



# How Can a Complex Geosite Be Enhanced? A Landscape-Scale Approach to the Deep-Seated Gravitational Slope Deformation of Pointe Leysser (Aosta Valley, NW Italy)

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## Abstract

Complex geosites represent important georesources as components of the geoheritage of a region. Regardless, their management in terms of promotion and geoconservation may be challenging. Among others, gravity-related landforms can be considered complex geomorphological features and are often neglected in the geosite inventories, even if their dynamic and related educational exemplarity, multiscalarity and aesthetic value are relevant and make them potentially complex geosites. The aim of this research is to discuss the possible approaches to a potential complex geosite in the Western Italian Alps. The area is characterised by an articulated and geodiverse set of landforms that concur to define a multifaceted geological and geomorphological setting due to the presence of one of the most significant gravity-related geofeatures of the Italian Alps: the Pointe Leysser deep-seated gravitational slope deformation. The entire context, as well as each single geological/geomorphological feature, will be presented and described enhancing and quantifying their geoheritage values (i.e. scientific value, additional value, the potential for use). Finally, proposals for virtual or field approaches will be discussed, considering the limitations and advantages of dealing with a complex geosite. The suggested strategies assume an important role with respect to both the promotion and geoconservation of complex geosites.

**Keywords** Complex geosite · Multiscalarity · Deep-seated gravitational slope deformation · Pointe Leysser (Western Italian Alps)

## Introduction

Deep-seated gravitational slope deformations (DSGSDs) are mass movements that encompass entire valley flanks and are propagated at very low velocities (mm/year) (Dramis and Sorriso-Valvo 1994; Agliardi et al. 2012). Such phenomena are common on mountain belts, particularly in valleys deeply carved by glaciers during the last glaciation. Although DSGSDs normally occur almost everywhere in the Alps (Agliardi et al. 2009, 2013; Ambrosi and Crosta 2006; Fioraso et al. 2011; Martinotti et al. 2011; Crosta

et al. 2013; Delle Piane et al., 2016; Fioraso 2017; Forno et al. 2020) and in other mountain areas (e.g. Alexandrowicz and Alexandrowicz 1988; Shroder et al. 2011; Jarman et al. 2014), and they have been extensively studied over the last several decades (first by Zischinsky 1966; Němčok 1972; Malgot 1977; Mortara and Sorzana 1987), these phenomena are essentially unknown to the general population and even to the inhabitants who live on them. The reason is to be found in the very large extension of this special type of gravity-related landform, which makes it not well visible as a whole; in the slowness of their activity, which does not make it perceived as a source of risk for the population; and finally, because DSGSDs are complex structures that are not easy to explain and disclose.

Accordingly, the Italian Landslide Inventory (IFFI; <https://idrogeo.isprambiente.it/app/>) includes 1645 DSGSDs (0.27% of the total number of Italian landslides, see ‘Landslides as elements of geoheritage’), but among them, only one (the ‘DGPV del Lago di Bargone’, Liguria Region) is

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inserted into the ISPRA National Inventory of Geosites (<http://sgi.isprambiente.it/GeositiWeb/default.aspx?ReturnUrl=%2fgeositiweb%2f>), which collects the sites of geological interest available for promotion as elements of Italian geological heritage. To gain insight into investigating a complex landslide geosite such as a slope featuring DSGSDs, including the other interconnected types of geomorphological features, we selected a case study in the Aosta Valley Region (Western Italian Alps).

The selected case is a slope featuring the second largest DSGSD in the region and one of the largest gravitational collapses in the Alps chain: the Pointe Leysser DSGSD. For this geomorphological element, wide literature is available concerning geology, geomorphology, paleoecology and geoarchaeology (see the following chapters). Despite this fact, it is not included in the ISPRA National Inventory of Geosite, and only two components of it (see ‘Becca France rock avalanche’ and ‘Badlands scattered geosites’) are included in the Geosites Inventory of the Aosta Valley region (<https://www.regione.vda.it/territorio/territorio/geositi/>).

Hence, to discuss a potential approach for assessing and proposing a DSGSD as a geosite (see ‘Deep-seated gravitational slope deformations as complex geosites’) and particularly as a *complex geosite* (sensu Mikhailenko et al. 2019), this paper will provide (i) a detailed description of the geological and geomorphological features associated with the P. Lesser DSGSD, according to the literature, and including original data coming from recent studies (see ‘The geoheritage sites within the P. Leysser-Becca France slope’); (ii) for each feature, a discussion on and quantitative evaluation of the attributes as geosites (see ‘The geoheritage sites within the P. Leysser-Becca France slope’); and (iii) a methodological proposal for managing complex geosites based on a spatial-scale approach (from landscape to single site; see ‘Discussion and conclusion’).

## Landslides as Elements of Geoheritage

Landforms related to gravity-driven processes may represent impressive features of the physical landscape that can be scenic for the remarkable scars they leave in the background (i.e. landmarks; Coratza and De Waele 2012), significantly modifying the geomorphic dynamics at the valley scale with potential long-lasting impacts (e.g. rock avalanches; Wang 2015; Stanczyk et al. 2019). They are also significant due to the high number of casualties caused by these movements (Guzzetti 2000). On the other hand, these kinds of landforms may become tools for raising awareness in the general population about the geomorphological hazards affecting their own territory (May 2008; Coratza and De Waele 2012; Calcaterra et al. 2014; Pelfini and Bollati 2014; Alcántara-Ayala and Moreno 2016; Bollati et al. 2019a). At such sites, local

administrations are gradually becoming involved with specialists in planning the most correct safety measures (May 2008; Nix and Marinoni 2006; Borgatti and Tosatti 2010).

