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ORIGINAL ARTICLE

The Chiavenna and Piuro Geosites: Man and Territory, for Better or for Worse

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Abstract
Since prehistoric times, alpine valleys have witnessed the development of populations that progressively mastered the exploitation of natural resources and environmental features, while also dealing with several natural hazards typical of this mountain setting. Several traces of this strong interconnection come from the area around Chiavenna and Piuro (Valchiavenna and Val Bregaglia, Central Alps, Sondrio Province, Italy), where different sites witness how the historical and cultural evolution of a society can be controlled, first and foremost, by the geological predisposition of the territory. The centuries-old extraction and manufacturing of soapstone testify to the long-term exploitation of local natural resources, while the so-called *crotti* natural cavities have represented, up to the present day, optimal food-storage spaces. Conversely, the alpine environment has often threatened the prosperity of local communities, due to the occurrence of gravitative processes affecting the steep mountain slopes of the area. The catastrophic 1618 Piuro landslide serves as a powerful reminder of these hazards. The gradual unearthing of the remnants of the *Ancient Piuro* provides tangible evidence of a lost settlement - once a flourishing economic center - preserved today through numerous archaeological and cultural sites. The region's distinct yet interconnected geosites represent a significant asset for territorial promotion and the dissemination of environmental and cultural values. To enhance this potential, this work identifies and describes the primary local geosites and proposes their multidimensional classification and quantitative assessment to objectively define their scientific, educational, and tourism value. Finally, the paper presents a new geo-itinerary, conceived as a common thread connecting these sites and serving as an educational platform to enhance the perception of natural resource value and to raise awareness regarding vulnerability to natural hazards in the alpine environment.

Keywords Geoheritage · Geo-itinerary · Hazard awareness · Val Bregaglia · Valchiavenna

Introduction

The deep-rooted relationship between the alpine environment and its inhabitants - characterized by adaptation, exploitation, and respect - is particularly evident in Valchiavenna and Val Bregaglia (Central Alps, Italy). These valleys exhibit a harsh environment, shaped by tectonic, glacial, and gravitative activity, and rapidly transition from low-altitude valley floors (250–300 m a.s.l.) to mountain peaks exceeding 3000 m a.s.l. The steep valley slopes are constantly affected by landslides and other gravity-driven processes, alternating with morphological terraces and generally flatter valley floors. The harshness of the climate - with long, cold winters, abundant snowfall, and the danger of avalanches along the slopes - made daily life a continuous challenge, often isolating communities for months. Floods triggered by torrential rains and laden with debris could sweep away entire villages and compromise vital communication routes. In addition, landslides and erosion processes typical of the steep alpine slopes represented a constant threat to the safety of local populations and settlements. Within the study area, the most emblematic and tragic example is the Piuro landslide of September 4th, 1618. This catastrophic event struck the homonymous village - then a flourishing commercial

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center renowned throughout Europe - destroying it under approximately 6–9 Mm^3 of soil and rock material that detached from the northern slope of Monte Conto (Pigazzi et al. 2022). The tragedy caused at least 1,000 casualties among the inhabitants and almost completely obliterated the village (Scaramellini et al. 1988). The archaeological remains of the Ancient Piuro, gradually brought to light by recent excavation campaigns, stand today as a stark reminder of the potential destructive power of this alpine environment. This dynamic and often inhospitable configuration has deeply shaped the human settlement, economy, and culture of the communities, forcing them to make the most of what the land had to offer and to seek means of subsistence along the mountain slopes or in higher-altitude areas. The high mountain landscapes have witnessed human presence and the exploitation of natural resources since the Mesolithic period (e.g., Fedele 2015; Fedele & Wick, 1990). Later, the same pastures provided nourishment for livestock, contributing to the development of breeding practices that became the backbone of local economies. The sun-exposed mountain slopes allowed the cultivation of agricultural products, chestnut trees and in some cases of vineyards, but only after generations of labor devoted to the construction of numerous dry-stone wall terraces. The *crotti*, natural cavities formed among massive landslide blocks, were used as cellars for the storage and preservation of food, highlighting the ability of local communities to take advantage of their territory and its peculiar characteristics. Furthermore, these valleys have long been exploited for their stone resources, foremost among them soapstone, which has been extracted, worked, and traded since the Roman period.

Today, this equilibrium between opportunity and natural hazard is still exemplified by sites of great cultural and geological significance (Fig. 1). In recent years, the international scientific community has increasingly recognized the importance of identifying and preserving such environments that belong to the geoheritage sphere. According to Brilha (2016), *geoheritage* (or *geological heritage*) comprises those elements of geodiversity – whether found in their original location or in collections – that possess high scientific value and may also hold educational, aesthetic, or cultural significance. Within this framework, a geosite is defined as an in-situ occurrence of such geodiversity elements, acknowledged for their scientific value (Brilha et al., 2018). Geosites represent suitable places for illustrating key geological features and processes that led to their formation, providing a contribution to geological knowledge. According to Panizza and Piacente (2003), these sites may also present additional values, including cultural, socio-economic, aesthetic, and ecological ones.

The Alps, shaped by complex geological processes and characterized by a remarkable variety of geological and geomorphological features (Bollati et al. 2017), represent then a strong geodiversity, that accounts for the high density of potential sites of interest within the realm of geoheritage. In mountain areas with a long history of settlement and frequentation, these sites frequently represent the foundation of local identity, where the geological substrate has directly dictated human settlement and resource exploitation. As emphasized by Pijet-Migoń and Migoń (2022), geoheritage and cultural heritage are deeply interlinked through spatial and causal relationships, where the abiotic environment acts as the primary stage for cultural development. This is particularly evident in the Valchiavenna and Val Bregaglia areas, where geological features have directly shaped social practices, from resource extraction to architectural adaptations. In this context, the application of geoheritage valorization, management, and conservation concepts is essential. These practices are crucial for sustainable tourism, especially given the extreme sensitivity of mountain environments to both natural environmental changes and anthropogenic impacts (Bollati et al. 2017; Giardino and Mortara 1999; Beniston 2003).

Geotourism is a specialized form of natural area tourism centered on geology and landscape, aiming to foster the understanding of Earth sciences through appreciation and learning (Newsome and Dowling 2010). Within this framework, geotrails and thematic nature trails (e.g., Burlando et al. 2011; Wrede et al., 2012; Martin 2010; Bollati et al. 2013) have emerged as primary tools for the promotion of geoheritage, facilitating the communication of complex scientific data to a broader audience (Dowling 2010). These paths are designed for a general audience and do not merely link geological features, and they act as the practical infrastructure through which geotourism is realized. By integrating geotrails, viewpoints, and guided activities, these itineraries promote the conservation of geodiversity while transforming scientific knowledge into an accessible experience for tourists (e.g., Perotti et al. 2020; Stolz and Megerle 2022; Alberico et al. 2023; Kang et al., 2023), facilitating field-based teaching and outreach activities and raising awareness regarding potential threats caused by both human and natural factors (e.g., Bollati et al. 2011, 2016; Garavaglia and Pelfini 2011; Pelfini et al. 2016). Rather than mere tourist paths, these itineraries serve as educational platforms where scientific value is integrated with cultural and historical narratives.

Over recent decades, the growing tourist economy in the Valchiavenna and Val Bregaglia area has driven the development of thematic trails aimed at promoting geo-cultural heritage. By following ancient communication routes and historic transit paths (such as the *Via Spluga* and *Via Bregaglia*, popular long-distance hiking trail that retrace the historic transit routes between Switzerland and Italy), local authorities have established a network that connects high

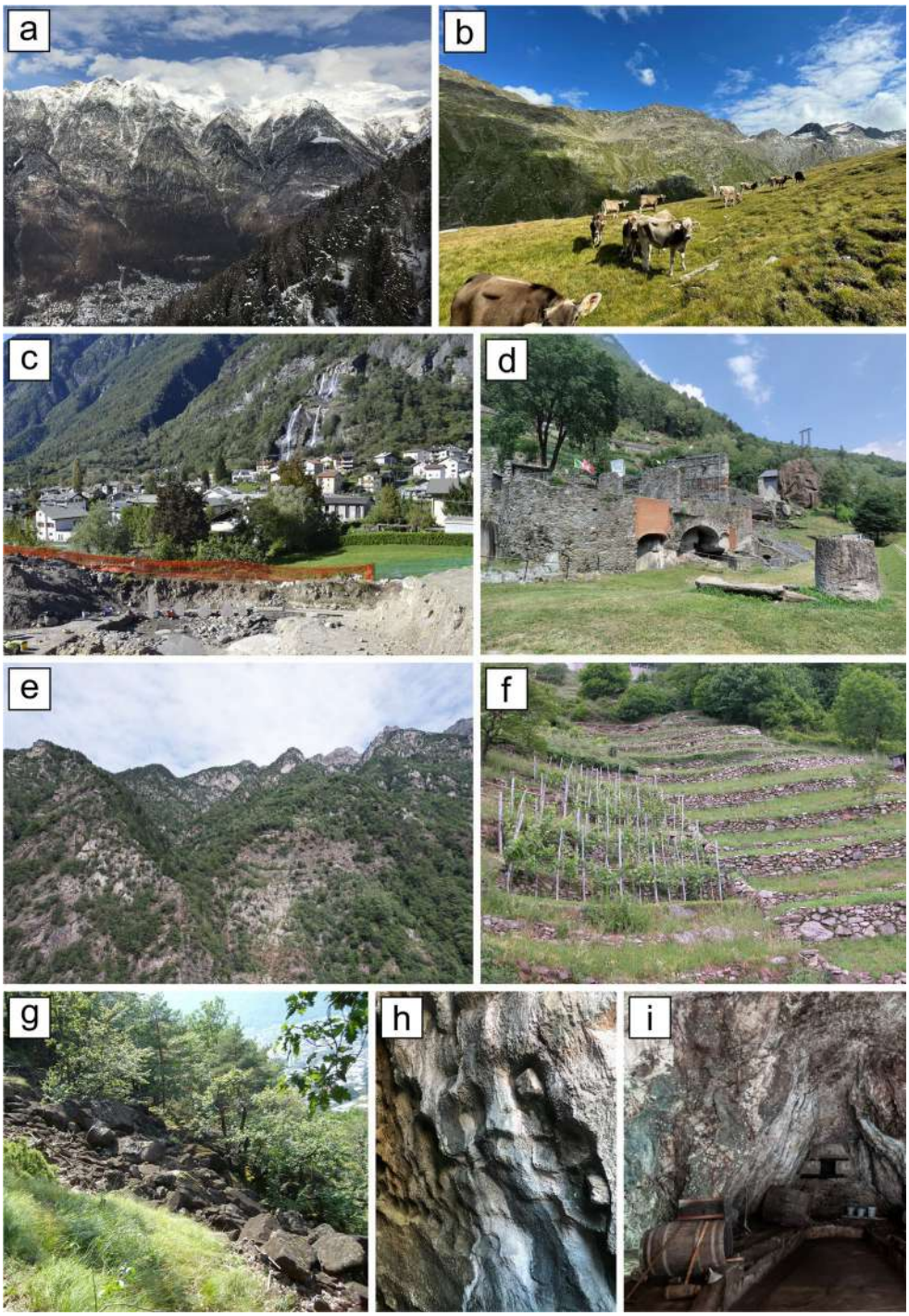

Fig. 1 Pictures illustrating the positive and negative influence of specific natural features of the alpine environment on the communities of Valchiavenna and Val Bregaglia. **a** Snow-covered, rugged slopes along the northern flank of Val Bregaglia. **b** High-mountain pasture in Val di Lei (municipality of Piuro). **c** The Piuro archaeological excavation site, where the remains of the village buried by the 1618 landslide are gradually being unearthed. **d** The Belfòrt Palace, which partially survived the Piuro landslide, represents an example of the touristic and educational enhancement of the Piuro landslide sites. **e** Steep slopes surrounding Chiavenna, typical of the alpine environment of the Central Alps. **f** Terraced hillsides near Chiavenna now dedicated to vineyard cultivation. **g** Meter- to decameter-sized landslide blocks at the base of the southern flank of Val Bregaglia. **h** Soapstone quarry traces along the southern flank of Val Bregaglia. **i** Interior view of a typical *crotto* in Valchiavenna (image courtesy of Consorzio per la Promozione Turistica della Valchiavenna)

value geoheritage clusters. The Comunità Montana della Valchiavenna, in collaboration with local municipalities and research institutions, has led efforts to preserve and valorize the region's geo-cultural heritage. Key initiatives include the management of museums and open-air sites, alongside the development of geotourism trails and the production of outreach and scientific publications (e.g., Rossi et al. 2012; Sciesa & Bedogné, 2003).

