases towards the NW, from upper amphibolite facies adjacent to the *Serie dei Laghi*, to granulite facies near the NW boundary of the zone along the CL (PEYRONEL *et alii*, 1967; SCHMID, 1967; ZINGG, 1983). The IVZ exposes a world-famous section of lower continental crust (FOUNTAIN, 1976, KISSLING 2012, and references therein). It mainly consists of a metamorphosed volcano-sedimentary sequence, referred to as the Kinzigite Formation, and gabbroic to dioritic intrusive rocks, referred to as the Mafic Complex, with minor quartzites, thin meta-carbonate horizons and interlayered metabasites (SILLS & TARNEY, 1984); mantle peridotite lenses, tectonically interfingered with the metasedimentary rocks (QUICK *et alii*, 1995), occur in the NW part, near the CL (Balmuccia in the Sesia valley and Finero in the Cannobina valley; ZANETTI *et alii*, 2013 and references therein).

The *Canavese Zone* (CZ), outcropping in the central portion of the study area (SA in Fig. 1c), is interpreted as the distal continental margin of Adria facing the Ligurian-Piemonte Ocean (FERRANDO *et alii*, 2004). It consists of a basement overlain by Permian silicoclastic sediments and Triassic-Liassic carbonate rocks (sedimentary and metamorphic), accreted to the IVZ margin before the Alpine metamorphic greenschists facies overprint (STECK *et alii,* 2013). The CZ is dismembered all over the outcropping area, due to late Alpine ductile shear zones and brittle faults (FERRANDO *et* *alii*, 2004). Anyway along the Loana Valley a stratigraphic section through the Paleozoic basement of gneiss (Scaredi Formation; STECK *et alii*, 2013) and its sedimentary cover is exposed (STECK *et alii*, 2013) (Fig. 1d). Moreover, the rocks show a very low-grade metamorphic overprint associated with a mylonitic to cataclastic deformation. According to FERRANDO *et alii* (2004), the rocks of the CZ show a sequence of different tectono-metamorphic events: Variscan, intermediate, Alpine. In particular, according to the author, the phyllonites (CB in Fig. 1c) should be associated to the intermediate event.

In the glacial plateau of the Loana Valley the effects of the *Canavese Line* (CL) (*sensu* SCHMID *et alii*, 1987; STECK, 2008; STECK *et alii*, 2013) are very evident. The CL, separating the Austroalpine and the South Alpine domains, is a major tectonic boundary that interacts with the activity along the nearby complex Centovalli and Simplon faults systems (STECK, 2008). In the study area the CL was considered as part of the NE-striking segment of the Insubric Line West of Locarno (Ticino Canton, Switzerland; SCHMID *et alii*, 1987; ZINGG & HUNZIKER, 1990; STECK, 2008). In the westernmost area (i.e., the Canavese geographical area), some authors distinguished between an *Internal Canavese Line* and an *External Canavese Line* (FERRANDO *et alii*, 2004; FESTA *et alii*, 2020). According to FESTA *et alii* (2020), the CZ includes only rocks outcropping between these two tectonic lines which, after their structural map, join together in the Insubric Line in our study area. The CL acted as an inverse fault during the Oligocene, influenced by a older structural inheritance (Late Carboniferous-Early Jurassic; FESTA *et alii*, 2020). It was responsible for the generation of a mylonitic belt, involving rocks of the SL, the CZ and the IVZ and known as *Fobello-Rimella Schists* (STECK *et alii*, 2013 and reference therein), already described as Canavese Zone s.l. by ARGAND (1910) and as *Zone 2* by KRUHL & VOLL (1976). The mylonitic belt related to the CL action is more than 1 km wide in the Ossola Valley, but becomes as narrow as around 100 m in the Loana Valley (ALTENBERGER *et alii*, 1987) (CB in Fig. 1c). These mylonitic rocks (i.e., phyllonites) underwent a temperature maximum related to the upper greenschists facies (ZINGG *et alii*, 1976, SACCHI, 1977; ALTENBERGER *et alii*, 1987).

As indicated by STECK *et alii* (2013) and described in detail by SCHMID *et alii* (1987), according to the protolithes of the mylonites, 3 main zones may be identified from SE to NW:

i) mylonites derived from the Austroalpine Domain, mainly represented in this area by gneisses of the Sesia Lanzo Zone and locally by *Pietra laugera* (i.e. talc and/or chlorite-rich metamorphic rocks, deriving from mafic - ultramafic protolithes; CAVALLO, 2017), outcropping along restricted bands (FERRANDO *et alii*, 2004);

ii) the Canavese belt (CB; Fig. 1c), consisting of mylonites originated from the Permo-Mesozoic cover rocks (REINHARD, 1966; SCHMID *et alii*, 1987): quartz-mica rich clastic sediments, dolomites, dark calcschists and siliceous-carbonate rocks. The metasedimentary sequence is dismembered and often imbricated with, or folded into, the IVZ-derived mylonites and thin ophiolite lenses. The CCR is part of this zone;

iii) mylonites originated from the basement of the South Alpine Domain, namely rocks of the IVZ.

In the Loana glacial plateau, the progressive mylonitization of the IVZ rocks is easily observed (SVGP, 2013), since the high-grade metamorphic rocks are transformed into greenschist facies mylonites and phyllonites. On the contrary, the relations between the SL and the CB, both belonging to the greenschist facies (SACCHI, 1977) are less clear. ZINGG & HUNZIKER (1990), using the K-Ar method, dated back the regional metamorphism in the head of the Loana Valley (Scaredi mountain hut) to 23.0 ± 0.3 - 25.6 ± 0.3 Ma (Late Oligocene-Early Miocene), at the boundary between uplift and strike-slip movements along the CL. More in the specific, 23.3± 0.3 Ma is referred to the mylonitization affecting quartz-pelitic rocks at the Cortenuovo site.

The carbonate rocks outcropping along the Loana Valley, and object of investigation, are represented by slightly metamorphosed carbonate (limestone and dolomite; Fig. 4a), forming the CCR, calcschists (Fig. 4b), and marbles. They pertain, as described before, to the Southern Alps sedimentary cover, hypothetically Triassic (REINHARD, 1966) or Jurassic (SCHMID *et alii*; 1987), and in particular to the CZ (zone ii; CB). The pure marble outcropping at the Marble Lake (G13 in

BOLLATI *et alii*, 2017b; Fig. 1c) belongs to the IVZ and contains pre-alpine amphibolite-facies relics (diopside and actinolite; SCHMID *et alii*, 1987). The CZ and IVZ carbonate rocks are very different according to their metamorphic facies (STECK *et alii,* 2013). Within the glacial plateau, the intercalation between the phyllonites and the carbonate (Fig. 4b) is particularly visible at the CCR geomorphosite. Here, the relief is transversally dissected by two main saddles that allow to observe the intercalation between the two types of rocks.