Among the gravity-related landforms, landslides, for example, may be very diverse, as per the traditional classification by Cruden and Varnes (1996), recently updated by Hungr et al. (2014), and represent an element concurring with the geodiversity of a region (Margielewski and Alexandrowicz 2004) in terms of different types of movement, diverse causes and effects and activity (i.e. active and inactive landslides; Tognaccini 2019). The geomorphodiversity (sensu Panizza 2009) is more amplified in detail by the different mechanisms characterising the movement (e.g. rock fall, rock toppling, lateral spreading, flow and combinations of them; Hungr et al. 2014), different predisposing factors (e.g. structural conditions of the bedrock and thrust geometry; Bucci et al. 2019) and triggering factors (e.g. earthquake, volcanic eruption, intense rainfall; Basilone et al. 2019) that are responsible for their occurrence and exhaustion.

All these features allow us to consider landslides and gravity-related landforms in general, first as *geodiversity sites* of a region (sensu Brilha 2016), then, when a specific scientific value is recognised, as *geoheritage sites* or *geosites* (sensu Grandgirard 1999) or *geomorphosites* (sensu Panizza 2001) if the interest is mainly related to geomorphology. In addition to scientific value, including educational exemplarity (Garavaglia and Pelfini 2011; Bollati et al. 2019a), related to their importance in delineating the mechanism of Earth's surface evolution, landslides can also be featured by cultural (e.g. Borgatti and Tosatti 2010; Niculiță and Mărgărint 2018; Cocean et al. 2019; Tognaccini 2019) and other additional values such as aesthetic or socio-economic ones (Bollati et al. 2016b, 2018b).

The ecological attributes of these landforms are relevant (Margielewski and Alexandrowicz, 2004; Bollati et al. 2018b; Niculiță and Mărgărint 2018). There is still an open discussion about whether the ecological support role of landforms should be considered within the scientific value (Bollati et al. 2015) or as an additional attribute (Niculiță and Mărgărint 2018). In both cases, Margielewski and Alexandrowicz (2004) strongly underline the relationship existing between geodiversity and biodiversity in such environments. Arboreal vegetation may become a useful tool to reconstruct landslide geomorphic dynamics (see a review by Šilhán 2020 and Bollati et al. 2018b), and authors working specifically on debris flow-like landslides underline the importance of trees as indicators in geoheritage assessment procedures, allowing multidisciplinary educational approaches (Garavaglia et al. 2009; Bollati et al. 2019a).

Material and immaterial cultural values may also characterise gravity-related landforms when associated with cultural assets or unique and impressive geoarchaeological

remnants. Considering the immaterial cultural value, it may derive from the beauty of landscapes sculpted by the geomorphic process, becoming inspirational for artists (Di Veroli et al. 2018). In such cases, landslides may acquire the specific label of cultural geosites/geomorphosites (Niculiță and Mărgărint 2018; Reynard and Giusti 2018) or even geo-archeomorphosites (sensu Brandolini et al. 2019). Furthermore, historical value can be associated with the memory of catastrophic events (Migoń and Pijet-Migoń 2019), as occurred in the area of the Becca France rock avalanche (Forno et al. 2012).

Then, as mentioned before, their scenic value at the landscape scale (Wang 2015; Stanczyk et al. 2019) is related to the sudden change in relief properties and appearance, as well as to vegetation colonising such deposits (e.g. recent examples: Alta, Norway, June 2020; Oso, Washington, USA, March 2014). Their socioeconomic value may instead be related to the potentiality of rocks involved in DSGSDs to host significant aquifers (De Luca et al. 2019; Gizzi et al. 2020).

Currently, geosite inventories (e.g. Chrobak 2015; Giovagnoli 2017; Ferrando et al. 2021) and geotrails connecting geosites include gravity-related features as hot spots of interest (e.g. several examples related to the Italian Alps and Apennines: Basilone et al. 2019; Bollati et al. 2019a, 2019b; Bucci et al. 2019; Filocamo et al. 2019). Regardless, for example, the National Geosites Inventory in Italy, managed by the Italian Institute for Environmental Protection and Research, Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA; <http://sgi.isprambiente.it/GeositiWeb/default.aspx?ReturnUrl=%2fgeositiweb%2f>; accessed on 16th May 2022; Giovagnoli 2017) reports only 13 landslides, including paleolandslides, plus 10 not available for promotion, out of 2059 geosites (i.e. in the complex, 23, < 1%). This is a relatively low value if considering the high susceptibility of the Italian territory to mass wasting processes (Trigila et al. 2013), as depicted in the Italian Landslide Inventory (Progetto Inventario dei Fenomeni Franosi in Italia (IFFI); <https://idrogeo.isprambiente.it/app/>; accessed on 16 May 2022), which includes 642,785 landslides.

This is in line with the fact that the analysis of the specific features of landslides as components of geoheritage is still poorly addressed (e.g. Chrobak and Cebulski 2014). In a very recent article, Morino et al. (2022) identified three aspects related to landslides as geomorphosites: their representativeness of past and present climate changes, their anthropic signature and, finally, their risk perception.

If we consider these landforms as geomorphosites in more detail (sensu Panizza 2001), we can discuss the three main features distinguishing geomorphological heritage sites according to Coratza and Hoblèa (2018): (i) aesthetic value,

(ii) dynamism and (iii) multiscalarity. The first attribute (the spectacular nature of landslides) has been previously mentioned in relation to the profound signs that landslides may leave in the landscape. Dynamism and multiscalarity will be described in detail for the landslide case.