Local municipalities and associations have also contributed by promoting the natural and touristic value of sites with high geological and cultural value, through in-situ interpretive panels and the development or upkeep of hiking trails. Several of these initiatives have been implemented with the support of the Earth Science Department "A. Desio" of the University of Milan and its branch office, the "Stazione Valchiavenna per lo Studio dell'Ambiente

Alpino". The University's work has addressed both geological and geomorphological issues as well as cultural, social, and geographical aspects (e.g., ALPTER Project, 2004–2008[1]; Strategia Nazionale Aree Interne – Valchiavenna, 2017–2022[2]; more details at: https://valchiavenna.unimi.it, accessed on 3 February 2026).

Among recent ones, the A.M.AL.PI.18 Project[3] has had a significant impact on the study and promotion of local geosites, as well as on education and outreach. The project aimed to implement innovative strategies for promoting natural and cultural heritage across the alpine region between the Swiss Engadine Valley and the St. Gotthard area. It connected sites that have experienced notable geomorphological and anthropogenic transformations, including large landslides with significant social impact (Arrigoni et al. 2023). The project significantly contributed to the knowledge of the Central Alps' major landslides, with a particular focus on the 1618 Piuro landslide. Among its main outputs is the AMALPI Trek, a geo-cultural hiking trail connecting Italy and Switzerland crossing Val Bregaglia and Valchiavenna, from Maloja to Gotthard. The trail connects large alpine landslides, tells their geological and geomorphological history and social implications, and links them to other local geo-cultural themes, thanks to a dedicated hiking guide (Apuani and Scapozza 2023). Central to this initiative is the AMALPI Center (International Center for Large Alpine Landslides) in Chiavenna, a hub dedicated to research, education and public engagement through school activities and promotion events.

Today, the legacy of the A.M.AL.PI.18 Project continues through the A.M.ALPI. MO.RE. (MOnitoring and REsilience) Project,[4] which has a more pronounced technical-scientific focus aimed at monitoring landslide processes at high altitude and their interconnections, while promoting awareness of climate change causes and consequences through joint outreach and training activities.

The active involvement of numerous institutions in the valorization of local geo-cultural heritage reflects both the geological wealth of the region and the necessity of its conservation, often preceding their promotion. Some of the sites discussed in this work – as well as several others nearby – are formally recognized and catalogued within the National and Lombardy Region Geosites Inventory (Regione Lombardia & Irealp, 2008), providing them with a specific legislative recognition and a formal framework for their protection.

In light of the above, this study aims to integrate geological, historical, and cultural data to provide a practical model for alpine geoheritage promotion. Specifically, the paper intends to: (1) identify and characterize a selection of primary geological and geomorphological features within the Chiavenna and Piuro area, enhancing their geoheritage value through a systematic classification based on their representativeness and potential for scientific outreach, and highlighting the synergy between geological and cultural features; (2) quantitatively assess the selected geosites, to objectively define their scientific, educational, and tourism value; (3) present and promote a one-day, easily accessible and multidisciplinary geo-itinerary. This trail is designed to function as an educational platform in which the geological features of the landscape are translated into a coherent narrative for a non-specialist audience; (4) provide a model for the valorization of alpine geo-cultural landscapes, with a particular focus on increasing awareness regarding the interaction between natural processes and human-induced transformations.

Geological and Cultural Framework

Geographic and Geological Setting

Valchiavenna is an alpine valley located in the Central Alps, separating the Lepontine and Rhaetian Alps. It runs along the Italian-Swiss border and covers approximately 578 km² (Fig. 2a, b). The valley is formed by the convergence of two narrow tributaries: the Val San Giacomo (flowing from the NNW) and the Val Bregaglia (extending from the Swiss Engadine region to the NE; Fig. 2c). Their respective main streams, the Mera and Liro rivers, join near Chiavenna, giving rise to the main, wider, N–S-oriented southern portion of the valley, known as the lower Valchiavenna.

This region of the Central Alps is characterized by a complex geology, where tectonic units of various provenances are juxtaposed, conferring strong geo-diversity to the area (Fig. 2d; for a general overview, see Schmid et al. 1996a; 2004; Sciesa 1991; Gouffon 2024, and references therein). Located north of the Insubric Line, most of the territory

[1] Interreg III-B "Alpine Space" 2005–2008 Cooperation Program. Project ALPTER – Paesaggi Terrazzati dell'Arco Alpino.

[2] Strategia Nazionale Aree Interne – Progetto Valchiavenna 2020 Intervento 5 C (2017–2022): La scuola, la montagna, lo sport: strategie e strumenti per la didattica e la divulgazione delle scienze della terra a salvaguardia e valorizzazione del territorio montano. Fondo Ministeriale "Legge di Stabilità".

[3] Interreg V-A Italy-Switzerland 2014–2020 Cooperation Program, Axis II "Cultural and natural enhancement"). Project ID 594274, "A.M.AL.PI. 2018 – Alpi in Movimento, Movimento nelle Alpi. Piuro1618–2018". https://progetti.interreg-italiasvizzera.eu/it/b/78/alpiinmovimentomovimentonellealpipiuro.

[4] Interreg VI-A Italy-Switzerland 2021–2027 Cooperation Program. Project ID 0200072, "A.M.AL.PI. MO.RE. (MOnitoraggio e REsilienza)". https://www.interreg-italiasvizzera.eu/wps/portal/site/interreg-italia-svizzera/DettaglioRedazionale/progetti/progetti-finanziati/amalpimore.

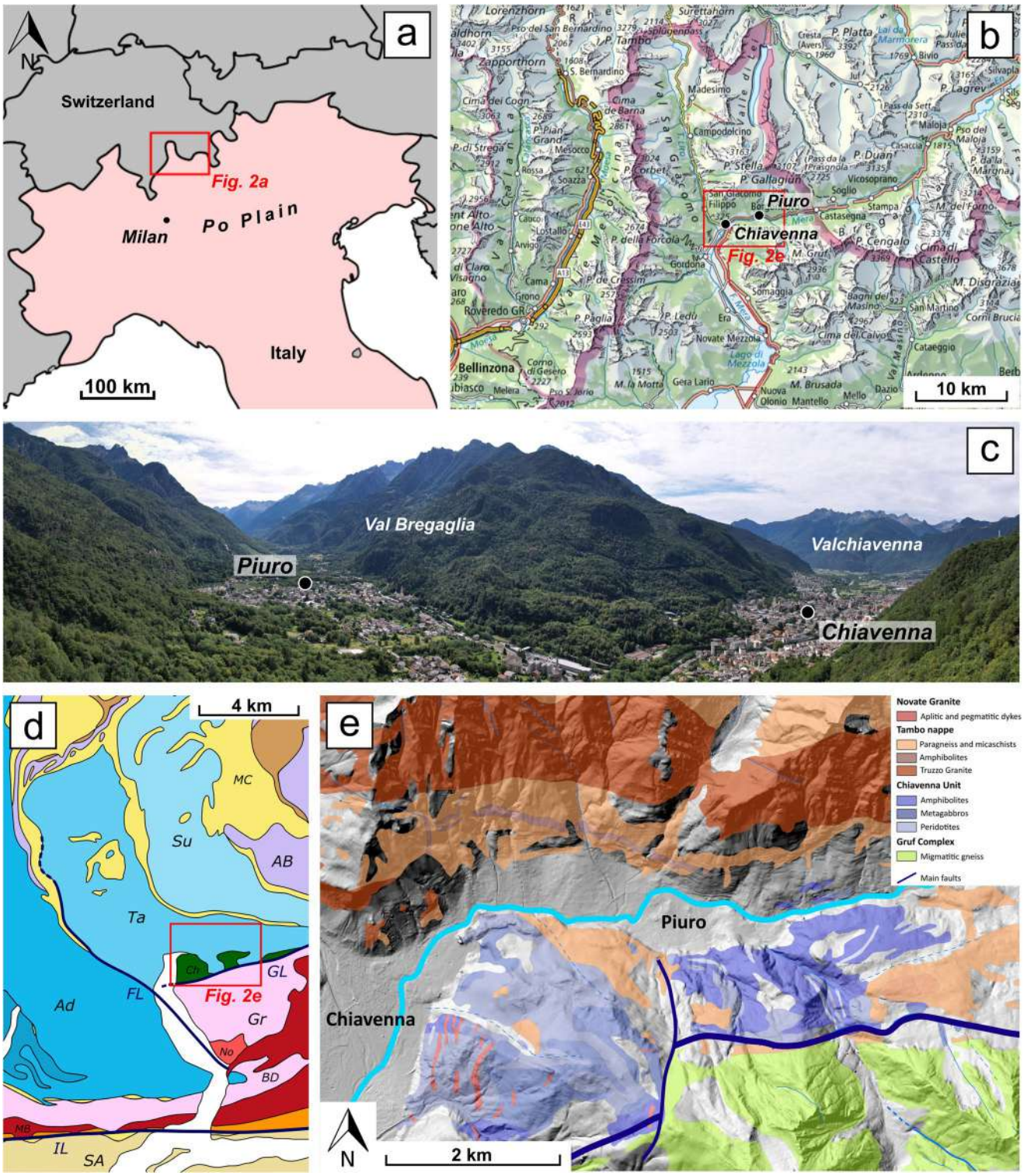

Fig. 2 Geographical and geological setting of the study area: **a** Regional geographical context along the Italian-Swiss border. **b** Local geographical setting of Valchiavenna and Val Bregaglia (topographic base from swisstopo, CN 1:500,000). **c** Panoramic view of the area between Chiavenna and Piuro (Val Bregaglia). **d** Regional geological setting (abbreviations: AB – Avers Bündnerschiefer; Ad – Adula nappe; BD – Bellinzona-Dascio Zone; Ch – Chiavenna Unit; FL – Forcola Line; GL – Gruf Line; Gr – Gruf Complex; IL – Insubric Line; MC – Metasedimentary covers; No – Novate Granite; SA – Southalpine basement; Su – Suretta nappe; Ta – Tambo nappe). Redrawn after Spicher (1980). **e** Local geological setting of the area between Chiavenna and Piuro (redrawn after Montrasio and Sciesa 1988; base map Lombardy Region 5 m cell DTM)

exposes poly-cyclic crystalline basement units belonging to the Penninic nappe stack (Adula, Tambo, and Suretta nappes) (Schmid et al. 1996a). These nappes, mainly composed of ortho- and para-derived rocks, are separated by slices of metasedimentary covers of highly variable thickness (Baudin et al., 1993; 1995).

Between Chiavenna and Piuro, in the lower Val Bregaglia, the Chiavenna Unit crops out, mainly consisting of amphibolites and peridotites (Schmutz 1976; Huber and Marquer 1998). To the southeast, it is in tectonic contact with the Gruf Complex, predominantly composed of high-grade metaintrusive rocks (Galli 2010; Galli et al. 2013) (Fig. 2e). Two Tertiary magmatic bodies, the Bergell Pluton and Novate Granite (Berger, 1996; Schmid et al. 1996b; Ciancaleoni and Marquer 2006, 2008), were emplaced in the southeastern portions of Valchiavenna within the Penninic basement units namely, the southeastern part of the Adula nappe, the Gruf Complex, and the Bellinzona-Dascio Zone, the latter being the southernmost Penninic unit of Valchiavenna. Several tectonic structures cross the area, the most important being the Forcola Line to the west, separating the Adula nappe from the Tambo nappe (Meyre et al. 1998), and the Gruf Line to the east, dividing the Gruf Complex from the Chiavenna Unit and the Tambo nappe (Tibaldi and Pasquarè 2008) (Fig. 2d). The Insubric Line to the south represents the main tectonic boundary separating the Penninic units and the Bergell Pluton from the Southalpine terrains (Schmid et al. 1996a) (Fig. 2d).

The harsh landscape of Valchiavenna and its surroundings largely originated during the Messinian salinity crisis (Bini et al. 1978; Finchk 1978; Willett et al., 2006), when accelerated erosion and denudation associated with the sudden drop of the Mediterranean Sea base level shaped the main morphological features of the area: overdeepened valleys and very steep slopes. Consequently, the region has been, and still remains, highly susceptible to gravitative phenomena. Following the Messinian crisis, valleys began to fill with fluvial and gravity-driven sediments. After that, the main agents shaping the landscape were Pleistocene glaciers, which occupied the valleys, sculpted the bedrock, and deposited large volumes of tills on valley floors and slopes.

During the Pleistocene glaciations, the Engadine Glacier flowed through the Val Bregaglia and lower Valchiavenna from northeast to south, receiving tributary glaciers, the most extensive of which originated from the Val San Giacomo (Tantardini et al. 2022; and references therein) (Fig. 6a). To the south, between the lower Valchiavenna and lower Valtellina, the Engadine Glacier merged with the larger Adda Glacier from Valtellina, forming a single trunk glacier that flowed directly into the Como Lake basin toward the Po Plain.

During glacial retreats and interglacial periods, slopes and valley bottoms were subjected to continuous fluvial and gravity-driven processes as well as weathering. Over time, valleys were filled with large volumes of sediments derived from slope denudation through landslides, mass transport, and fluvial erosion and deposition. Simultaneously, glacial deposits along the slopes were progressively denuded. These processes, amplified by the generally steep slopes, gradually reshaped the valley into its present-day landscape.

