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Abstract: Geomorphic processes driven by water are particularly active in mountain environments, especially under the current climate conditions. Erosion and dissolution processes shape meaningful landforms, in different kinds of deposits and rocks, and in some cases they are classified as geomorphosites. Such landforms, especially earth pyramids and rock pillars, are usually characterized by a high scientific value (e.g., representativeness, ecologic support role) and by additional values (e.g., cultural and aesthetic value) contributing to the local geoheritage. Mountain geomorphosites are growing in importance within scientific community and their morphological evolution can affect the global value of the site itself (e.g., integrity). In this paper, after a first review on the terminology used for classifying landforms modelled by water runoff and on their meaning within the mountain environment, the results of a detailed research performed at two sample sites, included in the Swiss National Inventory of Geosites, are presented. The two study sites are representative respectively of: i) water runoff on glacial deposits shaping earth pyramids (Pyramides d'Euseigne); ii) water dissolution on gypsum rocks, modelling articulate karst landscapes (Pyramides de gypse du Col de la Croix). For each site, landforms evolution was investigated and denudation rates were estimated by means of different methods: iconographic material analysis, quantitative geomorphology and dendrogeomorphology on exposed roots. Despite the long-term, average rates obtained by means of roots exposure for both water runoff on glacial deposits (e.g., 5.8 mm/y) and dissolution on gypsum rocks (5.6 mm/y) are comparable. Moreover, a strict relation between the activity degree of processes, the integrity of the site and the assignment of geomorphosites to a specific category (i.e., active, passive or evolving passive) emerged from the results.

Water driven processes and landforms evolution rates in mountain geomorphosites: examples from Swiss Alps

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Abstract

Geomorphic processes driven by water are particularly active in mountain environments, especially under the current climate conditions. Erosion and dissolution processes shape meaningful landforms, in different kinds of deposits and rocks, and in some cases they are classified as geomorphosites. Such landforms, especially earth pyramids and rock pillars, are usually characterized by a high scientific value (e.g., representativeness, ecologic support role) and by additional values (e.g., cultural and aesthetic value) contributing to the local geoheritage. Mountain geomorphosites are growing in importance within scientific community and their morphological evolution can affect the global value of the site itself (e.g., integrity). In this paper, after a first review on the terminology used for classifying landforms modelled by water runoff and on their meaning within the mountain environment, the results of a detailed research performed at two sample sites, included in the Swiss National Inventory of Geosites, are presented. The two study sites are representative respectively of: i) water runoff on glacial deposits shaping earth pyramids (Pyramides d'Euseigne); ii) water dissolution on gypsum rocks, modelling articulate karst landscapes (Pyramides de gypse du Col de la Croix). For each site, landforms evolution was investigated and denudation rates were estimated by means of different methods: iconographic material analysis, quantitative geomorphology and dendrogeomorphology on exposed roots. Despite the long-term, average rates obtained by means of roots exposure for both water runoff on glacial deposits (e.g., 5.8 mm/y) and dissolution on gypsum rocks (5.6 mm/y) are comparable. Moreover, a strict relation between the activity degree of processes, the integrity of the site and the assignment of geomorphosites to a specific category (i.e., active, passive or evolving passive) emerged from the results.

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1. Introduction

Water driven processes acting along mountain slopes typically shape spectacular deeply dissected landscapes (i.e., badlands-like landforms; Bl-LFs), with distinctive features due to different substrates (i.e., rocks and deposits), that are various for lithology and texture, and different morphoclimatic contexts which they are inserted in. Mountain chains, like Apennines and Alps, are characterized by peculiar landscapes mainly modelled by running waters.

Widespread and famous are the Italian badlands, modelled in arid, semiarid and humid environments, known as “calanchi”. They are shaped mainly in Pliocene clays outcropping diffusely along the Apennines (Buccolini & Coco, 2013), within regions affected by strong seasonal climatic differences (Della Seta et al., 2009). Such landscapes are characterized by a pattern of dense close-up small valleys and gullies, with steep slopes and sharpened edges, and they are often associated with mostly rounded-edged landforms called “biancane” (Alexander, 1980).

In the Alpine contexts water runoff acts on widely diffuse glacial deposits, constituted by elements of different grain sizes, from boulders to silt and clay, shaping other peculiar badlands-like landforms, the earth pyramids. These are columnar landforms resulting from a big boulder protecting the underlying deposits from water runoff (Erikstad, 2006; Crosta et al., 2014).

Where rocks and deposits consist of soluble components (e.g., evaporites or limestone) also the chemical action of water contributes to the mountain landscape modelling. Where dissolution rates are high, as on gypsum (Nicod, 1976), or where landforms are undergoing to such process for a long time, residual pillars characterize mountain landscapes. These features are in some cases called “pyramids” as well. Hence, rocky pinnacles and earth pyramids may be considered convergent landforms from a geomorphological point of view, due to their similar shape.

The high mountain regions are among the most sensitive to climate change and abundant is the inherent literature (e.g., Evans & Clague, 1994; Chiarle & Mortara, 2001; Ballantyne, 2002; Fischer et al., 2006; Chiarle & Mortara, 2009; Mercier, 2009; Pelfini et al., 2014; Reynard et al., 2012a; Stoffel et al., 2014). Nowadays the action of water under different states (glacier ice, ground ice, melting waters from glaciers, permafrost, ice cores of moraines, rainfall) is regulated by the current climate warming trend, whose effects are inducing landform changes. Glacier ablation is responsible of the huge glacier retreats and of the transition from a glacial to a paraglacial system, subject to the morphological work of water driven and gravity processes (i.e., weathering, splash, rill and gully erosion, through-flow and piping) (e.g., Mercier, 2009; Stoffel et al., 2014). The response of paraglacial systems to climate change may span from immediate reaction until million years as indicated by Mercier (2009) who underlined also that paraglacial systems lifespan may depend on different factors, mainly from sediments at disposal to be reworked, climate conditions and geological constraints.

Therefore, in such evolving landscapes, landforms may be more or less preserved mainly depending on the substrate, which they are shaped in, on the age of landforms and on the rates of geomorphic processes they underwent.

A meaningful example of changing landforms in high mountain environment, and in paraglacial systems in particular, is represented by lateral and ground moraines, well known as key sites for the reconstruction of glacial advancing phases and for the observation of the following modifications under different geomorphic processes. Under the current climatic conditions, moraine ridges are affected by geomorphological instability (e.g., Curry, 1999; Hewitt, 1999; Chiarle & Mortara, 2001; Mortara & Chiarle, 2005; Curry et al., 2006; Mercier, 2009; Smiraglia et al., 2009). Over-incision of frontal moraines, erosion at the foot of the moraine slopes, concentrated linear erosion on the inner flank of lateral moraines, that generate new supra-imposed gullies (Bl-LFs), and burial, due to debris falls/flows, are the main processes affecting moraines on the whole Alpine range (Chiarle & Mortara, 2001). The re-modelling of glacigenic sediments has been recognized as one of the most important paraglacial slope adjustments consisting in increasing gravity processes and the sudden development of gully systems. Sediment transportation and formation of debris cones at the base of moraine inner slopes progressively lead to the reduction of the overall slope gradients and concavity in moraine profiles allowing them to reach a new equilibrium (Curry, 1999; Curry et al., 2006). Huge quantities of water released during intense rainfall events and/or from moraine ice core melting favour the process efficacy.

Also at lower altitudes slopes are mantled by glacial deposits, related to the older glaciations and now covered by soils; nevertheless also deeply dissected moraine ridges, continuously reworked by running and channelized waters and by human impact are present.

In this changing morphoclimatic context, rocky outcrops, characterized by erosion glacial landforms (e.g., roches moutonnées, glacial striae, subglacial potholes), when consisting in soluble lithotypes can be reworked by karst processes (e.g. Chardon, 1996), whose action is added to the ones from other geomorphological active processes. In this context also pillars can develop, as mentioned before.

Water driven denudation processes are active with different rates in the mountain environment, from paraglacial areas as far as lower altitudes, depending on substrate, relief and climate factors (e.g., Delannoy & Rovera, 1996; Taminskas & Marcinkevicius, 2002). Denudation rates in mountain regions are significant at the drainage basin scale and crucial as they are strictly linked with the downstream physical and chemical water load (Descroix & Mathys, 2003). As reported by Chiarle & Mortara (2001), where huge coverage of loose debris are present extreme rainfall events can trigger mass wasting phenomena (as far as 5 x 10^6 m^3 in a single event; Avisio catchment, Eastern Italian Alps). In general, the climate influence on the water runoff processes has been detected in terms of rainfall regime and typologies of rainfall events. In mountain environments the increase in runoff intensities during wet years, following dry ones was detected (Bollati et al., 2012b; 2016a, c and reference therein) and intense rainfall events demonstrated to trigger slope erosion (Bookhagen & Strecker, 2012) and mass wasting events (Guida et al., 2008).

In this framework, denudation rates (i.e., erosion and dissolution rates in the case of the Bl-LFs examined in the framework of the present research) vary in space and time and different values (i.e., local or averaged) may be obtained from different methods of measurement (i.e., direct and indirect) considering among them the natural data archives like tree rings. They are diversely efficient depending also on substratum and active processes.

In a geoheritage perspective, “pyramids” modelled by water driven processes on different substrates may be sites of great geological-geomorphological interest not only for their scientific importance but also for aesthetic reasons and for their links with different components of culture as literature and art, as well as socio-economic and tourist issues (e.g., Giusti, 2012; Bollati et al., 2016a). Deep is the current attention of the scientific community towards mountain geoheritage for both geoconservation and geotourism purposes due to i) its scientific meaning, ii) the presence of various geomorphological features, also in term of landforms activity degree, iii) the particular sensitivity of this environment to climate change and related hazards and iv) its highly aesthetic value (e.g., IAG – Network on Mountain Geomorphosites; Reynard et al., 2011; 2016; Giusti et al., 2013; Ravanel et al., 2014; Bollati et al., 2016b; Reynard & Coratza, 2016). Hence, improving knowledge about mountain geoheritage evolution rates is crucial since the processes, which have shaped geomorphosites, can be the same that could degrade or destroy them (Hooke, 1994; Pelfini & Bollati, 2014; Bollati et al., 2016a). Analyses for estimation of changes in denudation rates are hence significant when considering changes in geoheritage for what concerns both conservation and impact and hazard assessment (Bollati et al., 2013; 2016a).

In this perspective, after a short review on badlands-like landforms in mountain environment and their meaning in the geoheritage framework, two will be the aims to be pursued: i) to present the results of a multidisciplinary analysis on denudation rates characterizing selected geomorphosites shaped by water driven processes (i.e., physical and chemical) acting on different substrates (i.e., glacial deposits and soluble rocks); ii) to integrate site specific results in a discussion on spatio-temporal evolution of geomorphosites, and the related classification, according to geomorphic processes activity they are affected by.

2. Badlands-like landforms in mountain environment and geoheritage issues

2.1 A short review of badlands-like landforms in the framework of climate change

Terminology used for classifying badlands-like landforms is quite diversified (i.e., pyramids, pillars, towers; Perna, 1963) and usually local names are applied, often linked with tradition and legends. A short summary is reported in Tab. 1 and some pictures are illustrated in Fig. 1.
Badlands-like landforms mainly derive from water action (physical erosion and chemical dissolution) on different kinds of substrates characterized by different textures (more or less heterometric in grain-size), consolidation/lithification degree (e.g., rocky and soft terrains) and, basically, with a structural control.
Among them, the most common and meaningful badlands-like landforms in the mountain environment are those developing on glacial deposits (i.e., earth pyramids) or on outcropping rocks prone to both mechanical erosion and chemical solution (i.e., gypsum pillars) (grey cells in Tab. 1). Hence, the herein focus was put towards two study areas falling in these categories and combining the presence of active and inherited landforms, more or less integer, with aesthetic value, and that are included in a National Inventory of Geosites, testifying their scientific and cultural relevance (e.g., Erikstad, 2006; Giusti, 2012; UNESCO, 2015; Bollati et al., 2016a). These features support the intention of deepening the knowledge about their long-term evolution and to monitor present day denudation rates.

2.1.1 Earth pyramids on glacial deposits

Earth pyramids are residual pillars developing as a consequence of water runoff on heterometric deposits where a cap rock locally protects the underlying sediments (Tab. 1, c; Fig. 1b). Different are the terms used to indicate this kind of badlands-like landforms and they are usually linked with local traditions, as reported in Tab. 1: ‘Ladies with hats’ or ‘Demoiselles coiffées’ (e.g., Heck 1985; Delannoy & Rovera, 1996; Giusti, 2012), ‘Organ pipes’ (e.g., Avanzini et al. 2005). Perna (1963), in a monograph describing the earth pyramids in Trentino-Alto Adige (Eastern Italian Alps), individuated almost 80 sites that allowed him to provide a great number of case studies and a classification of earth pillars developing on fluvioglacial deposits (Fig. 2). They may be singular pyramids or complex of pyramids, with or without the cap block. The earth pyramids without cap blocks are usually more frequent but rapidly evolving (e.g., Perna, 1963; Poesen et al., 1994) and are named ‘Organ pipes’ (e.g., Avanzini et al., 2005; Giusti, 2012). It is interesting to notice that the protection may be not only rocks but also vegetation growing on soil (Fig. 2, c, d) that, anyway, does not ensure a long protection as a rocky cap (Perna, 1963; Poesen et al., 1994).