## Dynamism of Gravity-Related Geomorphosites

The second feature characterising geomorphosites according to Coratza and Hoblèa (2018) is dynamism (ii). Pelfini and Bollati (2014) use the terms active and passive geomorphosites (i.e. Reynard 2004), also introducing the category of evolving passive geomorphosites to indicate those geomorphosites affected by and changing due to processes different from the genetic ones. Calcaterra et al. (2014) opened a discussion on activity affecting the specific category of landslide geomorphosites by introducing the concept of *moving geosites*: ‘an active geosite which changes its morphology and spatial position due to representative geological constraints and singular, long-term, geomorphological, gravity-driven slope processes, today in action and/or clearly observable on the ground and/or as effect on man-made structures’. The degree of landslide activity may also become an element concurring to increase the geodiversity of an area, allowing the proposal of meaningful geotouristic itineraries (Tognaccini 2019).

The landslide being a geosite itself or being the process a threatening feature to another geomorphosite (e.g. Nix and Marinoni 2006), the dynamism of such geomorphosites is apparently a relevant element capturing the attention of researchers, because there may be three main implications in the framework of geoheritage management:

- *Hazards potentially involving people and infrastructures*—Several gravity-related processes all over the world have been responsible for disrupting infrastructures or killing as many as thousands of people (e.g. 2000 people killed during the Vajont landslide on 09 October 1963, Eastern Italian Alps; Fig. 1a). On average, thousands of people die each year due to landslides (source United States Geological Survey (USGS): <https://www.usgs.gov/faq>) (Guzzetti 2000). Moreover, terrains undergoing deglaciation are affected by a particular instability due to paraglacial-type processes (Ballantyne 2002), including mass movements along slopes. When an area susceptible to landslides is open to the public, the geoheritage management procedure should be aimed at avoiding any risk to visitors (Nix and Marinoni 2006). One of the crucial points in geomorphosite (but in general geosite) management is the conflict between safe access and hazards (Nix and Marinoni 2006; Borgatti and Tosatti 2010), and the safety conditions for visit-



**Fig. 1** Implications of gravity-related landforms as geosites. **a** The virtual reconstruction of the Vajont landslide, one of the cruellest landslides of the Italian Alps in terms of casualties (source: Fondazione Vajont and UACE, <https://www.uace.eu/vajont-dam-sacile/3d-models/1963-landslide/?cn-reloaded=1>). **b** Rocca di San Leo spur involved in a landslide on 27th February 2014 that might have mined both the natural and cultural heritage <https://www.youtube.com/>

[watch?v=00Jp5BgoLW4&ab\\_channel=GiorgioPazzagli](https://www.youtube.com/watch?v=00Jp5BgoLW4&ab_channel=GiorgioPazzagli)). **c** Example of thematic mapping addressed to the general audience (geomorphological box; modified from Bollati et al. 2017). **d** Web-based amateur video showing a person making a movie of a landslide blocking a road and being hit to death in Cusco, Perú ([www.youtube.com/watch?v=AN0Czky1Yo](https://www.youtube.com/watch?v=AN0Czky1Yo))

ing geosites should be periodically re-evaluated (Bollati et al. 2013). Borgatti and Tosatti (2010) analysed the specific case of the Pietra di Bismantova geosite (Northern Apennines), where the vulnerable targets are climbers and hikers, but also, students involved in field activities in Earth sciences (e.g. Bollati et al. 2018a) or linear infrastructure (Geremia et al. 2015) may also be the category of vulnerable elements. Moreover, slopes modelled by gravity may have specific morphologies, characterised by slightly convex profiles (Cocean et al. 2019) or inaccessible escarpments (Niculiță and Mărgărint 2018), that have been influencing human settlements for a long time. In the first case, as explained by Forno et al. (2013, 2014), DSGSDs, for example, represented ideal locations for the settlement of prehistoric populations. In the second case, such landforms allowed ancient populations to find naturally defensive sites, and several fortified settlements have been built in areas susceptible to gravity-related processes. Relevant vulnerable elements may also be the cultural assets (e.g. ancient

villages, castles, churches) associated with rocky spurs undergoing landsliding (e.g. UNESCO World Heritage Sites, Lollino and Audisio 2006; Nix and Marinoni 2006). Several examples of rocky outcrops prone to landsliding and featuring cultural assets on the top are present around Europe (e.g. Scotland, Slovakia, Moldavian Plateau, Carpathian Mountains, Poland; Niculiță and Mărgărint 2018). In Italy, this kind of situation is recurrent along the Apennine chain: the Canossa Geosite was affected by both landsliding and gullyng (Tosatti 2008); the rocky spur of the Rocca di San Leo underwent a rock fall on 27th February 2014 (Borgatti et al. 2015; Fig. 1b); the Orvieto town (Bozzano et al. 2008) or the Civita di Bagnoregio, the last one known as ‘the dying town’ (Di Veroli et al. 2018; Cercato et al. 2020); the Rocca di Calascio, very famous for being the location of the blockbuster movie ‘Lady Hawke’ and undergoing rock falls in relation to the earthquake harassing Central Italy in 2016. Other intriguing geosites affected by gravity-related processes, where cultural assets or other vulnerable