The Chiavenna and Piuro geoheritage is strongly linked to the region's long geological evolution, which first produced the exposure of distinctive geological units and later generated a wide variety of geomorphic processes that shaped the landscape.

Historic-Cultural Framework

The oldest signs of human passage and settling in this region date back to pre-historic Mesolithic ages (Fedele and Wick 1996; Moe et al. 2007), while the earliest evidence of stable human fruition traces back to Late Bronze and Early Iron Ages (Fedele et al. 1990; 2015). Following the Roman settlement, the Valchiavenna area acquired a strategic role. The Romans, masters of infrastructure construction, recognized the importance of the Spluga and Maloja mountain passes as communication and trade routes between the Po Valley and the regions North of the Alps (Planta 1993). Local populations gradually adopted Roman language and customs (Mariotti 2018).

After the fall of the Roman Empire, Valchiavenna experienced a period of political uncertainty, falling under the rule of the Ostrogoths, the Longobards, and later the Franks. However, its strategic position preserved its significance. During the Middle Ages, local powers and lordships emerged, and from the 12th century onward, the extraction of soapstone (locally called *pietra ollare*) flourished (Castelletti 2012). Under the dominion of the Three Leagues of Grisons, from the XVI to the late XVIII century (Besta 1967), trade with Swiss and Central European regions intensified, enhancing Valchiavenna's role as a cultural and economic bridge (Fig. 3). The catastrophic 1618 Piuro landslide dealt a major blow to the region's economic importance, completely destroying the small yet prosperous village of Piuro.

Following the collapse of the Grisons Leagues and the Napoleonic Wars, Valchiavenna became part of the Cisalpine Republic. After a period of instability between French and Austrian control, the region was annexed to the Lombardy-Venetia Kingdom under Austrian rule. Consequently, its commercial importance began to decline, as railway transport shifted traffic to alternative trade routes, culminating in the opening of the Gotthard Tunnel.

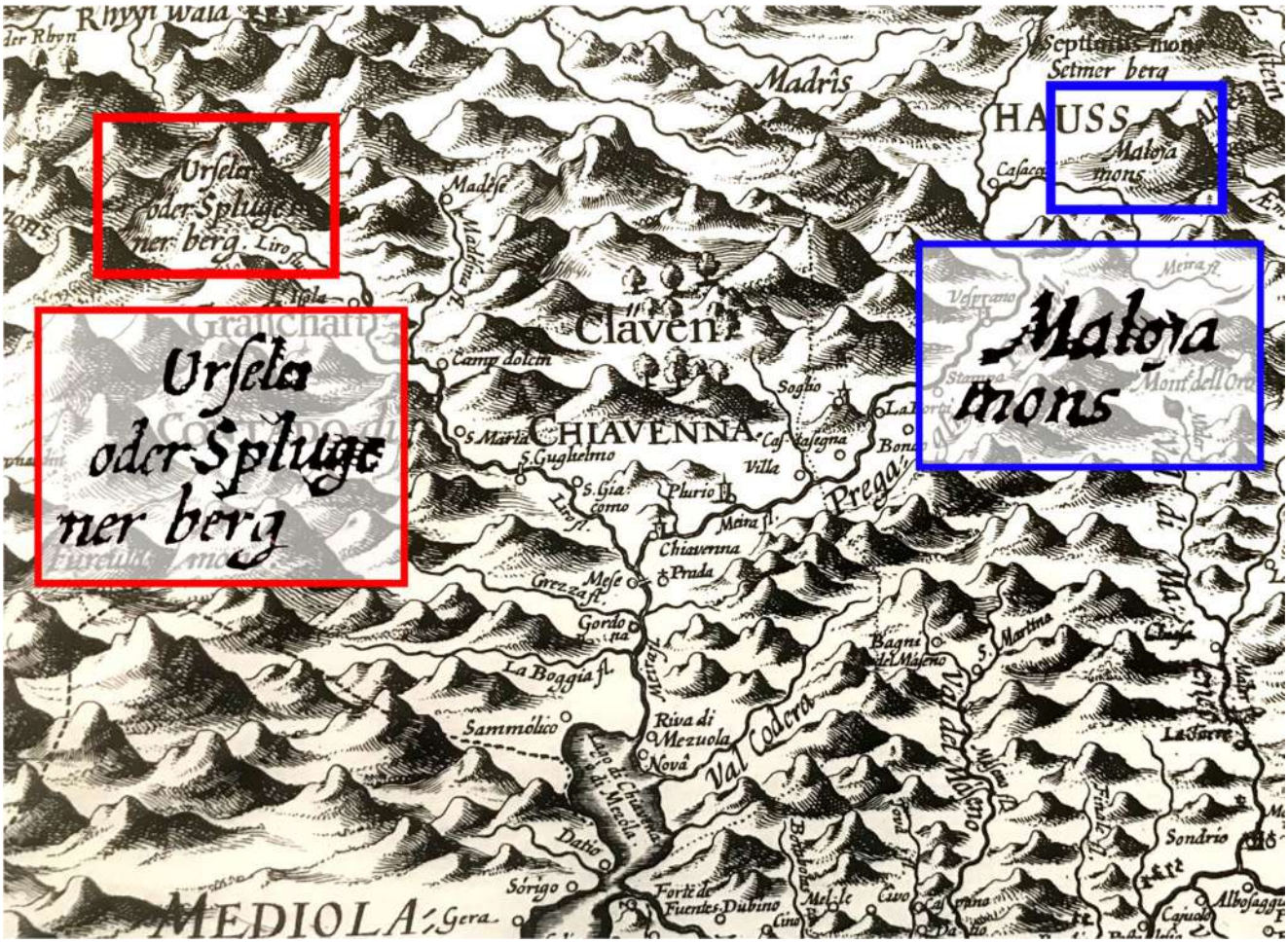

Fig. 3 Extract from "Carte et description générale de la Valtoline" by Tavernier Melchior (1625), showing the commercial routes through the Spluga ("Splugener berg") and Maloja ("Maloja mons") areas, long recognized as important trade routes

The XX century brought industrialization, primarily linked to the construction of dams and hydroelectric plants serving the city of Milan (Po Plain) and its industries, but also challenges such as geographical isolation and depopulation.

Today, Valchiavenna thrives on tourism, based on its stunning alpine landscapes, hiking and winter sports, gastronomy, and unique geo-cultural heritage.

Methods

The methodology adopted for this study follows an integrated, multi-step approach that combines bibliographic research and analysis, extensive field observations, and the classification and quantitative evaluation of the selected sites. The research capitalizes on a vast body of previous studies, reinterpreting them through the lens of geoheritage valorization. The initial phase focused on identifying and defining the primary geosites in the study area. This process was not merely a literature review but a comprehensive synthesis of multi-year research projects in which the University of Milan has been actively involved. The review of internal university studies and works and their cross-reference with local and scientific literature and archival data provided a solid starting point for the research. It should be noted that most of the selected locations are addressed here as *composite* geosites. This approach draws on the definition proposed by Coratza et al. (2021), where sites are categorized not as isolated features, but as groups of landforms related to a single dominant genetic process. Rather than focusing on isolated, small-scale outcrops, the analysis considers then broader, homogeneous areas that encompass multiple interconnected features - such as the Marmitte dei Giganti Natural Reserve, the *pietra ollare* quarries area, or the sites linked to the Piuro 1618 landslide. This integrated approach allows for a more consistent systematic classification and quantitative assessment, treating these clusters as single, coherent functional units based on their shared geological origin and historical narrative. The geological and geomorphological framework of the geosites is based on direct field surveys conducted by the authors

over several years as part of previous and ongoing research projects. These surveys allowed for the collection of original photographic documentation, the direct observation of geological features and geomorphological landforms and processes, and the production of reports and detailed thematic maps. Furthermore, the collected material was essential not only for data validation but also for producing the content of numerous information panels found along the itinerary, ensuring that the geological and historical descriptions are based on primary, up-to-date observations. To systematically analyze the selected sites, this study adopts the multidimensional classification framework proposed by Pijet-Migoń and Migoń (2022). This model addresses the increasing complexity of geo-cultural interlinks, a field rapidly expanding due to the growth of the UNESCO Global Geopark Network. The classification operates across different approaches (Table 1) that facilitate a comprehensive navigation of the relationships between the abiotic environment and human history.

The quantitative assessment of geosites was conducted following the methodology proposed by Forno et al. (2022), based on the attribute-based methodology for geomorphosites ranking of Bollati et al. (2017) and Bollati and Zerboni (2021). This approach evaluates the selected sites through three main macro-categories: *Scientific value*, *Additional values*, and *Potential for use*. The Scientific value is determined by aggregating scores across various specific indicators, including representativeness of geomorphological and geological processes, educational exemplarity, geodiversity, geohistorical importance, and integrity. Each parameter is scored on a scale (typically 0 to 1), resulting in a total range of 0–8. The Additional values account for the cultural, aesthetic, and socio-economic significance of the site, with a maximum score of 3. The combination of these two macro-categories defines the Global value. The Potential for use evaluates the site's suitability for visitors and educational activities. It considers factors such as temporal and spatial accessibility, the visibility of geo(morpho)logical elements, and the proximity of accommodations and services. Additionally, it accounts for the current number of tourists, the presence of sport activities, any legal constraints affecting use, and the potential for divulgation of both geoheritage and additional interests, as well as the presence of other genetically correlated sites in the surroundings. To further characterize the sites, two specific indices are derived: (1) Scientific index, that focuses on the core scientific attributes, and (2) Educational index, that combines educational exemplarity, aesthetic value, and accessibility to measure the site's didactic potential. The cumulative importance of the site is summarized by the Total score, which integrates the Global value and the Potential for use.

The final phase of the study involved the conceptual and physical assembly of the geo-itinerary. The route was constructed by integrating various segments of the pre-existing trail network, which were carefully selected and re-organized to form a cohesive new circuit. The resulting trail is the outcome of a rigorous evaluation process based on several balancing criteria. First, accessibility and transit difficulty were prioritized to ensure the route remains inclusive for a broad range of visitors. Second, the path was optimized to maximize the density of points of interest, ensuring that each stop serves as a functional link to the broader narrative, since the itinerary was specifically designed to intersect all the geoheritage macro-themes discussed in this work. This expert-based selection process ensures that the final route is not merely a path, but a structured educational tool capable of illustrating the complex geological and historical evolution of the territory through a single, easily accessible and continuous experience.

The Chiavenna and Piuro Geosites

The *Pietra Ollare Quarries*: Extraction and Processing

Soapstone (also known as "steatite") refers to talc-rich metamorphic rocks - primarily talc-chlorite-schists and amphibole-schists – occurring within the ultramafic rocks of the Chiavenna Unit (Schmutz 1976) (Fig. 4a). Due to its good workability and thermal properties, this material has been

Table 1 Different approaches proposed by Pijet-Migoń and Migoń (2022) for the classification of themes at the geoheritage - cultural heritage interface

Type of geoheritage	Type of human activity	Spatial scale	Temporal scale	Nature of evidence	Core values	Principal context
♣ Rocks/stones/minerals ♣ Fossils ♣ Geological structures ♣ Landforms ♣ Landscapes ♣ Springs and other hydrological phenomena ♣ Soils	♣ Building construction ♣ Farming ♣ Mining, quarrying and industrial architecture ♣ Tourism and travel ♣ Science and education ♣ Art ♣ Craft	♣ Cultural landscape ♣ Urban (town, city) ♣ Rural (village) ♣ Individual site/object ♣ Subterranean sites	♣ Prehistory ♣ Antiquity ♣ Medieval ♣ Modern era	♣ *Tangible* - in-situ - ex-situ ♣ *Intangible* - language - traditions, - customs - myths and - beliefs - history	♣ Geoheritage as core value ♣ Geoheritage as additional value ♣ Equal standing	♣ Geoconservation ♣ Geotourism ♣ Geoeducation ♣ Raising awareness