Finally, in the Loana Valley, the local occurrence of porphyritic dikes (Fig. 1c), according to different authors (REINHARD, 1966; SCHMID *et alii*, 1987; age determinations: 31.7 + 0.2 - 32.4 + 0.5 Ma; ROMER *et alii*, 1996), is probably related to the Oligocene activity, responsible for the emplacement, along the CL, of other plutons like the Biella-Traversella (ZANONI *et alii*, 2010; KAPFERER *et alii*, 2011).

1.2. Geomorphological setting

The Loana watershed has been only recently studied from a geomorphological point of view (i.e. CERRINA, 2002; BARBOLINI *et alii*, 2011; BOLLATI *et alii*, 2018a). The Loana and its related hydrographic basins are famous for the concomitant presence of a dissected bedrock and abundant loose deposits which, coupled with a climatic regime characterized by significant extreme meteorological events, favour hydrogeological instability events that affect severely the whole Ossola region (PECH, 1986; HANTKE, 1988; CAVINATO *et alii*, 2005; LUINO, 2005). This is particularly evident along the Centovalli Line running ESE-WNW along the Vigezzo Valley (DRESTI *et alii*, 2011; SURACE *et alii*, 2011).

The head of the Loana Valley is characterized by the outcrop of deformed and fractured rocks related to the mylonitic phase along the CL; similar conditions are also present in other Alpine regions, where the action of the Insubric Line is considered responsible for hydrogeological instability (SOLDATI *et alii*, 2006).

The glacial plateau at the head of the valley shows glacial relict landforms shaped, during the Pleistocene, by the Loana and Portaiola valley glaciers (HANTKE, 1988; BIANCOTTI *et alii*, 1998). In this area, the Loana glacier eroded pervasively phyllonites and carbonate rocks. Within the CCR a series of whaleback carbonate reliefs, elongated SW-NE, may be observed in the frontal part of the glacial plateau, immediately up-valley to the most prominent glacial step (G7 in BOLLATI *et alii*, 2017b in Fig. 4). At the CCR, but in general in all the study area, the dynamic interplay between tectonic evolution and surface processes is evident (*sensu* GHISELLI *et alii*, 2005). In particular, the trend of glacial landforms (like glacial cirque edge, over-deepenings, striae; GHISELLI *et alii*, 2005; 2015), and also of water- and gravity-related landforms, was deeply influenced by the bedrock structures, characterized by a mainly SW-NE oriented regional pattern (REINHARD, 1966). As analysed in high latitude environments by COQUIN *et alii* (2019), ancient paraglacial dynamics also, being in their turn guided by structures, could have influenced the location of the most recent glacial cirque at the Laurasca-Cortechiuso ridge.

In the area, visible erosion features are different according to the affected lithotype. Phyllonites show glacial *striae* superimposed on the intense schistosity, and local quartz veins that underwent a morphoselective action. All the calcareous lithotypes (light grey, very fractured to blocky carbonate at CCR, Fig.4a; dark grey calcschists, Fig. 4b; white marbles at the Marble Lake, Fig. 4c) behaved differently, also among each other, under the past glacial and current water-related processes. Karst related landforms are well developed, as for example the karren and scours, at the Marble Lake, near the spring of the Loana stream (Fig. 4c).

Down-valley the glacial step, characterized by a height of about 300 m and by intermittent waterfalls, water, gravity and snow-related landforms become dominant (polygenic cones and snow-avalanche corridors). Here, the Loana stream built an alluvial plain modified by human interventions during the 90's of the XX century for favouring grazing (CERRINA, 2002) in the nearby of the *Nucleo Alpino La Cascina*. This is the only human settlement in the valley bottom, seasonally occupied by shepherds and tourists; its protection is regulated by the Landscape Regional Plan (available at: http://www.regione.piemonte.it/territorio/pianifica/ppr.htm).

3. Methods

A multidisciplinary method, taking into account the geo(morpho)logical specificities of the analysed site, was applied to quantify the dissolution rates of the CCR, taking advantage of the arboreal vegetation colonizing its surface (Fig. 2). More in detail: i) geomorphological mapping and morphometric measures were performed to spatially represent the relations between rocks, landforms and deposits; ii) dendrochronological and dendrogeomorphological analyses were used to detect the age of the trees colonizing the CCR surfaces and to calculate the rates of the surface lowering by means of exposed roots analysis. The previous achievements on CCR as sites of geomorphological interest will be, hence, integrated and discussed with the potential consequences of degradation herein illustrated.

3.1 Geomorphological mapping and morphometric analysis

The geomorphological map of the VGNP by BIANCOTTI et al (1998) covers only for a limited portion the head of the Loana Valley. More recently, CERRINA (2002) elaborated a geomorphological map at 1: 10,000 scale of the whole Loana Valley.

In the present research we focused more in detail on the geomorphological mapping of the Loana glacial plateau (Supplementary File B, a). After the field survey, indispensable to reach a good detail of landforms mapping especially in glacial areas (SMITH *et alii*, 2006), the analysis of available orthophotos and Digital Elevation Model (5 m resolution; DEM, here after) was performed. Data were retrieved from the ISPRA Web Maps Services (WMS) (http://geoportale.isprambiente.it/tematiche_pt/servizi-wms/) and the Geoportale of the Piemonte Region (http://www.geoportale.piemonte.it/geocatalogorp/?sezione=catalogo).

Lithologies were grouped according to their response to modelling processes (PANIZZA, 1972). For this reason, the carbonate rocks pertaining to the CZ and to the IVZ are not distinguished on the map, since both may undergo dissolution. In order to emphasize the role of geomorphic processes, landforms were classified and coloured on the map according to the system proposed by the Italian Working Group for geomorphological mapping (e.g. CAMPOBASSO *et alii*, 2018), with adaptations due to the scale of the map and to specific local features (BOLLATI *et alii*, 2018b). Geomorphic landforms characterizing the area were hence distinguished in structural-related (brown), slope (red), water-related (green), glacial (violet), periglacial (blue), and weathering-related (orange) ones. Often, geomorphic processes combine to generate complex or polygenic landforms (PECH, 1986), in that case, one of the following combination of colours was used: blue and red for the snow- and gravity-related landforms, green and red for the water- and gravity-related landforms; green and brown for the water-related landforms influenced by structures. A broader distinction between *active* and *relict/inactive* landforms is adopted in the legend of the map, using a different intensity of the colours. Morphometric measurements of length, width and elevation variations across the whaleback reliefs were finally performed using the DEM, previously corrected with the *Fill Sinks* function in the Arc Toolbox of ArcGIS 10.2 (i.e. Arc Hydro Tools, Terrain Preprocessing, DEM manipulation, Fill Sinks).