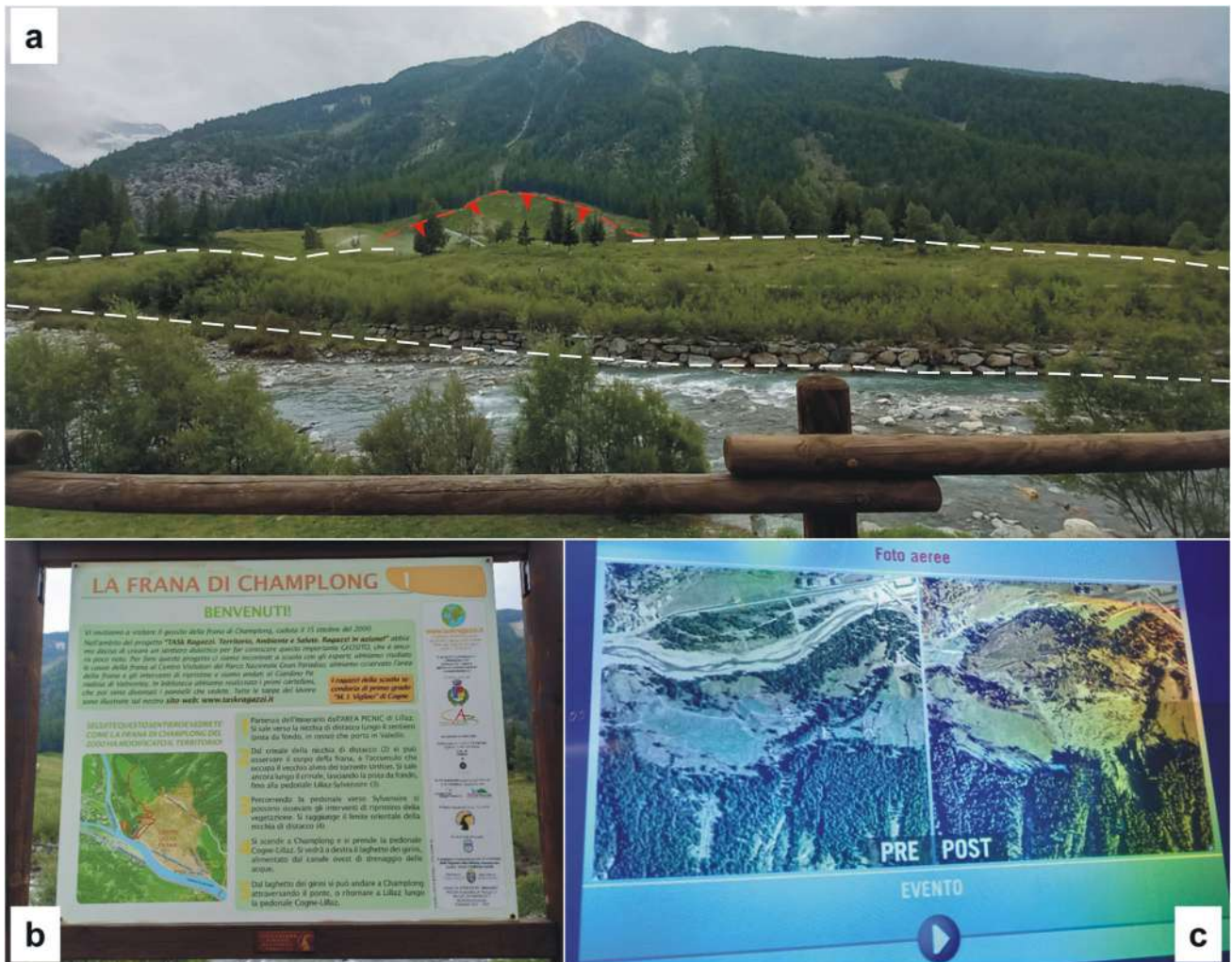
elements are located, are also set along coastal cliffs (e.g. May 2008). In this context, one of the most fragile examples of geosites undergoing landsliding in the Italian territory is the Tharros archaeological area in southern Sardinia (Canuti et al. 2005).

In all the mentioned contexts, specific protocols of management, including documentation analysis, mitigation measures and correct communication strategies for the local population (Alcántara-Ayala and Moreno 2016), should be adopted by local administrations (Borgatti and Tosatti 2010). The relationship with man in hazardous contexts, led Zorina and Silantiev (2014) to propose the category of *engineering geosite*, which reflects outstanding mass wasting and other phenomena relevant to construction and other forms of the anthropogenic activity, very well fitting with the landforms considered herein.

- *Change of the value of the geomorphosite (gravity-related landforms itself or other)*—According to different authors (Komac et al. 2011; García-Ortiz et al. 2014; Pelfini and Bollati 2014), geomorphic processes affecting geomorphosites (i.e. active or evolving passive geomorphosites) may alter the property of such sites, inducing a lowering of their scientific value (i.e. representativeness, integrity, rareness), cultural value (material and immaterial), as well as, in some specific cases, the aesthetic of such sites (Bollati et al. 2016a; Niculiță and Mărgărint 2018) and their potential for use.
- *Educational exemplarity*—Active geomorphosites are recognised as the most suitable sites to understand geomorphic processes and related hazards (Reynard et al. 2007; May 2008; Coratza and De Waele 2012; Calcaterra et al. 2014; Chrobak and Cebulski 2014; Pelfini and Bollati 2014; Alcántara-Ayala and Moreno 2016; Tognaccini 2019), evidently if the safety conditions for observing an ongoing process are satisfied (Nix and Marinoni 2006; Pelfini et al. 2009; Bollati et al. 2013; Niculiță and Mărgărint 2018) (e.g. Figure 1d). Coratza and De Waele (2012) identified landslides in three out of eight sites spread all over the Italian territory, which may be considered iconic to teach geomorphological hazards to society. Regardless, this suitability may also depend on the types of evidence of an ongoing process: DSGSDs (i.e. slowly moving geomorphosites) are a category, together with inactive landslides (i.e. potential passive geomorphosites), for which the evidence of the current or past movements is difficult to perceive from a nonexpert perspective (e.g. Bollati et al. 2012). Additionally, in this case, interpretive tools such as 3D reconstructions (Fig. 1a) or simplified thematic maps (Fig. 1c; Martin 2014; Bollati et al. 2017) could help people understand the causes and effects.