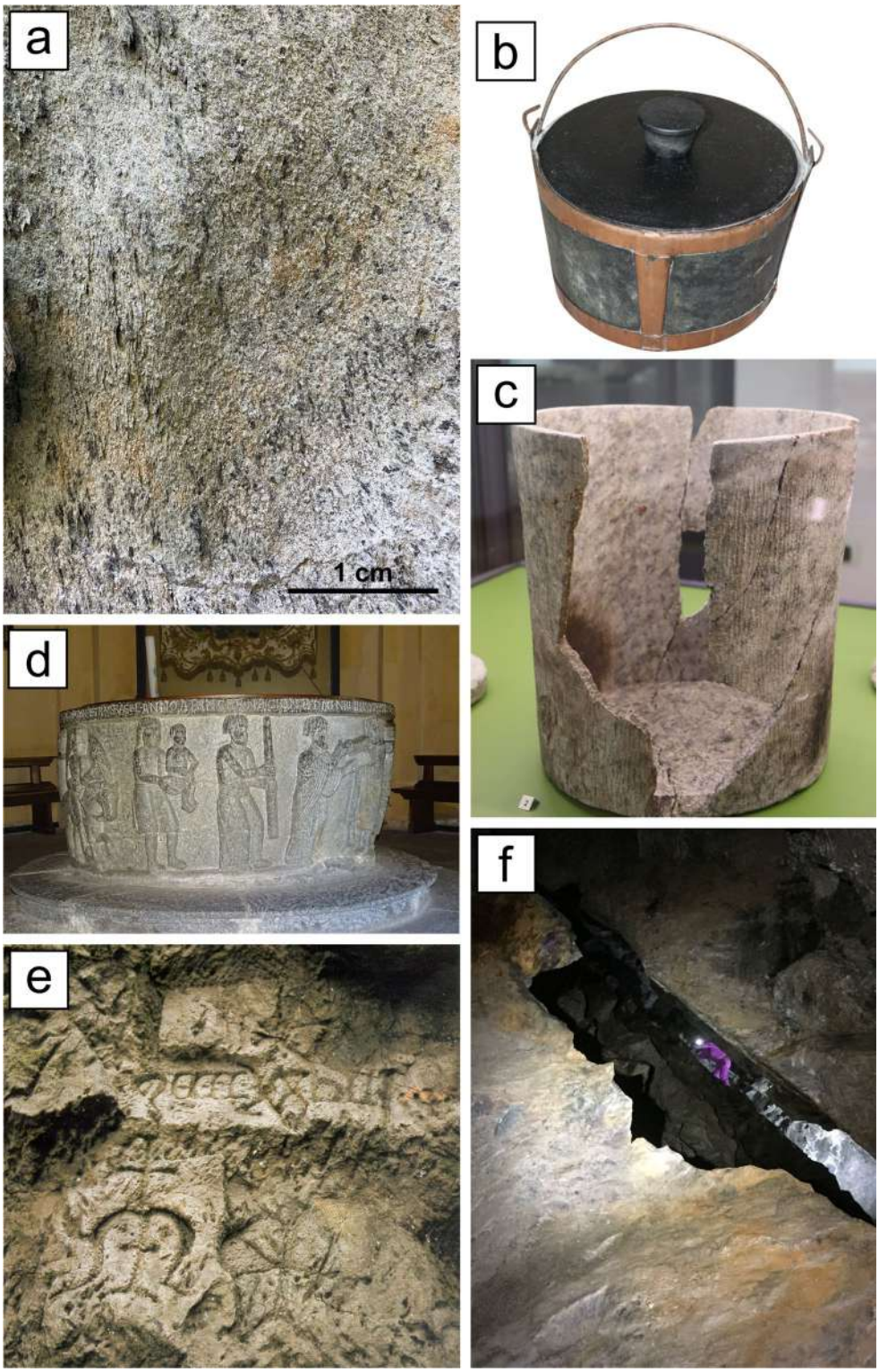

Fig. 4 Examples of soapstone extraction, processing, and artifacts from the Chiavenna and Piuro area: **a** Talc-schist of the Chiavenna Unit, cropping out along the southern flank of the lower Val Bregaglia. **b***Lavecc*, a typical cooking pot made of soapstone. **c** Ancient soapstone artifact on display at the Valchiavenna Archaeological Museum. **d** The baptismal font at San Lorenzo Church (Chiavenna), entirely carved from soapstone. **e** Ancient rock engravings on soapstone cropping out within the quarry area. **f**. Interior view of one of several underground soapstone quarries located along the southern flank of the lower Val Bregaglia

historically utilized for the production of everyday objects such as cooking pots (locally called lavecc) and vessels, as well as architectural elements and dimension stones, as extensively documented by several monuments and historic buildings of Chiavenna and Piuro (Fig. 4b, c and d). The exploitation of soapstone in the area follows a long-standing tradition, since traces of extraction dates back to the Roman era (Mariotti 2018; Bergamini 1977), reaching its peak between the XV and XVII centuries, followed by near-total abandonment of the quarries in the XX century

(Castelletti 2012). For centuries, the trade of soapstone artifacts represented a primary economic resource, with products exported across central and southern Italy and as far as north-central Europe (Santi et al. 2005; Fantoni et al. 2018). Recent surveys have identified 35 open pit quarries and 46 underground quarries (Castelletti 2012), locally called *trone* (Fig. 4e), most of them concentrated at the junction between Valchiavenna and Val Bregaglia. When not directly visible, their presence is indicated by engraved boulders, which served as markers to locate the sites and to indicate ownership (Fig. 4f). Hundreds of rock engravings have been documented in the area, spanning nearly two millennia.

The Paradiso Archaeo-Botanical Park

The Paradiso archaeo-botanical Park is a key site for understanding the local geoheritage, as it uniquely combines multiple geological, geomorphological and cultural features in a single location. The park stands on a peridotite mount that defines the Paradiso and Castellaccio hills. The peculiar exposure of the promontory and the specific lithological composition of the bedrock are key factors in creating a characteristic microclimate that supports the growth and conservation of different and even exotic botanical species, anomalous in an Alpine terrain (Melada et al. 2024). Furthermore, the area preserves clear evidence of subglacial landforms. Within this multidisciplinary setting lies the *Càurga*, the largest Roman-age quarry in Chiavenna. The site features extraction incisions several meters high within the peridotite hill (Fig. 5), and it is officially listed in the National and Lombardy Region Geosites Inventory. The park serves as a multidisciplinary hub where geological evolution, biodiversity, and archaeological remains coexist. Furthermore, the onsite Valchiavenna Archaeological Museum preserves significant findings related to the daily life and tools of the Roman workers whose dwellings were located near the quarry.

The Marmitte dei Giganti Natural Reserve

The geomorphology of the Chiavenna and Piuro area is largely defined by Pleistocene glacial processes. The massive peridotite and amphibolite outcrops of the Chiavenna Unit preserve hundreds of subglacial landforms, including potholes and mounded rocks, providing a detailed record of the ice flow originated from the Engadine region (Fig. 6a; Tantardini et al. 2022). These features are encompassed within the Marmitte dei Giganti Natural Reserve. The area is also a major component of the National and Lombardy Region Geosites Inventory, representing a primary example of subglacial erosion in the Central Alps. The name *Marmitte dei Giganti* ("Giant's potholes") refers to the bowl- or cylinder-shaped depressions formed by the erosive action of pressurized subglacial water (Fig. 6b). While the term is often associated with fluvial processes in Italy, these features are here of primary subglacial origin. They occur alongside ice-smoothed outcrops and are often associated with other subglacial landforms such as interconnected

Fig. 5 The Paradiso (left) - Castellaccio (right) peridotite hill, divided by the *Càurga* ancient quarry. The Paradiso archaeo-botanical Park is located upon and around the two reliefs

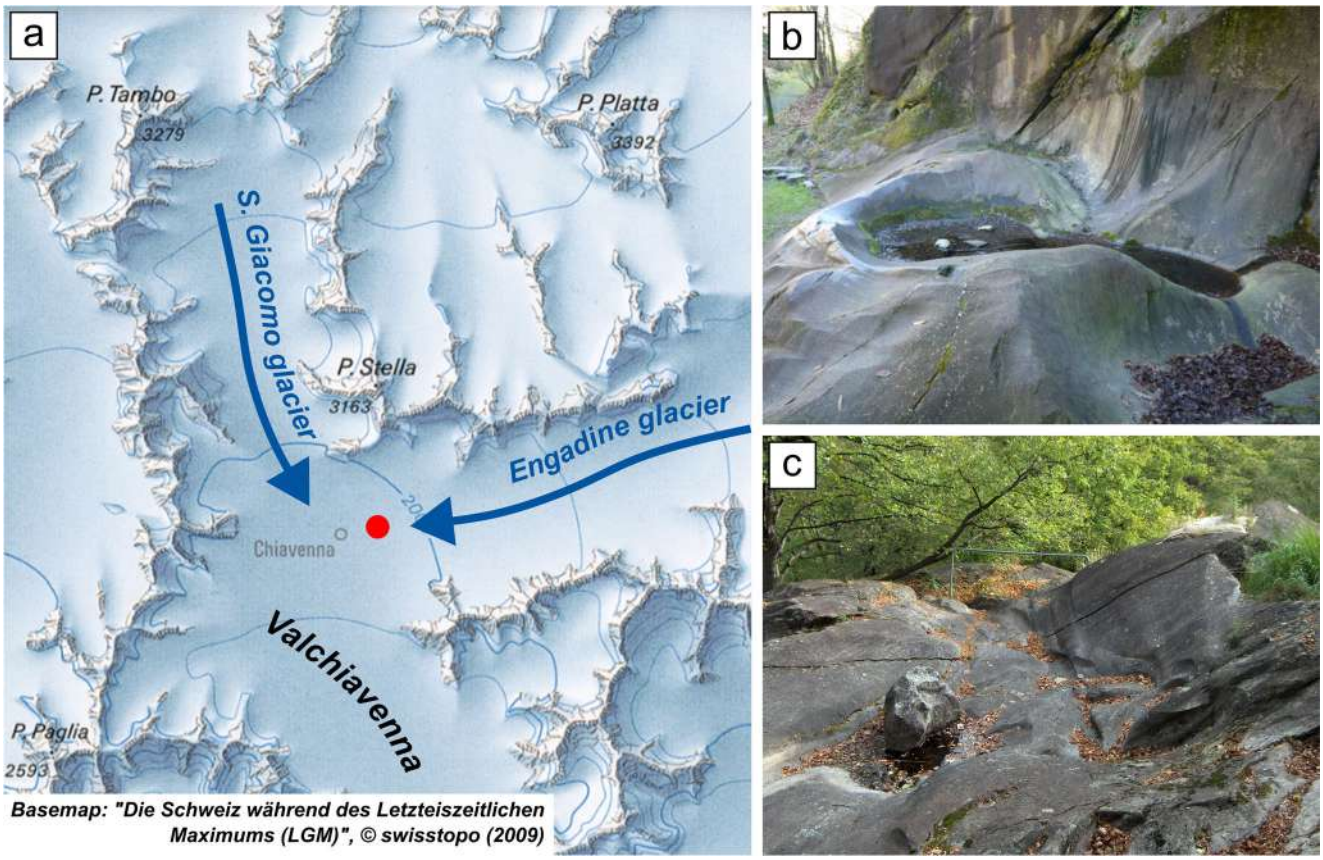

Fig. 6 Potholes of the Marmitte dei Giganti Natural Reserve: **a** Main ice bodies in the Valchiavenna area at the LGM, modified after Bini et al. (2009) (red dot indicates the location of the park). **b** Typical bowl-shaped glacial pothole within the park. **c** Example of associated subglacial landforms, including interconnected channels, basins and pools

channels, basins, pools and exaration striae (Fig. 6c). The high concentration and remarkable preservation of these features represent a primary example of subglacial erosion in the area (Regione Lombardia & Irealp, 2008).

The reserve's environmental value is complemented by millennia of human activity. The same valley flanks house several soapstone quarry entrances and rock engravings. Several descriptive panels along the paths provide information on the glacial landforms and the historical soapstone quarries. In addition, the thematic route *"Anello delle Antiche Cave"* ("Ancient Quarries Ring-shaped Trail") guides visitors to the main sites related to soapstone extraction.

The Piuro 1618 Landslide Sites

The catastrophic landslide that destroyed the *Ancient Piuro* village occurred during the night of September 4th, 1618, when more than six million cubic meters of rock and earth collapsed onto the valley floor settlements (Scaramellini et al. 1988), burying the village in a matter of a few minutes (Fig. 7). The magnitude of the disaster was immediately recognized by Fortunat Sprecher, Grisons Commissioner for the Chiavenna county, who promptly visited the site, organized search and rescue operations, and submitted a detailed report of the event to the Grisons government (Falappi 2012). Approximately one thousand lives were lost, with only a few survivors, and news of the catastrophic event quickly spread across Europe, where Ancient Piuro's merchants and bankers were widely renowned (Scaramellini 2009; Buňatová 2022; Scaramellini et al. 1995).

Only a few buildings in peripheric position or far from the village survived the collapse (Fig. 7). Among the architectural remnants, the most significant are Palazzo Belfòrt ruins and Palazzo Vertemate-Franchi, the latter situated at the outskirts of the village. Since the 1960 s, ongoing archaeological excavations have been essential in uncovering the buried history of the *Ancient Piuro* (Fig. 1c). Numerous artifacts, including coins, gold and silver objects and soapstone tools, have been recovered over the years providing tangible evidence of the former wealth and prominence of the *Ancient Piuro*.