According to Perna (1963), conditions that are necessary for earth pyramid formation are: i) the heterogeneity in grain size, variable from clay and silt to boulders; ii) the consolidation degree; iii) the presence of cap blocks of a certain shape. Moreover, their elevation is influenced by other factors among which, the debris consolidation degree, favoured by the weight proper of the structure, and the slope gradient are the most important. Crosta et al. (2014) analyzed three famous earth pyramids complexes in the southern side of the Alps, modelled in glacial and fluvioglacial deposits (i.e., Zone and Postalesio, Lombardy; Segonzano, Trentino Alto-Adige). They obtained similar average in grain size classes with sand slightly prevailing in all the sites (gravel, 27%; sand, 43,3%; silt and clay, 29,7%). The relatively low cohesion for the cases analyzed by Crosta et al. (2014) was associated to a small percentage of clay particles while the over-consolidation was found only in correspondence of lodgment till. Comparable grain size percentages were found for earth pyramids in the Swiss Alps by Bollati et al. (2016a) but with a slight prevalence of gravel.

The efficacy of water runoff can vary from site to site in relation with particular meteorological conditions. For example, in the Alpine contexts the alternation of dry and wet years may favour the intensification of erosion (i.e., Bollati et al., 2016a). The amount of precipitation and the intensity of events may accelerate the dismantling of earth pyramids till threatening the survival of the site when the substrate has a good permeability allowing water infiltration, as indicated by Perna (1963). Sudden water release or increase in rain-wash may also favour a concentrated erosion at the base of the pyramids inducing their destabilization (Erikstad, 2006; Bollati et al., 2016a). Moreover, earth pyramids are very sensitive to external perturbations both natural and human-induced (i.e., seismic or human-induced shaking, gravity, remodelling of topography) that, if associated with runoff, concentrated especially at the base of the structures, may threaten their stability (e.g., Perna, 1963; Heck, 1985; Crosta et al., 2014).

According to the different ages and relative altitudinal position of glacial deposits undergoing water runoff, diverse are the badlands-like landforms that may develop. In Fig. 3, two exemplary cases of altitudinal transects in the mountain environment, from paraglacial to distal systems, are reported: gullies on Little Ice Age (LIA) moraines deposits, relatively close to current glaciers position, and earth pyramids developing on Pleistocene age deposits, at relatively low altitudes. Such different features are linked with landforms maturity. The selected sites are situated on the southern and northern sides of the Alps (a-c, Hérens valley, Western Swiss Alps ; d-f, Upper and Lower Valtellina, Central Italian Alps; Fig. 4) but several are the similar cases in other Alpine sectors (Chiarle & Mortara, 2009) and in general in mountain ranges (e.g., Curry et al., 2006; Ballantyne, 2002). This differentiation is reflected also on the denudation rates. In this sense, Curry (1999) proposed a classification for moraines systems in relation with their modelling stage within paraglacial systems. The LIA moraines, reported in Fig. 3 (a, d), located at an altitude of about 2000-2500 m a.s.l. and characterized by evident gullies, may be classified as the T2 moraines system (i.e., "gullies are furthest from the present glacier margin but still within LIA glaciers limit"). The maximum intensities of erosion in these contexts (90-95 mm/y, Curry, 1999; Curry et al., 2006 at Glacier du Mont Miné, Fig. 3; 300 mm/y, Smiraglia et al., 2009 at Forni Glacier, Fig. 3) are recorded immediately (i.e., 50 years) after deglaciation. Earth pyramids (Fig. 3b, e), developing after long exposure to water runoff on much older glacigenic deposits and located at lower altitude (750-950 m a.s.l.), are instead characterized by relatively lower denudation rates (Curry, 1999). In the evolutionary framework traced by Curry (1999), earth pyramids may represent the long-lasting stage of ancient moraines (i.e., erosion maturity) that underwent several erosion phases characterized by differences in intensity of water runoff. They may be considered as evolving landforms (Perna, 1963; Giusti, 2012; Bollati et al., 2016a).

In this evolutionary framework, it is hence possible to imagine that LIA moraines will evolve, in the future, in earth pyramids and that it will be possible to find earth pyramids at higher altitudes where now we observed LIA moraines characterized by gullies and higher erosion rates.

2.1.2 Gypsum pillars

In mountain environments water and ice actions may combine and where glacial exharation operates on soluble rocks glaciokarstic landforms are common. They are frequently described for example on limestone (e.g., Grigne Massif, Southern Italian Alps; Désert de Platé, Haute-Savoie, French Alps; Tsanfleuron-Sanetsch area, Swiss Alps; Dinaric Alps). In this research, the attention is paid to the suggestive mountain landscapes modelled by the combination of glacial erosion and chemical dissolution, ruled by water, on gypsum.

The evaporitic outcrops are quite widespread in the Alps and all over the world (Nicod, 1976). Nevertheless, the attention paid to karstic features developing in gypsum (parakarst, Cigna, 1978; evaporitic karst, Lowe, 1992) is low if compared to limestone karst. The word "karst" is instinctively automatically gathered to limestone even if several are the differences between limestone and gypsum karst: i) chemical dissolution in gypsum, and in evaporitic rocks in general, is not ruled by the acidification degree of water, i.e., by CO_2 content in water (e.g., Nicod, 1976; Rovera, 1998); ii) low temperatures characterizing mainly high (and middle) mountain environments, should not represent a limiting factor; iii) vegetation on limestone speeds up the dissolution by adding CO_2 to the system, while on gypsum it acts as a protection against water action (e.g., Chardon, 1996; Rovera, 1998); iv) solubility of gypsum and anhydrite (2,5 - 3 g/l; Cigna, 1986; Gutiérrez & Cooper, 2013) and chemical dissolution rates are calculated to be higher (e.g., fifteen times, Chardon, 1996) compared with those characterizing the less soluble limestone (0,2-0,5 mg/l; Cigna, 1986) and hence the persistence of landforms is threatened (e.g., Nicod, 1976; Klimchouk, 1996; Schoeneich & Imfeld, 1997; Forti, 2004; Yilmaz, 2012; Gutiérrez & Cooper, 2013). Taminskas & Marcinkevicius (2002) expressed the dissolution rates in terms of number of sinkholes forming in a defined time interval and they related the increase in sinkhole formation in recent times primarily with the increase in temperature and runoff, and secondarily, with human impact (e.g., dam construction, water extraction). According to Chardon (1996) the sinkholes' size can be related to their age: small (346-951 years), medium (2744-7535 years) and large (6000-10'000 years). Waltham & Fookes (2005) calculated an increase in size of 1 m/100 y in response to climate change. In the Alpine environment, the chemical dissolution rates are also regulated by snow coverage (Nicod, 1976) and they may be 4-5 times higher than in other morphoclimatic environments (e.g., Mediterranean, Delannoy & Rovera, 1996).

The most characteristic badlands-like landform complexes deriving from water action on gypsum outcrops in mountain environments are the "dômes écumoires" (i.e., riddled dome; "honeycomb karst", "point karst" for Schoeneich & Imfeld, 1997), which are large domes of gypsum exposed after glacial retreat, since the beginning of Holocene and which are perforated by numerous deep sinkholes, one to ten meters large on domes surface (Chardon, 1992; Fig. 5, a). According to Schoeneich & Imfeld (1997) with an increase of the slope steepness, sinkholes transform into systems of gullies separated by sharp edges (Fig. 5, b).

The evolution phases of "dômes écumoires" is hence fast (e.g., Nicod, 1976; Chardon, 1992, 1996) and may lead to the formation of narrow canyons and isolated pillars due to the coalescence of sinkholes on ice-free surfaces (Chardon, 1992) (Tab. 1, F). It may be summarized as follows: i) glacier retreat phase: domination of underground water flow and formation of hypogean karst landforms; ii) genesis of bare surfaces, and related (micro and macro) landforms, consequent to glacial exharation and successively of sinkholes, due to the action of snow melting waters. Within the "dômes écumoires" glacial erosion microforms modelled during the Pleistocene glacial advances are visible where glacial deposits do not protect the surface anymore. Their persistence through time is threatened by the high dissolution rates. As for earth pyramids, on glacial erosion surfaces developing on soluble substrates, landforms of different age (i.e., maturity) are present in relation with altitude (Chardon, 1992, 1996) (Tab. 2). As for the water runoff on glacial deposits, also in the case of gypsum glaciokarst landscapes, the evolution rates diminish with the altitude.

2.2 Meaning of badlands-like landforms in mountain geoheritage framework

The badlands-like landforms, that are exemplary of geomorphic processes, may be recognized as geomorphosites (Panizza, 2001). They are characterized by attributes used for assessing their values (for a review on the values see Brilha, 2016) and, as a general rule, their global value (sensu Bollati et al., 2016b) may increase thank to both scientific (e.g., representativeness, integrity, rarity) and additional attributes (e.g., cultural, aesthetic). Some of the values, like the aesthetic one (Smrekar et al., 2016), are very subjective but, together with the educational exemplarity, become very meaningful in the framework of Earth Sciences dissemination.

Active geomorphic processes may have a great impact on geomorphosites in different ways (Hooke, 1994; Komac et al., 2011), affecting also, as a cascade effect, regional geodiversity that depends, among the others, by the variety of landforms (e.g., Prosser et al., 2010; Gordon et al., 2012; Erikstad, 2013). This is particularly evident when geomorphosites are dismantled and/or new ones are formed (e.g., newly emerging subglacial sites in the expanding proglacial areas; Diolaiuti & Smiraglia, 2010). As described in detail by Pelfini & Bollati (2014), the possible fallouts of geomorphic processes on geomorphosites, be they positive or negative, are: i) the degradation of the sites themselves (Hooke, 1994) in terms of global value and sub-attributes (integrity, rarity, educational exemplarity, sensu Bollati et al., 2012a); ii) the changes (often increase) in risk scenarios (Pelfini et al., 2009; Smith et al., 2009; Comănescu & Nedelea, 2015); iii) the creation of meaningful opportunities for education and geotourism since the active processes allow students to get in touch with the role of geomorphic processes in shaping the physical landscape (Reynard & Coratza, 2016) and allow tourists to enjoy changing sites (Bollati et al., 2013); iv) the influence on the other ecosystem components (e.g., vegetation) due to the ecologic support role exerted by some geomorphosites (e.g., Garavaglia et al., 2010; Brazier et al., 2012; Hjort et al., 2015; Bollati et al., 2012b; 2015; 2016a, c).

The classification of geomorphosites according to the activity degree and type of geomorphic processes affecting their evolution is reported in Tab. 3 (modified from Pelfini & Bollati, 2014).

Active, passive and evolving passive geomorphosites (sensu Pelfini & Bollati, 2014) are meaningful not only from a scientific point of view, but also in an educational perspective, as they witness respectively present (AGs), past (PGs) and past plus present (EPGs) morphogenetic and morphoclimatic conditions (Bollati et al., 2016a, c).

In general, the investigated earth pyramids and gypsum rock pillars systems show the contemporary presence of active and inherited landforms, more or less integer, with a high aesthetic value. They are considered components of the geoheritage and, indeed, they are inserted within the Swiss National Inventory of Geosites.

More in detail, among badlands-like landforms, the well-developed earth pyramids are classic examples of geomorphosites because of their high representativeness, paleogeographical meaning (sensu Reynard et al., 2007) and educational exemplarity. This last attribute become important due to the aesthetic value and to the cultural values, linked with various myths and legends coming from local traditions. Pelfini & Bollati (2014) and Bollati et al. (2016a) widely described these aspects. It is worth to be noticed how in the case of earth pyramids some authors are used to consider them simply as active geomorphosites focusing only on the current stage of evolution (differential water runoff) and considering exclusively the processes currently active on landforms (Giusti, 2012). They deny the past stages of evolution of the site whose signs, in specific cases, may be integer and conserved, and that can help in unravel the past history of the site itself (i.e., paleogeographical meaning, sensu Reynard et al., 2007).