## Multiscalarity of Gravity-Related Geomorphosites

The third feature characterising geomorphosites according to Coratza and Hoblèa (2018) is multiscalarity because dm-dimension to km-dimension landforms may coexist, in some cases nested with each other. In some cases, a landscape-scale site may be labelled a *complex geosite* (sensu Mikhailenko et al. 2019), including other types of geosites, not geomorphological, which are even more valuable in terms of geodiversity (sensu Gray 2004). The presence of different-scale sublandforms was specifically investigated for gravity-related landmarks by Margielewski and Alexandrowicz (2004), including the large-scale features, slope-scale landforms (e.g. rock avalanches, DSGSDs) and the relatively smaller landslide elements, the trenches, the residual rock pillars, the scars, the landslide bodies and the related depressions and peat bogs. The classification of landslides (e.g. Cruden and Varnes 1996; Hungr et al. 2014) indeed includes a category named *complex* indicating landslides deriving from the concurrence of different mechanisms, induced by predisposing-preparing-triggering factors, when a unique type cannot be assigned. In the complexity of such geosites, it is important to also consider peculiar local conditions such as geological features (e.g. lithology, structures) and morphometry features (e.g. hydrography, morphology), which are able to influence the different susceptibilities to triggering factors, such as earthquakes or intense rainfall events (e.g. Tosatti 2008; Wang 2015). In the case of complex geosites such as landslides affecting landscapes at the slope scale, communicating their dynamics to the general audience may be challenging. Even if the complexity of gravity-related features is highly relevant from a scientific point of view due to geodiversity, it is also evident how rich the opportunities are and how high the suitability of a ‘simple’ landslide is for being used as a geosite and as a tool to raise awareness in people, and school students in particular, towards geomorphological hazards (Morino et al., 2022). A relevant example is the Champlong landslide (Fig. 2), a translational sliding triggered by heavy rainfalls inducing a river diversion, where a very effective approach has been used involving local populations (i.e. school students). The aim was to promote knowledge about the effects and remediation strategies in relation to a serious meteorological event and consequent hydrogeological instability affecting the Western Italian Alps during 13–15 October 2000. Regardless, in several contexts, individual geosites are *not sufficient to tell the story*, including in a single-type movement landslide such as this, as argued by Migoń and Rózycka (2021). For example, in the case of landslides, whether or not they are geosites, their activity can affect the landscape at the valley scale (sometimes at the channel network scale; Korup 2005), and it is not enough to consider



**Fig. 2** The Champlong landslide that occurred on 13 October 2000 in the Cogne Valley (Aosta Valley, Western Italian Alps). The landslide (a) is a regional geosite promoted through panels on sites (b) and off-

site multimedia contents (c) located at the visitor centre of Gran Paradiso National Park. Red triangles: detachment niche; white dashed line: landslide body

them as stand-alone landforms (Wang 2015; Bollati et al. 2019a; Mikhailenko et al. 2019; Stanczyk et al. 2019).

The last consequence of multiscalarity and complexity is the increasing geodiversity associated with these landforms, which has been the starting point for recent proposals for educational itineraries, for example, in the Italian peninsula (Coltorti and Firuzabadi 2011; Garavaglia and Pelfini 2011; Bollati et al. 2019a; Tognaccini 2019).

### Deep-Seated Gravitational Slope Deformations as Complex Geosites

Among complex geosites, DSGSDs could be very relevant, even if few of them have yet to be considered proper geosites. Coltorti and Firuzabadi (2011) indicate how various types of gravity-related landforms are associated with

DSGSDs (i.e. geomorphodiversity), indirectly inducing even more potential geomorphological hazards. The signs of the movements characterising DSGSDs are rarely perceptible by untrained people, even if their surface is often edified (Cocean et al. 2019). Moreover, several different geomorphological elements, even valuable as geoheritage sites, are associated with such contexts, and their evolution may be strictly related to DSGSD dynamics (Bollati et al. 2019b; Forno et al. 2021). DSGSDs have been recently investigated as potential geosites with the aim of detecting potential indicators to promote, protect or use them as a tool for education purposes towards natural heritage (Cocean et al. 2019). Some authors (Niculiță and Mărgărint 2018; Cocean et al. 2019) compared different DSGSDs, evaluating them according to the scientific value, the functional value and the additional values, including the impact deriving from the exploitation use.

The cultural value of DSGSDs has been enhanced by Forno et al. (2013, 2014), as mentioned before, for whom they represented ideal locations for the settlements of pre-historic populations.