The geological evolution of the Piuro area has been shaped by events spanning from the Last Glacial Maximum (LGM) to the present day (Pigazzi et al. 2024). In the

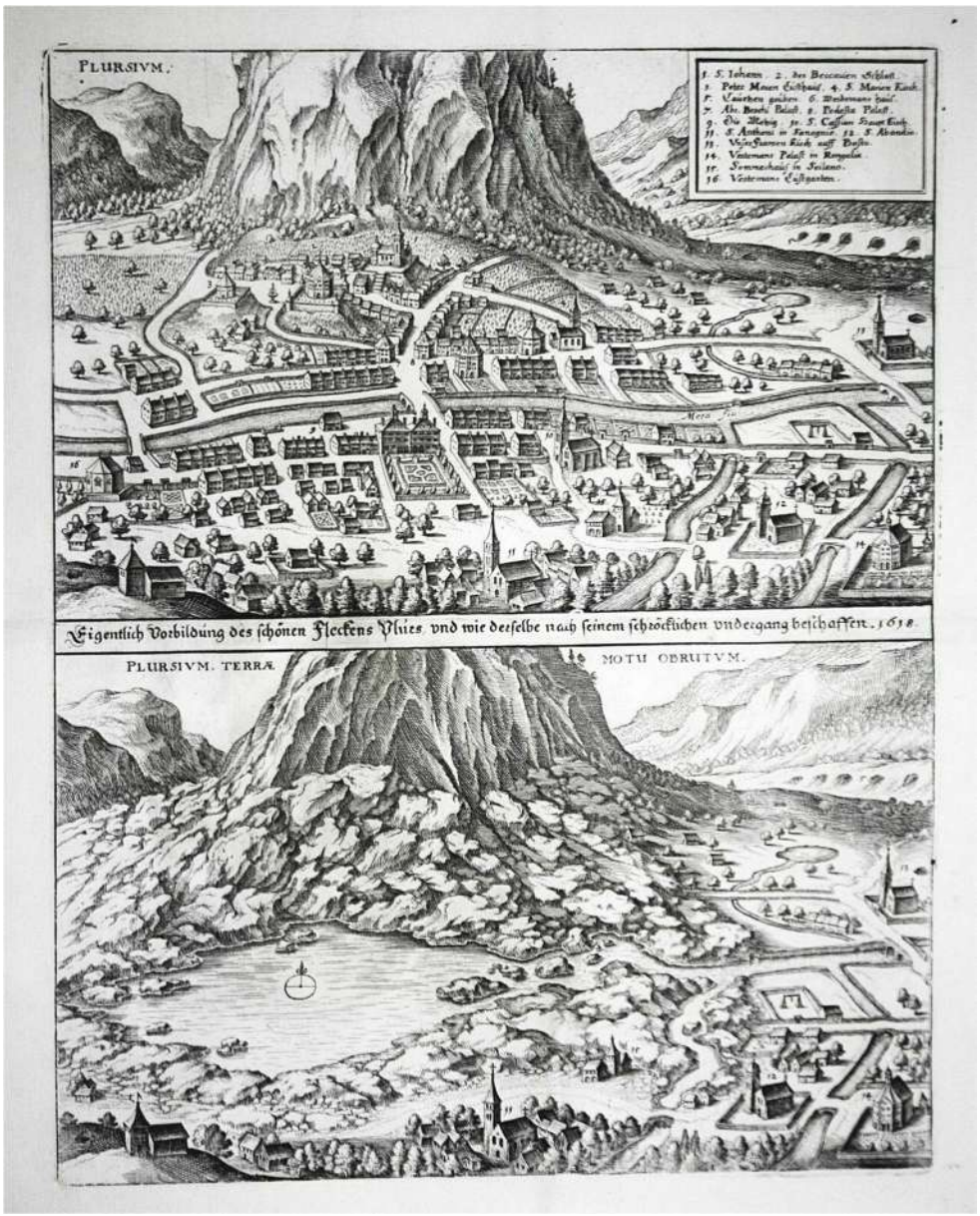

Fig. 7 The *Ancient Piuro* area, before and after the great landslide of September 4th, 1618, which detached from the southern flank of Val Bregaglia. Illustrations by Mattheus Merian, 1640

broader Val Bregaglia area, post-Last Glaciation glacier retreat is considered a primary predisposing factor to geological instability of slopes and landslides triggering (e.g., Morcioni et al. 2023). With the ice mass no longer providing lateral support, the valley's rock slopes were subjected to a change in geomechanical stresses and exposed to weathering from temperature fluctuations and precipitation. This exposure enhanced fracturing and structural failure, particularly along lithological contacts or weakened zones, leading to catastrophic landslides. Several other landslide deposits, such as those from Monte Rosa and Monte Saragiolo, lie northeast of Piuro and testify to recurrent mass-wasting events (Pigazzi et al. 2022, 2024).

The detachment zone of the 1618 landslide is located in a highly complex and structurally deformed area, where rocks from different tectonic units are juxtaposed along fault surfaces. The primary tectonic feature in the detachment zone is the Gruf Line, which separates the Chiavenna Unit metabasites and metaperidotites and the Tambo nappe gneisses to the north from the migmatitic gneisses of the Gruf Complex to the south (Fig. 8). Historical records also report that heavy rainfall in the days preceding the event further destabilized the already fractured bedrock, ultimately triggering the failure of the loose rock slope and of the glacial deposits along the valley flank.

Contemporary chronicles provide crucial insights into the dynamics of the disaster, documenting the vast extent of the landslide deposits. Survivors described the collapse as instantaneous, accompanied by a tremendous rumbling and a rapidly rising, dense cloud of dust. The mass of

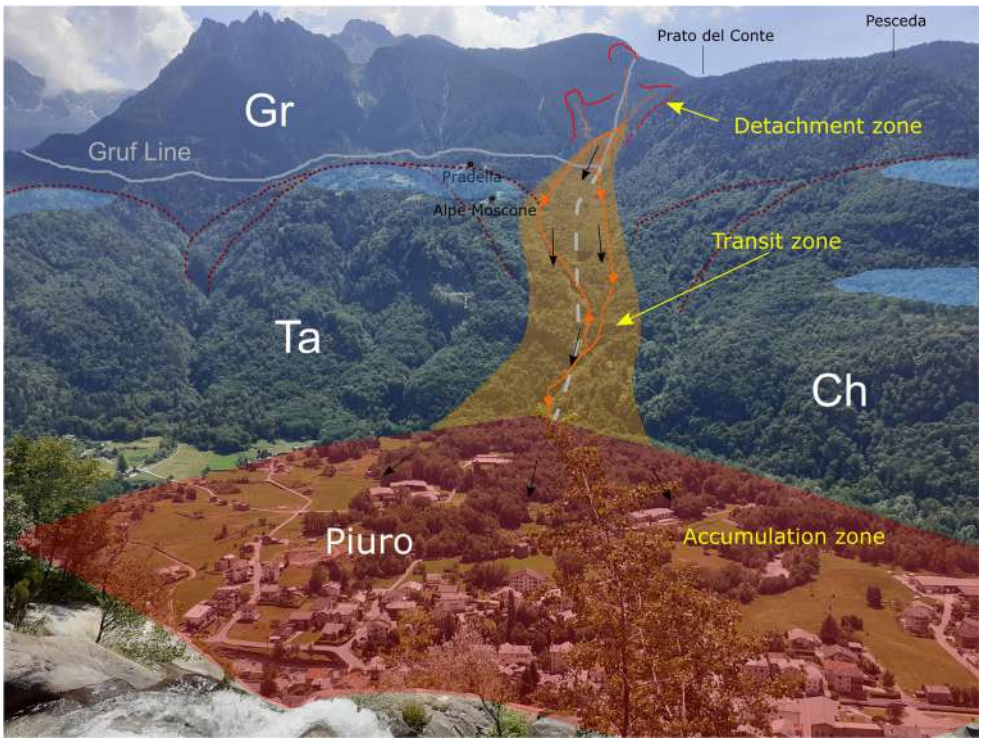

Fig. 8 Geological overview of the southern flank of lower Val Bregaglia, in the vicinity of the Piuro landslide, as seen from the opposite side of the valley. The Gruf Line highlights the boundary between distinct tectonic units, which are structurally weakened along their contact: Gr – Gruf Complex; Ta – Tambo nappe; Ch – Chiavenna Unit.Redrawn after Apuani and Scapozza (2023).

debris posed a secondary hazard by temporarily damming the Mera River, raising concerns that the natural barrier might breach and unleash a devastating flood downstream toward Chiavenna. Fortunately, the river eventually carved a new course through the landslide accumulation, preventing further damage. Many years after the 1618 landslide, the settlement of Borgonuovo (that literally means "new village") was established on the northern slopes of the valley. Today, the geological and cultural significance of the site is being redefined. Detailed geomorphological and sedimentological surveys of the Piuro valley floor, performed in recent years in the frame of the A.M.AL.PI.18 Project have allowed the reconstruction of the geological evolution of the area (Pigazzi et al. 2022; 2024; Apuani et al. 2024). To enhance public awareness of natural hazard vulnerability and to illustrate the interaction between natural and human-induced landscape transformations, descriptive panels have been installed near the main sites of interest (Fig. 9). Due to its extraordinary scientific and historical value, the landslide site is included in the National and Lombardy Region Geosites Inventory.

The Crotti: Natural Cellars

The southern flank of Val Bregaglia is characterized by extensive gravitative collapses (Tibaldi and Pasquarè 2008). Over millennia, these processes have mobilized large portions of the valley flanks, depositing extensive landslide bodies onto the valley floor (e.g., Tantardini 2016). The slope rock masses are heavily fractured, often forming large, isolated blocks, characteristic of Deep-seated Gravitative Slope Deformations (DGSDs) - mountain slope volumes with depths of hundreds of meters and lateral extents of even kilometers that undergo slow

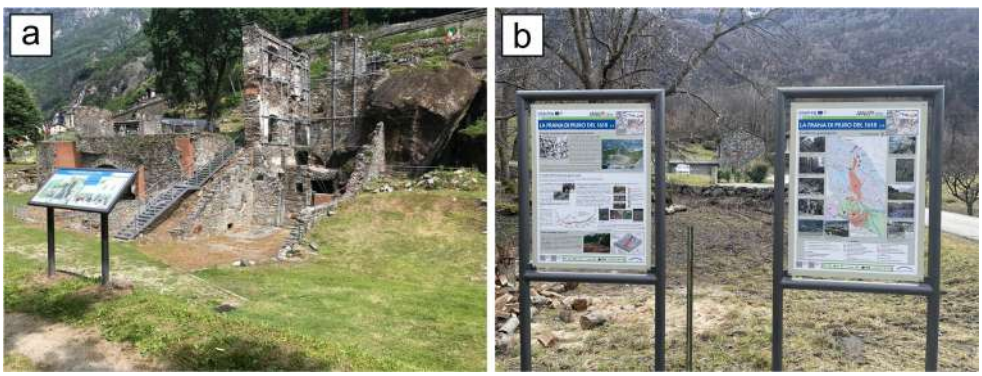

Fig. 9 Examples of illustrative panels installed around Piuro: **a** in the Belfòrt area and **b** in the archaeological excavations area

gravitative movements, typically on the order of mm/year. Their occurrence is driven by intense bedrock fracturing along the Gruf Line fault and due to the lithological variability of this area (Fig. 10a). DGSDs have played a major role in the Holocene post-glacial landscape evolution of the region. Their eventual collapse produces massive rock avalanche deposits in the valley bottom (Fig. 10c). Historically, local communities adapted to these processes by situating settlements atop the raised morphologies to gain natural protection against floods.

Within the cavities formed by these large block accumulations, a unique natural refrigeration system emerged: the *crotti* (Fig. 10b). A constant airflow - locally known as *sorél* - circulates through the fissures within the landslide bodies (Fig. 10e), maintaining stable year-round temperatures of approximately 8–10 °C. For centuries, these natural cellars have been utilized for the preservation and aging of local products such as meat, cheese and wine, becoming integral to the local economy and culture. This practice has evolved into a significant tourism asset; many *crotti* now function as traditional restaurants (Fig. 11d), where visitors can enjoy dishes prepared with products aged inside these natural cellars, some cooked in *Lavecc*. *Crotti* are distributed at the foot of various slopes within the study area, where they typically occur in dense spatial clusters.