After the geomorphological map was completed (Supplementary File B, a), a series of *Geomorphological Boxes* (*sensu* BOLLATI *et alii*, 2017b) were realized, one for each potential geomorphosites that underwent the assessment with the procedure and parameters included in the Supplementary File A. They consist of a simplified version of the geomorphological map obtained within the GIS environment by symbolizing only the landforms assigned to the field "*geomorphosites_element*", in the Attribute table. The background for the geomorphological boxes is a satellite map (in this case provided by ESRI Environmental Systems Research Institute, Digital Globe & GeoEye, GIS User commonly; http://microsites.digitalglobe.com/arcgis/), that is a very familiar format to the general public. This simplified map has a twofold aim: i) the mapping of the sites is relevant to provide administrations with a cartographic tool to manage the interventions on the territory considering the need for geoheritage conservation (FUERTES-GUTIÉRREZ I. & FERNÀNDEZ-MARTÌNEZ, E., 2012; SÀNTOS-GONZALEZ & MARCOS-REGUERO, 2018); ii) simplified versions of geomorphological maps offer to the general public an opportunity to understand physical landscape features (BOLLATI *et alii*, 2017b).

The Geomorphological box of the CCR is herein presented in the Supplementary File B, b).

3.2 Dendrogeomorphological analyses

The CCR surface is characterized by the presence of trees of the species of *Larix decidua* Mill. (Fig. 1, d), a pioneer species able to colonize in borderlines conditions. Since trees can react and record the possible stresses induced by their precarious position (i.e. environmental conditioning; SCHWEINGRUBER, 1996), we decided to investigate the response of trees to geomorphological dynamics affecting this site by means of dendrochronological and dendrogeomorphological analyses. A similar approach was applied by BOLLATI *et alii* (2017a) to analyse the response to variations in relief shape and stability induced by dissolution processes on another kind of soluble rocks (i.e. gypsum).

17 trees of *Larix decidua* Mill. were sampled on the CCR surface, during the summer of 2015 and 2016. 24 trees were also sampled in a control cluster, not affected by active geomorphic processes and located about 4 km northward, at a mean altitude of about 1,800 m a.s.l.

Two trunk core specimens for each tree were extracted using a Pressler increment borer, at a standard height of 1.30 m (breast height), when no disturbance was detected. In other cases, specific sampling height were adopted. For roots analysis, disks were cut using a saw. In alternative, cores were extracted. The distance between the top of the tree root and the actual ground surface was measured. If different conditions of exposure were detected, more than one sample for each root was taken, with the relative distance measure.

In the Loana Valley bottom, a series of dendrogeomorphological analyses have been already performed by BOLLATI *et alii* (2018a) for characterizing a series of polygenic debris cone. Trees in that cases did not show exposed roots useful for a significant analysis but the attention was focused on the scar and trauma deriving from the combined action of snow avalanches and debris flows. In the CCR case, instead, roots exposure was used to detect the lowering of an erosion surface where damage indicators demonstrated not to be relevant. In this sense, the specificity of the processes affecting a site allow to apply the most adequate methodology based on the different response of the arboreal vegetation to geomorphic processes.

After a first qualitative microscopic analysis using the Lintab system^{TM} (RINN, 1996), tree rings widths were measured (accuracy of 0.01 mm), according to their features, using the Lintab and TSAP systems^{TM} (RINN, 1996) and/or by means of image analysis performed with WinDENDRO^{TM} software (RÉGENT INSTRUMENT INC., 2001). The mean chronologies from both the disturbed and undisturbed groups of trees were cross-dated using TSAP and the growth trends were removed applying a spline detrending using Arstan (HOLMES *et alii*, 1986). Moreover, to detect the possible suffering of trees, the Negative Anomaly Index (NAI; BOLLATI *et alii*, 2016 and reference therein) was calculated for each year of the chronologies. The NAI allows to compare the tree ring widths of each year with the average width of the four previous years, calculating the positive or negative percentage of variation. Looking, then, to the thresholds of 40% and 70% of negative percentage of variation, it is possible to detect eventual time intervals during which trees particularly suffered. Besides NAI, attention was also paid to Compression Wood (CW), a particular, resistant and denser kind of wood produced by the tree in response to the tilting of the stem related to soil creep or other destabilizing processes, such as the ones induced by snow weight (e.g. TIMELL, 1986; BOLLATI *et alii*, 2018a).

After analysing trunk cores, exposed roots underwent microscopic morphometric analysis and measurement using Lintab and TSAP systems (RINN, 1996) in order to perform denudation rates estimation. The change of micromorphology of roots, from the production of root type wood to a trunk type wood, as a consequence of exposure, was dated (GÄRTNER, 2007; STOFFEL *et alii*, 2013). Using this time interval (*A*), and the distance between the tree root top and the actual ground surface (*D*), the original formula proposed by HUPP & CAREY (1990) was used as starting point. The formula was slightly modified to reduce the under-estimation of the denudation rate deriving from the use of the complete sampling year in the *A* factor (BOLLATI *et alii*, 2019). Hence, for calculating the average denudation rate, the *Year Fraction* (*YF*) coefficient was considered. The *YF* is calculated considering in the time interval(*A*), the number of the months of the year of sampling instead of the whole year. The *YF* was hence calculated as:

$YF = (1/12) * N° \ months$

Then, the *YF* is added to the number of the years preceding the sampling year. Hence the HUPP & CAREY (1990) updated formula became:

$$ER = D/(A+YF)$$

Since the sampling month was August (months number 8), the YF was considered equal to 0.667 and in this case the formula becomes:

$$ER = D/(A+0.667)$$

Local Denudation Rates (LDRs) at single tree root sample were calculated as well as the *Average Denudation Rates (ADRs)* over long periods and all over the site (e.g. BOLLATI *et alii*, 2019).

4. Results

4.2 Geomorphological map and morphometric analysis

4.2.1 Geomorphological map description

The whole geomorphological map was realized at a 1: 5,000 scale and reported here at 1: 10,000 scale (Supplementary File B, a; Coordinate system Projection: UTM, Fuse 32N; Datum: WGS 84). It covers an area of about 2 km^2, between the elevations of 1,300 m a.s.l. (glacial step foot) and 2,192 m a.s.l. (Laurasca Mount).

Amphibolite, paragneiss and local marble intercalations of the Southern Alps domain crop out in the south-eastern portion of the area. The central portion of the mapped area is mainly occupied by the phyllonites (Fig. 5a) showing an almost vertical attitude towards NNW. Carbonate rocks are intercalated with the phyllonites, a relation that is particularly visible at the elongated ridge (e.g. CCR site).