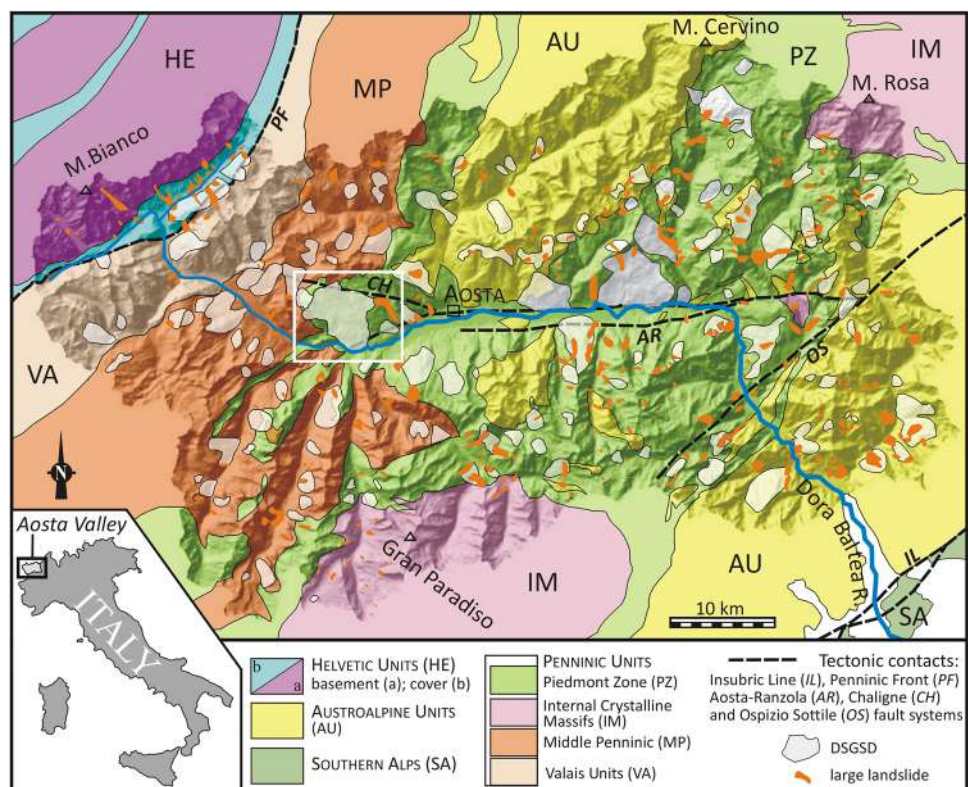
A particular mention is worth noting regarding the *ecological support role* of DSGSDs since they also influence vegetation growing on surfaces. This attribute increases the scientific value of a geo(morpho)site (Pelfini et al. 2010; Bollati et al. 2015). More specifically, Pánek and Klimeš (2016) and Šilhán (2020) underlined the importance of using vegetation as a high-resolution dating method covering the last few centuries in cases when other dating methods or monitoring techniques may not be suitable. They also underlined the difficulty of applying such techniques mostly in alpine contexts because several DSGSDs are partly located above the tree line, and a disconnection exists between surficial vegetation and deep-seated movements. Even though there are several examples of dendrogeomorphological analyses on generic landslides (Šilhán 2020) that study tree features such as annual ring width, trunk eccentricity, reaction wood, traumatic resin ducts, and root exposure (Stoffel and Corona 2014), only a few are closely related to DSGSDs (e.g. Fantucci and Sorriso Valvo 1999; Guida et al. 2008; Pelfini and Santilli 2008; Van Den Eeckhaut et al. 2009; Leonelli et al. 2021). Bollati et al. (2019b) focused on analyses at the border of a DSGSD, studying the erosion rates along the deep gullies developing along the DSGSD edges

through dendrogeomorphological techniques, emphasising the ecological support role of geosites represented by such landforms. Dendrochronology has also been demonstrated to be a useful tool to date sediments within DSGSD trenches (Pasquarè Mariotto and Tibaldi 2016).

### Geological and Geomorphological Setting of the Study Area

The Aosta Valley is a 3263-km<sup>2</sup>-wide mountain catchment consisting of a 92-km-long trunk valley (Dora Baltea Valley) and approximately thirty major tributary valleys deeply incised across the inner and axial sectors of the Western Italian Alps. Monte Bianco (4810 m), Monte Rosa (4634 m), Monte Cervino (4478 m) and Gran Paradiso (4061 m) are the highest peaks (Fig. 3). The very high average altitude (2100 m, the highest of the Alps) promoted the growth of a 130-km-long valley-piedmont glacier during the Pleistocene glaciations and allowed the survival of 175 glaciers (covering 120 km<sup>2</sup>, 3.7% of the basin; Diolaiuti et al. 2012). This glacially sculpted basin shows high average gradients of more than 1500 m between the valley floors and the watershed ridges (3500 m is the largest difference in height recorded in the Monte Bianco Massif). Significant gravitational collapses in the valley slopes evolved with the retreat of the main glaciers during the Lateglacial (19–11.7 ka BP)

**Fig. 3** Location of the Pointe Leysser DSGSD (white square) in the Aosta Valley (DTM by Regione Autonoma Valle d’Aosta). The geological sketch map is derived from the sheets of the Geological Map of Italy (Dal Piaz et al. 2010; Carraro et al. 2012; Polino et al. 2015b). DSGSDs and large landslides have also been reported (Ratto et al. 2007)



and subsequently during the Holocene through the emplacement of numerous DSGSDs (263 areas covering 441 km<sup>2</sup>, i.e. 13.5% of the whole basin; Ratto et al. 2007; Martinotti et al. 2011; Fig. 3).

The investigated area, approximately 10 km west of Aosta town, extends on the southern-facing side of the middle Aosta Valley, downstream of the Pointe Leysser (2770 m a.s.l.)–Mont Fallère (3061 m)–M. Aouilletta (2616 m)–curved rocky ridge (Fig. 4). This area (25 km<sup>2</sup> wide) includes the Plan di Modzon flat surface, the Becca France relief and the wide morphologically varied slope up to the Dora Baltea Valley floor, showing an altitude difference of 1730 m, between 2380 and 650 m. The area is bounded by the Gaboè and Clusellaz tributary torrents, westwards and eastwards, respectively.

The Pointe Leysser DSGSD is a wide 23-km<sup>2</sup> collapse of the south-facing left side of the Dora Baltea Valley in the Saint-Pierre, Saint-Nicolas and Sarre municipalities (Forno et al. 2012, 2013; Delle Piane et al. 2016). This DSGSD, the second largest in the Aosta Valley, also represents one of the largest gravitational collapses in the Alps chain, given the average area of 6 km<sup>2</sup> of the 1033 phenomena mapped in the European Alps DSGSD inventory ranging from 0.1 to 110 km<sup>2</sup> (Agliardi et al. 2013; Crosta et al. 2013). This large phenomenon has not been reported in the first Italian Alps DSGSD Catalogue (Mortara and Sorzana 1987), but only its most deformed central sector has been mapped as a landslide (Fig. 4a) (Elter 1987; De Giusti et al. 2004). It was more extensively recognised during the surveys (from 1995 to 1998) of the Aosta Sheet of the Geologic Map of Italy (Polino et al. 2015a, 2015b) and reported in the Italian Landslide Inventory (IFFI) and derived maps (Ratto et al. 2007). An extension of the DSGSD beyond the main watershed in the upper Verrogne Valley (Plan di Modzon area) was more recently highlighted, even if an upper boundary is currently not well constrained (Comina et al. 2015; Forno et al. 2016).