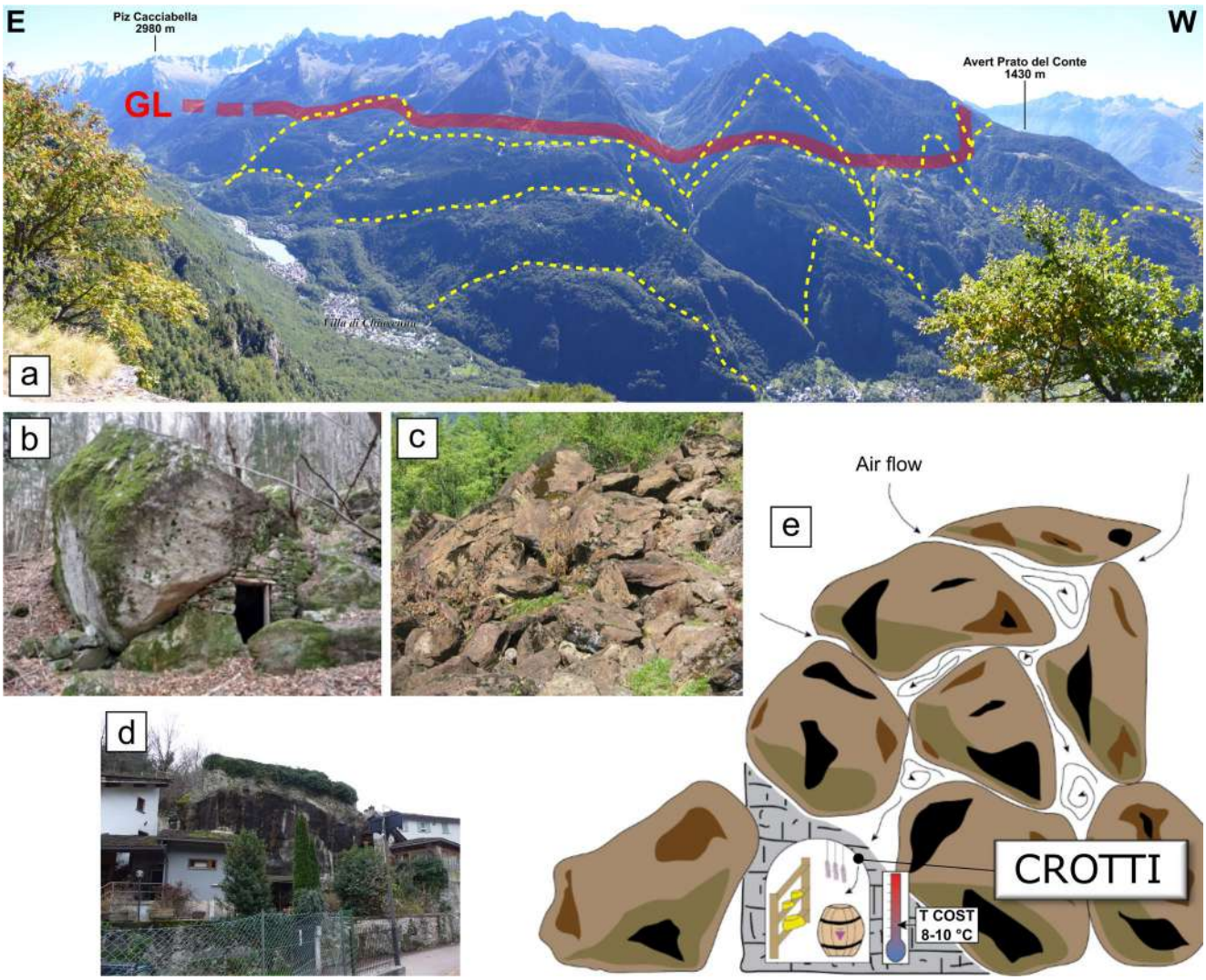

Fig. 10 Example figures illustrating the main features of Valchiavenna's *crotti*: **a** Panoramic view of the southern slope of Val Bregaglia, largely dominated by DGSDs. Yellow dashed lines delineate the upper limit of the affected slope sections, aligned with the Gruf Line (semi-transparent red line), the main structure of this sector. Modified after Pigazzi et al. 2022. b Typical entrance of a crotto among large blocks. c Meter- to decametre-sized block landslide deposit along the southern flank of lower Val Bregaglia, between Chiavenna and Piuro. d The crotti area in Chiavenna, currently renowned for its restaurant businesses. e Schematic reconstruction of a crotto structure (after Pigazzi et al. 2023)

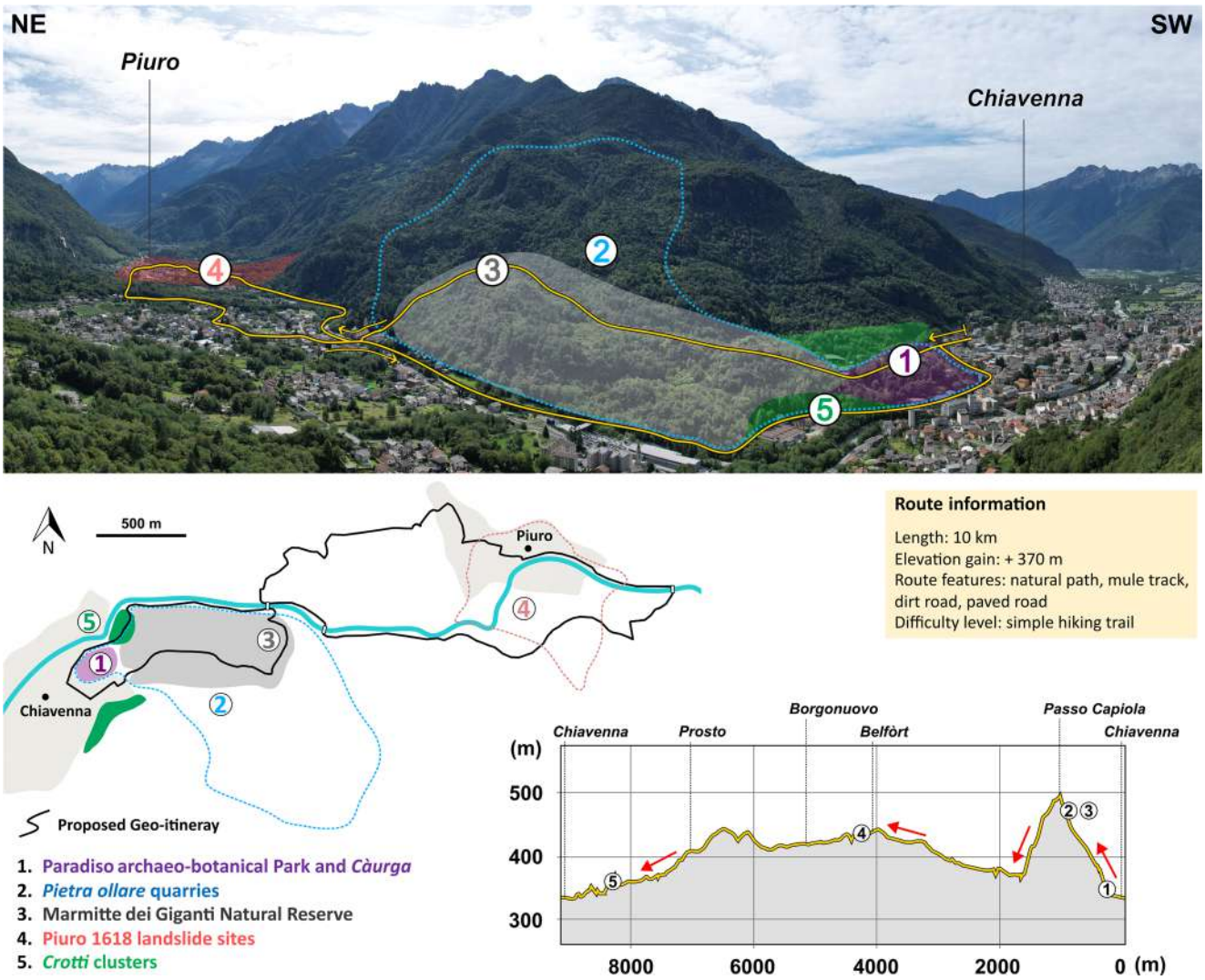

Fig. 11 The proposed geo-itinerary between Chiavenna and Piuro touches several different and intertwining geo-heritage sites of the area. Minimum technical information, as well as altimetric and length data are provided

Classification and Quantitative Assessment of Geosites

The sites presented in this work were evaluated through a dual approach, combining qualitative classification of the geo-cultural interlinks with quantitative assessment of their values (see Methodology section for detailed technical specifications regarding assessment criteria, and classification systems). To better define the relationship between the geological substrate and the historical-cultural development of the study area, the classification framework proposed by Pijet-Migoń and Migoń (2022) has been applied to this study. This choice is dictated by the necessity to treat human-geosphere interactions as core components rather than secondary attributes. In a context like the study area, where geological processes and human-historical legacy are inextricably linked, this framework provides the most effective tool to capture the site's authentic geo-cultural identity. The results of the qualitative classification (Table 2) highlight this duality across all investigated sites. The sites predominantly fall under the category of landforms, with the notable exception of the *pietra ollare* quarries, which focus on rocks/stones/minerals as the primary type of geoheritage. A significant remark is the prevalence of "equal standing" for sites linked with the Piuro 1618 landslide and for the Paradiso archaeo-botanical Park and *Càurga*. In these cases, the geological event or landform cannot be separated from the archaeological and historical narrative. Conversely, *crotti* clusters, are better defined by "geoheritage as additional value", since they are primarily known for their cultural heritage values. Finally, the Marmitte dei Giganti Natural Reserve and *pietra ollare* quarries are

Table 2 Different classification approaches for the presented geosites, based on the method of Pijet-Migoń and Migoń (2022) for themes at the geoheritage-cultural heritage interface

Geosite	Type of geoheritage	Type of human activity	Spatial scale	Temporal scale	Nature of evidence	Core values	Principal context
Marmitte dei Giganti Natural Reserve	Landforms	Science and education	Cultural landscape	Medieval/Modern era	in-situ	Geoheritage as a core value	Geotourism/ Geoeducation
Piuro 1618 landslide sites	Landforms	Science and education	Cultural landscape	Medieval/Modern era	in-situ	Equal standing	Raising awareness
Paradiso archaeo-botanical Park and *Càurga*	Landforms	Science and education	Cultural landscape	Antiquity/Medieval/Modern era	in-situ	Equal standing	Geoconservation/ Geotourism
Crotti clusters	Landforms	Tourism	Cultural landscape	Medieval/Modern era	in-situ	Geoheritage as additional value	Geotourism
Pietra ollare quarries	Rocks/stones/minerals	Quarrying	Cultural landscape	Antiquity/Medieval/Modern era	in-situ	Geoheritage as core value	Geoconservation

characterized by "geoheritage as a core value", since the geological uniqueness provides the essential foundation for subsequent tourism and conservation efforts. Notably, every site is categorized within the cultural landscape spatial scale, underlining that the geological features of this study are not merely isolated outcrops but are foundational elements of the regional cultural identity. Regarding the temporal scale, the sites span from antiquity to the modern era. The principal contexts identified for these sites are geotourism and geoconservation, with the exception of the Piuro landslide sites, that play a crucial role in risk awareness.

The quantitative evaluation of the same geosites, reported in Table 3, follows the established scoring system for geoheritage evaluation proposed by Forno et al. 2022. The Piuro 1618 landslide sites and the Marmitte dei Giganti Natural Reserve hold the highest Scientific value (respectively, 6.01 and 6.11) among the presented ones. Regarding Additional values, which account for aesthetic and cultural factors, the Paradiso archaeo-botanical Park and *Càurga* achieve the maximum obtainable score of 3.00, indicating a deep integration of geological features with the local cultural landscape. In terms of practical application, The Piuro 1618 landslide sites stand out with the highest Potential for use (10.38), driven by superior spatial accessibility and robust services. The Marmitte dei Giganti Natural Reserve, *crotti* clusters, and the Paradiso archaeo-botanical Park and *Càurga* maintain high scores (9.79, 9.73, and 9.66, respectively). Ultimately, the Total score (TS) identifies the Piuro 1618 landslide sites (18.50) as the most well-rounded site in the study group.

The Becca France rock avalanche, evaluated by Forno et al. (2022), serves as a high-level, external benchmark to contextualize the standing of the study sites. While the reference site exhibits the highest Scientific value (7.00), several geosites of the current study present high values in specific sub-criteria. Notably, the Paradiso archaeo-botanical Park and *Càurga* achieve the maximum Additional Value (3.00), surpassing the benchmark (2.67) by integrating geological features with exceptional cultural and aesthetic attributes. Furthermore, many of the examined sites achieve Potential for Use values that are closely comparable to the score of Becca France rock avalanche (9.45). According to the assessment framework, this suggests high spatial accessibility, visibility, and available services for these sites. Although Becca France rock avalanche remains the most scientifically robust site, the Scientific Index of Piuro 1618 (0.81) is slightly higher, indicating a marked representativeness of geomorphological processes and geohistorical

Table 3 Numerical scores obtained by the sites ranked according to the method proposed by Forno et al. (2022), compared to the scores obtained by the Becca France rock avalanche. The maximum obtainable values are indicated in the last row

Geosite	Scientific value	Additional value	Global value	Potential for use	Scientific index	Educational index	Total score
Piuro 1618 landslide sites	6.01	2.11	8.12	10.38	0.81	0.75	18.50
Marmitte dei Giganti Natural Reserve	6.11	2.28	8.39	9.79	0.70	0.63	18.18
Paradiso archaeo-botanical Park and *Càurga*	5.34	3.00	8.34	9.66	0.59	0.72	18.00
Crotti clusters	5.39	2.33	7.72	9.73	0.66	0.63	17.45
Pietra ollare quarries	3.94	1.89	5.83	7.72	0.44	0.46	13.55
Becca France rock avalanche (Forno et al. 2022)	*7.00*	*2.67*	*9.67*	*9.45*	*0.77*	*0.81*	*19.12*
Maximum obtainable value	8	3	11	12	1	1	23

importance. Hence, the discussed sites emerge as highly balanced geoheritage assets; while maintaining significant scientific interest, they offer high potential for educational outreach and geotourism due to their accessibility and multifaceted cultural values.