The glacial processes are no more active while, all over the mapped area, water, gravity and snow related processes could locally be active or not. More in detail, the most relevant geomorphological features reported in the map are:

i *Structural landforms*: the CL is located in the upper part of the geomorphological map, with a main SW-NE trend. Structural scarps and depressions occur along the same direction and are particularly evident in the calcareous rocks at the CCR site. Fractures, following the general trend but also along a conjugate direction (NW-SE), are well distinguishable in the area eroded by glaciers. The structural trend locally influences the hydrography and the water related features (see point iii and vii).

ii *Slope landforms and deposits.* Slope deposits, both coarse and fine, characterize the foot of the slopes (scree slopes and debris cones; Fig. 5d, e). Some of them are more or less partly vegetated, and hence relatively inactive, especially at lower altitudes. Debris flow channels, mainly affecting slope deposits, and related cones, characterize the foot of the glacial step and a lateral tributary valley in the N sector (Fig. 5b).

iii *Water-related landforms and deposits*. Surface drainage is significantly controlled by structures. Fluvial gorges are locally present along the Loana stream (Fig. 5f) with a particular concentration in correspondence of the glacial step, where waterfalls intermittently activate. Locally, water runoff affects slope deposits.

iv *Glacial landforms*. A wide part of the mapped area is characterized by relict erosion features related to the action of the Pleistocene glaciers. The glacial cirque edge runs along the ridge between Mount Laurasca and Mount Cortechiuso (Fig 5a, e), at the southern border of the area. In correspondence of the Scaredi mountain hut, the glacio-structural transfluence saddle between Loana and Portaiola Valleys is located (Fig. 5a). Glacial exharated surfaces on phyllonites, amphibolites and carbonate rocks occupy the central-southern part of the mapped area as far as the glacial step, that is characterized by an elevation of 300 m. The exharated area shows *glacial striae*, especially on phyllonites, and it is also featured by *rôche moutonnée* or sheep-back (Fig. 5a). Over-deepenings are present in the Laurasca-Cortechiuso glacial cirque bottom (Marble Lake and Cortevecchio alpine pasture, Fig. 5d), whose location maybe influenced by structural conditions. They are sometimes occupied by lakes (i.e. Marble Lake, Fig, 4c), locally evolving into small peat bogs.

v *Periglacial and snow-related landforms.* Snow avalanche corridors and related deposits are widespread mainly along the perimeter slopes where steepness increases, and along the glacial steps (Fig. 5b). Moreover, block fields are locally present.

vi *Weathering landforms*. The outcropping carbonate rocks are affected by dissolution as testified by typical karst related landforms (karren, holes and widened joints and scours). These features are especially evident in the area of the Marble Lake, where the bedrock is not pervasively fractured as at the CCR (Fig. 4c).

vii *Polygenic landforms*: as common especially in alpine areas, landforms and deposits deriving from the interplay between different morphogenetic agents are present: snow-avalanche corridors are also sites for debris discharge or V-shaped valleys (Fig, 5b) and fluvial gorges are more incised than usual being located along tectonic features (Fig. 5f).

At these altitudes the human influence can be considered irrelevant except for the grazing activity in the surrounding of the Alpine pastures (Cortenuovo and Cortevecchio), that could locally increase erosion.

The simplified representation of the morphological and morphogenetic characters of the geomorphosite for a non-specialist public (i.e., *Geomorphological Box*) is reported at the 1: 3,000 scale (Supplementary File B, b), reporting only a selection of features for a general audience.

4.2.2 Morphometric analysis on geomorphological map at CCR site

The CCR is comprised between 1,680 m a.s.l. (top of the glacial step) and 1,750 m a.s.l.. The elongated ridge, following the regional structural trend (SW-NE), presents a relatively rounded morphology, due to the modelling by the Loana glacier during the Late Pleistocene, and two lateral scarps, at whose feet small temporary streams flow. In the lateral depressions, small ponds and peat bogs are present. The analysed portion of the ridge is transversally dissected in 3 main sectors (A, B, C; Fig. 6), separated by SE-NW oriented saddles, probably located in correspondence of a system of conjugated fractures. The southernmost saddle (between B and C reliefs) is particularly incised and it exposes very clearly the intercalation between phyllonites and carbonate (Fig. 4a). The analysed portion of the ridge is 260 m long and the width of the ridge varies between 40 and 50 m. The positive elevation difference between the top of the ridge and the foot of the lateral scarps, the V-shaped valley bottom, reaches a maximum value of about 15 m on the NW edge. Lower elevation differences down to 0 m, or also negative (inverse relief), are found in correspondence of the saddles, located 70 m and 213 m from the SE border (Fig. 6). The elevation of the ridge with respect to the surroundings could be interpreted as a consequence of the differential erosion acting now and in the past on the two lithotypes, but a differential uplift along the regional structures related to the CL and bordering the ridge could not be excluded and might deserve future investigations.

4.2 Dendrogeomorphological analyses

The analysed chronologies of the trees colonizing the CCR cover the time interval comprised between 1971 and 2014. Despite the apparently not favourable location, suggested by the shape of trunks and crowns that confer to the trees a suffering appearance, relative old ages were found. The age trend is decreasing toward higher altitudes (sector C, Fig. 6), where the average age is 20-25 years, whereas at lower altitudes (sector A, Fig. 6), in correspondence of the glacial step edge (Fig. 1d) (i.e. G7 in BOLLATI *et alii*, 2017b), the average age increases till 40-50 years with a peak of 100 years.

Concerning the NAI analysis, in figure 7 the calculated values are reported for the common period 1971-2014. The CCR trees show particularly negative values in certain time intervals (1975 - 1985, 1991 - 2004 e 2006 - 2014); in particular, in the 1980's a decrease greater than 70% interested 90% of the trees (i.e. 1980). Comparing such values with the reference site (REF in Fig. 7), some very negative values (e.g. 1976, 1980, 1984-1985, 1994-1995, 2012-2013) could be considered a consequence of a common effect (e.g. climate). On the contrary, during the time intervals 1981-1983, 1996-2003 and 2008-2013, the suffering of trees at CCR seems to remain constant and particularly strong.

Especially during the years 1991 - 2002 (Fig. 8), several trees belonging to cluster C (Fig. 6) are characterized by a very pervasive compression wood. Moreover, after 2009 the trees on the C relief are continuously characterized by CW, especially during the years 2009, 2010 and 2014 (75%-90% trees interested by the CW).

The calculated denudation rates for each sample and tree (LDRs) and for the whole site (ADRs), reported in Table 3 and figure 6, testify a quite regular denudation intensity all around the site. Both the minimum (0.12 cm/y) and the maximum (1.93 cm/y) values were found at the top of the southernmost relief (area C; Fig. 6), where an intense production of CW was observed also in the youngest trees. Moreover, sector C is characterized by high denudation rates also along the lateral scarps, where abundant CW was detected testifying instability conditions.

5. *Discussions and conclusions*

According to the literature overview on the geological and geomorphological features, and to the geosites inventories, the study area resulted to be relevant from a scientific point of view. More in detail, the Loana Valley has been considered by different Authors (REINHARD, 1966; KRUHL & VOLL, 1976; ALTENBERGER *et alii*, 1987; SCHMID *et alii*, 1987; STECK *et alii*, 2013) as an important section for the study of the CL action on rocks of the Austroalpine and South Alpine domains. In such areas, where the bedrock effects on morphogenesis are particularly evident, the application of a specific assessment procedure to geomorphosites, that balances the geological and the geomorphological representativeness, could be considered the most suitable approach (BOLLATI *et alii*, 2014; 2017b).