The study area is located within the Middle Penninic (northern sector) and Piedmont Zone (southern sector) of the Western Alps (Fig. 3). This chain is part of a typical collisional belt developed from the Cretaceous by subduction of a Mesozoic oceanic lithosphere and collision between the Adriatic margin (Austroalpine–Southalpine domains) and the European continental margin (Penninic–Helvetic domains) (Dal Piaz et al. 2003).

The Middle Penninic consists of a Palaeozoic basement of the Gran San Bernard Nappe, made of garnet micaschist and albitic paragneiss, with some minor bodies of metabasite and covered by discontinuous Lower Mesozoic dolomitic metabreccia and marble. The overlying Piedmont Zone, referred to as an oceanic environment here represented by the Upper Tectono-Metamorphic Unit (as defined by Forno et al. 2012) belonging to the Aouilletta Unit (Polino et al. 2015b), consists

of a prevailing carbonate calcschist that alternates with decimetric marble layers and rare prasinite and serpentinite slices. Both the Middle Penninic and Piedmont zones were strongly deformed under blueschist metamorphic conditions, followed by widespread recrystallisation under greenschist-facies metamorphism.

The WNW–ESE–trending high-angle strike-slip Chaligne Fault system represents the main brittle tectonic discontinuity, comprising the Aosta–Fallère Fault which repeatedly displaces the Piedmont Zone basal thrust (Polino et al. 2015b). Other fracture systems have NW–SE, SW–NE and N–S trends.

The area is now completely free of glaciers but shows some evidence of glacial shaping. The main glacial landforms are linked to subglacial erosion, consisting of numerous cirques (Fig. 4b), wide relicts of the glacial valley slopes and significant glacial valley floors, strongly hanging on the Dora Baltea Valley, with some metre-high rounded rocky ridges separated by troughs (Forno et al. 2013, 2014). Subglacial overconsolidated deposits are discontinuously preserved, characterised by a greater abundance of various size angular clasts, with sporadic, mostly decimetric and partially rounded erratic boulders mixed in a poor matrix. The subglacial abrasion is also responsible for the formation of relatively wide overdeepened depressions, likely hosting lakes now filled by lacustrine sediments and peat bog organic planar-bedded palustrine sediments.

Short and low lateral moraines indicate the local presence of ice-marginal deposits essentially formed by centimetric to decimetric subangular to angular clasts mixed in a poor sandy-silty matrix, often defining inclined bedding. These normally consolidated and weakly cemented sediments also contain rare subangular boulders up to 1 m<sup>3</sup> in size.

The glacial landform distribution and the petrographic composition of glacial sediments indicate a link with tributaries (mainly Gaboè and Verrogne glaciers) and less with the Dora Baltea Glacier. The location of glacial deposits and forms suggests an age from the Last Glacial Maximum (LGM) to the Lateglacial.

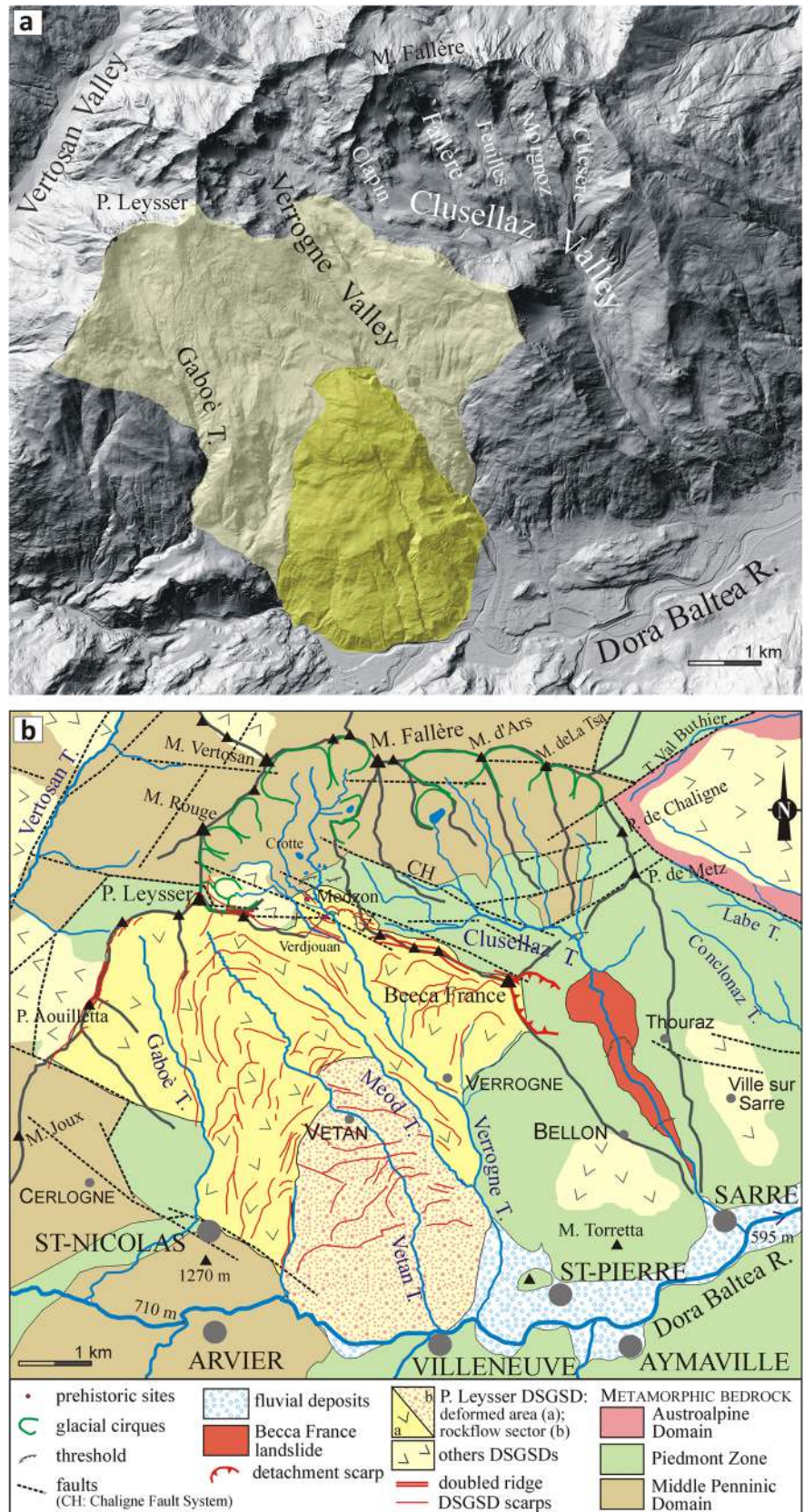
Landslide deposits and debris are widespread at the foot of the rocky walls, while torrential and avalanche deposits are confined to the valley floor (Forno et al. 2016). Glacial and other sediments are locally reworked by runoff, forming colluvial deposits that consist of centimetric to decimetric angular clasts with monotonous petrographic composition, mixed in a matrix rich in millimetric rock fragments.

