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The 'management perimeter': A proposal for effective conservation of geomorphosites

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A R T I C L E I N F O

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A B S T R A C T

Geomorphosites, i.e. geosites with geomorphological interest, have a great spatial variability. Geomorphological heritage is visible at all scales, thus the area of a geomorphosite may include a single landform, groups of landforms, up to larger portions of a landscape. However, in many cases, landforms and processes included in the area of a geomorphosite interact with other processes acting outside of it. Therefore, the evolution and eventual degradation of the geomorphosite can be affected by active processes outside its perimeter, be they natural or anthropogenic. This poses an issue in geoconservation and geoheritage management – the perimeter of the site may be not enough to ensure its conservation and prevent it from degradation. In this paper the identification of a second perimeter, called the 'management perimeter' (MP), is proposed for each geomorphosite. The MP is delineated on a geomorphological basis, by individuating the active processes which influence the evolution of the geomorphosite, and including the whole area on which they act. Thus, the extent of the MP depends on the intrinsic characteristics of the geomorphosite and the surrounding geomorphological context. The methodology was tested on two study areas: the Liguria region (North-western Italy), and the Hérens valley (Valais canton, Switzerland), which are characterised by very different geomorphological settings, thus they permit to apply the methodology on a wide variety of geomorphosites. The identification of a MP based on geomorphological evidence could allow for effective conservation and management. The results of this research highlight the systemic dimension of geomorphology and geomorphosites, and emphasise how a systemic look has great significance when dealing with the issues of geoconservation.

1. Introduction

Among all the various types of geosites, geomorphosites (i.e., geosites of geomorphological interest) have specificities that differentiate them from others. These specificities are threefold (Reynard, 2009; Coratza and Hobléa, 2018): i) the aesthetic dimension (Reynard, 2020), whereby geomorphosites have a preponderant aesthetic as well as scientific value; ii) the dynamic dimension, because geomorphosites display the processes that currently shape the Earth's surface; iii) the imbrication of scales, because geomorphological heritage is visible at different scales, from a single landform to the whole landscape (Grandgirard, 1997; Bussard and Reynard, 2022).

Concerning the dynamic dimension, geomorphosites are divided in two categories: i) active geomorphosites, where the active process is the same one that generated and modelled the geomorphosite, and ii) passive or inactive geomorphosites, generated in the past by processes that are no longer active, and currently modelled by other processes (Reynard, 2004; Coratza and Hobléa, 2018). In the case of active geomorphosites, the main interest is often the active process as such, and not so much the landforms associated with it. In contrast, in inactive geomorphosites, the interest lies in relict landforms, and current active processes contribute to their dismantling, constituting a factor of degradation (Pelfini and Bollati, 2014).

Geomorphosites, and geosites in general, can vary greatly in size, depending on which is the main element of interest: a single landform, a group of landforms, a process, or a group of interacting processes. Over the years, a number of proposals have been made for the spatial classification of geomorphosites (Grandgirard, 1997; Perret, 2014; Santos et al., 2019; Coratza et al., 2021; Bussard and Reynard, 2022; Santos et al., 2022). These classifications follow two paths. The first

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distinguishes the geometry of the geomorphosite, which can be point, linear or areal (or polygonal) – the latter of which can be more or less complex (Fuertes-Gutiérrez and Fernández-Martínez, 2010). This distinction depends on the needs of digitising geomorphosites within a database, and is highly dependent on the adopted survey scale – a geosite may be considered point-like at a given scale but can be considered areal if it is surveyed at a more detailed scale.

The second way concerns the number and complexity of geomorphological features included within the geomorphosite. Adopting the definitions of Grandgirard (1997) and Santos et al. (2022) one can distinguish: i) single landform; ii) group of landforms, similar to each other; iii) geomorphological complex, when there are several landforms united by the same morphogenetic process; and iv) geomorphological system, when there are several landforms modelled by different morphogenetic processes. A slightly different proposal was made by Coratza et al. (2021), which discerned: i) simple geomorphosites, i.e. single landforms related to one dominant genetic process; ii) composite geomorphosites, i.e. groups of landforms related to one dominant genetic process; and iii) complex geomorphosites, i.e. group of landforms related to more than one dominant genetic process.

It is important to note that the spatial delineation of geomorphosites depends not only on the geomorphological context, but also on the surveyor compiling the inventory. There is a degree of subjectivity in assigning a value to a given geomorphological context and in deciding which and how many geomorphological elements have value (Cameron, 2024).

The specificities of geomorphosites pose issues during the phase following the inventorying, i.e., the geoconservation phase in its broadest sense (Henriques et al., 2011; Crofts and Gordon, 2015; Reynard et al., 2016; Brilha et al., 2018; Coratza et al., 2021). According to Prosser et al. (2018), geoconservation is divided into two main phases: (i) conservation needs analysis, in which the use of the geosite is defined and the threats to which it may be exposed are identified; and (ii) conservation planning and delivery, in which the actual management, conservation and monitoring actions are decided and applied.

In the 'conservation needs analysis' phase, one of the fundamental requirements to be achieved is the analysis of the degradation risk of the geosite (Wimbledon et al., 2004; Gordon, 2019). Although there is still no scientific consensus on the methodologies to be adopted for degradation risk analysis, the assessment is generally based on the concepts of fragility and vulnerability, which have been used in research over the last 20 years (e.g., Sharples, 2002; Gray, 2004; Carcavilla Urquí et al., 2007). García-Ortiz et al. (2014), in a review of the specific terminology, define fragility as "the sensitivity of a geosite to being damaged or destroyed by intrinsic factors", and vulnerability as "the sensitivity of a geosite to being damaged or destroyed by extrinsic factors that are natural or anthropic in origin". In recent years, a number of geosite degradation risk assessment methods have been introduced, both qualitative (e.g., García-Ortiz et al., 2014) and quantitative (e.g., Brilha, 2016; Selmi et al., 2022). In many cases the quantitative assessment of degradation risk is incorporated within the broader geosite assessment procedure (Brilha, 2018).

In the degradation risk assessment and particularly in the analysis of geomorphosite vulnerability, the spatial issue is particularly important (Sharples, 2002; Pescatore et al., 2023). The process that shapes the geomorphosite may act over an area much larger than the one inside the perimeter, for instance a fluvial landform is influenced by processes happening upstream in the river catchment. In other cases, a disturbance to a geomorphological process acting even several kilometres away from the geomorphosite may alter the dynamics of the geomorphosite itself. Therefore, a question arises: how far away from the geomorphosite should one look in order to have a correct assessment of the risk of degradation of the geomorphosite itself? The spatial variability of geomorphosites can make the answer rather complex and varied.

In this work, the identification of a second perimeter – called 'management perimeter' (MP) – is proposed for each geomorphosite. The MP is defined on a geomorphological basis, and it includes a more or less extensive area around the geomorphosite in which geomorphological processes directly contribute to its evolution. Thus, the MP could be useful for effective geoconservation planning (e.g., Gordon, 2019), as it constitutes a geomorphological evidence based 'buffer zone' around the 'core zone' of the proper geomorphosite.

The methodology was tested on two inventories of geomorphosites, in Liguria (northwestern Italy) and the Hérens valley (Valais canton, Switzerland). The two areas are quite different in terms of their geographical and geomorphological context: Liguria is a region facing the sea, with a considerable variety of environments from coastal to mid-mountain; Hérens valley is a mountain valley located in one of the highest parts of the Alps. The two areas therefore provide a very broad spectrum of geomorphological processes and landforms, and related geomorphosites.

2. Study areas

2.1. Liguria (north-western Italy)

Liguria (Fig. 1a) is a region located in the north-western part of Italy. In the south it is bordered by the Ligurian Sea, in the west it borders France and on the other sides the Italian regions of Piedmont, Emilia-Romagna and Tuscany. The region's territory is almost completely mountainous, with the arc of the Ligurian Alps (Mt. Saccarello, 2201 m) and the Ligurian Apennines (Mt. Maggiorasca, 1804 m) rising immediately behind the sea. Due to the proximity of the mountain watershed to the Ligurian Sea, the slopes facing the sea are very steep and narrow, with short watercourses. The opposite side of the Alpine-Apennine chain drains towards the basin of the Po River, which flows into the Adriatic Sea. This slope is wider, with longer and gentler valleys.

Liguria is set at the meeting point of two orogens: the Alps and the Apennines, which overlap in a vast area known as the 'Ligurian Knot' (Molli et al., 2010; Capponi et al., 2016) and make up for high geological diversity. In the western portion of the region, the Alpine tectonic-metamorphic units outcrop, subdivided into the following domains from top to bottom (Cortesogno and Vanossi, 1984): i) Provençal Domain, corresponding to the European Palaeocontinent; ii) Brianzonese and Pre-Piedmontese Domains, corresponding with the Palaeo-European continental margin; and (iii) metamorphic Ligurian-Piedmontese units, of oceanic origin. To the east lies the Northern Apennines fold and thrust belt, consisting of: (i) non-metamorphic oceanic Ligurian and Subligurian Units; and (ii) Tuscan Units, corresponding with the Palaeo-African continental margin (e.g. Marroni et al., 2010 and references therein). The Alpine-Apennine tectonic units are overlain in discordance by less deformed *syn-* and post-orogenic sedimentary rocks.

The geomorphology of the region is dominated by gravitational and fluvial processes, as well as coastal processes in the area adjacent to the sea. The whole morphological asset of the region is strongly influenced by Quaternary uplift, that brought a rerejuvenation of the Ligurian Alps-Apennines mountain chain (Fanucci and Nosengo, 1977; Ferraris et al., 2012). Fluvial valleys are steep and narrow, especially on the southern side of the mountains, while gentle undulating paleo-surfaces are found on the watersheds – sometimes these paleosurfaces extend for several tens of kilometres (e.g. Mt. Beigua massif, in the interior between Savona and Genoa). The hydrographic network is strongly influenced by Quaternary tectonics as well. The main watercourses are sub-perpendicular or sub-parallel to the direction of the main Alps-Apennines watershed. Stream capture elbows, entrenched meanders, gorges and waterfalls are frequent along the watercourses (Fanucci and Nosengo, 1977).

Recent uplift is evident also along the coastline, where marine terraces and erosional surfaces have been dated from the Pliocene onwards (Carobene and Firpo, 2002; Carobene et al., 2010). The coast is predominantly high and rocky, with cliffs that can reach heights of up to

Fig. 1. Geographical setting of the two study areas. a) Liguria; b) Hérens valley (1) and Réchy valley (2). Elevation and shaded relief taken from SRTM data; other elements are OpenStreetMap data. The background for the overview map is the ESRI shaded relief map.

300 m. The low stretches of coastline are located at the mouths of the main watercourses and are heavily anthropised. Many beaches are naturally receding and are maintained through periodic beach nourishment (Corradi et al., 2004).

The Ligurian mountains are greatly affected by gravitational processes: from rapid surface landslides triggered by intense weather phenomena (Brandolini et al., 2018; Roccati et al., 2018; Pepe et al., 2019), to slow and complex landslides that host many of the inland settlements (Allasia et al., 2021; Balbi et al., 2021). A widespread phenomenon, especially in the Ligurian Apennines, are deep-seated gravitational slope deformations (DSGSD; Faccini et al., 2009a; Sacchini et al., 2016), especially in the very heterogeneous rock masses of the Ligurian Units.