The head of the Loana Valley is part of the ISPRA National Inventory of Geosites, however, no precise indications about singular landforms are specified. In the list of the UNESCO Sesia-Val Grande Geopark, instead, no geosites are considered in the Loana hydrographic basin. The analysed CCR outcrop is interestingly reported by the Italian Alpine Club, as Natural Monument, in a map addressed to excursionists (Geo4Map, 2018), testifying the interest of mountain hikers towards these landforms. After BOLLATI *et alii* (2017b), CCR obtained the highest scores due to its: i) petrographic and structural importance (i.e. *representativeness of geological processes*; *geohistorical importance*); ii) outstanding landforms (i.e. *representativeness of (paleo)geomorphological processes*; *geodiversity*; *educational exemplarity*); iii) relevance at regional level (i.e. *rarity*); iv) colonization of calcareous flora and arboreal vegetation, relatively old and located in an unfavourable place (i.e. *ecological support role*). Moreover, carbonate rocks, similar to those used in the valley bottom to produce lime ("*Le Fornaci della calce*" geoarcheosite), may be considered georesources (i.e. *cultural value*).

The geomorphological map of the study area, at scale 1: 10,000 (Supplementary File B, a) shows the relation between structures and modelling. A particular detail (e.g. 1: 3,000) was dedicated to the survey of the active and relict geomorphic processes at the CCR. Hence, a selection of the most relevant landforms has been reported, in a simplified way, on the *Geomorphological Box* (Supplementary File B, b).

The CCR relief may be classified as an *evolving passive geomorphosite* (sensu PELFINI & BOLLATI, 2014), since it had been previously eroded by glaciers and now, after the glaciers retreat, it is undergoing water- (dissolution on carbonates), snow- (accumulation) and gravity-related (local debris falls) processes. The structural control operated by the regional structures related to the Canavese Line is particularly evident. CCR can be also defined as a *potential vulnerable geomorphosite* where processes rates have been determined, in the framework of this research, through specific indicators (GARCÌA-ORTIZ *et alii*, 2014; BOLLATI *et alii*, 2017a and reference therein). The dendrogeomorphological analysis on the groups of trees growing on the top of the CCR allowed to detect different trends in the examined indicators along the studied ridge. Age increases towards the more stable down-valley portion of the ridge (N, sector A in figure 4), while CW and LDRs increase toward the unstable up-valley portion (S, sector C in figure 6). The age trend could be related to the treeline upward shift in response to climate change, but at CCR this trend results to be particularly disturbed by relief energy, outcropping bedrock affected by fractures, dissolution and local debris fall, an interference that could be relevant in such environments (MASSEROLI *et alii*, 2016). With respect to the Reference chronology, the NAI values at the studied sites find good correspondence in certain years (i.e. 1976, 1980, 1984-1985, 1994-1995, 2012-2013), while in other ones the NAIs are present only in the CCR (i.e. 1981-1983, 1996-2003 and 2008-2013). The abundant CW observed in the C area during the years 2009, 2010 and 2014, could be related to particular intense snowfalls which occurred in the area in that periods (BOLLATI *et alii*, 2018a and reference therein).

It is possible to compare the ADRs (0.44 cm/y at site scale, with a peak of 1.93 cm/y in the C upper portion) with those obtained in other sites (e.g. Pyramides de Col de la Croix; Vaud Canton, Switzerland), characterized by a soluble bedrock (i.e. gypsum) and analysed through comparable investigation methods. At Col de la Croix, the surface undergoing erosion (i.e. dissolution) is characterized by a general less steep top surface, by several sinkholes that are sometimes coalescent, and, globally, by a sort of negative relief. The ADRs at Col de la Croix, adjusted with respect to BOLLATI *et alii* (2017a), considering the *YF* coefficient, is of 0.68 cm/y, with a greater variability all around the site. These results support the greater predisposition to solubility of gypsum, with respect to calcareous rocks (NICOD, 1976). Other values reported in literature for soluble lithotypes in similar morphoclimatic environments span between 0.01 cm/y (under vegetation coverage; ROVERA, 1990) and 0.07 cm/y to 0.15 cm/y in periglacial environment (CHARDON, 1992). In those cases, where human impact becomes significant, the denudation rates are reported to increase to 0.4 cm/y (CHARDON, 1992). In the study area, since in proximity of grazing areas, cows and goats passage could increase the erosion.

According to the calculated denudation values, at CCR the current natural processes (related to water, snow and gravity), different from the genetic ones (related to glaciers action), induce a possible pressure enhancing the *vulnerability* of the site according to the definition proposed by GARCÌA-ORTIZ *et alii* (2014). Also the potential sampling of rocks by tourists, attracted by the shining white colour, could mine the *integrity* of the site, possibly speeding up erosion. This *vulnerability* is, in fact, translated into a potential loss of integrity of the landforms as well as a change in scientific attributes if the previous features of the landforms would be totally cancelled (GARCÌA-ORTIZ *et alii*, 2014; PELFINI & BOLLATI, 2014; BOLLATI *et alii*, 2017a). In this specific case, since the calcareous outcrops in the area are restricted to local bands, the continuous denudation could lead to their gradual disappearance with the loss of important geological witnesses and of calcareous flora. If geomorphic conditions remain constant in the future, the results obtained in the present research by integrating data coming from different disciplines (geology, geomorphology and dendrogeomorphology), will allow a rough estimate of the times of evolution of the relief. If we consider the maximum dissolution value (1.93 cm/y) obtained through dendrogeomorphology and the maximum height (22 m), obtained through morphometric measurements on geomorphological map and DEM, we can hypothesize a relevant local lowering of the topographic surface along the CCR in about 1140 years. Instead, the human impact by quarrying for lime kilns is no more a threat to the site.

Considering the presented results, the inventories of geoheritage sites in the region should mandatorily include local analysis on the *risk of degradation* of sites (*sensu* GARCÌA-ORTIZ *et alii*, 2014; BOLLATI *et alii*, 2018a), integrating data coming from different disciplines (i.e. multidisciplinary approach), chosen accordingly to the site feature. This makes it possible to assess how changeable the substrate and the relief are according to specific processes. This is particular needed for sites of high scientific value and restricted spatial extension, like the CCR investigated in the present research. In the framework of the *Usable Science* (*sensu* GIORDAN *et alii*, 2015), moreover, proposing simplified version of the geomorphological map (i.e. *Geomorphological Boxes*; *sensu* BOLLATI *et alii*, 2017b), that could be furtherly accompanied by numerical data on evolution rates and risk of site degradation (FUERTES-GUTIÉRREZ I. & FERNÀNDEZ-MARTÌNEZ, E., 2012), could allow: i) local administrations to pay attention to the importance of abiotic natural resources and to spatially delimit the geoheritage site for future spatial planning strategies (SÀNTOS-GONZALEZ & MARCOS-REGUERO, 2018) and ii) the public to become aware of the mutability of the physical landscape for a better fruition of mountain environment.