Also karst geomorphosites developing in gypsum have a great educational value as they allow solving the common misunderstanding, in the general public, responsible of the automatic connection “karst = limestone”. Values of gypsum sinkholes and related landforms (i.e., isolated pillars) in the framework of geoheritage, were delineated for example by Bianco et al. (2003) for the Italian region, where only 1% of the topographic surface is estimated to be characterized by gypsum, and for this reason they represent a rarity. Yilmaz (2012), focusing on the Turkish Region, analyzed the main attributes usually adopted in geomorphosite assessment and that contribute to significance of sinkholes in gypsum as geomorpho-heritage. Concerning the scientific value, according to Yilmaz (2012), gypsum sinkholes may be considered significant since they: i) provide (in)direct information to localize structural lines and control; ii) indicate the presence of soluble rocks; iii) allow calculating the magnitude of dissolution processes, which is under investigation in the present research; iv) provide information on possible underground drainage systems. The geological representativeness, partially corresponding to the paleogeographical value of Reynard et al. (2007, 2016), is related to the rocks themselves, deposited in ancient arid-semiarid environments characterizing, within the Alpine setting, the borders of the Tethys ocean. In the framework of the scientific value, ecological support role of gypsum is recognized by different Authors (Rovera, 1998; Latella et al., 2003; Tuyukina, 2009; Yilmaz, 2012). For example, Latella et al. (2003)

underlined how an exclusively gypsophilic flora does not exist, but lichens and mosses may require this specific substrate. The Authors reported how ecosystems formed on hard gypsum bedrock or in the water drained from gypsum sinkholes lakes are rare and for this reason very valuable. Moreover, for the Authors, gypsum karst systems are characterized by different geomorphic features and by a high scenic value of sinkholes of different size, especially if filled in by water. The main issue dealing with geoconservation in gypsum is related to the rapidity of dissolution and the consequent fast dismantling of such badlands-like landforms and related landforms. This feature may affect primarily the geosite integrity (Hooke, 1994; Pelfini & Bollati, 2014).

3. Study areas

The two study sites are included in the Swiss National Inventory of Geosites (SNIG) (Reynard et al., 2012b) (C and E, Fig. 4) and are located in the Western Swiss Alps. Both are named "Pyramids" even if the modelling process is different: i) Pyramides d'Euseigne - PE (Canton Valais) are earth pyramids shaped by water runoff on ancient glacial deposits; ii) Pyramides de gypse du Col de la Croix - PCC (Canton Vaud) are rock pillars deriving from chemical dissolution on gypsum outcrops. Both areas were modelled by past glacial action. They may be considered a case of morphological convergence that provides similar landscapes, especially for the non-specialists.

3.1 Earth pyramids geomorphosites: the case of Pyramides d'Euseigne

The first study site is located at the confluence between the Hérens and Dixence valleys, in a southern tributary valley of the Rhone River, in Canton Valais , at an altitude of 950 m a.s.l.. Earth pyramids (Fig. 6) are cut in chaotic glacial deposits originally shaped in a Late Glacial moraine located at the confluence of glaciers flowing in the Hérens and Dixence valleys (Lambiel et al., 2016). In the surroundings, stratified deposits locally outcrop, related to the deltaic and lacustrine sedimentation systems characterizing the area during the last stages of the Würm glaciation (Coutterand, 2012). Pyramids develop exclusively in the chaotic facies confirming the strict relation between their formation and the texture of deposits (Perna, 1963; Bollati et al., 2016a). A large part of earth pyramids may be classified in some of the categories proposed by Perna (1963, p. 21), reported in Fig. 2 and in particular within the 'b' - 'group of connected earth pyramids where one of them lost the boulder cap and it is vanishing' (a in Fig. 2) and 'm' - 'squat pyramid with a very big boulder cap' (Bollati et al., 2016a) (b in Fig. 2). The area occupied by pyramids is about 1 km^2 wide and it is characterized by the presence of a touristic trail (Fig. 6) that allows the visitors to cross through such peculiar and spectacular geomorphosite and it is equipped with an informative panel.

Moreover a cantonal road cuts the geomorphosite and strategies for risk mitigation, among which interventions and periodical refurbishments, are adopted.

Pyramides d'Euseigne is the only earth pyramids complex listed in the SNIG (Swiss Geosite 053; Fig. 4, C; Fig. 6) in virtue of the primary geomorphological value and the secondary aesthetic and landscape values (Reynard et al., 2012b). It must be hence considered the most exemplary case of the Swiss Alps. The site is characterized by educational exemplarity and aesthetic value that make it suitable for interpretive purposes. The scientific value is high since the deposit allows unravelling how wider was the territory occupied by the glaciers in the past and also what was the power of the following huge environmental changes (paleogeographical value; Reynard et al., 2007, 2016). Moreover, information on the paleodrainage setting may be carried out by analyzing the provenance of the rock fragments forming the deposits. The cultural value of Pyramides d'Euseigne is supported by the presence of the touristic trail and of a monument in the Euseigne village. Additional details are available in Bollati et al. (2016a).

3.2 Gypsum pillars geomorphosites: the case of Pyramides de gypse du Col de la Croix

The second study case (Fig. 4, E; Fig. 7, a) is located in the Diablerets Massif, at an altitude of 1778 m a.s.l. and it is characterized by chemical dissolution on gypsum outcrops previously exharated by glaciers. Other similar dissolution landforms are present along the Zone des Cols, in particular at Col du Pillon and also in the Derborence valley (Pyramides de gypse de La Tour; Fig. 7, b).

Gypsum outcropping at Col de la Croix are characterized by dolomite intercalations (Fig. 7, a). The genesis of the gypsum and the following modelling phases due to exogenous processes were quite complex (Schoeneich & Imfeld, 1997). The deposition of gypsum of the Bex-Laubhorn Nappe (Ultrahelvetic Domain of the Alps) dates back to the Triassic period, as most of the gypsum deposits around the Alps (i.e., Permo-Triassic gypsum systems; Gutiérrez & Cooper; 2013), when an arid climate dominated the Tethys passive margin. The gypsum levels acted as "décollement" zone between structural nappes during different tectonic events and currently they represent a weakness zone prone to superficial processes like those ruled by water and gravity (Nicod, 1976).

During the Last Glacial Maximum only the higher peaks of the region were glacier free (i.e., Les Diablerets Massif), as nunataks. Hence, the glacial erosion modelled the Col de la Croix gypsum outcrops with various intensity through time, generating exharation surfaces. Plasticity and ductility of gypsum may have preserved gypsum from the possible complete dismantling that might derived from glacial exharation (Nicod, 1976; Chardon, 1992; 1996; Gutiérrez & Cooper, 2013).

Karst at Col de la Croix is a typical example of gypsum denudated karst (Klimchouk, 1996) or more specifically of "dômes écumoires" (i.e., riddled dome; "honeycomb karst", "point karst" for

Schoeneich & Imfeld, 1997; see paragraph 2.1.2.), where sinkholes are separated by thin ridges, pillars and monoliths at the edge of the massif, especially in contact with other lithotypes. Locally the sinkholes, especially in the western part of the Col de la Croix, are elongated following the E-W oriented preferential direction controlled by tectonic lines. On the eastern side of the Col de la Croix, they are more circular and more homogeneously distributed (Fig. 8, c). The pyramidal effect, due to the coalescence of sinkholes that isolates rock pillars, is more evident when slope steepness increases (Schoeneich & Imfeld, 1997) (stage 2, c; Chardon, 1992) since these badlands-like landforms differentiate according to this topographic factor (Nicod, 1976; Schoeneich & Imfeld, 1997) (Fig. 5, b). More the slope steepness increases, more the elongated sinkholes shape prevails generating sharp edges and gullies (Fig. 8, d). On the gypsum surface, especially on the vertical cliff of sinkholes, rillenkarrens are common (Fig. 8, b). Interstrata karst process are frequent in gypsum (Klimchouk, 1996) and, in the area, hypogean caves are also present at the contact between gypsum and anhydrite (Schoeneich & Imfeld, 1997). At the site of Pyramides de gypse du Col de la Croix analyses on vegetation and soils were performed by Biedermann et al. (2014) who classified the soil as Dolomitosol and who detected that vegetation is constituted by calcareous and drought tolerant species.

The site is inserted in the SNIG (Swiss Geosite 049) basing on a primary geomorphological value, a secondary aesthetic value and landscape and educational values (Reynard et al., 2012b). At Pyramides de gypse du Col de la Croix, gypsum karst offers the opportunity to acquire, (in)directly, information to localize structural lines and control and the attribute of geomorphological representativeness as a "dôme écumoire" in medium Alpine environment is particularly significant. Moreover, Pyramides de gypse du Col de la Croix are characterized by an 'internal geodiversity', especially by a spatial differentiation of features controlled by steepness of the slope (Schoeneich & Imfeld, 1997), and by integrity, in relation to their stage of evolution.

Among the additional value, aesthetic is emerging at the study site, as indicated by Schoeneich & Imfeld (1997): the pleasant view is provided just from the different dimensions of single landforms. The cultural value is also important since the Battle of Col de la Croix took place at the Col on 3rd March 1798 between French and Bernese armies since the area represented, due to physiographical conditions, an easy passage towards the Bernese Alps (Schöpfer, 2011). All these features concur to the increase of the global value of Pyramides de gypse du Col de la Croix as geomorphosite.

4. Materials and methods

The sensitivity of an area to erosion may be determined considering mainly the morphometric factors (e.g., drainage density and setting, length of the slope or relief ratio, exposure and slope angle), the geological features (e.g., lithology, structures affecting drainage patterns) and the vegetation coverage (Latulippe & Peiry, 1996; Descroix & Mathys, 2003; Gyssels et al., 2005). In the Alpine environment, measurements of denudation rates, in relation with different substrates, have been performed for a long time, using different indirect and direct techniques (see reviews by Chardon, 1996; Latulippe & Peiry, 1996; Delannoy & Rovera, 1996, Descroix & Mathys, 2003). The indirect methods are aimed at providing average erosion/dissolution rates at catchment scale measuring hydrological parameters: suspended load from water runoff (e.g., Della Seta et al., 2009 and reference therein); temperature, pH, conductivity, total dissolved salts (Ca^{2+}, Mg^{2+}, HCO_3- and SO_4^{2-}) for chemical dissolution (e.g., Chardon, 1996; Taminskas & Marcinkevicius, 2002). The direct methods are used to estimate the entity of erosion at hillslope scale, by locally measuring the lowering of topographic surface by means of, among the others, plaques for chemical dissolution (e.g., Rovera, 1990), iron pins for water runoff (e.g., Della Seta et al., 2009 and reference therein). Direct morphometric measurements to detect changes on earth pyramids are also often performed through image analysis (e.g., Perna, 1963), field measurements of lenght, height, depth, width and density of gullies and edges (e.g., Curry, 1999; Curry et al., 2006) or laser scanning (e.g., Smiraglia et al., 2009; Ravanel et al., 2014). Curry et al. (2006) proposed a *'gullying index*' for moraines in paraglacial environments, that considers the number of gullies per kilometre. Other direct methods allow the measurement of erosion using tree roots exposure. This technique has been recently applied on changing landforms (e.g., Hupp & Carey, 1990; Pelfini & Santilli, 2006; Gärtner, 2007; Bollati et al., 2012b, 2016 a, c; Ballesteros-Cánovas et al., 2013; 2015; Stoffel et al., 2014), including badlands-like landforms, in different morphoclimatic contexts also integrating data from tree rings analysis with data coming from traditional geomorphological techniques (e.g., Guida et al., 2008; Ballesteros-Cánovas et al., 2013; Bollati et al., 2012b, 2016a, c). Using such technique, it is worth to pay attention, in specific contexts, to the bias due to secondary roots growth (Bodoque et al., 2015). Arboreal vegetation therefore represents a powerful tool to quantify spatio-temporal environmental changes due to geomorphic processes (i.e., dendrogeomorphology, Alestalo, 1971; Stoffel et al., 2010). The specific methods applied at each study site are described below.

4.1 Pyramides d'Euseigne: earth pyramids

Erosion analysis was performed at different time scales and using different “direct methods” providing various categories of data:

i) *morphometric measurements on historical photographs* (Fig. 9a): the measures were carried out spanning more than one century: 1890, 1906, 1925, 1970, 2011. The quantitative analysis regarded two or three groups of pyramids (Group 1, 2 and 3) depending on the spatial width of each picture. The values of defined segments on the pictures were measured for estimating relative erosion entity through time (Tab. 4). As photographs were not taken from a fixed point on the ground, a distortion was considered and different lengths should be expected year by year. The different lengths of segments, hence, could not be attributed exclusively to erosion. In order to avoid/minimize these errors, for each measures' group, a reference segment was identified (i.e., R1, R2, R3 in tab. 4). These reference measurements were defined as the distance between two fixed points on the pictures (e.g., boulders capping or emerging by two close earth pyramids) that may be considered almost completely static in the investigated time interval. These reference segments were chosen as close as possible to the earth pyramid measured for erosion rate estimation.