Liguria is characterised by the presence of numerous karst areas, with more than 2000 caves catalogued in the Regional Inventory of Caves (https://www.catastogrotte.net/liguria/it/map_caves/, *accessed on July 2024*). Most of them are developed in heavily deformed Mesozoic limestones and dolomites, belonging to the Alpine and Apennine tectonic units. Only the Finalese karst area, west of Savona, is characterised by a dissected karst plateau, developed in post-orogenic Miocene limestones (Brandolini et al., 2011).

In the higher portions of the Ligurian Alps and Ligurian Apennines, relict landforms of periglacial origin can be found, tentatively dated to the Last Glacial Maximum (LGM; Firpo et al., 2006; Rellini et al., 2014). In the Ligurian Alps, near Mt. Saccarello, small relict glacial cirques related to the last glaciation are observed, while their presence in the Ligurian Apennines is debated (Faccini et al., 2012).

2.2. Hérens valley and Réchy valley (Valais, Switzerland)

The Hérens valley (Fig. 1b) is located in the canton Valais in Switzerland, south of the capital Sion. It lies on the northern slope of the Pennine Alps, and joins the Rhone valley floor at Bramois, a hamlet of Sion. In just a few kilometres, the valley overcomes a considerable difference in altitude, stretching from Dent Blanche (4357 m) to the approximately 500 m of Bramois. The valley is drained by the Borgne River, and is divided into several branches. The Réchy valley lies immediately to the east of the Hérens valley, between the latter and the Val d'Anniviers.

From a geological point of view, the Hérens and Réchy valley traverses from south to north the main tectono-metamorphic units of the Western Alps, consisting of: (i) continental margin units belonging to the Austroalpine domain; (ii) ophiolitiferous oceanic units belonging to the Penninic domain; and (iii) continental margin units belonging to the Penninic domain (Steck et al., 1999).

From a geomorphological point of view, the two valleys are mainly marked by glacial, periglacial, gravitational and fluvial processes (Delaloye, 2004; Lambiel et al., 2016; Lambiel, 2021). Glacial and glaciolacustrine deposits dating from the Lateglacial period can be observed in the valley. Some of these deposits, subsequently modelled by runoff erosion, gave rise to distinctive landforms such as the Euseigne earth pyramids (Bollati et al., 2016, 2017). Active glaciers are located in all the upper reaches of the valley. They are in severe retreat due to climate change, which makes these environments very dynamic (Lane et al., 2017; Carrivick et al., 2018).

The lower limit of discontinuous permafrost is located approximately between 2400 m and 2700 m (Lugon and Delaloye, 2001; Lambiel and Reynard, 2003). Above this altitude, active periglacial landforms, including numerous rock glaciers, can be observed (Delaloye, 2004; Delaloye et al., 2010). Extensive relict rock glaciers, formed in the Lateglacial, are also present at lower altitudes (Lambiel et al., 2016).

Gravitational phenomena are frequent in the valley, often remobilizing morainic deposits. Talus slopes are widespread in the higher stretches of the valley, fed by frequent rock falls (Lambiel et al., 2016). In the northern part, numerous DSGSDs due to paraglacial decompression can be recognised (Lambiel et al., 2016). Torrential activity is widespread in the steep side basins of the valley (Maillard et al., 2013). The main watercourses have a stepped profile, with suspended flood plains connected by entrenched stretches.

As far as anthropogenic action is concerned, the Hérens valley has been marked by exploitation for hydroelectric production. The Hérémence side valley hosts the Grande Dixence dam, the highest in Europe (285 m), and its reservoir (Lac des Dix). In order to supply water to the lake, a huge system of water intakes and tunnels has been built involving many upper branches of the Printse, Hérens and Vispa valleys (Park, 1980). This influences the hydrological and sedimentological regime of the streams in these valleys, as well as their ecology (Bezinge et al., 1989; Gabbud and Lane, 2016; Bakker et al., 2018; Gabbud et al., 2019).

From here on in the text, we will refer to the study area of the Hérens and Réchy valleys as simply “Hérens valley”.

3. Materials and methods

3.1. Inventory of geosites of Liguria (Italy)

In Liguria, 120 geosites have been recognised and assessed in previous studies (Ferrando et al., 2021, 2023b). Among them, 97 have become part of the Italian National Inventory of Geosites (http://sgi.isprambiente.it/GeositiWeb/default.aspx?ReturnUrl=%2fGeositiWeb%2fricerca_geositi.aspx, *accessed on September 2024*).

The inventory includes geosites of all types and primary interest, from stratigraphy to hydrogeology. For this research, 73 geomorphosites were considered from the inventory by Ferrando et al. (2021), i.e., those geosites for which geomorphology was reported as a primary or secondary interest (Fig. 2). Out of the geosites considered, the most represented morphogenetic processes are fluvial (17 sites), structural (14 sites), gravitational (12 sites), karst (11 sites) and coastal (11 sites).

In terms of spatial classification according to Grandgirard (1997) and Santos et al. (2022), the most abundant class is that of single landforms (29), followed by group of landforms (21), geomorphological complex (12) and finally geomorphological system (7). There are 59 active geomorphosites and 14 inactive geomorphosites.

3.2. Inventory of geomorphosites of Hérens valley (Valais, Switzerland)

The inventory of the Hérens valley consists of 44 geomorphosites (Fig. 3), selected from previous work by Grangier (2013, unpublished), Reynard et al. (2016) and Santos et al. (2019), supplemented with data from new field surveys. Four of these sites are part of the inventory of Swiss geotopes (available online at: map.geo.admin.ch, *accessed on September 2024*).

The most represented category is that of glacial geomorphosites (11), then fluvial (9) and periglacial (6). From the point of view of spatial classification according to Grandgirard (1997) and Santos et al. (2022), the most abundant class is that of single landforms (16), followed by geomorphological systems (13), groups of landforms (12) and finally geomorphological complexes, which are less represented (3). 33 geomorphosites are active, while 11 are inactive.

3.3. Delineation of the management perimeter

The delineation of the MP is based on a site-specific geomorphological analysis, which takes into consideration both the area included in the perimeter of the geomorphosite and the morphological context in which it is located. To identify the MP, three phases are proposed: 1) identification of the geomorphological processes that contribute to the evolution of the site; 2) analysis of the time scale on which these processes act; 3) delineation of the area interested by these processes.

Phase one involves the identification of the ‘reference active processes’, i.e. the geomorphological process (or processes) that act on the site, modifying it and in some cases leading it to degradation or destruction. In the case of active geomorphosites, the main reference active process is the genetic one (i.e., the glacial process in glacial geomorphosites etc.), but there can be other different processes interacting with it. In the case of inactive geomorphosites, the genetic process is not active anymore, and the reference active processes are different from it. In this framework it's useful to define a third category, that is ‘stabilised geosites’. This category includes geomorphosites which have been stabilised by human action, at least in a short time scale.

The time scale of the geomorphological process(es) active in the reference area is an issue to be considered. As far as this work is concerned, only those processes that can produce substantial modifications to a geomorphosite on a short time scale (100 years, roughly corresponding with a human lifetime) have been considered. Processes producing evolution on a longer time scale were not taken into account.

Once the reference active processes were identified, the perimeter of the area over which these processes are active was established. Specific methodological indications are given in Section 3.4.

3.4. General procedures for the delineation of the management perimeter

While the process to delineate the MP is primarily site-specific, some categorizations can be made, taking into account the state of activity and the morphogenesis of the geomorphosites. Active geomorphosites have been grouped by the primary morphogenetic agent, according to the categories proposed by Reynard et al. (2016). Among them, seven are relevant for the considered geomorphosites: coastal, fluvial, glacial, gravitational, karst, periglacial and structural geomorphosites. One more category has been added for geomorphosites in which a primary

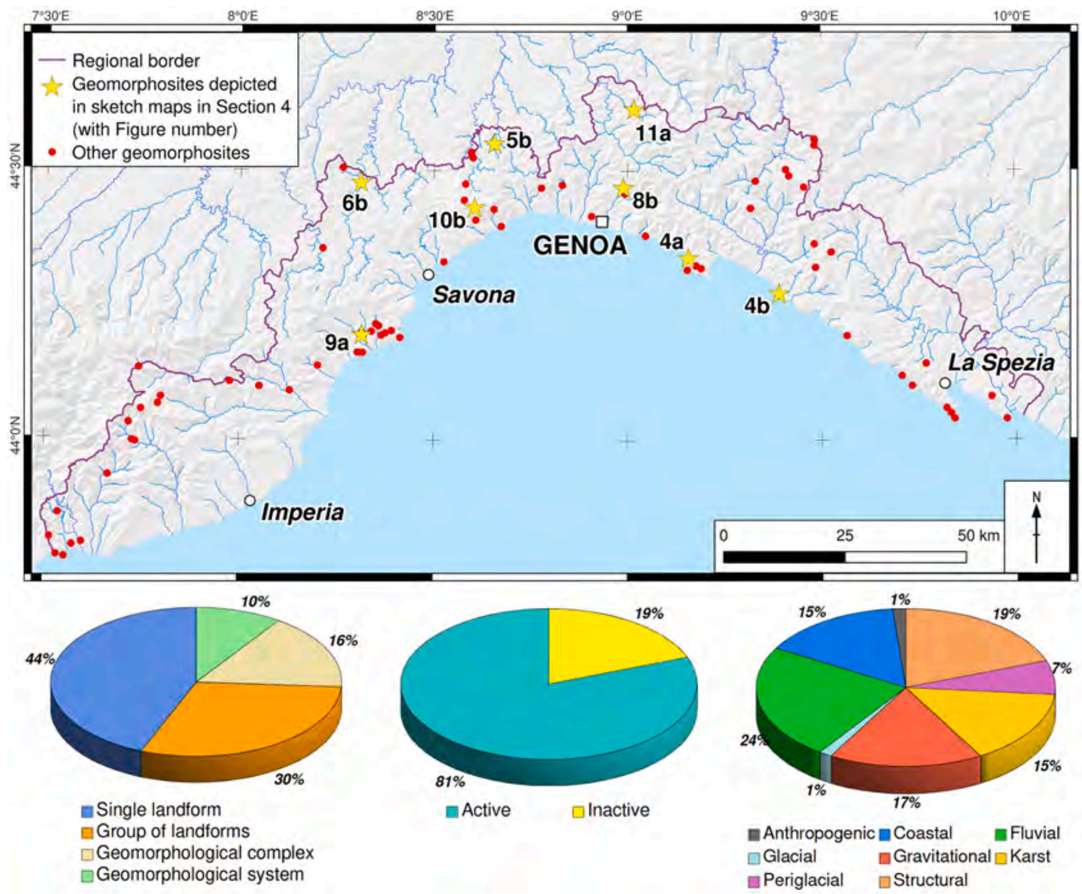

Fig. 2. Distribution of geomorphosites in Liguria. The diagrams show the spatial classification (according to Grandgirard, 1997; see Section 1 for further detail), the state of activity and the primary morphogenetic agent of the geomorphosites.

morphogenetic agent cannot be identified, such as slope systems or other geomorphological systems. For each category, the general procedures are summarized in Table 1.

In the case of coastal erosional landforms, the MP was made to coincide with the perimeter of the landform, plus a buffer above wavebase. The extent of the buffer therefore depends on the depth of the seabed. Considering the submerged part is important, as changes in the submerged part may influence the evolution of the emerged part. Geomorphosites involving coastal depositional landforms are unfortunately lacking in the inventory we considered, so they have not been addressed.