As it often happens, geosites that, although very close to Natural Protected Areas (here, the VGNP), are not included in them and they cannot benefit from the same protection rules. In this particular case the area is part of the Sesia Val Grande Geopark and if the extension of the protected area of the Val Grande National Park is not plausible, even if desirable (SÀNTOS-GONZALEZ & MARCOS-REGUERO, 2018), at least a legal recognition of the site as geosite and component of the geoheritage, with a specific regulation for its protection, could prove to be strategic.

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Figure captions

Fig. 1. Overview on the study area. a) Geographic position of the Loana hydrographic basin, the Sesia Val Grande Geopark (SVGP), and the Val Grande National Park (VGNP) (modified from BOLLATI *et alii*, 2017b); b) Simplified tectonic sketch of the Alps with the location of the study area (black star), modified from BOLLATI *et alii*, 2014 and reference therein; the black line represents the Insubric-Canavese Line. c) Extrapolation from the geolithological map by REGIONE PIEMONTE (1981) (modified from BOLLATI *et alii*, 2017b) with the position of Cortenuovo Calcareous Ridge (CCR) (white star); c) Main geological features of the head of the Loana Valley from the right hydrographic water divide with positions and codes of the geomorphosites analysed by BOLLATI *et alii* (2017b). The excursionist trail is reported with a black dotted line; d) Cortenuovo Calcareous Ridge (CCR) from the trail directed to the head of the valley. Arboreal vegetation growing on the top of the relief is evident.

Fig. 2. Sketch of the relations existing between the different branches of geoheritage researches. In the centre of the figure, the proposed outputs (geomorphological box and data on evolution rates on geomorphosites) in relation with the literature context. The dimension of the check marks is proportional to the abundance of literature regarding a topic.

Fig. 3. Quantitative results of the comparison between the CCR (Cortenuovo Calcareous Ridge) and the Pozzo Vecchio Loana Waterfall geomorphosites after BOLLATI *et alii* (2017b). SV = Scientific

Value; AV = Additional Values; GV = Global Value; SIn = Scientific Index; PU= Potential for Use; EIn = Educational Index (see Supplementary_File_A for more details).

Fig. 4. Different carbonate lithotypes cropping out in the area. a) Slightly metamorphosed carbonate of the CCR (Cortenuovo Calcareous Ridge) and the contact with the Canavese phyllonites; b) calcschists outcrop and collected sample along the eastern water divide; c) karst features at the Marble Lake: karren, holes, widened joints and scours.

Fig. 5. Examples of representative landforms of the study area. a) the glacial saddle with the Scaredi Hut, in correspondence of the Canavese Belt with, on the left, a particular of the phyllonites outcropping with an attitude towards NNW; b) Snow-avalanches on the glacial step and along a structural-controlled V-shaped valley during 2019/2020 winter season (on the left); debris-flows and snow-avalanche channel along the same V-shaped valley, in summer mode (on the right); c) geomorphological map with indicated the locations of the pictures; d) the glacial overdeepening nearby the Cortevecchio Hut; e) Scree slope deposits along the Laurasca-Cortechiuso ridge; f) Fluvial gorge incising the glacial plateaux and controlled by the regional trend of fractures. All pictures are of the Authors.

Fig. 6. Denudation rates (upper) and elevation data (lower). Upper: Local Denudation Rates (LDRs) and Average Denudation Rates (ADRs) at CCR site plotted on a picture of the site taken from the excursionist trail (visible in the right corner) leading to the border of the VGNP. Lower: topographic profiles along the ridge (CCR) and the NW and SE edges with the absolute difference in elevation between the CCR and the lateral edges. The topographic profiles were created using the Digital Elevation Model (DEM; 5 m resolution) of the Geoportale of the Piemonte Region (http://www.geoportale.piemonte.it/geocatalogorp/?sezione=catalogo).

Fig. 7. Negative Anomaly index (NAI) at Cortenuovo Calcareous Ridge (CCR) and Reference (REF) sites. In the table below the graph, the presence of significant NAI is reported as "X" and the correspondence between sites is highlighted in grey.

Fig. 8. Percentage of trees affected by Compression Wood (CW) (grey histogram) in comparison with the number of trees for each year (black line). Thresholds of 40% and 70% of trees are reported as black dotted lines.

Tables

Table 1. Conceptual framework of degradation risk and geomorphosites definitions according to the literature.

GARCÌA-ORTIZ *et alii*, 2014	*Interested target*	REYNARD (2004) PELFINI & BOLLATI (2014) BOLLATI *et alii* (2017a)
Sensitivity: susceptibility or predisposition of a geosite to damage or destruction or the likelihood that its characteristics will be damaged or destroyed		
Fragility: sensitivity of a geosite to be damaged or destroyed by intrinsic factors (lithology, genetic processes)	→	*Active geomorphosite*: a geomorphosite that allows the visualization of its genetic geomorphological processes in action, that could affect it
Vulnerability: sensitivity of a geosite to be damaged or destroyed by extrinsic factors (natural: processes other than the genetic ones; human derived: economic, touristic or scientific exploitation of the site)	→	*Evolving passive geomorphosite:* a geomorphosite that allows the visualization of geomorphological processes different from the genetic ones in action and that could affect it

Table 2. Main features of the CCR geomorphosite after BOLLATI *et alii* (2017b). Supplementary File A contain all the parameters and formula applied.

Scientific Value	
Representativeness of (paleo)geomorphological processes	Glacial modelling controlled by structural patterns
Representativeness of geological processes	Rocks deformation related to the CL action
Educational Exemplarity	Outstanding reliefs with easily identifiable rocks
Site Extrinsic Geodiversity	Different response of carbonates and phyllonites to glacial modelling
Geohistorical importance	Presence of the CL and related deformation zone
Ecologic Support Role	Presence of a particular concentration of arboreal vegetation
Integrity	By now, the reliefs are quite integer and recognizable
Rarity	Rare at regional level
Additional Value	
Scenic value	Really outstanding relief both for shape and colour
Cultural value	The calcareous rocks were locally used to produce lime
Socio - economic value	It is inserted in a touristic circuit
Potential for Use	
Temporal accessibility	From late Spring to late Autumn
Spatial accessibility	Through an excursionist path
Visibility	Well outstanding
Services	Not far from 5 km
Number of tourists	Medium (since along the main entrance to VGNP)
Sport activities	Hiking
Legal constraints	None
Use of the Geomorphological Interest	None (in preparation)
Use of the Additional Interests	None
Presence of Geomorphosites in the surrounding	Yes, see Bollati *et alii* (2017b)