Relative values obtained considering the ratio between the lengths of segments measured on earth pyramid undergoing erosion and the corresponding reference measure (e.g., A1/R1 in Tab. 4) may be considered an estimate of erosion (natural or human induced). Also the trend of the ratio between two lengths (e.g., A1/A2 in tab. 4) may be considered proportional to the erosion intensity through time.

ii) *iron pins monitoring* (Fig. 9b): iron pins is one of the techniques used to estimate sediment budget if applied for long last monitoring times. In this case, iron pins were put in specific location covering the whole area of the geosite, during the time interval 2010-2013 to measure variations in the emersion of the pins from the ground and in the geometry of specific geomorphic elements (ridges). This was aimed at determining Local Denudation Rates – LDRs and Average Denudation Rates – ADRs; (corresponding to LER and AER respectively of Bollati et al., 2016a). For more details on the method see Della Seta et al. (2009 and references therein) and Bollati et al. (2016a). Results were compared to the ones obtained by other Authors in both similar and different morphogenetic and morphoclimatic contexts.

iii) *dendrogeomorphological analysis on exposed roots* (Fig. 9c): the investigated trees of *Larix decidua* Mill. grow in the upper portion of the site and quite marginally to the bare erosion surface. The cores and roots sections were analyzed through traditional dendrochronological techniques and softwares (i.e., LinTab, Windendro, TsapWin, COFECHA, Arstan; for further details see Bollati et al., 2016a). LDRs and ADRs over a time interval (corresponding to LER and AER respectively of Bollati et al., 2016a) were calculated using the most frequently applied formula to estimate erosion by means of tree roots exposure proposed by Hupp & Carey (1990):

E = D/A (where E is erosion rate; D -is distance between the current ground surface and the tree root collars; A is age of the micro-morphologic change in root) (data reprised from Bollati et al., 2016a).

4.2 Pyramides de gypse du Col de la Croix: gypsum pillars

Dendrogeomorphological analysis on exposed roots were carried out to quantify erosion. The sampling of trunks and roots of *Picea abies* (L.) Karst were concentrated in the eastern part of the geosite, an area that is currently not interested by the touristic frequentation along the geosite trail (Fig. 11, see paragraph 5.2.1). This was due mainly to avoid the human contribution to erosion but also to the permission to perform fieldwork only outside the touristic path. The dendrogeomorphological methods are the same applied at earth pyramids site (see paragraph 4.1, iii) and the results of roots analysis are original. It is worth to precise that the calculated LDRs and ADRs for rock chemical dissolution take into account also the contribution of soil erosion. Also in this case, the values obtained were compared with those calculated by several Authors in similar morphogenetic and morphoclimatic contexts (Nicod, 1976, Rovera, 1990; Chardon, 1992; 1996).

5. Results

5.1 Erosion on earth pyramids: the case of Pyramides d'Euseigne

5.1.1 Morphometric measurements on historical photographs

The analysis of the iconographic material allows evidencing the progressive morphological changes of the site since the end of the 19th century (Fig. 9, 10).

One of the most evident changes is related to Group 1, characterized by the fall of a big boulder (A1 and A2, Fig. 9) that verified in the time interval 1906-1925. Therefore, after the fall of the block, the earth pyramid underlying the boulder has been evidently thinning more rapidly than the surrounding pyramids. In Group 1, the difference in height between the top of the two earth pyramids increases over time, while the length of the segment representative of earth pyramid lowering (A2) decreases over time (Fig. 10a). Considering the A1/A2 trend in the graph related to the Group 1, it increases over time testifying the undergoing erosion linked with the fall of the block. The same trend was detected for the Group 3 but for this cluster only two pictures were available (i.e., 1890, 2011) (Fig. 10c).

Another critical point within the geomorphosite is represented by the big boulder located immediately above the tunnel, in correspondence of the Group 2 (B1 and B2, Fig. 9). During the restoring of the road (finalized in 1947), some interventions were performed on this portion of the

area to prevent boulders and fine debris fall from above over the road (i.e., artificial stabilization of one side of the earth pyramid). The aim was to preserve the landform and to prevent risk on the road. The interventions are visible observing the differences between 1970 and 2011 pictures. For what concerns Group 2, the chosen reference measure (R3) worked differently in comparison to the others. Unlike previous cases, the top of the earth pyramid undergoing erosion (B1) is in fact located above the top of the reference segment (R3) generating a mirrored trend of the graph related to the segments length variations (Fig. 10b) but that testifies again an increase in erosion.
Since these badlands-like landforms are sensitive to tremors and external perturbations, the building/refurbishment of the road cutting the deposits may have triggered and favoured the fall of blocks and runoff intensification in certain periods. A knee point, for Group 1 and 2, where the record is more continuous, is indicative of an intensification of height loss and of increasing erosion, natural or human induced, at the middle of the 20th century, in correspondence of the human interventions on the road (and on the tunnel). This is index of a not completely linear trend of erosion through time even if the time-gap between images should be taken into account. This effect is particularly significant for Group 2, directly related to the tunnel and road. Unfortunately, the record of pictures for Group 3, not concerned by road works, is, currently, not complete.

5.1.2 Iron pins monitoring

Results of iron pins monitoring, during the period 2010-2013, allowed obtaining an ADR of 35,7 mm/y on the whole site as described by Bollati et al.(2016a). Erosion rates vary in different portions of the geomorphosite (Tab. 5; from Bollati et al., 2016a). During the monitoring phase, some iron pins fell down progressively in the upper part, and were buried by sediment or hit by boulder falling in the middle and lower portions of the site. This testifies a dynamicity also at a smaller time scale if compared with the iconographic analysis covering a longer time interval.

5.1.3 Dendrogeomorphological analysis on trunks and roots

The ADRs obtained by means of roots exposure analysis on *Larix decidua* Mill., span a longer time period 1982-2010 (i.e., 5,8 mm/y). Roots resulted to be exposed since the beginning indicating an instable substrate that was anyway colonized by trees. As described by Bollati et al. (2016a, The exposure period coincided well with a time interval during which both seasonal and annual rainfall amounts had been over the average for several consecutive years.).

5.2 Dissolution at gypsum pillars: the case of Pyramide de gypse du Col de la Croix

5.2.1 Dendrogeomorphological analysis on trunks and roots

Trees of *Picea abies* (L.) Karst.. colonize quite homogeneously the sinkhole area, clinging the roots on the residual terrain between sinkholes and pillars and on thin soils and fractures. The tree roots seem to adapt to the precarious position, anchoring to the gypsum rocks, occupying fractures and favouring their widening at the same time (i.e., bioclastism). The roots also develop along the coalescent sinkholes walls. Not all the trees present exposed roots. The root exposure rates, where available, are reported in Fig. 11 and Tab. 6. The calculated ADR is of 5,66 mm/y and LDRs are variable all around the site and between roots of a single tree. Most of the exposed roots (about 75%) emerged from the ground in the 1970-1980 time interval. 23% of roots testify average values lower than 1 mm/y, 46% greater than 1 mm/y and 31% greater than 10 mm/y. The highest LDRs were recorded in the central portion of the study area where runoff seems to be particularly active (tree 15, ADRs = 9,38 mm/y; Tab. 6, Fig. 11).

6. Discussion

6.1 Denudation rates at the study sites in comparison with literature data

In Tab. 7 a summary of the quantitative values of erosion on glacial deposits available in literature is reported, in comparison with those obtained in the present research.

According to Latulippe & Peiry (1996) the erosion on glacial deposits (as are Pyramides d'Euseigne) should be considered qualitatively "very strong" due to their unconsolidated structure. Nevertheless this is not true for very compact lodgement till, as observed in some cases for earth pyramids (Crosta et al., 2014), where erosion is quite slow in a short timescale. According to Curry (1999), earth pyramids ADRs respectively of 5,8 mm/y by means of roots exposure and 35,7 mm/y by iron-pins monitoring, even if obtained for different time interval, confirms the lower erosion rates for this kind of mature badlands-like landforms located at lower altitude, where glaciers retreated long time ago, respect to the LIA moraines values, more proximal to the current glacier front (i.e., 90 mm/y; Curry, 1999; 300 mm/y, Smiraglia et al., 2009). The obtained erosion values are also lower than those obtained by Perna (1963) on earth pyramids (i.e., 160 mm/y) by means of iconographic material analysis. Moreover the ADRs are lower from those obtained in other morphoclimatic environments on sediments slightly different for compaction and texture (e.g., clay; for more details see Bollati et al., 2016a). A general erosion trend, and not absolute values, was also extrapolated, in the framework of this research, through historical pictures analysis. Since the examined badlands-like landforms are sensitive to tremors and external perturbations, the building/refurbishment of the road cutting the deposits may have triggered and favoured the fall of blocks and runoff intensification in certain periods (i.e., middle of the 20th century), as reported in other cases in literature (Perna, 1963; Heck, 1985; Crosta et al., 2014). A more timely detailed monitoring is hence necessary, evaluating from time to time the causes of erosion.

Concerning denudation rates on soluble rocks (i.e., Pyramides du Col de la Croix), in Tab. 8 a summary of the quantitative values related mainly to dissolution, derived from literature, is compared with those obtained in the present research.

Latulippe & Peiry (1996) reported qualitative “strong” levels of erosion. It depends, within the Alpine area, on climate and particularly on rainfall and temperature regimes (Nicod, 1976; Chardon, 1996; Delannoy & Rovera, 1996). Chardon (1996) described the evolution of “dômes écumoires” in the Alpine environment as very fast in these morphoclimatic conditions. Chardon (1992) provided an analysis on the karst processes in gypsum and limestone, comparing denudation rates within the subdivisions of the mountain environment according to altitude and rainfall regime. Col de la Croix is located at 1778 m a.s.l. and the region is characterized by an average rainfall of 1300 mm/y. These features fits with the “middle mountain” (1000-2000 m a.s.l.; 1100 mm mean rainfall) of Chardon (1992) characterized by denudation rates of 0.7-1 mm/y measured by the Author through indirect methods. The denudation rates at the Pyramides de gypse du Col de la Croix by means of dendrogeomorphology (ADR = 5,66 mm/y) are similar to those obtained on glacial deposits but higher if compared to those reported in literature for gypsum outcrops. The rates usually calculated through indirect methods consider the contributes of underground water, subsurface drainage and surface corrosion but they are limited to the contribution of chemical dissolution. Applying dendrogeomorphological analysis on roots exposure means working on lowering of topographic surface due to denudation generated by the combination of active processes (e.g., dissolution, gelifraction, bioclastism and gravity processes).

6.2 Geoheritage of mountain regions under the perspectives of climate related evolution

Badlands-like landforms shaped by erosion and dissolution, can be proposed as geomorphosites when characterized by certain attributes and values (e.g., Bollati et al., 2016a).

For this reason, since they may be considered valuable for geoconservation, researches on surface processes affecting them are key points. In fact, surface processes may affect, with different rates, the geomorphosites’ scientific value and related attributes (e.g., representativeness, integrity, rarity), and, consequently, their global value.

The achieved results on rates of water related processes should be hence contextualized in the framework of the classification of the geomorphosites into a specific category according to their evolutionary history (i.e., active geomorphosites, passive geomorphosites, evolving passive geomorphosites; Pelfini & Bollati, 2014). The class can change in relation to the integrity of the site which, in turn, depends on the process efficacy on a specific substratum. More in detail, where ancient landforms, representing the traces of past processes, have been totally obliterated by new currently and fast active processes, new landforms and new geomorphosites will generate. These ones can be included in the category of active geomorphosites. Instead, where modelling signs deriving from different processes, active in different times (past and present), are recognizable, the sites can be considered as evolving passive geomorphosites.

In Fig. 12 the time-dependent shifting of climate conditions according to altitude is translated in terms of processes and related landforms (and geomorphosites) characterizing mountain environment (as already illustrated in Fig. 3). The sketch reports the spatio-temporal passage between glacial to paraglacial systems in term of processes (a) and related landforms, using study cases as examples (b), and, as a cascade, between active geomorphosites and evolving passive or passive geomorphosites (c) where new processes affect, respectively, pervasively or not geomorphosites. For considerations about the spatial distribution of the investigated landforms and the related maturity degree refer to paragraph 2.1.1. (Pyramides d'Euseigne) and 2.1.2. (Pyramides de gypse du Col de la Croix).

The Pyramides d'Euseigne are particularly meaningful from a geoheritage point of view, due to the sharp edges and defined shape (i.e., aesthetic value) (e.g., Chiarle & Mortara, 2001; Giusti, 2012; Bollati et al., 2016a). The water runoff process revealed to be active at different timescales, as emerges using different methods (i.e., analysis on iconographic material of different times and iron pins monitoring) and for this reason in literature earth pyramids are considered as active geomorphosites (Giusti, 2012). Nevertheless, the signs of past geomorphological history are preserved at Pyramides d'Euseigne: the profile of a depositional landform deriving from past glacial processes, a moraine, is still recognizable even if it has been successively and currently reworked by running waters, shaping new badlands-like landforms, the earth pyramids of Euseigne. This site may therefore be classified as an evolving passive geomorphosite (white star in Fig. 12) (Pelfini & Bollati, 2014; Bollati et al., 2016a). Just because the ancestor moraine and the earth pyramids are both recognizable, educational exemplarity increases and dissemination purposes become more significant in this kind of sites.