The evolution of active depositional fluvial landforms is directly dependent on sediment availability in the catchment area leading to the landform itself. Changes in water and sediment supply in the upstream catchment directly and rather rapidly influence the evolution of the landform. Thus, the MP should include the whole hydrographic basin upstream of the landform. Erosional fluvial landforms on rock substratum (gorges, embedded meanders, waterfalls) can be considered stable at the human time scale. For their management, other than the geomorphosite itself, lateral basins can also be included, if deemed appropriate. For geomorphosites including landforms due to runoff erosion (i.e. badlands, earth pyramids), the MP should include the whole area affected by denudation. In some cases, the MP could be extended downstream of the runoff landforms to account for regressive erosion.

Active glacial geomorphosites are a particularly complex and dynamic category of geomorphosites. The glacial complex consists of a heterogeneous set of landforms, comprising the glacier and its proglacial area, i.e. the area between the current glacial front and the moraines of the Little Ice Age (19th century; Schiefer and Gilbert, 2007; Slaymaker, 2011; Bollati et al., 2023), which corresponds to the last major stage of advancement before the current retreat phase. Within this, one can find active glacial landforms (the glacial tongue, cirque, present-day moraines, etc.), active fluvio-glacial landforms (the proglacial plain) and inactive landforms (the LIA moraines) that evolve passively, shaped by paraglacial processes. The strong retreat of Alpine glaciers due to ongoing climate change means that this set of landforms and processes is constantly and rapidly evolving with the expansion and upward migration of the proglacial area (D'Agata et al., 2020). The rapid evolution of the glacial system results in the evolution of its heritage values, that will depend more and more on inherited landforms rather than the active glacier itself (Bussard and Reynard, 2023). Moreover, in the areas recently abandoned by glaciers, there is an important ecosystem response, with the development of a vegetational sequence starting with pioneer species and and culminating with the forest (e.g., Matthews, 1992). For this reason, in the case of active glacial geomorphosites, the entire geomorphological system comprising the current glacier and its proglacial area should be included inside the MP.

With regard to gravitational geomorphosites, the MP depends on the type of movement, its speed, the factors triggering the movement and the extent of the source area.

Hypogean karst landforms are peculiar because they are typically represented as point geosites, where the point corresponds with the entrance to the cave. However, they present a hypogeal development that can be more or less important, and that can even extend far from the entrance where the point geosite is located (Gauchon et al., 2007; Hobléa et al., 2008). In the case of geomorphosites with internal circulation, i.e. active cave systems and karst springs, the MP has been made to coincide with the entire hydrogeological basin leading to the spring. If the limits of the hydrological basin are not known, the entire extension of the karst complex to which the cave belongs, and any non-karstic basins pertaining to it, can be considered as a precautionary

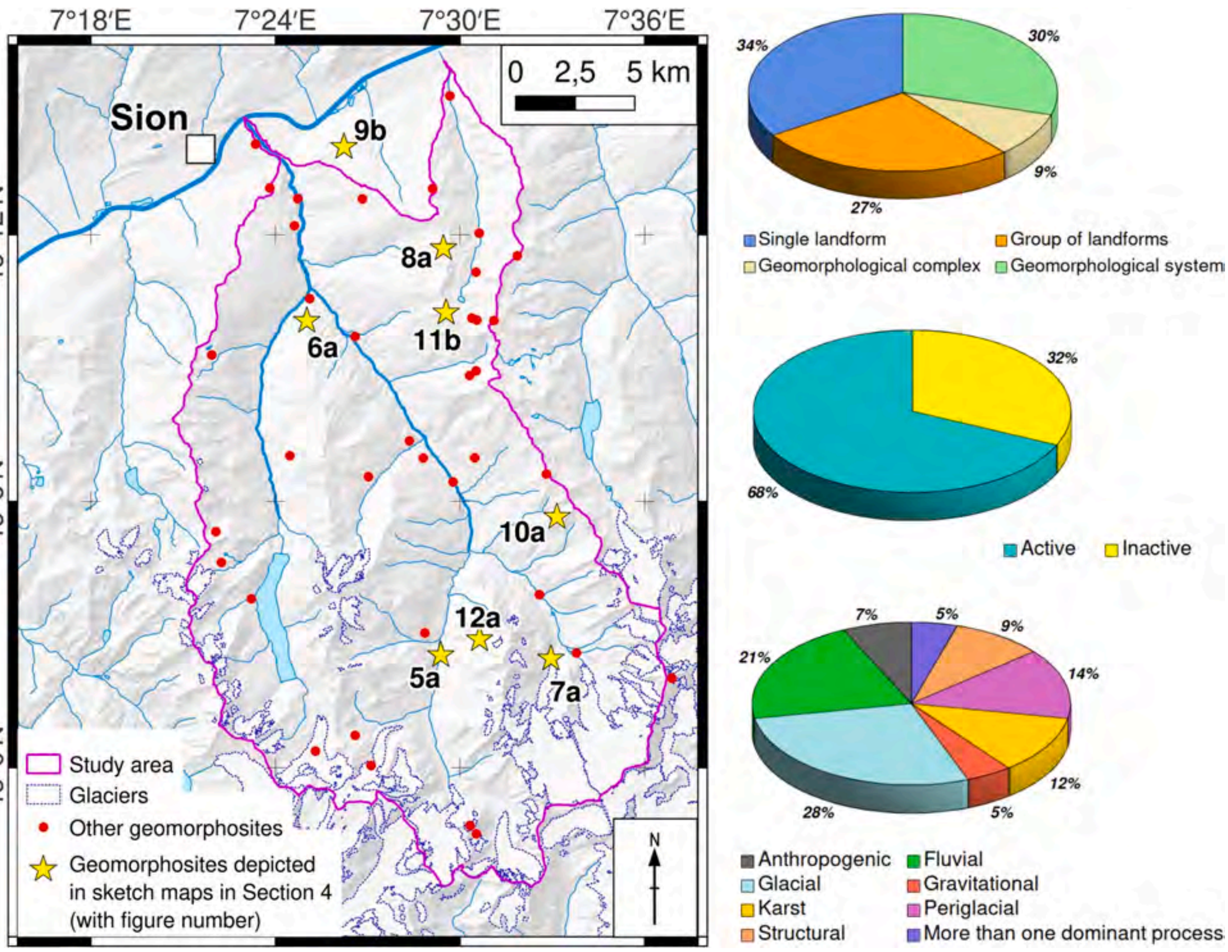

Fig. 3. Distribution of geomorphosites in the Hérens valley (Switzerland). The diagrams show the spatial classification (according to Grandgirard, 1997; see Section 1 for further detail), the state of activity and the primary morphogenetic agent of the geomorphosites.

measure. In the past, there have been examples of karst sites that have undergone severe degradation due to mismanagement of the karst area, e.g., the Hidden River Cave in Kentucky, USA, (Worthington, 2011) and caves in the Apuan Alps, Italy (Nannoni et al., 2021).

In the case of epigean karst landforms such as dolines and poljes, the hydrographic basin has been delimited, as any phenomena occurring in the basin in question may affect the geomorphological dynamics of the landform itself (e.g., obstruction of a sinkhole with sediment following a landslide).

The MP of periglacial geomorphosites have been delineated to include the main periglacial landform(s) and the source area of the rock material which feeds them.

In the case of structural geomorphosites, the MP depends on their intrinsic characteristics – such as type and heterogeneity of the bedrock, and the structure of the landform – but also on the type, velocity and extent of other processes shaping them (e.g., gravity, runoff erosion, glacial erosion etc.). Slender rock towers are more fragile than a massive pyramid-shaped mountain. Generally speaking, the MP may coincide with the perimeter of the geomorphosite, with at most a buffer further up or down the slope if evident regressive erosion phenomena are identified.

High mountain slope systems have been considered as a category of their own, as a prevailing morphogenetic agent is not clearly identifiable. In most of these cases, the geomorphosite perimeter include the whole slope, from the watershed to the valley floor – as the interest of these geomorphosites lies in the visibility of the different processes of sediment transfer from the high parts of the slope, which act as a source, to the foot of the slope, and their contribution to the sediment cascade (Davies and Korup, 2010). If the geomorphosite perimeter includes the whole slope, the MP matches it; if not, the MP should be extended to include the whole slope.

In the case of inactive geomorphosites, the MP depends on the type and extent of the current active processes. In the case of stabilised geomorphosites, the natural evolution of the landforms is constrained by anthropogenic action, so the MP matches the perimeter of the geomorphosite.

4. The management perimeters of geomorphosites: examples from the study areas

Significant cases from the investigated study areas are given below, divided by morphogenetic agent. A simplified geomorphological sketch is provided for the selected cases, including the perimeter of the geomorphosite, the proposed MP and the main landforms present in the area. For each example, the rationale behind the delineation of the MP is briefly explained. The location of the geomorphological sketches in Figs. 4–12 in the context of Liguria Region and the Hérens valley is given in Figs. 2 and 3.

4.1. Coastal geomorphosites

The San Rocco di Camogli geomorphosite (Liguria; Fig. 4a, c, d) includes one of the most prominent coastal cliffs in Liguria (Brandolini et al., 2007; Faccini et al., 2009b, 2018). The cliff is about 1 km wide, approximately 90 to 250 m high, set on weak, highly folded and fractured marly-limestone flysch. In this vast geomorphological system,

Table 1
Summary of the methods used to delineate the MP of geomorphosites. More detailed explanations are given in Section 3.4. The table reports only cases analysed in the paper.

State of activity	Morphogenesis	Methodology to delineate the management perimeter (MP)	
Active	Coastal	- *Erosional landforms*: the MP includes a buffer corresponding to the area of seabed interacting with the waves.	The MP delineated with the indications given on the left was then reassessed, taking into account local geomorphological conditions (e.g. the presence of other active processes interfering with the main one, evidence of the geosite being disconnected from areas included in the MP etc.)
	Fluvial	- *Depositional fluvial landforms*: the MP encompasses the whole hydrographic basin uphill of the landforms - *Erosional fluvial landforms*: the MP matches the perimeter of the geomorphosite. It can be extended to lateral basins leading to the geomorphosite, if deemed necessary. - *Runoff landforms*: the MP includes the whole area affected by runoff erosion in which the geomorphosite is located, i.e., also downstream due to regressive erosion processes.	
	Glacial	The MP includes the glacial system and its proglacial area.	
	Gravitational	The MP depends on the type of movement, its speed, the factors triggering the movement and the extent of the source area.	
	Karst	The MP includes the whole hydrogeological basin in which the geomorphosite is included. If the limits of the hydrogeological basin are not known, the MP should include the whole exokarst system.	
	Periglacial	The MP includes the periglacial landform(s) and the source area of the rock material shaped by the periglacial process.	
	Structural	The MP matches the perimeter of the geomorphosite. A buffer up or down the slope can be added if evident regressive erosion or other phenomena are identified.	
	Slope systems	The MP includes the whole slope, from the watershed to the valley floor.	
Inactive	All	The MP depends on the extent of the current active processes shaping the geomorphosite	
Stabilised	All	The MP matches the perimeter of the geomorphosite	

many different gravitational phenomena can be observed, triggered by the erosive action of the sea at the foot of the cliff. The rapid evolution of the geomorphosite constitutes a factor of risk for the village of San Rocco, located on the edge of the cliff itself. The perimeter of the geomorphosite encompasses the whole geomorphological system. The MP has been extended to include submerged areas above wavebase.