Table 3 - Local Denudation Rates (LDRs) and Average Denudation Rates (ADRs)

TREE	**CORE/DISK**		**Core or disk LDRs (cm/y)**	**Tree LDRs (cm/y)**	**Site ADR (cm/y)**
166	1	2002	0.71	*1.14*	***0.44***
	2	2010	1.93		
	3	1998	0.78		
168	1	2000	0.55	*0.25*	
	2 - A1	1986	0.12		
	2 - A2	1986	0.12		
	2 - B1	2002	0.28		
	2 - B2	1990	0.14		
	3	2000	0.41		
177	1	1995	0.20	*0.22*	
	2 - A	1977	0.21		
	2 - B	1975	0.25		
179	1 - A	1920	0.21	*0.22*	
	1 - B	1926	0.23		

	SCIENTIFIC VALUE (SV)	
RGmP	0	Poor/None representativeness of a morphogenetic system
Representativeness of (paleo)Geomorphological Process	0,33	Discrete representativeness of a morphogenetic system
	0,67	Good representativeness of a morphogenetic system
	1	Exemplar representativeness of a morphogenetic system
RGP	0	Poor/None representativeness of a geological process
Representativeness of Geological process	0,33	Discrete representativeness of a geological process
	0,67	Good representativeness of a geological process
	1	Exemplar representativeness of a geological process
EE	0	Representativeness without any educational value
Educational Exemplarity	0,33	Representativeness with poor educational value
	0,67	Representativeness difficult for non experts
	1	Representativeness with excellent educational value
Gd	0	1 lithology, 1 main landform
Site Intrinsic Geodiversity	0,5	1 lithology, n-landforms
	1	n- lithologies, n-landforms
GI	0	Without production or scientific divulgation
Geo-historical importance	0,33	Low frequent topic for scientific research
	0,67	Relevant topic for scientific research
	1	Fundamental for the development of Earth Sciences in general
ESR	0	Without any connection with the biologic element
Ecologic support role	0,33	Presence of interesting flora and fauna
	0,67	The geo(morpho)logical features condition the ecosystems
	1	The geo(morpho)logical features determine the ecosystems
In	0	Essential geo(morphological elements are not preserved
Integrity	0,5	Essential geo(morpho)logical elements are just preserved
	1	Essential geo(morpho)logical elements are intact
Ra	0	Frequent also at level of the study area
Rareness	0,5	Rare at level of the study area, abundant at national level
	1	Rare at national level
	ADDITIONAL VALUES (AV)	
Cu	0	Any cultural feature in the surroundings
Cultural value s.s.	0,5	Presence of cultural features not correlated with geo(morpho)logical features
	1	Presence of cultural features correlated with geo(morpho)logical features
Ae	0	Not relevant
Aesthetic value	0,5	Strong contrasts in landforms, lithologies and colours, spatial limited
	1	Strong contrasts in landforms, lithologies and colours
SEc	0	Element without exploitation or insertion in an economic area (Not touristic)
Socio-Economic value	0,33	Element with exploitation or insertion in an economic area (Not touristic)
	0,67	Element inserted in an economic-touristic area
	1	Element inserted in an economic-touristic circuit

POTENTIAL FOR USE (PU)

TA	0,25	Only in summer
Temporal Accessibility	0,5	Except in winter
	0,75	Except in rainy days
	1	All over the year
SAc	0,2	On foot, Expert Excursionists*
Spatial Accessibility	0,4	On foot, Touristic/Excursionist*
	0,6	On foot for numerous group, because difficult access for bus
	0,8	Allowed to means of transportation
	1	Allowed to means of transportation, access also to disables
Vi	0	Not observable or great difficulties in observing it
Visibility	0,2	Just visible or with special tools (artificial lights, ropes..)
	0,4	Reasonable visibility but limited by vegetation
	0,6	Good visibility but with need of moving to improve it
	0,8	Good visibility for all geo(morpho)logical elements
	1	Excellent visibility for all geo(morpho)logical elements
Se	0	Hotels and services far from 25 Km
Services	0,67	Hotels and services far from 5 - 10 Km
	1	Hotels and services far from 5 Km
NT	0	Few
Number of Tourists	0,5	Medium
	1	Abundant
SA	0	None
Sport Activities	0,5	Yes, not correlated with geo(morpho)logical features
	1	Yes, correlated with geo(morpho)logical features
LC	0	Total protection, prevented use
Legal Constraints	0,33	Protection, limited use
	0,67	Under protection but with few or any prevention for use
	1	No protection or limitation in use
UGI	0	No divulgation or use
Use of Geo(morpho)logical Interest	0,5	Use in academic ambit
	1	With divulgation and use as geo(morpho)site
UAI	0	Any divulgation or use
Use of the Additional Interests	0,5	Use of additional interests
	1	Naturalistic or cultural paths already started
SGs	0	Any sites in the study area
Geo(morpho)sites in the Surroundings	0,5	Sites in the neighbourhood but not genetically correlated
	1	Sites in the neighbourhood and genetically correlated

Ti	0	Any traces	**GM**	0	Ice
Tipology	0,2	Traces	Ground Material	0,2	Snow
	0,4	Path		0,4	Coarse debris coverage
	0,6	Mule tracks		0,6	Medium debris coverage
	0,8	Dirt road		0,8	Fine or soil debris coverage
	1	Paved road		1	Bed rock or dirt/paved road
Sl	0	Yes	**SM**	0	Fractured rock, soils, snow and ice
Sloping	1	No	Slope Material	1	Rocks and coherent deposits
SI	0	> 61°	**St**	0	High
Slope Inclination	0,25	51°-60°	Steepness	0,5	Medium
	0,5	41°-50°		1	Low-null
	0,75	31°-40°			
	1	<30°			
TI	0	No	**WSP**	0	Yes
Tourist Information	1	Yes	Water/Snow on path	1	No
Wi	0	<30 cm	**DC**	0	Very bad
Width	0,25	30-50 cm	Degree Of Path Conservation	0,33	Fairly good
	0,5	50-100 cm		0,67	Good
	0,75	100 cm		1	Excellent
	1	>100 cm			