Connecting Geosites: A Proposal For A Multi-Disciplinary Geo-Itinerary

Building upon the detailed characterization, classification and assessment of the sites presented in the previous section, this chapter integrates these elements into a cohesive, multidisciplinary geo-itinerary. Along the route, visitors can learn about the territory on several intertwining thematic levels and linking them through their spatial connections. The guiding principle is represented by the deep relationship between man and the alpine environment, that is the matter addressed in this work. The following sections detail the technical specifications, the trail infrastructure, and the thematic sequence of the trail, demonstrating its potential as a tool for sustainable territorial valorization. An overview of the geo-itinerary with its planimetric track, altitude information and location of connected geo-sites is presented and summarized in Fig. 11. The trail develops as a circular loop of approximately 10 km, connecting the historical center of Chiavenna with the municipality of Piuro, and can be completed by an ordinary hiker, without hurry, in about 6–7 h. The route is characterized by a moderate elevation gain of 370 m, reaching its peak at Passo Capiola, and is classified as a simple hiking trail suitable for a broad audience. The path follows a combination of natural trails, ancient mule tracks, dirt roads, and paved sections, spanning from urban environments to proper mountain paths. The proposed geo-itinerary is entirely based on pre-existing trail networks, ensuring high standards of safety and navigability. All segments are officially marked with the characteristic red-and-white signs of the Italian Alpine Club (CAI), the standard for mountain orientation in Italy. Trail marks are periodically renewed by volunteers from the local CAI section to guarantee constant visibility. Furthermore, the route is equipped with comprehensive directional signage at every junction, facilitating smooth transitions between the various localities. The maintenance of the paths - encompassing both routine upkeep and extraordinary interventions - is frequently supported by funding from local authorities, ensuring the trails remain clear and safe for hikers. Along the route, numerous descriptive panels and labels are strategically positioned to assist hikers in fully understanding the territorial elements. These in-situ resources provide detailed explanations of both geological and cultural themes, bridging the gap between the visible landscape and its scientific significance. The presence of this pre-existing interpretive infrastructure enhances the educational value of the trek, allowing for an autonomous and multidisciplinary exploration of the region's geoheritage. Along the geo-itinerary, visitors will be encouraged to observe the intimate relationship between geology, territory and human settlement, visualizing how the historical and cultural evolution of a society can be influenced, first and foremost, by the geological predisposition of the territory.

Description of the Geo-Itinerary

The geo-itinerary crosses five different environment, all linked with the local geoheritage themes and sites previously introduced (Fig. 11): (1) Paradiso archaeo-botanical Park and *Càurga*; (2) *Pietra ollare* quarries; (3) Marmitte dei Giganti Natural Reserve; (4) Piuro 1618 landslide sites; (5) *Crotti* clusters.

The trail is structured around 13 primary stops, offering direct engagement with the area's most significant points of interest (all technical details and stop descriptions are listed in Table 4; Figs. 11 and 12). It starts at Chiavenna railway station and follows the Pratogiano paved road towards the *Càurga* quarry and the Paradiso archaeo-botanical Park (stop 1), where thematic panels and museum installations guide the visitor into the soapstone extraction theme from both a geological and historical-cultural point of view. From here, directional signage leads inside the Marmitte dei Giganti Natural Reserve area through an easy stone-paved hiking trail with stone stairs, reaching the panoramic point (stop 2) on the peculiar environment of the area (subglacial landforms, traces of soapstone excavations and natural setting). The route continues toward Passo Capiola, the heart of the park (stop 3). Here, interpretive displays explore the intersection of subglacial landforms and soapstone quarrying. This location serves as the starting point for the *Anello delle Antiche Cave*, which branches out along the mountain slope amidst extensive boulder deposits left by prehistoric rock avalanches. Leading down to the village of Prosto, the path reaches the historic center characterized by the local *lavecc* exhibition and handwork, the ancient church and the mill (stop 4). On the descent, the view opens onto the northern flank of Val Bregaglia, highlighting the extensive alluvial fan created by the frequent and destructive flooding of the Drana stream. The itinerary now follows the asphalt cycle lane from Prosto to the hamlet of Scilano (stop 5). This picturesque route along the Mera River offers significant scenic value; from here, at the foot of the mountainside, the geomorphological features related to the devastating 1618 landslide become clearly visible. In the area surrounding Scilano, the route reaches the symbolic sites of the Piuro landslide, passing through the main archaeological excavation site and the Piuro InfoPoint (stop 6); the latter serves as a visitor information center and

Table 4 Description of the proposed geo-itinerary. Main stops and route technical details (hiking time, elevation gain, trail surface)

Main stop	Description
	Itinerary technical details
Geo-itinerary START: Chiavenna railway station	
	~ 5 min, ~ 480 m, + 5 m elevation gain; asphalt/paved road.
1	Càurga: *pietra ollare* Roman quarry, Chiavenna Unit rocks, thematic panels. Accessible Museums: Valchiavenna Archaeological Museum; Paradiso archaeo-botanical Park.
	~ 10 min, ~ 300 m, + 90 m elevation gain; easy stone-paved hiking trail and stone stairs.
2	Panoramic point; subglacial landforms, exaration striae, Chiavenna Unit rocks and *pietra ollare* quarry.
	~ 10 min, ~ 300 m, − 30 m/+ 110 m elevation loss/gain; easy stone-paved hiking trail and stone stairs.
3	Capiola Pass: subglacial landforms and rock avalanche deposit, Chiavenna Unit rocks, thematic panels.
	~ 20 min, ~ 750 m, − 131 m elevation loss; easy stone-paved hiking trail and stone stairs.
4	Prosto: *lavecc* exhibition and handwork, ancient church, mill and governor palace, panoramic view of Drana debris fan.
	~ 20 min, ~ 1400 m, + 35 m elevation gain; asphalt cycle-lane.
5	Scilano: panoramic point on Piuro 1618 landslide accumulation.
	~ 10 min, ~ 700 m, + 20 m elevation gain; asphalt roads.
6	Scilano: *Ancient Piuro* archaeological site, thematic panels. Accessible Museums: Infopoint Piuro Archaeological Museum.
	~ 15 min, ~ 950 m, −10/+ 10 m elevation loss/gain; asphalt roads and dirt paths.
7	Belfòrt Palace: remnants of the building, only partly buried by Piuro 1618 landslide, panoramic view on Piuro 1618 landslide accumulation, transit and detachment zone, thematic panels.
	~ 5 min, ~ 250 m, 0 m elevation loss/gain; asphalt roads and dirt paths.
8	Borgonuovo: panoramic view of river Mera and of the sediments and terraces of the temporary lake formed after the Piuro 1618 landslide that partly buried Belfòrt Palace.
	~ 10 min, ~ 500 m, + 15 m elevation gain; asphalt road.
9	Borgonuovo: settlement after Piuro 1618 landslide.
	~ 5 min, ~ 230 m, + 15 m elevation gain; asphalt roads.
10	Borgonuovo: limit of Piuro 1618 landslide on the slope opposite of the detachment, Acqua Fraggia waterfall natural monument.
Proposed lunch break - Picnic area/Restaurants	
	~ 10 min, ~ 700 m, −10/+10 m elevation loss/gain; asphalt/paved roads.
11	Old St. Abbondio church bell tower: remnant of the 1755 Drana fan flood, thematic panels. Accessible Museums: Piuro Archaeological Museum.
	~ 15 min, ~ 1000 m, −20/+20 m elevation loss/gain; dirt roads and paths.
12	Prosto: Renaissance Vertemate-Franchi Palace (*Ancient Piuro*), panoramic view on the DGSDs phenomena of Val Bregaglia southern slope. Accessible Museums: Palazzo Vertemate-Franchi.
	~ 30 min, ~ 1700 m, −80 m elevation loss; asphalt roads and cycle lane.
13	Poiatengo: *crotti* natural cellars.
	~ 15 min, ~ 750 m, −15 m elevation loss; asphalt/paved roads.
Geo-itinerary END: Chiavenna railway station	
Total hike time (without point of interest breaks + lunch break): 3 h. *Estimated point of interest breaks/visits + lunch break total time: ~ 3–4 h.* *Total length (sites visits not considered): 10, 01 km.*	

houses an interesting exhibition of the most recent findings. Throughout the area, thematic panels assist visitors in understanding the event from both a geological and historical-cultural perspective. Through a dirt path and crossing the Mera River, the route now reaches Palazzo Belfòrt, one of the few buildings that partially survived the landslide (stop 7). Numerous descriptive panels provide graphic reconstructions of what the palace once looked like. Heading toward Borgonuovo along the riverbanks (stop 8), the visitor crosses the area where the Mera River successfully breached the landslide barrier, forcing a new path through the massive debris accumulation. Once reached Borgonuovo (stop 9), the itinerary explores a site constructed entirely after the 1618 catastrophe, serving as a historical testament to the area's resilience and rebirth. The route moves toward the northern side of the valley to reach the Acquafraggia Waterfalls (stop 10), a Natural Monument of the Lombardy Region of significant naturalistic and geological interest, even described in the *Codex Atlanticus* by Leonardo da Vinci. The waterfalls are also formally listed in the National and Lombardy Region Geosites Inventory, ensuring the conservation of its unique geomorphological features. The presence of extensive green spaces, picnic tables, and numerous dining options makes this the ideal location for a lunch break in the middle of the

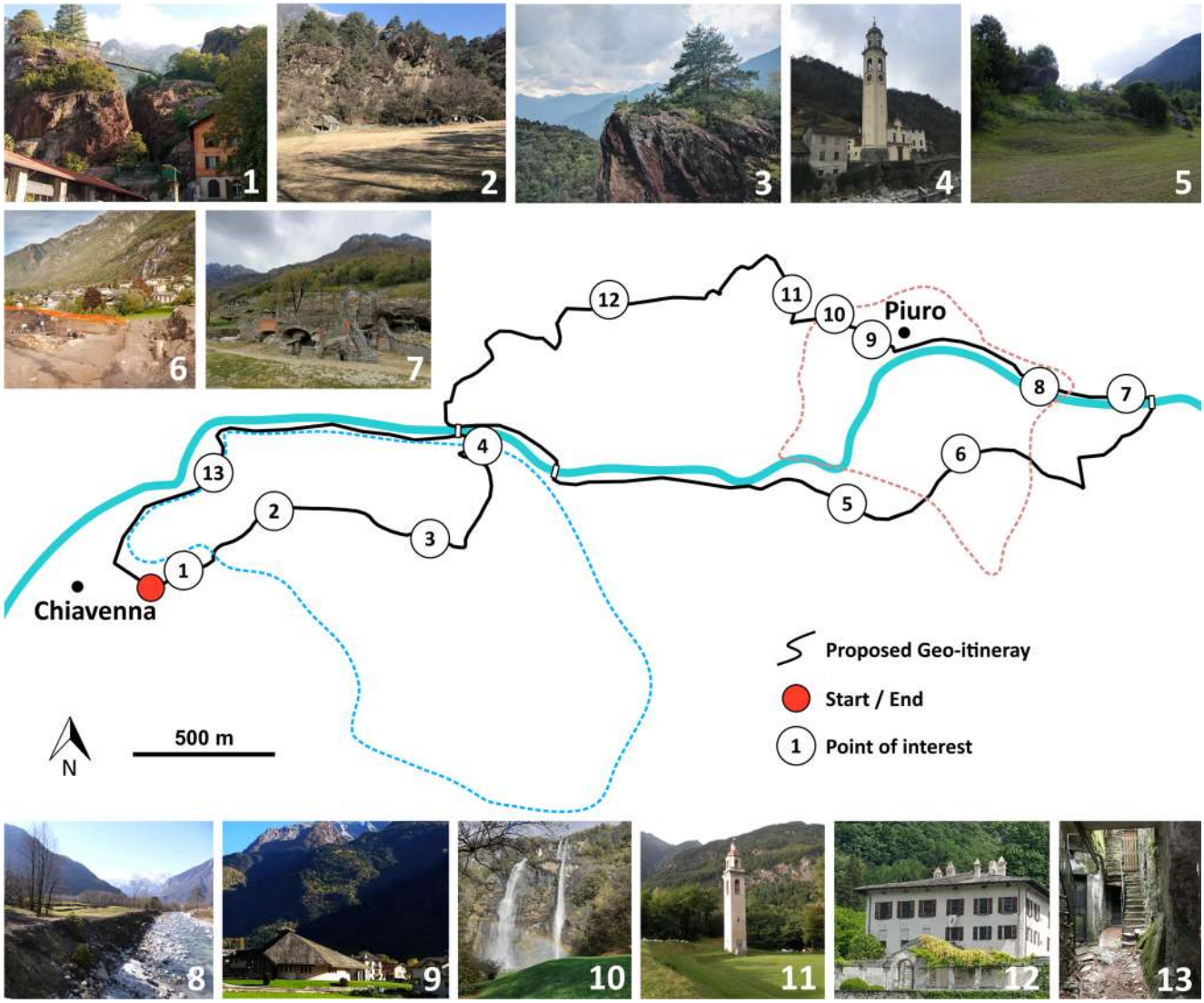

Fig. 12 Planimetry of the proposed geo-itinerary and main stops (see Table 4)