The Sestri Levante tombolo (Liguria) is shown in Fig. 4b, e. The gravelly-sandy tombolo connects the mainland to a small island, and hosts the historical centre of the city of Sestri Levante. Under natural conditions, the sedimentary contribution to the tombolo would depend on sediment supply by nearby rivers and streams (Cortemiglia, 1987). Currently, the tombolo is stabilised by the presence of the built-up area, while coastal defences have reduced the sedimentary input from nearby watercourses. The two beaches on either side are maintained by periodic nourishment (Di Matteo and Milli, 2008). As the geomorphosite is stabilised by anthropogenic activity, the proposed MP coincides with the perimeter of the geomorphosite.

4.2. Fluvial and runoff geomorphosites

In the case of the Satarma alluvial plain (Hérens valley; Fig. 5a, c), the MP encompasses the entire basin upstream of the alluvial plain, as sediment availability is influenced by geomorphological processes taking place throughout this area (Lambiel et al., 2016), while water availability depends essentially on snow and glacier melt. Both factors are also influenced by anthropogenic action, and especially by the presence of numerous water intakes along the tributaries of the Borgne d'Arolla, which bring water to the Lac des Dix reservoir located in the adjacent valley (Gomez, 1983; Bakker and Lane, 2017; Bakker et al., 2018).

The alluvial fan of Bramois (Hérens valley; Fig. 5d) is located at the point where the Borgne river flows into the Rhone valley. In natural conditions, the supply of sediment to the fan would depend on sediment availability and hydrological regime in the valley upstream. Thus, the MP could hypothetically extend over the entire Hérens valley. However, the fan has been extensively modified by anthropic action (Brandolini et al., 2020) and its natural evolution is therefore impeded. For this reason, the MP has been made to coincide with the limits of the geomorphosite.

The Val Gargassa geomorphosite (Liguria), which includes a gorge carved in Oligocene conglomerates (Marescotti et al., 2022), is shown in Fig. 5b, e. The geomorphosite as a whole is rather stable, but gravitational phenomena – such as rock falls and debris flows – can occur during particularly intense meteorological events. They do not lead to a loss of integrity of the geomorphosite, but rather to the degradation of individual elements within the site (e.g. collapse of rock towers in the 1970s is documented in local chronicles; Calissano et al., 1999), or to the interruption of the visitor path, thus posing problems for the fruition of the site itself.

For what concerns geomorphosites including runoff landforms, examples are shown in Fig. 6. The Euseigne earth pyramids (Hérens valley; Fig. 6a, c), carved into Lateglacial morainic deposits (Lambiel, 2021) are one of the best-known geomorphosite in the Hérens valley. They have been extensively studied in terms of their rate of evolution and geoheritage value (Bollati et al., 2017, 2016). The geomorphosite includes not only the main earth pyramids, but also other denudated areas to the north-east, with pseudo-badlands and gullies. Since the perimeter of the geomorphosite extends to the entire outcrop of Quaternary deposits and as far as the valley floor, the proposed MP matches it.

The badlands and "stone mushroom" are the two main geosites of the Piana Crixia Natural Park (Ferrando et al., 2023a; Fig. 6d, e). In the surroundings of Piana Crixia (Liguria), badlands are particularly widespread at outcrops of Oligocene marls and claystones (Maerker et al., 2020). The geomorphosite comprises only a particularly significant and scenic part of these badlands, developed around a small impluvium. The proposed MP matches the perimeter of the geomorphosite.

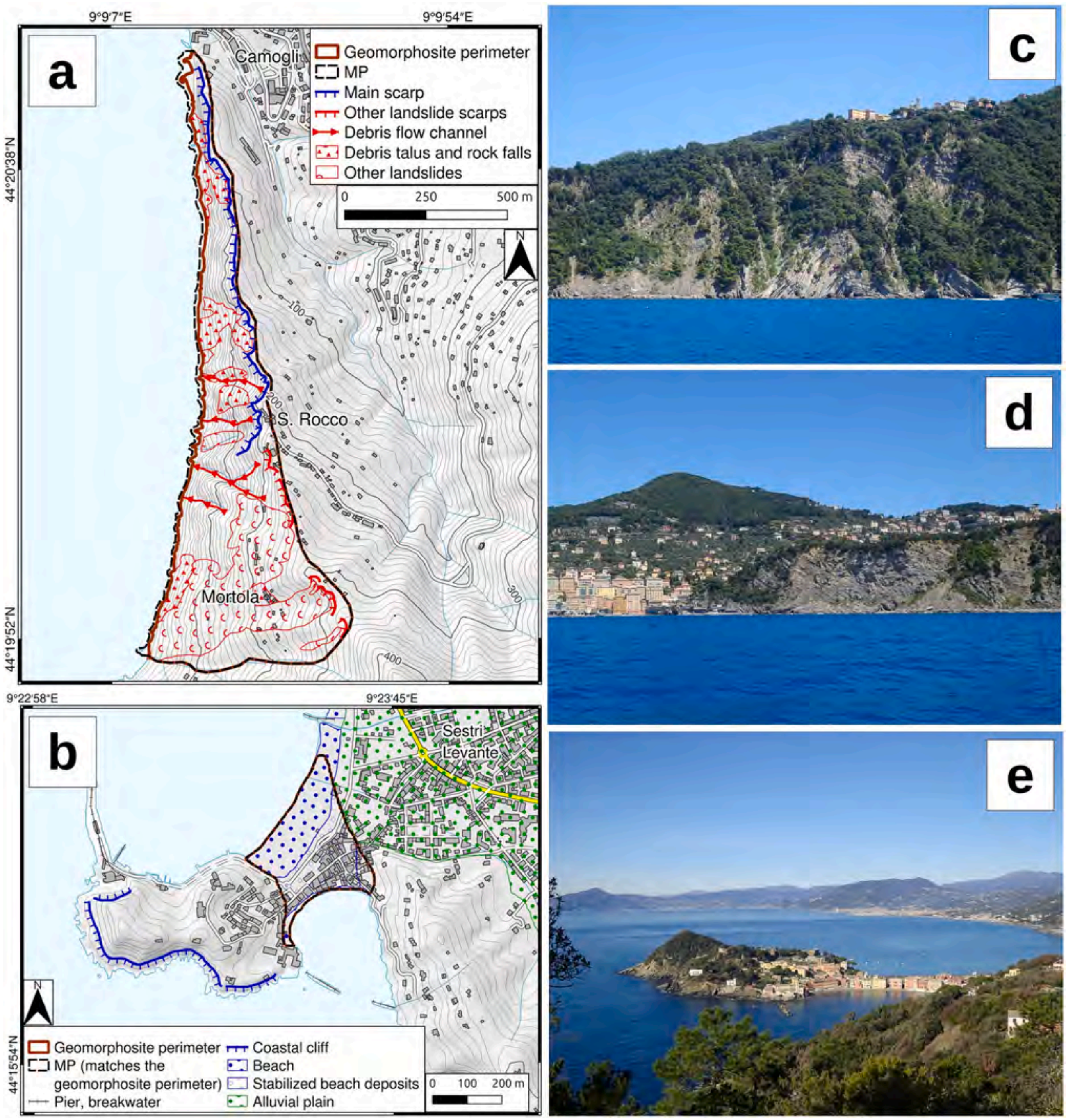

Fig. 4. a) Geomorphological sketch for the San Rocco geosite; b) Geomorphological sketch for the Sestri Levante geosite; c) The hamlet of San Rocco above the main scarp of the coastal cliff; d) The northern stretch of the San Rocco coastal cliffs, with the city of Camogli on the left; e) Sestri Levante and the "Isola" (i.e. the "island"). MP = management perimeter.

The Piana Crixia "stone mushroom" is a lone hoodoo, carved in Oligocene conglomerates. The morphogenetic process is similar to that of the Euseigne pyramids – runoff erosion on a very heterogeneous granular substrate – but the material is a consolidated rock. It is therefore likely that the rate of evolution of the "stone mushroom" is slower than in the Euseigne pyramids. As the "stone mushroom" is a single hoodoo, it has been mapped as a point geomorphosite. The proposed MP also includes the surrounding denudation scarp, which is genetically linked to it.

4.3. Glacial geomorphosites

The Mont Miné glacier (Hérens valley) is an interesting case in terms of the relationship between the extent of the geomorphosite and the area to be considered in the MP. The geomorphosite includes the Mont Miné glacial system (Fig. 7a), with the cirque, the tongue (Fig. 7b), its proglacial area and the LIA moraines (Fig. 7c). However, the evolution of this system is influenced by processes occurring in a much larger area, which also includes the valley of the Ferpècle glacier. During the LIA, the Ferpècle glacier flowed into the Mont Miné glacier (Bezinge and Kunz, 2001), while today, the two glaciers are separated. However, the proglacial stream of the Ferpècle glacier flows into the proglacial plain of

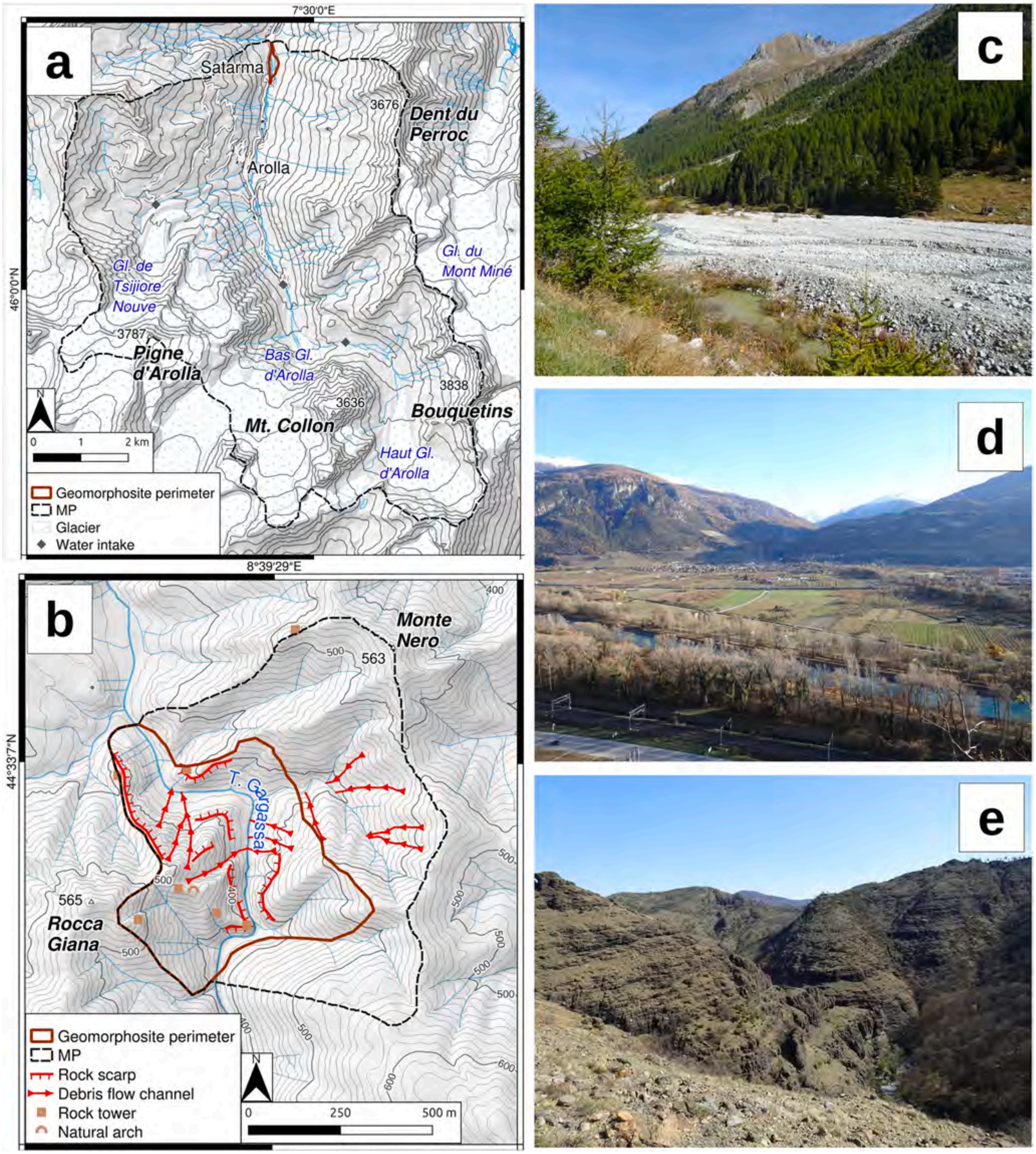

Fig. 5. a) Geomorphological sketch of the Arolla valley and the Satarma alluvial plain geomorphosite; b) Geomorphological sketch of the Val Gargassa geosite; c) The alluvial plain of Satarma; d) The Bramois alluvial fan (with the embanked Rhone river at the first plan); e) A stretch of the Gargassa gorge. MP = management perimeter.

the Mont Miné glacier, and thus influences its hydrological and sedimentological regime. The same applies to the various sub-basins with torrential systems that descend from the slopes of the main valley into the aforementioned proglacial area.