In the case of Pyramides de gypse du Col de la Croix, deriving from coalescence of sinkholes, glaciers represent the erosion agent acting in the past producing the exharation surfaces prone to chemical dissolution. The substratum, modelled before by glaciers, has been continuously dissected by karst process, generating sinkholes and pillars. In this case, the signs of past geomorphological history are labile due to the high rates of dissolution that compromise the conservation of the original geomorphic features especially if small (e.g., striae and scours) (e.g., Nicod, 1976; Klimchouk, 1996; Schoeneich & Imfeld, 1997; Forti, 2004; Yilmaz, 2012; Gutiérrez & Cooper, 2013). A passage between an erosion landform (glacial) to another erosion one (karstic) has been verified. Also this second site could be classified, even if less clearly, as an evolving passive geomorphosites. In alternative, since the tracing of the past modelling are not so evidently preserved, it should more correctly be considered as a new complex of landforms (i.e., sinkholes and pillars) shaped by a new currently dominant and active process (i.e., chemical dissolution). For this reason, it can be more straight classified as (new) active geomorphosite (grey star in Fig. 12). In both cases it emerges that a complete and multitemporal analysis on landforms, including denudation rates, for defining types and stages of processes activity is required and periodically should be revisited, in relation to the type of landforms and rates of geomorphic processes affecting them.

7. Conclusions

From the short review on badlands-like landforms in mountain environment, it emerges that water driven processes related to climate are significant modelling agents in mountain environments. They can change in intensity and frequency, during different time periods and in relation with the involved substratum, producing landforms transforming through times. Results obtained from multidisciplinary and multitemporal analysis on mountain landforms, changing under water action, allowed us to establish specific denudation rates at different time scales (i.e., erosion and dissolution) depending on geological and geomorphological contexts and on the specific method adopted in each context.
Since investigated landforms (Pyramides d'Euseigne and Pyramides de gypse du Col de la Croix) are official geosites included in the Swiss National Inventory of Geosites, the results of this study also allows some conclusions on the role of water action on geoheritage assessment procedures, especially in mountain environment, characterized by high process intensity. In fact, changes in geomorphosites features may affect both the global value and single attributes, as integrity. This implies to develop specific management and conservation procedures, regarding for example the protection of landforms against erosion. Concluding, active geomorphosites and evolving passive geomorphosites, as the two illustrated cases, are very suitable for educational purposes as they allow us to observe respectively the working geomorphic processes and also previous ones, where traces of past modelling are conserved. Experts and scientists contributions are necessary for detailed investigations on landforms changing rate as well as for dissemination of scientific results, that are crucial to raise awareness on the dynamicity of sensitive mountain environments.

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Figure captions

Fig. 1 – Examples of landforms reported in tab. 1. a) Badlands in shales in Civita di Bagnoregio (Viterbo Province, Italy) (photograph: I. Bollati); b) Earth pyramids in glacial deposits in Segonzano (Trento Province, Italy) (photograph: E. Reynard); c) Earth pyramids (local name: Ciciu) in mass wasting deposits in Villar Costanzo (Cuneo Province, Italy) (photograph: I. Bollati); d) Rock pyramids in sandstones at Los Mallos de Riglos, Aragon, Spain (photograph: E. Reynard); e) Rock pyramids in limestones (local name: tsingys) in Bemaraha National Park (Madagascar) (photograph: P. Coratza).

Fig. 2 – Earth pyramids evolution and classification. a-d examples of types of earth pyramids, modified from the classification proposed by Perna (1963): complex of pyramids (a), rocky caprock (b), soil as caprock (c), vegetation as caprock (d). e) Typical earth pyramids landscape in mountain environment where cap rock may come not only from the deposit itself but also from the slopes.

Fig. 3 – Examples of spatial relations and ideal time evolution between two typologies of Bl-LFs in the glacial and paraglacial morphoclimatic systems in Northern and Southern Alps. a) and d) Little Ice Age (LIA) moraines of the Glacier du Mont Miné (Hérens valley, Western Swiss Alps) and of the Forni Glacier (Upper Valtellina, Central Italian Alps); b) and e) earth pyramids of Euseigne (Hérens valley) and Postalesio (Lower Valtellina) (photograph: I. Bollati); c) and f) location of the two study cases that allows the perception of current spatial relation between them. The locations are also reported in Fig. 4 (b, e = A; a, d = B).

Fig. 4 – Location of the study sites (C and E) and of the sites mentioned in Fig. 2 (A, B, D). A) Postalesio earth pyramids; B) Little Ice Age (LIA) moraine in the Valtellina; C) Pyramides d'Euseigne; D) LIA moraine in the Ferpècle valley; E) Pyramides de gypse du col de la Croix

Fig. 5 – The structure of a "dôme écumoire". (a) Genesis and evolution of a "dôme écumoire" (modified from Chardon, 1992): during the main phase of glacial retreat following the Little Ice Age (LIA) the now sub-aerial gypsum outcrops are continuously modelled and dissolved by water that acts both in the underground and on the surface. The result is a sinkholes-dominated landscape. (b) "Dôme écumoire" features depending mainly on slope steepness (modified from Schoeneich & Imfeld, 1997).

Fig. 6 –Pyramides d'Euseigne (Canton Valais, Swiss Alps) and examples of cap blocks. a) Metric boulder on one of the stems (Fig. 1a, b); b) soil with grass that protect the stem (Fig. 1, c); c) the earth pyramids complex of Pyramides d’Euseigne and the touristic trail allowing their visit (photographs: I. Bollati, M. Pellegrini).

Fig. 7– Examples of gypsum pillars in the Western Swiss Alps shaped in Triassic evaporite rocks. a) Pyramides de gypse du Col de la Croix; b) Pyramides de gypse de La Tour in the Derborence valley (photographs: I. Bollati).

Fig. 8 – Overview of features of Pyramides de gypse du Col de la Croix. a) Rillenkarren on gypsum outcrop; b) gypsum and dolomite inclusions; c) sinkholes and vegetation colonization; d) development of ridges and incised rills, where slope steepness increases, close to the road of the Col de la Croix towards Les Diablerets (photographs: I. Bollati, M. Pellegrini).

Fig. 9 – Multidisciplinary approach to investigate badlands-like landforms. a) historical photographs of the site of Pyramides d’Euseigne, object of morphometric measurements. The codes reported for the measurements refer to Tab. 4. Evident changes have happened since the 1970s. (Pictures: personal collection Hervé Mayoraz); b) iron pins monitoring at Pyramides d’Euseigne; c) roots exposed, at Pyramides de gypse du Col de la Croix, on which dendrogeomorphological analysis were performed

Fig. 10 – Results of the morphometric measurements by means of iconography on the groups of earth pyramids at Pyramides d’Euseigne. The reported values are without units of measurements since they are the ratio of two lengths. The parameters are indicated in Tab. 4 and reported in the pictures in Fig. 8. In the graph related to Group 3 the lines are dashed since only the values related to years 1890 and 2011 were calculated.

Fig. 11 – Geomorphological sketch of the investigated area of Col de la Croix (from Google Earth) reporting the distribution of the trees and Average Denudation Rates (ADRs) values, for trees presenting exposed roots, as indicated in Tab. 4. Numbers are related to investigated trees.

Fig. 12 – Spatio-temporal evolution of processes, landforms and geomorphosites according to climate change in mountain environment. a) Example of time-dependent transition in mountain environment between processes typical of glacial and paraglacial morphoclimatic systems; b)

investigated landforms (and geomorphosites) as example of the spatio-temporal transition between glacial and paraglacial morphoclimatic and morphogenetic systems; c) time dependent evolution between categories of geomorphosites according to typology and activity degree of processes. AGs = Active geomorphosites; NEW AGs = New Active Geomorphosites, grey star ; PGs = Passive geomorphosites, black star; EPGs = Evolving passive geomorphosites; white star); Lfs = Landforms,; LIA = Little Ice Age; PE = Pyramides d’Euseigne; PCC = Pyramides du Col de la Croix.

Tables and captions

LANDFORMS/LANDSCAPES	LOCAL NAMES	SUBSTRATE	Examples
Badlands (e.g., gullies)		Loess	Titel loess plateau (Vojvodina, Northern Serbia)
	Calanchi, Biancane	Clay	Civita di Bagnoregio (Lazio, Italy; fig. 1, a)
Earth Pyramids/Pillars/Pinnacles	Demoiselles coiffées, Cheminées de fées, Organ pipes, Ladies with hats, Smoothing pyramids	(Fluvio)glacial deposit	Zone, Renon, Segonzano (fig. 1, b), (Italian Alps) Pyramides d'Euseigne (Swiss Alps)
	Ciciu	Mass wasting deposits	Villar Costanzo (Piemonte, Italy; fig. 1, c)
Rock Pyramids/Pillars/Pinnacles, Pedestal Rocks, Hoodoos	Longastones, Mushroom, Rocas fungiformas, Roches champignons, Pilzfelsen, Balze	Sandstone	Bryce Canyon (Utah, USA) Los Mallos de Riglos (Aragon, Spain) (fig. 1, d)
	Balze	Conglomerate	Piana Crixia conglomerate (Liguria, Italy)
	Fairies' Chimneys, Peribacası	Volcanoclastic	Cappadocia (Turkey)
Rock Pyramids/Pillars/Pinnacles, Stone Forest		Gypsum	Pyramides de la Zone des Cols (Swiss Alps)
		Cargneule	Le Monolithe de Sardières (Vanoise National Park, France)
		Limestone	Shilin (Yunnan, China) Tsingy (Bemaraha National Park, Madagascar) (fig. 1, e)

Table 1 – Summary of types of badlands-like landforms (Bl-LFs). The classification is based on the categories defined after Sacco (1934), Perna (1963), Heck (1985), Goudie (2004) and Giusti (2009). Grey cells indicate the landforms typology considered, in the present research, for measuring denudation rates.

Altitude (m a.s.l.)	LFs	Age of glacier retreat (ky)
2800-3000	metric sinkholes, subject to strong dissolution rates	
2300-2800	decametric sinkholes characterized by dissolution processes active for a longer time	10
1800-2300	"honeycomb domes", characterized by (pluri)decametric sinkholes deriving from the coalescence of smaller single sinkholes are typical. Sediments trapped at the sinkhole bottom allow the formation of small lakes and alpine meadows are present.	15
1000-1800	pluridecametric sinkholes, slowly evolving	15-18

Table 2 – Dissolution landforms on gypsum outcrops present at different altitudes in relation with glacier retreat according to Chardon (1992, 1996).

Typology	Definition	Example
ACTIVE GEOMORPHOSITE - (AG)	A geomorphosite that allows the visualization of the genetic geo(morpho)logical processes, still active in the current morphoclimatic system	Lateral moraine (currently being deposited)
PASSIVE GEOMORPHOSITE - (PG)	A geomorphosite that testifies past processes not more in equilibrium with the current morphoclimatic system	Lateral moraine (Late Glacial)
EVOLVING PASSIVE GEOMORPHOSITE - (EPG)	A passive geomorphosite that is rapidly changing under the action of processes different from the genetic ones and that are in equilibrium with the current morphoclimatic system	Lateral moraine (LIA) dissected by gullies

Table 3 - Typologies of geomorphosites according to the activity of processes (modified from Pelfini & Bollati, 2014). LIA = Little Ice Age.

GROUP	MEASURE (Absolute value)	Meaning	MEASURE (Relative value)
1	**A1**	Length proportional to erosion	**A1/R1**
	A2		**A2/R1**
	R1	Reference measure	**A1/A2**
2	**B1**	Length proportional to erosion	**B1/R2**
	B2		**B2/R2**
	R2	Reference measure	**B1/B2**
3	**C1**	Length proportional to erosion	**C1/R3**
	C2		**C2/R3**
	R3	Reference measure	**C1/C2**

Table 4 - Summary of the measurements performed on iconographic material regarding groups of earth pyramids in the site of Pyramide d'Euseigne.

AREA OF PE	**ADRs (mm/y) by means of dendrogeomorphology (1982-2010)**	**ADRs (mm/y) by means of iron pins monitoring (2010-2013)**
Upper area with prevalent erosion	5,8	61,7
Middle area		22,5
Lower area with prevalent deposition		-3,3
ADRs over the whole geosite (mm/y)	5,8	35,7

Table 5 – Values of erosion rates (mm/y) as reported by Bollati et al. (2016a) by means of iron pins monitoring and dendrogeomorphology at Pyramides d'Euseigne (PE). ADRs = Average Denudation Rates.

Tree	Root	Exposure time interval	LDRs (mm/y)	ADRs (mm/y) (Tree)	ADRs (mm/y) (Site)
5	1	1939-2013	4,50	4,32	*5,66*
	2	1920-2013	4,14		
15	1A	1978-2013	10,54	**9,38**	
	1B	1978-2013	8,89		
	2A	1977-2013	17,36		
	2B	1977-2013	17,08		
	3	1979-2013	11,35		
	4A	1972-2013	0,17		
	4B	1973-2013	0,26		
	4C	1973-2013	0,2		
16	1	1979-2013	5,94	3,29	
	2	1888-2013	1,75		
	3	1920-2013	2,17		

Table 6 – Local Denudation Rates (LDRs) and Average Denudation Rates (ADRs) as calculated in the Pyramides de gypse du Col de la Croix area for those trees showing exposed roots. The spatial distribution is reported in Fig. 11 and different grey cells indicate various groups of exposure age.