itinerary. The path then resumes, following the asphalt road for a short distance to the Archaeological Museum of Piuro, a must-see stop to appreciate the historical findings from the area. Following the signs, a gravel road leads a short way to the remains of the St. Abbondio church bell tower (stop 11), which was severely affected by several flood events of the Drana stream between the XVII and XVIII centuries, as documented by the in-situ descriptive panels. Returning to Prosto, the path reaches the Renaissance Vertemate-Franchi Palace (stop 12), where guided tours are available through one of the best-preserved historic palaces in the region. This location offers a prime vantage point to observe the DGSDs and their characteristic convex morphologies along the lowermost portions of the southern flank of the valley (Fig. 10a). Finally, the path descends once again toward the historic center of Prosto, intersecting with the outbound trail, and continues down to Chiavenna along the cycle path. It eventually reaches the Poiatengo *crotti* cluster (stop 13), built at the foot of the massive landslide deposits. From here, the Chiavenna railway station can be reached in just a few minutes, serving as both the starting and ending point of the proposed geo-itinerary.

Discussion and Conclusions

Human-Environment Interaction: From Landslide Hazards to Geo-Cultural Resources

The Valchiavenna and Val Bregaglia region, straddling the Swiss and Italian Alps, offers an interesting case study of the complex and intimate coexistence between man and the alpine territory. This relationship, forged over millennia,

has always been a two-sided coin (Fig. 13): the territory provided crucial resources that enabled life and commerce but also exposed communities to sudden, devastating natural disasters. The dynamics of mountain landscapes are intrinsically linked to intense geological processes, where floods and slope instabilities are not merely destructive events but agents that actively shape the landscape, with direct consequences for human societies.

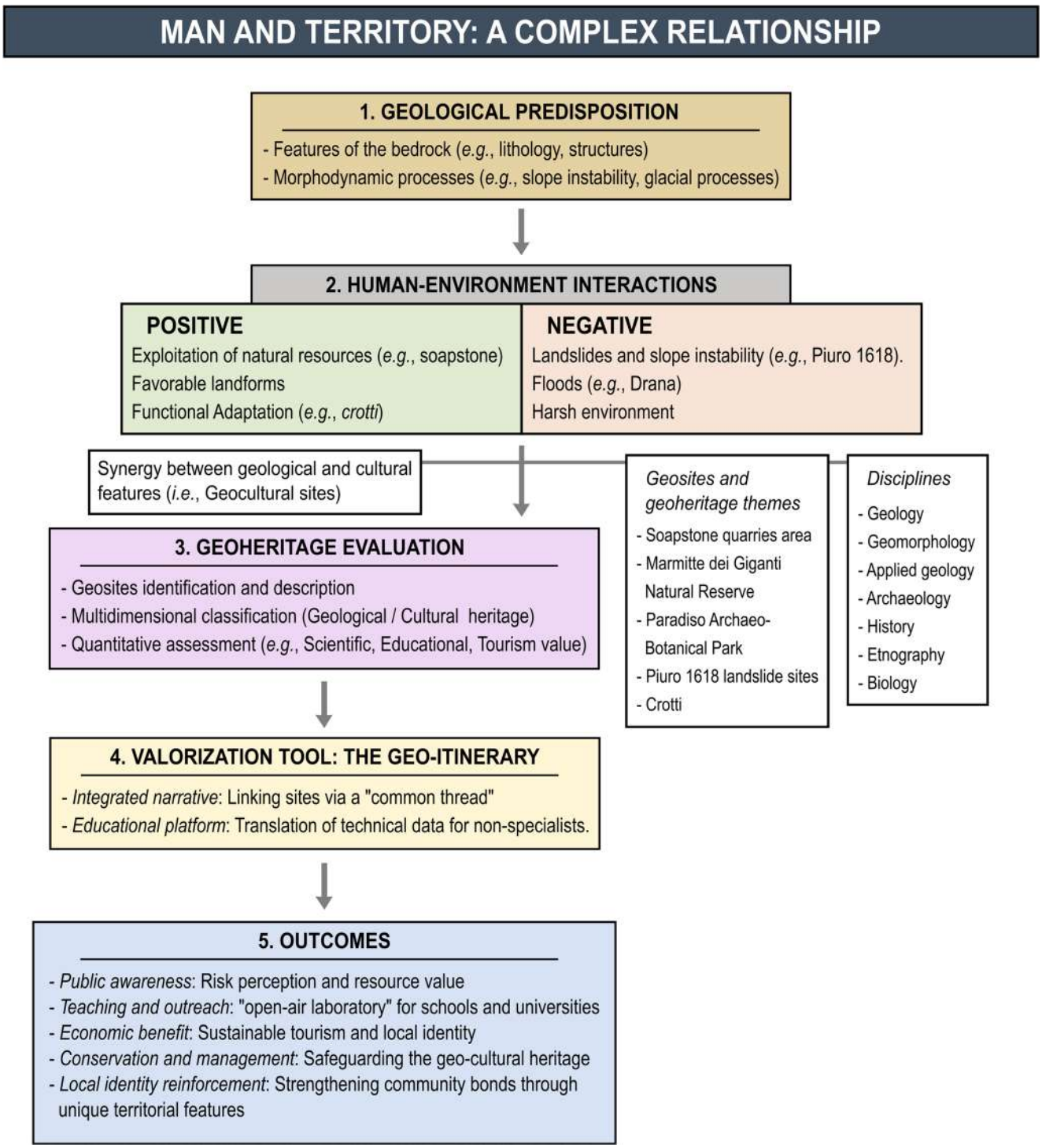

Fig. 13 Conceptual flowchart of the study, illustrating the complex relationship between geological predisposition of the territory and local populations, which defines the regional geosites and geoheritage themes. The final outcomes emphasize the role of geo-itineraries as platforms for teaching and outreach, hazard awareness, territorial management and asset for the local economy

Landforms related to gravity-driven processes represent impressive features of the landscape that often act as true landmarks due to the remarkable scars they leave in the territory, and that may represent ideal places to promote geological education (Coratza and De Waele 2012). Although, in the past years, gravity-related features have received scarce attention in geosite inventories, they constitute fundamental components of a region's geodiversity (Forno et al. 2022; Margielewski and Alexandrowicz 2004), reflecting the evolutionary dynamics of slopes and the landscape response to environmental changes. Gravity-driven processes possess a profound geomorphological value, acting as unique indicators of landscape dynamics and environmental changes both at human and geological timescale, and recent examples demonstrate the growing interest on this topic (e.g., Apuani and Scapozza 2023; Forno et al. 2022; Tognaccini 2019; Niculiţă and Mărgărint 2018; Krishnapriya et al. 2025; Morino et al. 2025). In this framework, sites connected to the Piuro 1618 event serve as a primary example of landslides in the geoheritage, where a catastrophic event is transformed into a fundamental landform for understanding global geological heritage. Insights into specific geoheritage sites and themes can provide tools and methods to raise awareness of natural hazards, particularly concerning slope instability in mountain environments (Morino et al. 2022; Coratza and De Waele 2012; May 2008).

Beyond the destructive potential of gravitational events, the local geoheritage reveals a sophisticated anthropogenic adaptation to these landforms, turning geological constraints into socio-economic opportunities. Similarly, the geoheritage related to soapstone extraction reflects a deep-rooted technological adaptation to the geological environment. This long-term exploitation of local stone resources for economic development is a key example of positive human-environment interaction. Such a link between the community and geological features of the environment mirrors the interlinked heritage approach seen in other Alpine areas where local traditions and geological features are recognized as a shared cultural asset (e.g., Bollati et al. 2023). While being a continuously evolving model, this coexistence provides lessons in resilience, adaptation, and responsibility, prompting reflection on human impacts and the necessity of safeguarding natural environments, including geosites. These should be considered not merely as resources to be exploited but as valuable assets to be preserved for future generations, consistently with the medium-to-high scores yielded by the main geosites through quantitative assessment.

A Multidisciplinary Tool for Education and Territorial Valorization

The proposed geo-itinerary represents a concrete initiative designed to achieve multiple objectives, ranging from land use and territorial planning to environmental management, territorial marketing, and tourism, and encompassing several disciplines such as geology, geomorphology, applied geology, archaeology, history and ethnography (Fig. 13). It is intended both as a geo-touristic itinerary for hikers who wish to spend a day learning more about a territory than what can be observed during a standard mountain hike, and as a resource for school education, offering a complementary perspective of a territory and its geological-historical heritage, which can be studied in detail from multiple angles. The effectiveness of this itinerary relies on the functional synergy between abiotic and anthropic components. According to the framework established by Pijet-Migoń and Migoń (2022), such a relationship reflects the spatial, causal, and thematic interlinks between geoheritage and cultural heritage. This synergy is objectively validated by the results of the quantitative assessment, which assigned high scores to the selected sites across scientific, educational, and cultural criteria, confirming their primary role as regional geo-cultural landmarks. The geo-itinerary could also serve as an interesting proposal for touristic operators, who will find in this paper some ready-to-use materials essential for organizing such activities, such as a map of the path and a complete summary of the itinerary with walking times and the location of points of interest (Fig. 12; Table 2).

The extensive geo-cultural heritage of Chiavenna and Piuro then represents an excellent opportunity to promote the territory and its history, integrating geology, history, and culture. These sites continue to be the focus of several projects and initiatives aimed at their dissemination and valorization, particularly for educational and outreach purposes. These initiatives, summarized in Table 5, constitute a virtuous example of promotion, dissemination, fruition, and conservation of the local geo-cultural heritage, often supported by installations and infrastructures that stimulate local geotourism.

The development of a geotrail connecting local geosites could not only integrate them into a single, coherent narrative but also support alternative and effective methods for teaching local culture to schools and disseminating this knowledge among the population, as evidenced by other recent cases (e.g., Perotti et al. 2020; Guerini et al. 2026; Bucci et al. 2019). This approach forms part of so-called "Third Mission" activities, referring to the economic and social mission of universities through the valorization of knowledge and its transfer to communities and territories

Table 5 List of the main geoheritage themes in the Valchiavenna and Val Bregaglia area along with their respective geosites, instruments for valorization, and purposes

Geoheritage themes	Geosites	Instruments for promotion	Valorization tools and deliverables
Pietra ollare extraction, processing and trade	- Soapstone quarries - Historical buildings (with soapstone architectural elements) - Monuments - Valchiavenna Archaeological Museum - Paradiso archaeo-botanical Park and *Càurga*	- Thematic itinerary (*Anello delle Antiche Cave*) - Illustrative panels - Publications/guides	- Conservation and safeguarding - Teaching and outreach - Research and dissemination
Crotti	- *Crotti* clusters (e.g., Chiavenna - Pratogiano, Poiatenco, Pianazzola etc.; Piuro - Scilano, Cranna, Aurogo, etc.)	- Several dining establishments - Tourism initiatives - Publications/guides - Local traditional festivals	- Tourism attractiveness - Spreading of cultural identity
Subglacial landforms (marmitte)	- Marmitte dei Giganti Natural Reserve - Paradiso archaeo-botanical Park	- Illustrative panels - Thematic itineraries - Publications/guides	- Conservation and safeguarding - Teaching and outreach - Research and dissemination
Ancient Piuro and 1618 landslide	- Archaeological excavation sites - Belfòrt area - Vertemate-Franchi Palace - Piuro Archaeological Museum	- Publications/guides - Illustrative panels - Thematic itineraries - Informative events - AMALPI Center	- Teaching and outreach - Research and dissemination - Risk awareness - Conservation and safeguarding

(Compagnucci and Spigarelli 2020). Outreach activities of this kind contribute to enhance public perception on local geoheritage conservation, education, and even natural hazard awareness (Fig. 13). This example of local geoheritage valorization could serve as a model for other regions, particularly along the Alps, where geology and human history are closely intertwined and deserve recognition and appreciation.

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Declarations

Competing interests The authors have no competing interests to declare that are relevant to the content of this article.

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