In the case of relict landforms, the cases analysed seem to be rather stable. The geomorphosite of the Lac Bleu moraines (Fig. 7d; Hérens valley) is particularly frequented by tourists and hikers. In this case, the main degradation factor is represented by the trampling of hikers, which leads to a rapid erosion of the turf that covers the moraines, and therefore also of the underlying soil (Santos et al., 2019). There's no need to extend the MP further. The glacial cirque of Mt. Frontè (Fig. 7e) is one of the few relict glacial cirques in the Liguria region. Active processes that cause the evolution of its slopes (mainly gravitational phenomena) are included inside the perimeter of the geomorphosite, so the MP matches it.

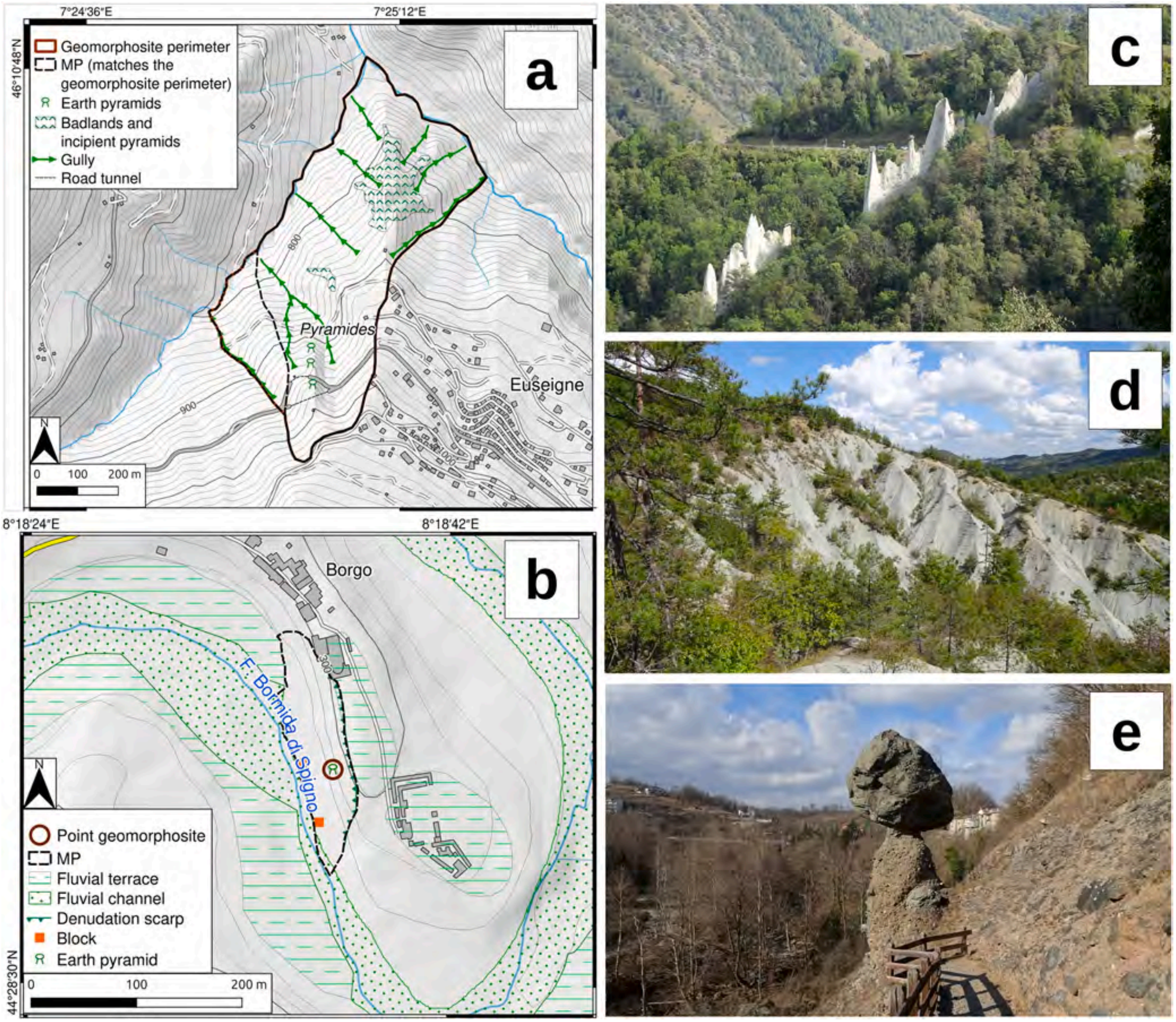

Fig. 6. a) Geomorphological sketch of the Euseigne earth pyramids; b) Geomorphological sketch of the Piana Crixia 'stone mushroom'; c) the Euseigne earth pyramids; d) The Piana Crixia badlands; e) The Piana Crixia 'stone mushroom'. MP = management perimeter.

4.4. Gravitational geomorphosites

Among gravitational geomorphosites, the Mont Gautier DSGSD trench (Hérens valley) is reported as a case study (Fig. 8a, c). The main active processes in the area of the geomorphosite are rock falls and gelifluction (Sartori and Epard, 2011), but none of these pose a particular threat to the integrity of the geomorphosite. For this reason, the MP follows the perimeter of the geomorphosite. In other cases (e.g., the geomorphosites of Agoraie, Pian d'Oneto, Lago di Bargone and Prato della Cipolla in Liguria), DSGSD trenches host wetlands of ecological importance (Aita et al., 1979; Faccini et al., 2009a). Thus, the management of these landforms encompasses both geoconservation and bioconservation.

An interesting case of a relict gravitational geomorphosite is represented by Prato Casarile (Genoa, Liguria), an ephemeral lake that originated due to a paleo-landslide (now inactive) that dammed the course of the Geirato stream. Prato Casarile, filled with fluvio-lacustrine sediments, appears for most of the year as a meadow (Fig. 8d), which only floods during intense and prolonged rainfall (Fig. 8e; Paliaga et al., 2019). The MP (Fig. 8b) has been extended downstream of the ephemeral lake because the Geirato stream, through regressive erosion, is slowly incising the landslide dam. The landslide body this constitutes a source of loose material, which is carried downstream during flooding events, such as the one that caused the Genoa flood of 1970 (Mandarino et al., 2021). Thus, Prato Casarile can be classified as a gravitational inactive geomorphosite, and the 'reference active process' is the fluvial one – regressive erosion on the landslide body and deposition on the ephemeral lake. The MP encompasses the entire Geirato basin upstream of the foot of the landslide body.

4.5. Karst geomorphosites

The Pollera-Buio karst complex (Liguria; Fig. 9a, c) has an underground development of just over 2 km. The Pollera Cave, an inactive swallow hole, constitutes its main entrance. The active part of the cave heads southwards, until it re-emerges at the Arma del Buio karst spring (Cosso et al., 2014). The main absorption points are located at the karst valley of Pian Marino, with other inactive swallow holes in the vicinities. The MP of the geomorphosite includes the entire hydrogeological basin leading to the Arma del Buio karst spring. While the western side of the

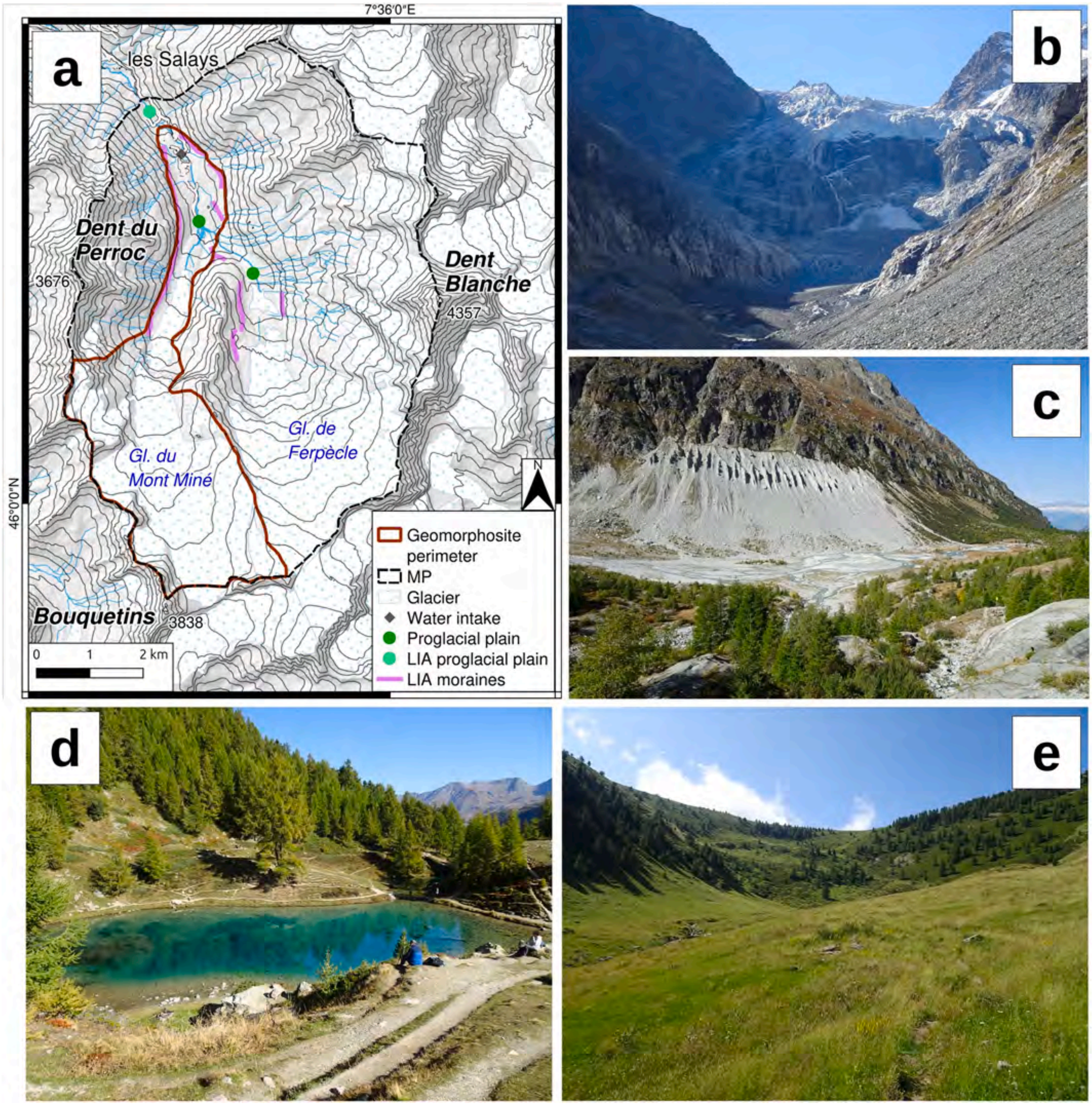

Fig. 7. a) Geomorphological sketch map of the Mont Miné glacier geomorphosite; b) The Mont Miné glacier, with the lower part of the glacier tongue disconnected from the upper part; c) The heavily eroded LIA moraine of the Mont Miné glacier, and the current proglacial plain; d) The Lac Bleu; on the surrounding slopes there is evident soil erosion due to hikers trampling; e) The relict glacial cirque of Mt. Frontè in the Ligurian Alps. MP = management perimeter.

basin is well defined, there is a lack of information concerning the eastern side, specifically on the underground path of the water that is absorbed in the dry valley south of Bric del Frate. Therefore, as a cautionary measure, the MP was extended to include this valley, which topographically falls within the adjacent catchment.