Author	**Method**	**Denudation rate (mm/y)**
MORAINES IN RECENTLY DEGLACIATED AREAS (LIA)		
Perna (1963)	Morphometric measurements	160
Curry (1999)	Morphometric measurements	90
Smiraglia et al. (2009)	Laser Scanner	300
EARTH PYRAMIDS AT LOWER ALTITUDES		
Present research	Roots exposure	5,8
	Iron pins monitoring	35,7

Table 7 - Comparison of denudation rates obtained in literature and in the present research on glacial deposits. LIA = Little Ice Age.

Author	Method	Particular conditions	Denudation rate (mm/y)
Nicod (1976)	Indirect		1,066
Rovera (1990)	Direct	Vegetation coverage	0,125
		Human intervention	4
		Sinkholes bottom	1,37
Chardon (1992)	Indirect	Periglacial	1,5
		Middle mountain, forest, meadows	0,7-1,0
Chardon (1996)	Indirect	High mountain environment	1,212
Present research	Direct	Sinkholes edges	5,66

Table 8 - Comparison of denudation rates on gypsum outcrops, obtained, in literature and in the present research, using different investigation techniques (direct and indirect).

Research Highlights

- Water driven processes in mountain environments are space and time-dependent.
- Denudation rates are different depending on bedrock and geomorphic features.
- Badlands-like landforms are meaningful as active/evolving passive geomorphosites.
- Knowledge of geomorphic dynamics/rates is necessary to properly manage geoheritage.

Figure_1
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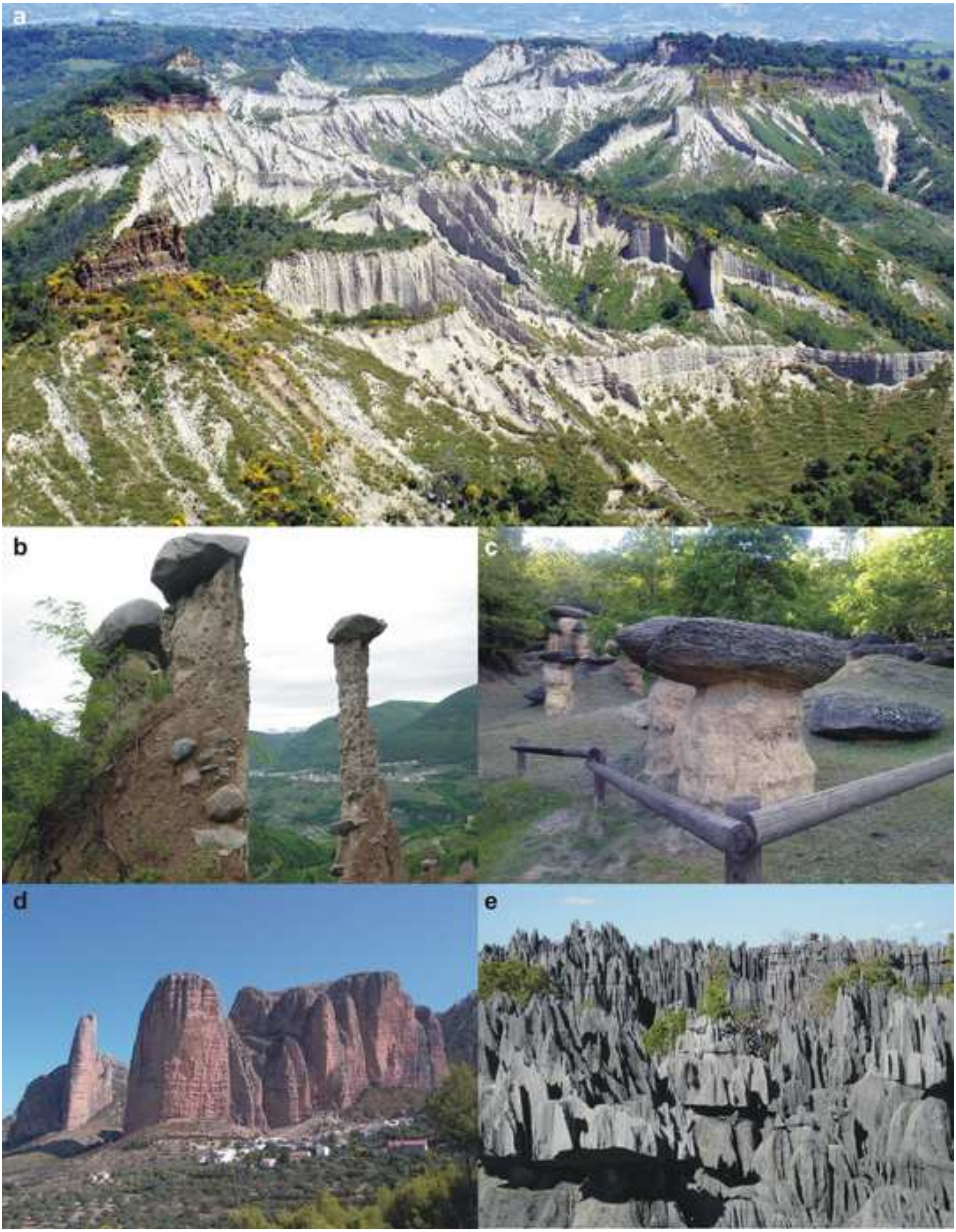

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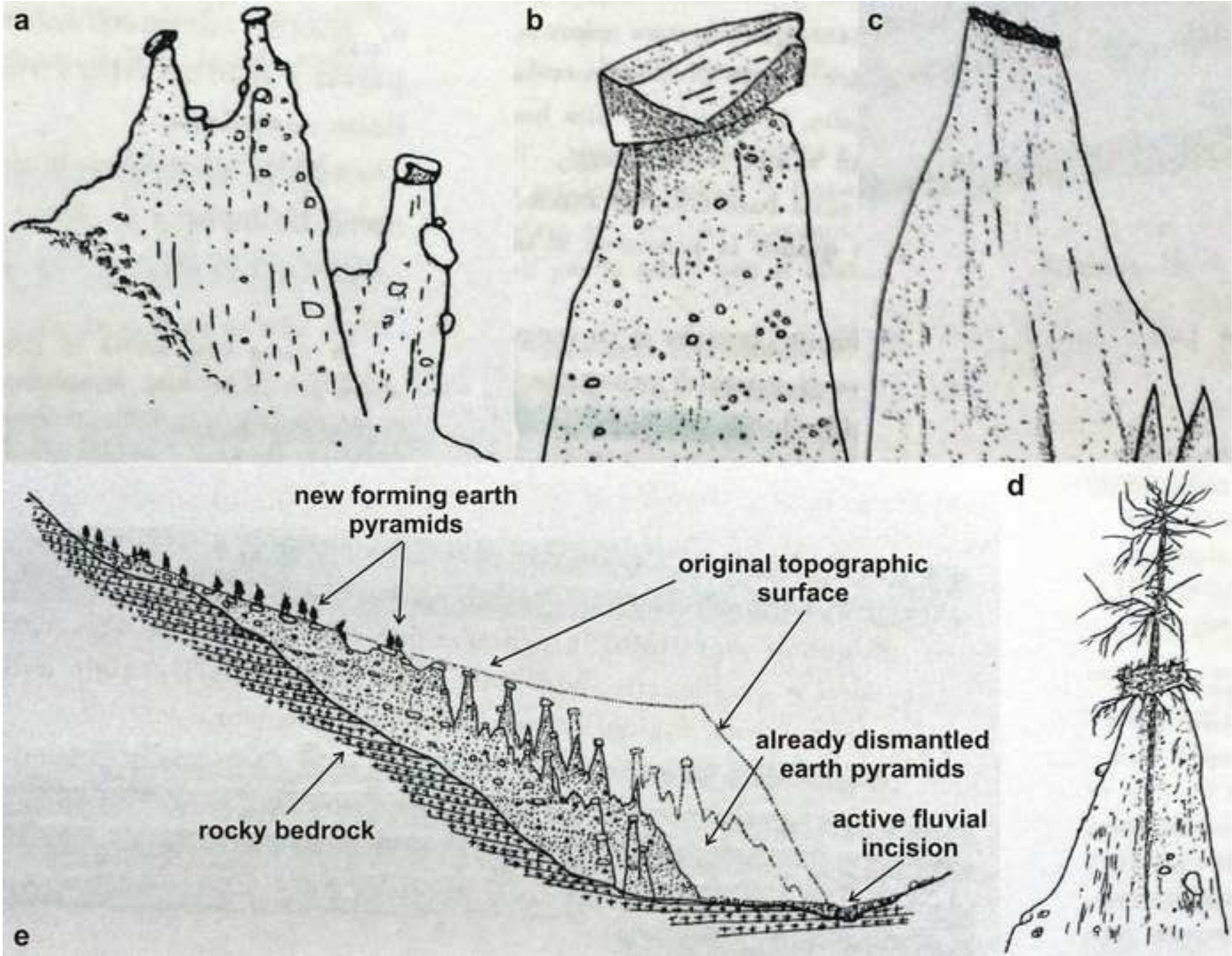

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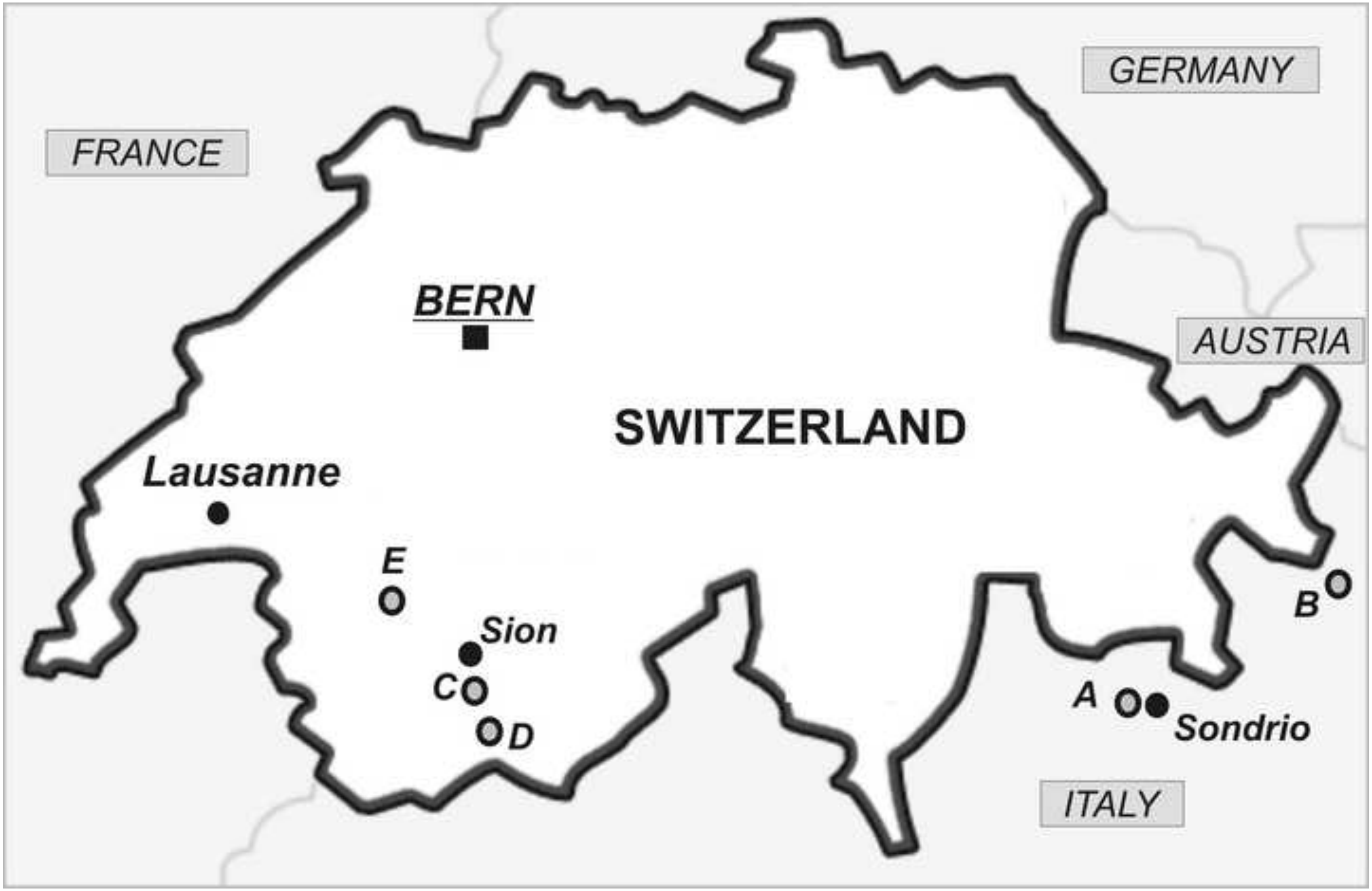