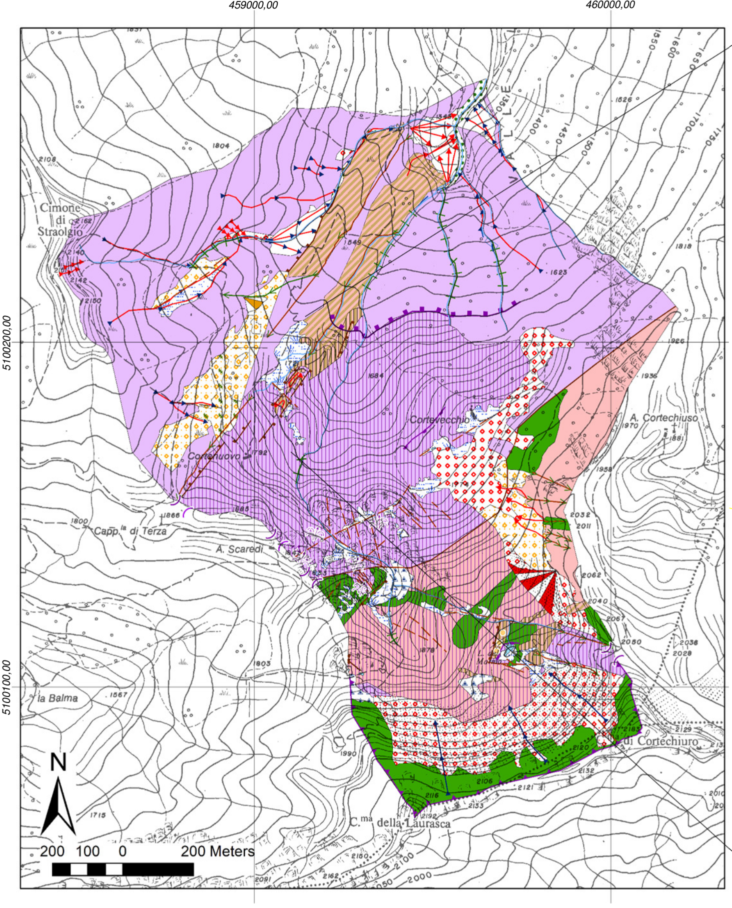
HI	0	Present and increasing vulnerability
Human Interventions	0,33	Absent
	0,67	Present not influencing
	1	Present and reducing vulnerability

EQUATIONS		
SV *-SCIENTIFIC VALUE*	*SV = (GM+PgM+EE+Gd+GI+EI+OI+In+Ra)*	*0-8*
AV *-ADDITIONAL VALUES*	*AV = (Cu+Ae+SEc)*	*0-3*
GV *-GLOBAL VALUE*	*GV = (SV+AV)*	*0-11*
IU *-Index of Use*	*IU = EE+ Ae*	*0-2*
Potential for Use s.s.	*PUss = (TA+Vi+Se+NT+SA+LC+UGI+UAI+SGs)*	*0,25-9*
PPU *-Partial potential for Use*	*PPU = (PUss+IU)*	*0,25-11*
CA *-Calculated Accessibility**	*CA = (Ti+St+Sl+Wi+GM+WSP+SI+SM+DC+HI+TI)*	*0-11*
AFc *-Accessibility Factor (on foot)*		*0-0,5*
AFs *-Accessibility Factor (other)*	*if SAc≤0.4; AFc = (CA/11)*0,5*	*0,6-1*
	if SAc≥0.6; AFs = SAc	
PU *-POTENTIAL FOR USE (on foot)*	*PUc = PPU +AFc*	*0,25-12*
PU- *POTENTIAL FOR USE (other)*	*PUs = PPU+AFs*	
SIn *-Scientific Index*	*SIn= (GM+PgM+GI)/3*	*0-1*
EIn *-Educational Index*	*EIn= [EE+Ae+(A_Fc/s)]/3*	*0-1*
TS *-TOTAL SCORE*	*TS = GV+PUc/s*	*0,25-23*

a - GEOMORPHOLOGICAL MAP OF THE LOANA GLACIAL PLATEAUX

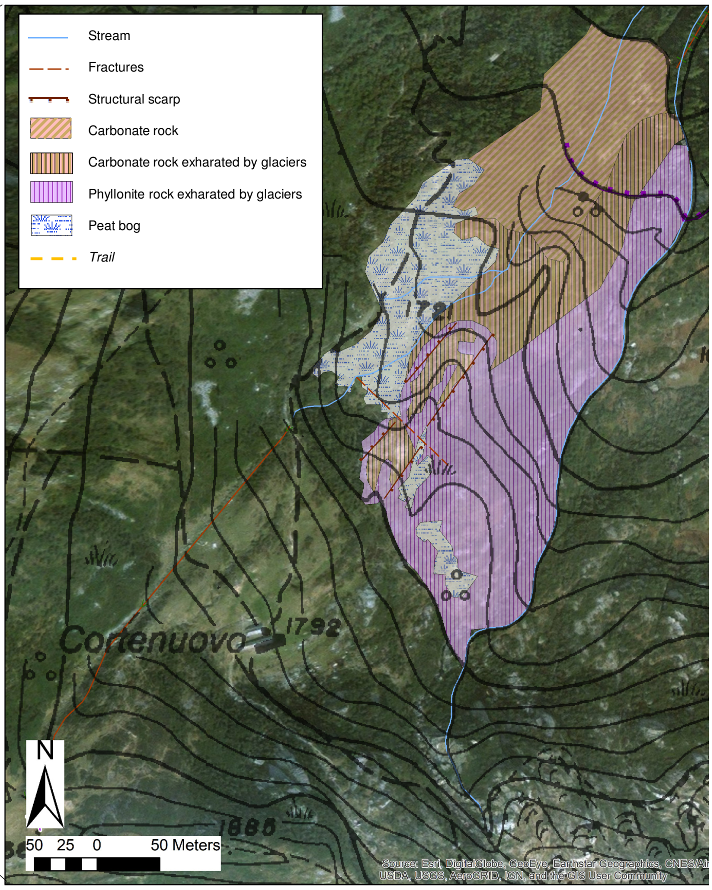
Spatial scale 1:10000

Coordinate system
Projection: UTM, Fuse 32N; Datum: WGS 84
Grid: Planimetric Coordinate System



b - GEOMORPHOLOGICAL BOX OF THE CORTENUOVO CALCAREOUS RIDGE

Spatial scale 1:3000



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Ai
USDA, USGS, AeroGRID, IGN, and the GIS User Community

GEOMORPHOLOGICAL MAP LEGEND

Lithologies

- Paragneiss
- Amphibolite
- Phyllonite
- Carbonate rock (including marble)

Structures

- Main fractures
- Canavese Line (CL)

Structural landforms

- Structural scarp

Water related landforms influenced by structures

active

- Fluvial gorge
- V-shaped valley

Slope landforms and deposits

active *inactive*

- Debris fan
- Coarse slope deposit
- Scree slope deposit
- Debris discharge channel
- Debris flow channel
- Degradation scarp

Water related landforms and deposits

active

- Alluvial deposit
- Water runoffed deposits
- Fluvial gorge
- V-shaped valley

Glacial landforms and deposits

inactive

- Exharated surface
- Glacial cirque edge
- Overdeepening edge
- Glacial step
- Rôche moutonnée
- Saddle

Periglacial and snow-related landforms

active

- Block field
- Snow avalanche corridor

Polygenic landforms

active

- Debris flow and snow avalanche channel

Weathering landforms

- Karst features (karren, grooves, holes)

Hydrography

- Lake
- Stream
- Peat bog
- Waterfall