With regard to inactive caves the example given is the Grotta dell'Edera (Fig. 9d; Liguria), a small inactive cave consisting of two rooms, one underground and one partially epigean, with a rock arch. In the present state, the cave evolves essentially by gravitational phenomena (rock falls and collapses). The MP is a buffer around the cave.

The Nax dolines (Hérens valley; Fig. 9b, e) are a group of dolines developed on gypsum rocks (Bitterli, 1998; Santos et al., 2019). The area is rather urbanised, as the hamlet of Nax lies on the western edge of the geomorphosite. Only one of these swallow holes absorbs a perennial watercourse. The MP was drawn around the basins adjoining the dolines. In the eastern part, it was extended to include the Nax golf course because, according to the Swiss topographic map (map.geo.admin.ch), the golf course waters are drained within another doline.

4.6. Periglacial geomorphosites

The Liapey d'Enfer (Hérens valley; Fig. 10a, c) is a complex inactive

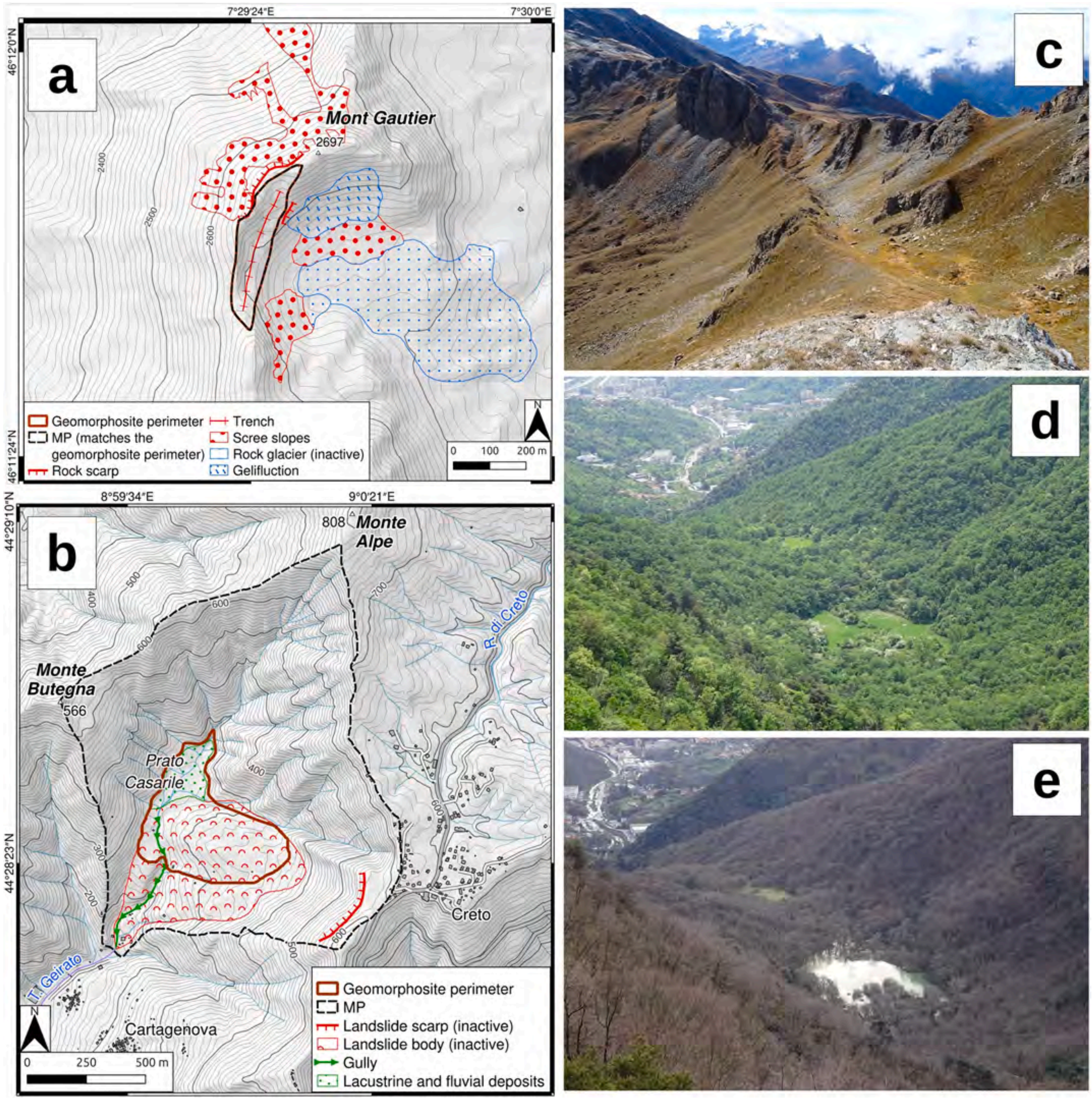

Fig. 8. a) Geomorphological sketch map of Mont Gautier; b) Geomorphological sketch map of Prato Casarile; c) The DSGSD trench of Mont Gautier; d) The meadow of Prato Casarile in normal conditions; e) The Prato Casarile ephemeral lake filled up after heavy rains in March 2024. MP = management perimeter.

rock glacier (Lambiel et al., 2016). The MP includes not only the landform as such, but also its former source area, consisting of a steep rock slope. The evolution of this slope, mainly occurring by gravitational phenomena, is nevertheless important, as these phenomena can lead to the partial modification or covering of the inactive rock glacier.

The second example, concerning relict landforms, is the Pian del Fretto blockstream (Liguria; Fig. 10b, d). The active reference process appears to be the surface alteration to which the rock blocks are exposed, as well as possible erosion by runoff waters. In both cases, the evolution is very slow, and the landform can be considered stable at the human time scale – thus the MP matches the geomorphosite perimeter.

4.7. *Structural geomorphosites*

The Castello della Pietra (Liguria; Fig. 11a, c) is a medieval castle built in between two conglomerate towers. The biggest rock tower is approximately 100 m high. The towers could be subject to rock falls, although no relevant episodes in this respect are known in recent times. The slopes at the foot are in lithological continuity with the towers. Geomorphological evidence does not suggest any reason to extend the MP.

The Maya (Hérens valley; Fig. 11b, d) is a 100 m high rock tower in a more complex geological framework. The tower is made up of resistant marble, but is bounded at the base by rather soft calcschists (Marthaler

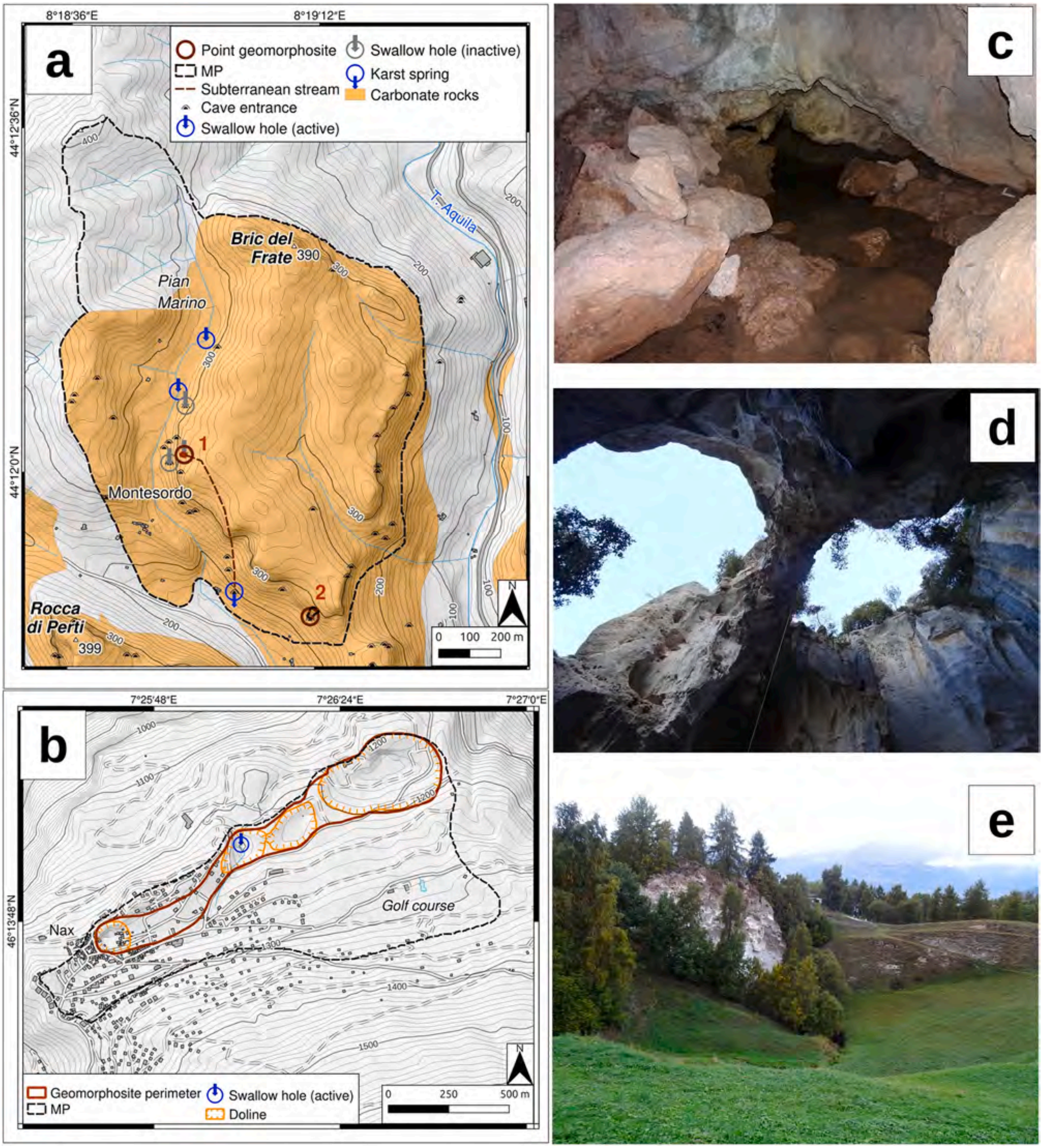

Fig. 9. a) Geomorphological sketch of the Pollera cave and Edera cave; b) Geomorphological sketch of the Nax dolines; c) Subterranean stream in the Pollera-Buio cave complex; e) The rock arch in the Edera cave; e) One of the Nax dolines. MP = management perimeter.

et al., 2008). The slopes below the Maya have extensive scree slopes with signs of recent activity, while upper slopes can be affected also by periglacial and nival processes leading to their degradation. The Maya rock tower therefore appears to be more rapidly evolving than the Castello della Pietra rock towers, and the lithological influence of the lower portion of the slopes suggests that the MP should be extended outside of the geomorphosite perimeter.