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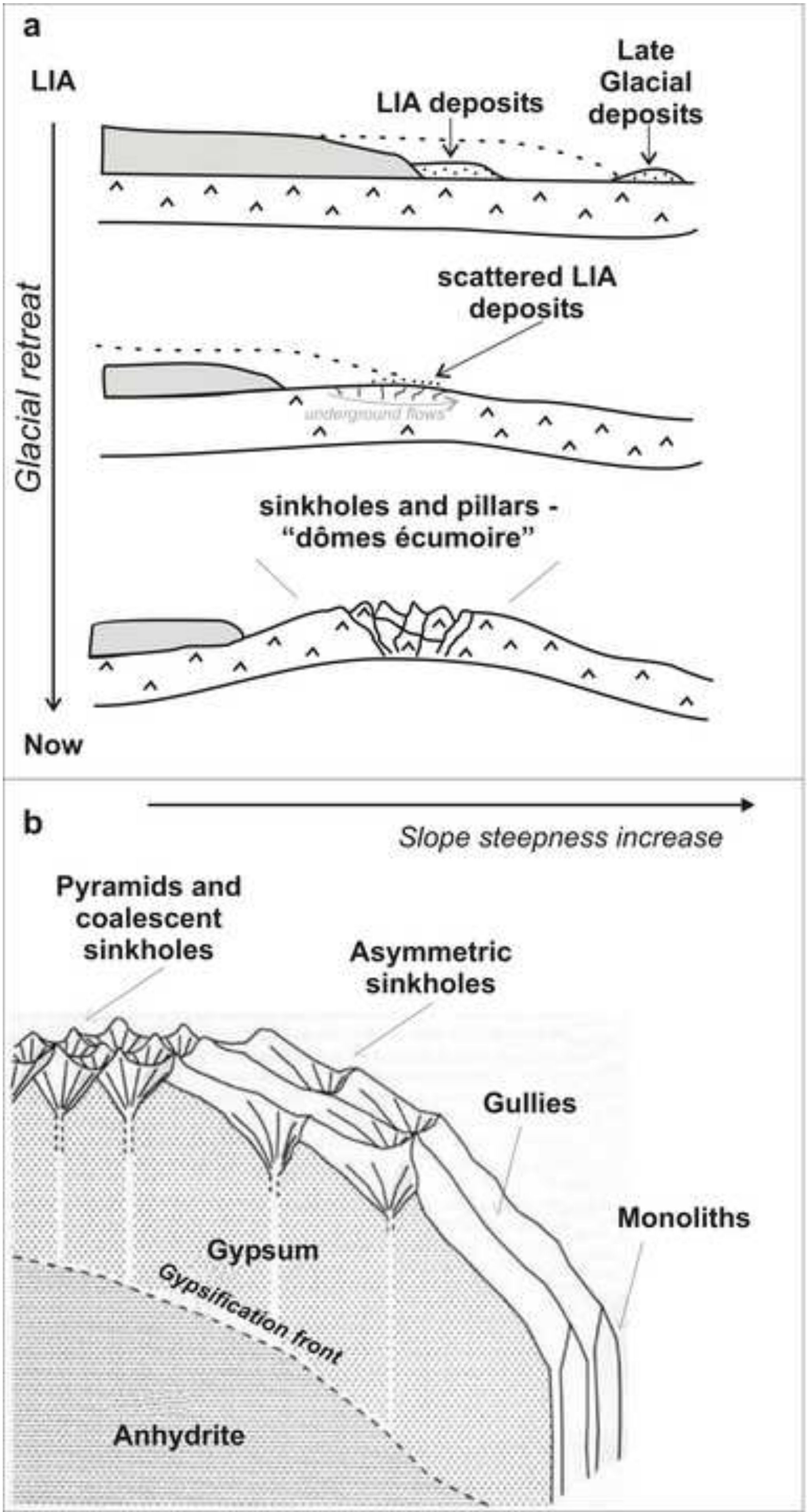

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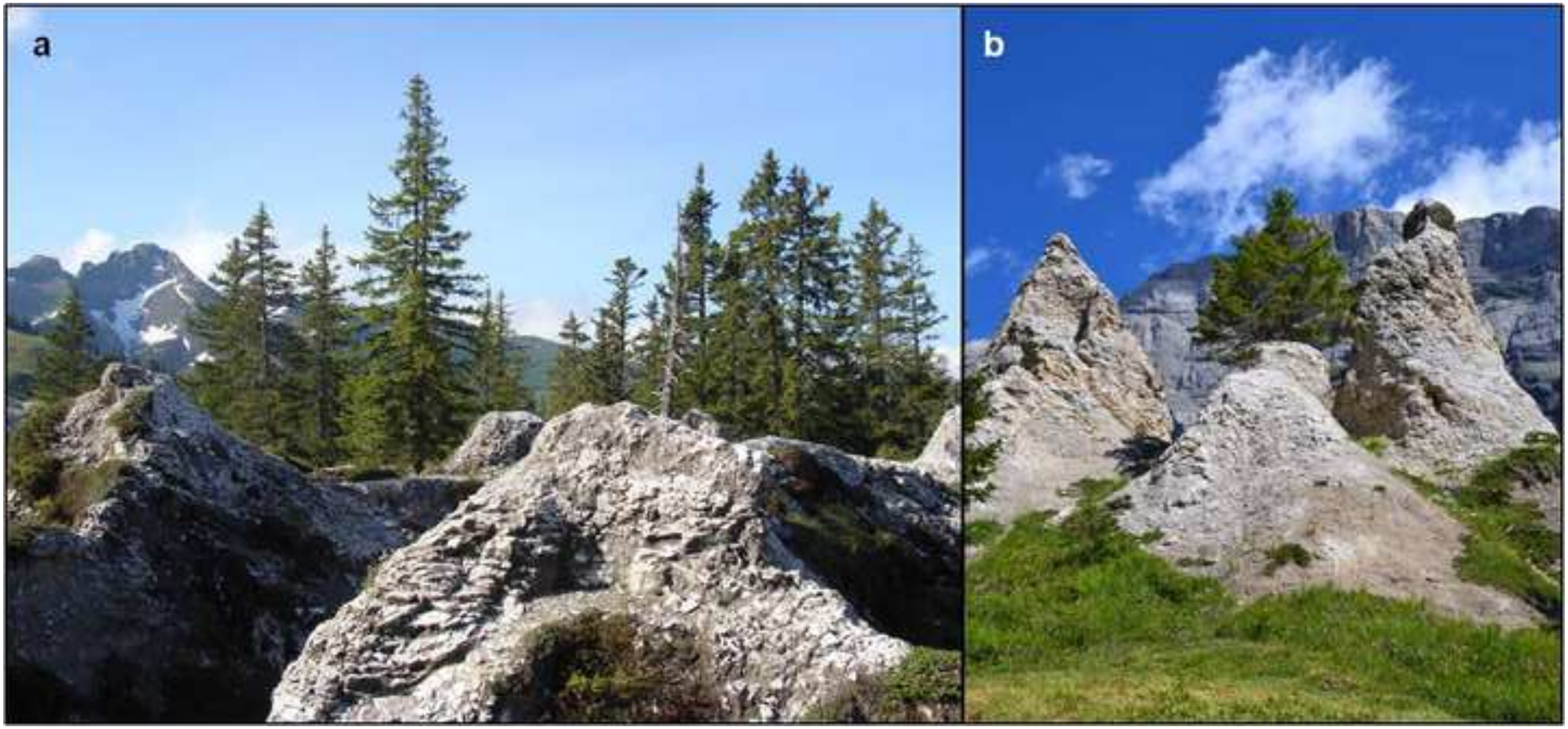

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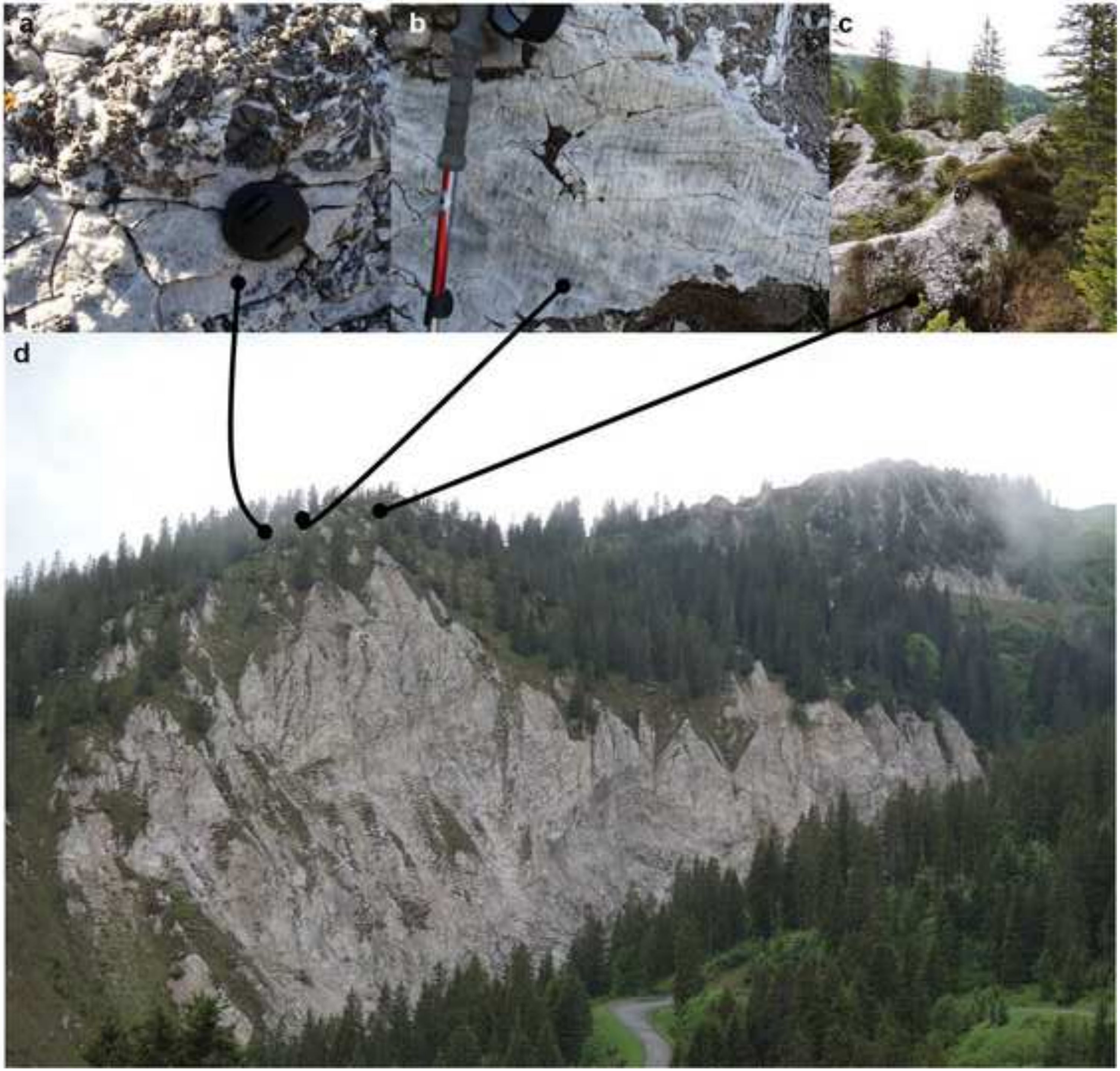

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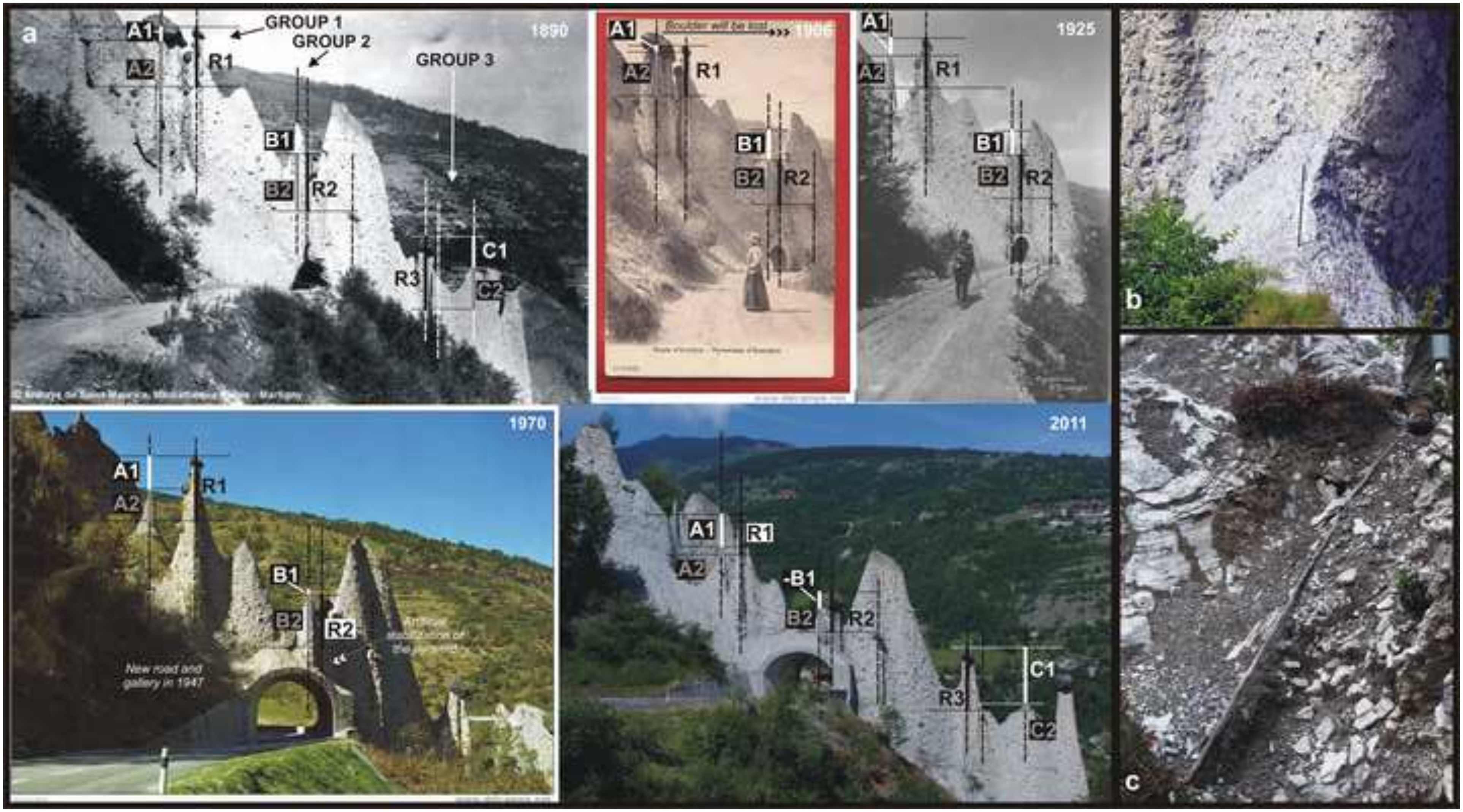