4.8. Slope systems

The Tsarmine slope system (Hérens valley) is shown in Fig. 12. Along this slope, the transfer of sediment occurs due to a combination of glacial, periglacial, gravity and fluvial processes (Reynard et al., 2012; Lambiel et al., 2016). Moving from north to south, laterally along the slope, three adjacent subsystems are observed in which sediment transfer occurs in three different ways (Fig. 12a).

The interest of the geomorphosite lies in the fact that, although the Tsarmine landforms (debris covered glaciers, moraines, rock glaciers, debris flow channels, rockslides, etc.) can be observed in many other locations in the Alps, it is rare to find places where the interaction between them is so clearly visible in a limited space. The perimeter of the geomorphosite includes the entire Tsarmine slope (Fig. 12a) and the MP

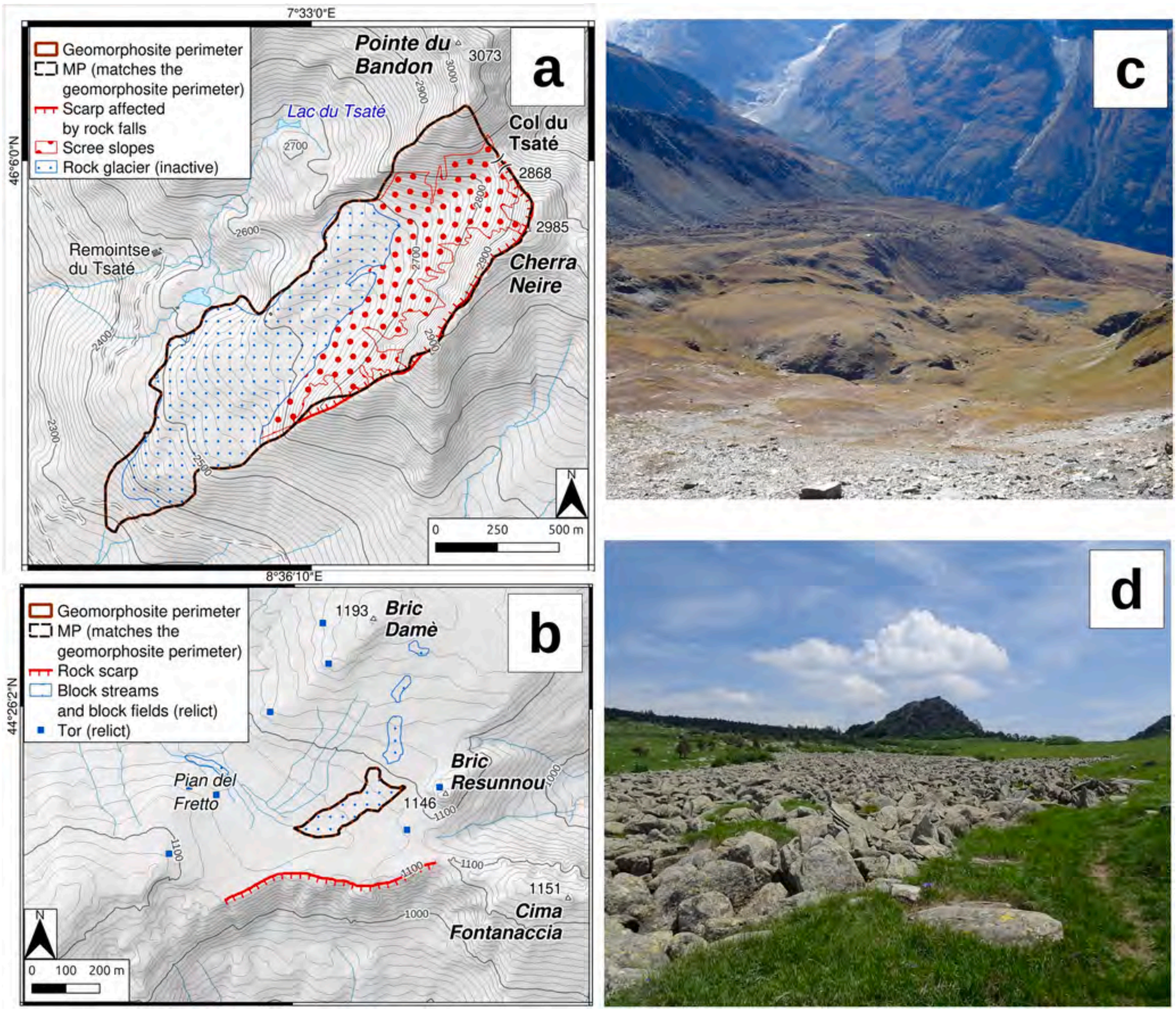

Fig. 10. a) Geomorphological sketch of the Liapey d'Enfer geosite; b) Geomorphological sketch of the Pian del Fretto geosite; c) The Liapey d'Enfer inactive rock glacier; d) The Pian del Fretto relict blockstream with a tor (Bric Resunnou) on the background. MP = management perimeter.

matches it.

5. Discussion

The inventories of geomorphosites in Liguria and the Hérens valley provide a fairly broad overview of different geomorphological contexts and environments. Most of the main morphogenetic agents have therefore been taken into account within this study. Some categories of geomorphosites are missing – e.g., geomorphosites of volcanic or aeolian origin. In other categories, some special cases are missing, e.g., low coasts that are not framed by anthropogenic action, or fluvial geomorphosites in a non-confined environment.

The case studies reported in Section 4 show how the delineation of the MP is essentially site-specific and depends on the geomorphological context around the geomorphosite. The MP does not even depend that much on the morphogenetic type of geomorphosite, but rather on the local conditions. Still, some general considerations can be made.

It is important to note that the two geomorphosite inventories present differences in approach and scale. The Ligurian inventory is a regional-scale inventory, so the spatial density of geomorphosites is rather low, and it is rare to find two geomorphosites belonging to the same geomorphological system. Moreover, as can be seen from the spatial classification shown in Fig. 2, geomorphosites are mostly defined as single landforms or groups of landforms, with relatively few geomorphological systems.

The inventory of geomorphosites in the Hérens valley considers a much smaller territory. The spatial classification shows a greater number of geomorphological systems, which is a result of both the rationale followed for the perimeter of geomorphosites and the great geomorphodiversity and dynamism of high mountain environments. Geomorphosites have a much higher spatial density, which is why it is common to see active geomorphosites interacting with one another. In a way, the entire Hérens valley can be seen as one vast geomorphological system evolving coherently and through various interrelated processes since the LGM.

The systemic nature of geomorphology, and therefore of geomorphosites, is particularly evident when considering the upper Arolla valley, a branch of the Hérens valley (Fig. 13), which includes three glacial geomorphosites (Tsijiore Nouve glacial system, Arolla glacial system and Mont Collon ice cap), one periglacial geomorphosite (Tsena Réfien rock glaciers), one fluvial geomorphosite (Satarma alluvial plain) and a slope system (Tsarmine slope system). The respective MPs overlap

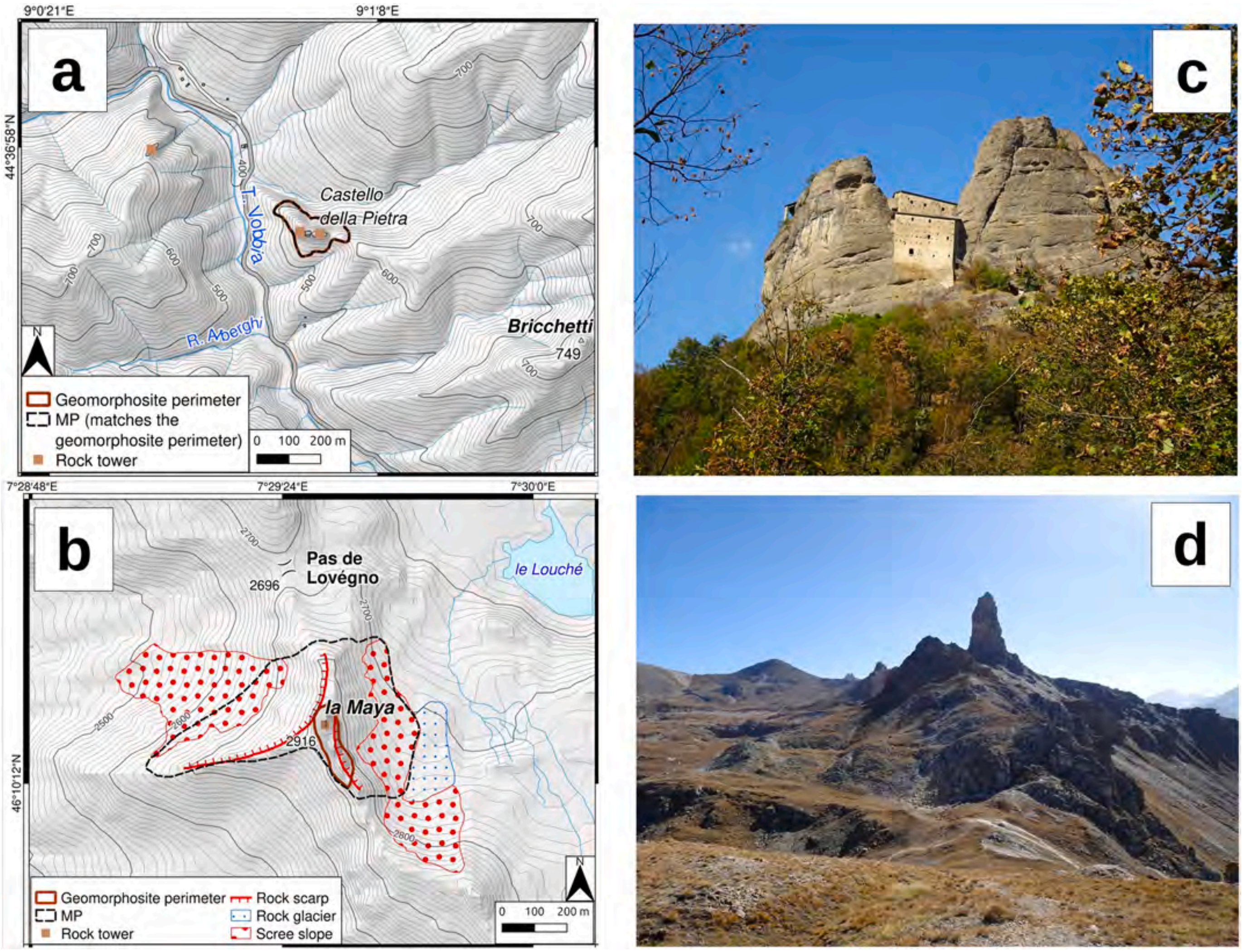

Fig. 11. a) Geomorphological sketch of the Castello della Pietra; b) Geomorphological sketch of La Maya; c) The Castello della Pietra and its conglomerate rock towers; d) La Maya rock tower. MP = management perimeter.

at several points, and the MP for the Satarma alluvial plain includes all the others. It is evident how any disturbance to the geomorphological processes upstream has a direct reflection on the evolution of the landforms located downstream.