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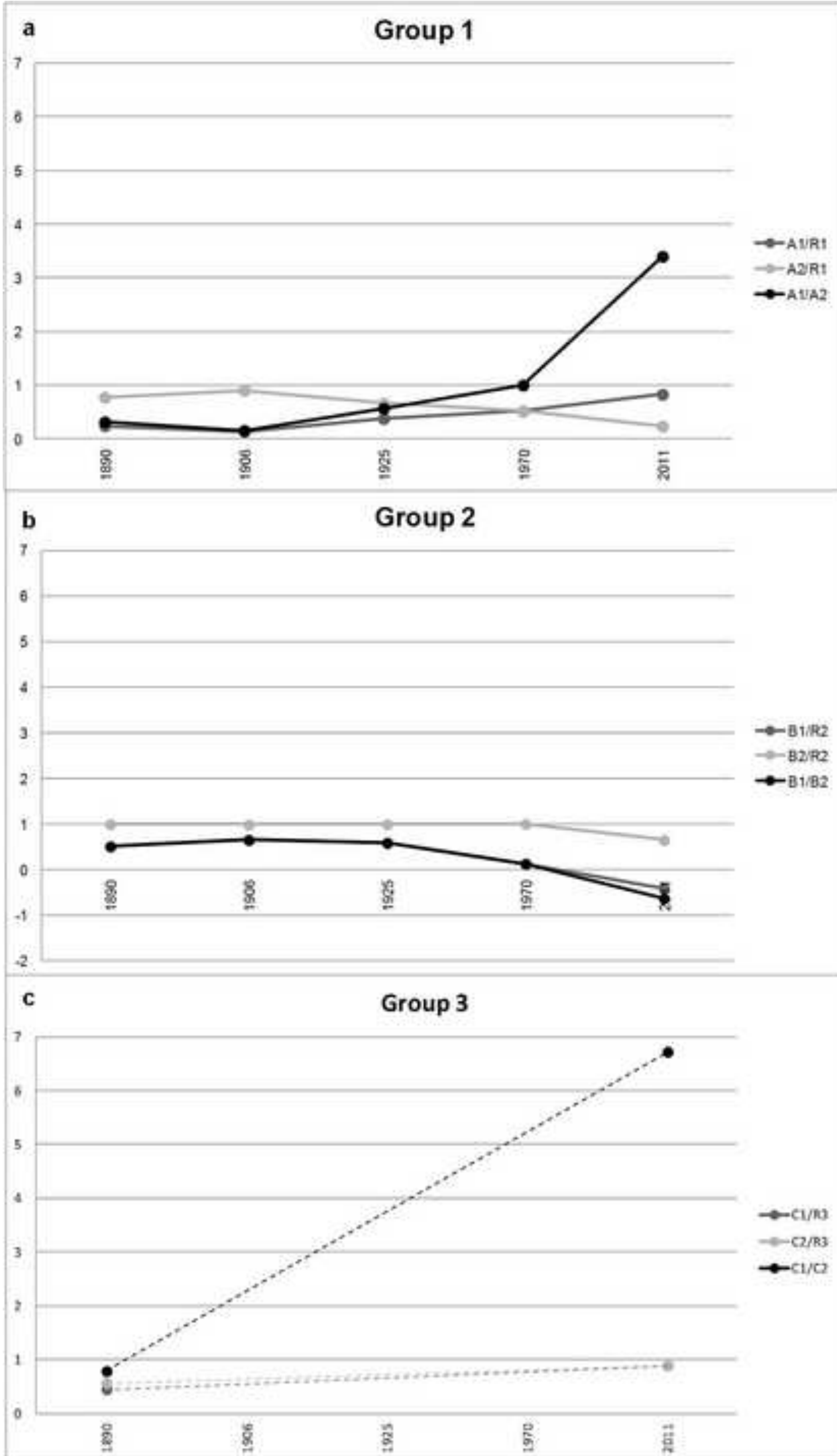

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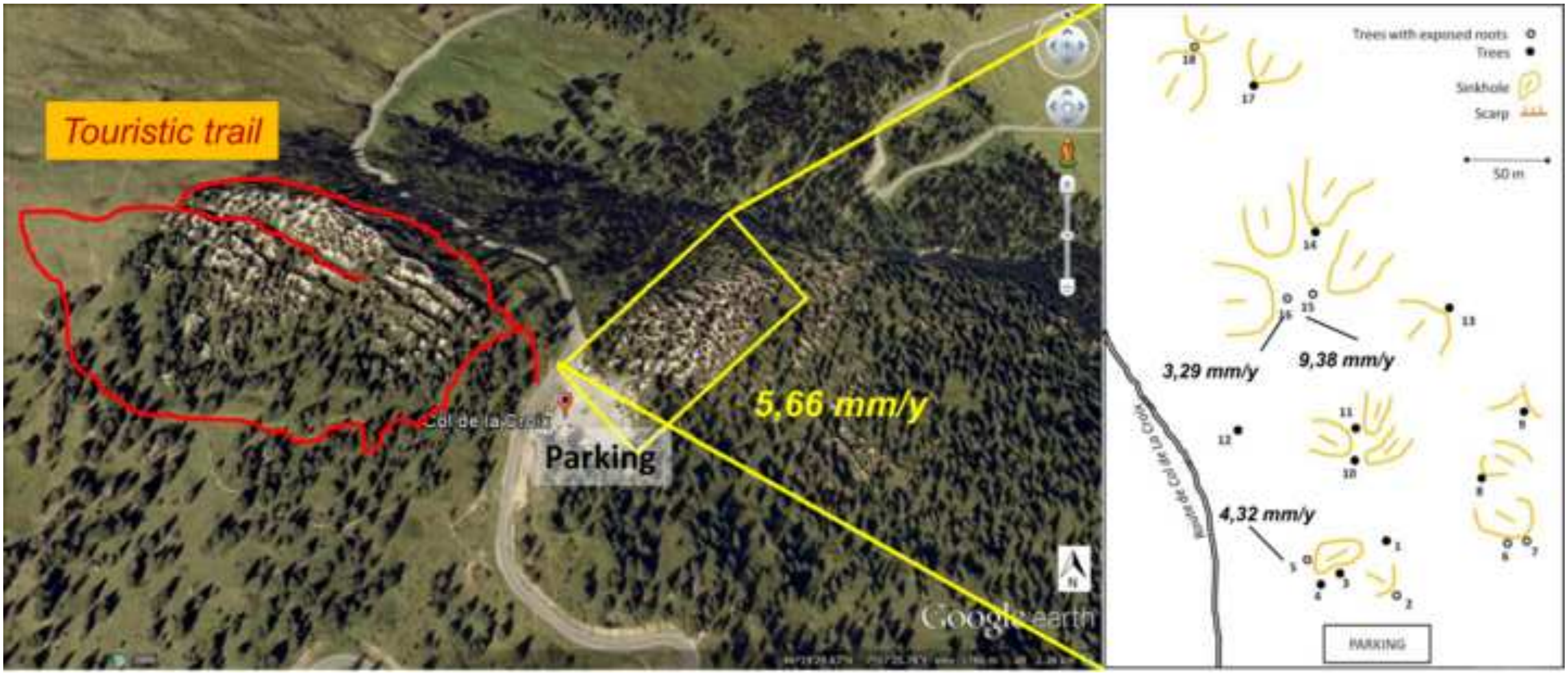

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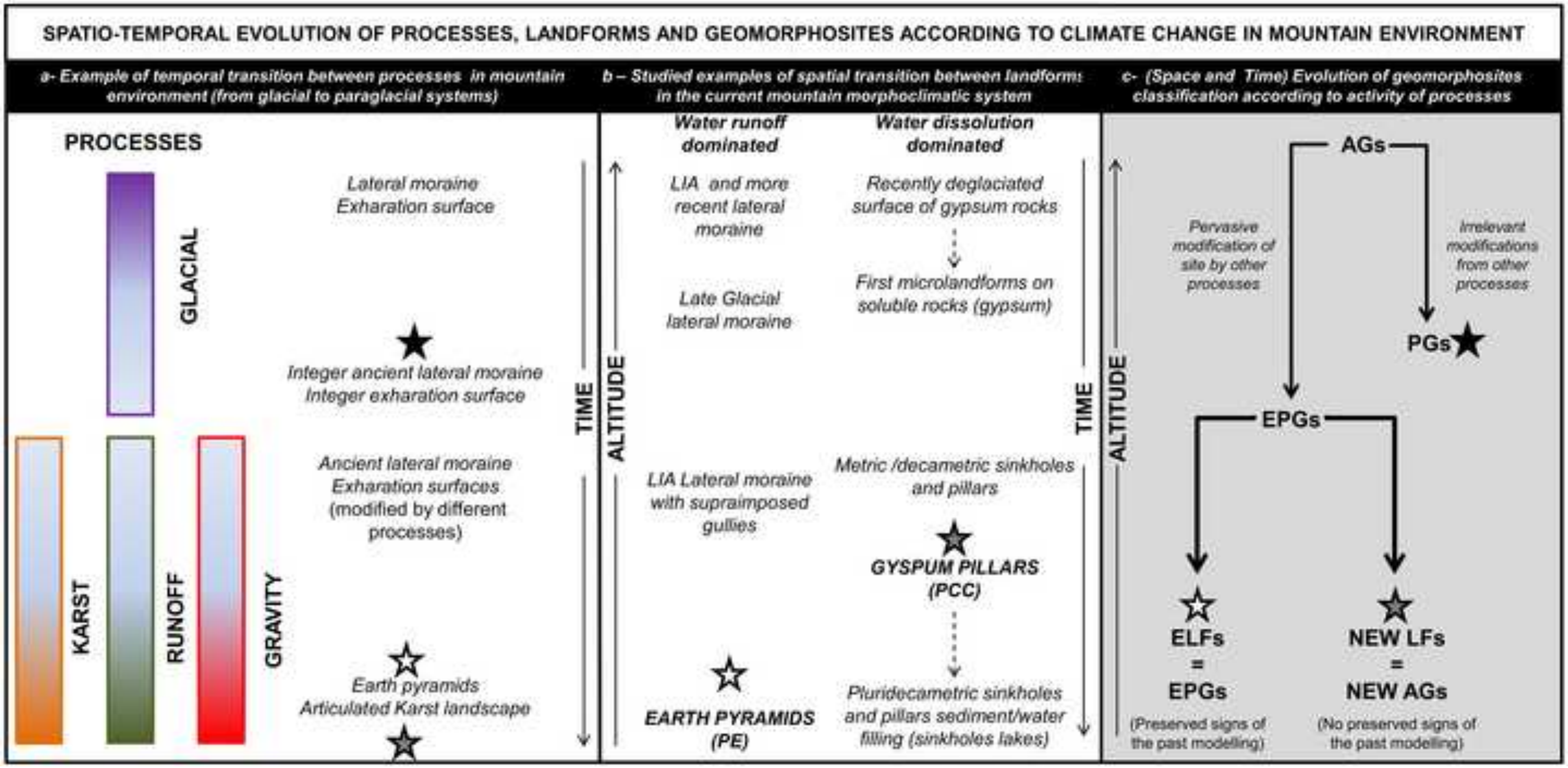

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