The spatial delineation of geomorphosites does not seem to have much influence on the extent of the MP, and the way it deviates from the perimeter of the geomorphosite itself. Many geomorphological systems show a correspondence between the two perimeters, but there are exceptions, such as the Mont Miné geomorphosite (Fig. 7a, b, c).

There are aspects that have not been explored in this work, but should be considered with further studies when defining the geomorphosite management strategy. The first one is the extent to which the reference active processes may cause degradation of the geomorphosite itself. In many cases, active processes may lead to changes in the geomorphosite, even rapid and significant ones, but which do not affect its intrinsic values.

The two case studies shown in Fig. 6d, e are an example of this. For both, the reference active process is the process that generated the geomorphosite, i.e. runoff erosion. Badlands are a classic example of an active geomorphosite in continuous and rapid evolution (Bollati et al., 2016). However, this rapid evolution does not lead to the disappearance of the landform, but to changes in the morphology of the badlands. On the contrary, in the case of the Piana Crixia 'stone mushroom', runoff erosion will eventually lead to the thinning of the stem, to the collapse of the caprock and to the loss of the geomorphosite.

Thus, it has to be analysed whether: the morphogenetic processes active within it actually contribute to the degradation of the geomorphosite, how and how quickly; a disturbance to the active processes (e.g. anthropogenic activity) may lead to degradation of the geomorphosite. On the basis of the results, subsequent management actions can be defined – among these, works to protect the geomorphosite, possible restrictions on tourist fruition etc.

The second issue concerns the extent of the MPs as, according to some of the rules we proposed, the outcoming buffer zones would turn out to be very large. For instance, the MP a fluvial depositional landform at the mouth of a major river would encompass the whole river basin, which may extend well over 100,000 km^2, even across different states. This issue could be worked around in two ways. First, a quantitative geomorphological analysis on the far effects of processes happening in the distal parts of the buffer zone could lead to better redefine the MP and the degree of contribution of different areas to the evolution of the site. Second, there should be a correct calibration of management rules to be applied in the identified buffer zones. Given that MPs could have very different extents, it will be necessary to adopt ad hoc regulations for each case, also depending on the political situation and regulations already in place.

The adoption of management regulations is a very delicate issue in itself. The possibility of placing constraints on areas dedicated to

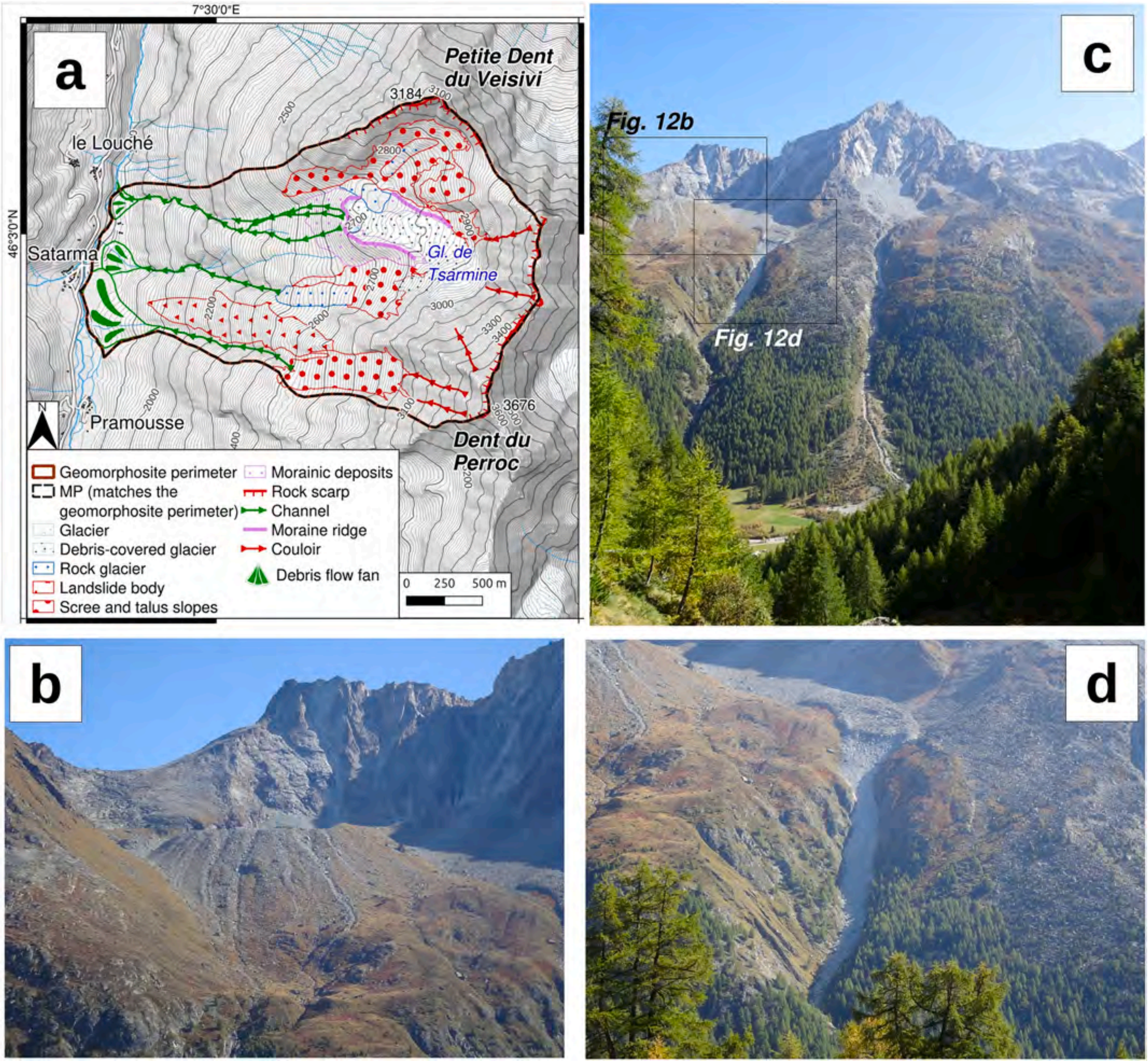

Fig. 12. a) Geomorphological sketch of the Tsarmine slope system; b) The Tsarmine LIA moraine eroded by torrential gullies; c) Panoramic view of the Tsarmine slope system; d) The Tsarmine rock glacier, with its collapsed front feeding a steep channel. MP = management perimeter.

economic activities, such as agricultural or tourist use, could have a negative impact on the public perception of the geoconservation initiative. This would be detrimental, as public engagement is fundamental for conservation initiatives to be effective (Brilha, 2002; Linnell et al., 2015; Dos Santos et al., 2019). A case example in this respect is the Choranche Caves (Vercors, France). When the caves were enlisted to become a UNESCO World Heritage Site, a quite large buffer zone was delineated (Gauchon et al., 2007) – it included much of the overlying karst plateau as there was evidence of forestry activities impacting the formation and composition of speleothems in the cave (Perrette et al., 1997, 2008). This led to hard confrontations between the promoters of the UNESCO candidature and local villagers and stakeholders, and to the eventual cancellation of the UNESCO candidature (Hobléa et al., 2008).

6. Conclusions

Over the last twenty years, studies on geomorphological heritage and geoconservation have advanced considerably. The present study aims to highlight a specific part of the geoconservation procedure (Gordon, 2019), namely that which involves the identification of threats and risks to the geomorphosite and subsequent management zoning. A methodology is proposed in which, based on geomorphological analysis, a MP is drawn for each geomorphosite. The MP includes the area in which there are active morphogenetic processes that cause the evolution of the geomorphosite on a human time scale. The proposed MP is understood as a focus area around the actual geomorphosite, which must be taken into account in the analysis of degradation risk.

The methodology was applied to two inventories of geomorphosites, one in the coastal Liguria region of northern Italy and the other in the alpine Hérens valley in the canton of Valais, Switzerland. The two study

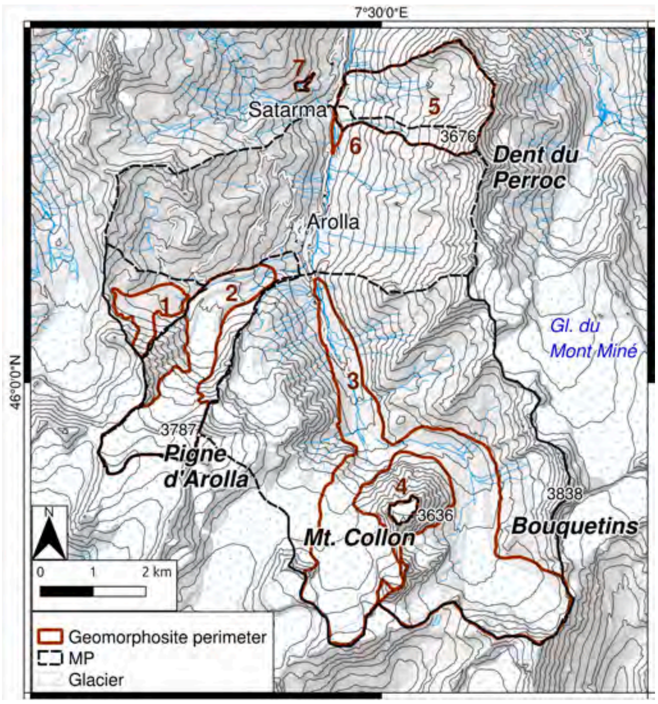

Fig. 13. Geomorphosites and their management perimeters in the upper Arolla valley (Hérens valley). 1) Tsena Réfien rock glaciers; 2) Tsijiore Nouve glacial system; 3) Arolla glacial system; 4) Mt. Collon ice cap; 5) Tsarmine slope system; 6) Satarma alluvial plain; 7) Lac Bleu moraines. MP = management perimeter.

areas provide a good overview of many different morphogenetic processes and landforms – still, some specific categories of geomorphosites are missing (e.g., aeolian geomorphosites, volcanic geomorphosites etc.) and further studies would be necessary to understand how to define MPs in these environments.

The results obtained highlight that, in many cases, geomorphosites are profoundly influenced by processes acting outside their perimeter. Neglecting this aspect could lead to an incorrect implementation of the subsequent steps of the management strategy, and thus to an ineffective geoconservation effort.

This study also highlights the systemic dimension of geomorphology and geomorphosites – which could be considered a fourth specificity to add to the three peculiarities of geomorphosites (aesthetic dimension, activity of processes, and imbrication of scales) classically considered (Reynard, 2009; Coratza and Hobléa, 2018). Geomorphological processes are affected by each other and influence each other, and often the individual landforms are best understood by looking at the entire geomorphological context in which they are inserted. In highly dynamic environments, such as high mountains, which are also deeply marked by climate change, this aspect is particularly evident. The evolution of some geomorphosites has a direct impact on the evolution of other geomorphosites, as they are included within a larger-scale geomorphological system. Hence, geoconservation of geomorphological features should have a systemic approach to be truly effective.

CRediT authorship contribution statement

Andrea Ferrando: Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Francesco Faccini:** Writing – review & editing, Validation, Methodology, Investigation. **Paola Coratza:** Writing – review & editing, Validation, Supervision, Methodology. **Emmanuel Reynard:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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