## The Geoheritage Sites Within the P. Leysser–Becca France Slope

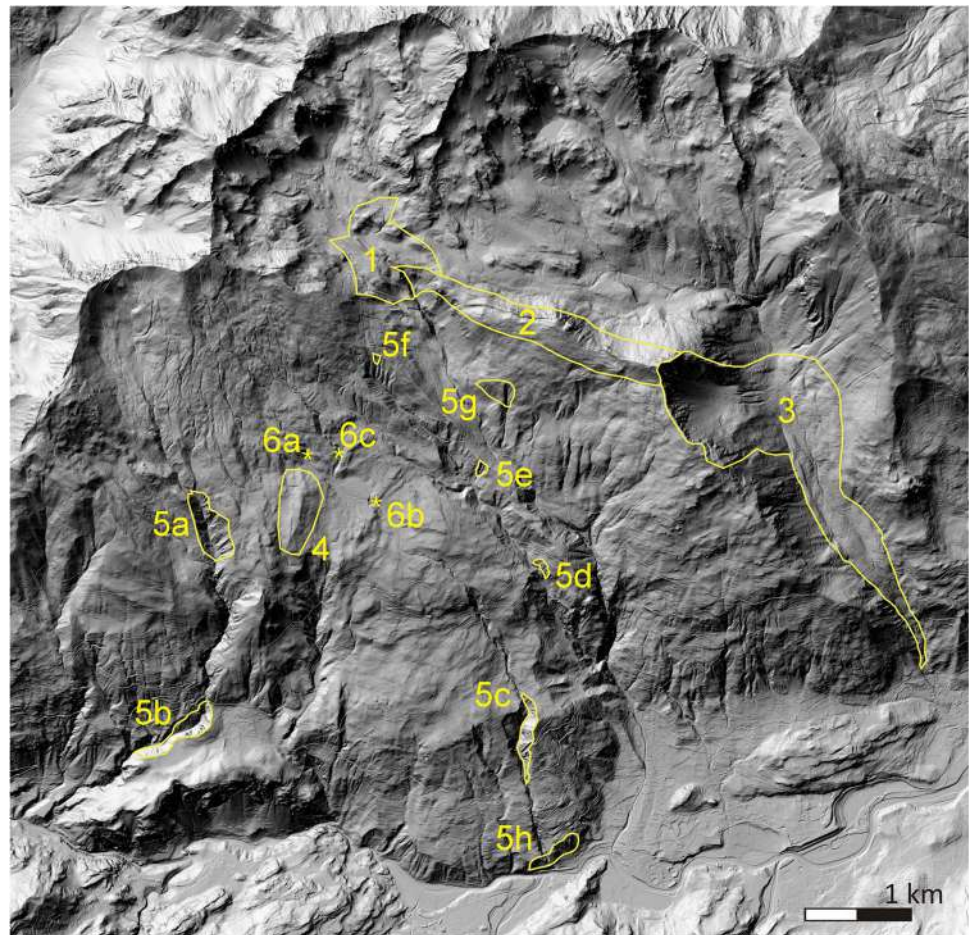
A site-scale analysis is proposed in the following subsections. Each of the individual sites (six sites in Fig. 5) will be described, discussing their potential values among



**Fig. 4** Location of the Pointe Leysser DSGSD on the northern side of the Dora Baltea Valley. **a** Shaded relief map (courtesy by Regione Autonoma Valle d'Aosta) with the currently known P. Leysser DSGSD (light yellow) and its most deformed sector (dark yellow). **b** Geological sketch map. See captions of Figs. 3 and 5



**Fig. 5** The complex Pointe Leysser geosite formed by localised geosites (1, 2, 3, 4) and two scattered geosites (5, 6): Plan di Modzon and Verrogne glacial diversion (1), Becca France relief and doubled ridges (2), Becca France rock avalanche (3), tilted bedrock block (4), badlands (5a: Leytanettaz; 5b: Fossaz; 5c: Chantel; 5d: Meod; 5e: Vulmian; 5f: upper Meod; 5g: Or; 5h: Montovert), and calcareous tufa (6a: Chatelanaz; 6b: Vetan Dessous; 6c: Thoule). Asterisks indicate punctual geosites (< 1 ha wide). The shaded relief map is derived from a 2-m cell-size LIDAR elevation model (courtesy of Regione Autonoma Valle d'Aosta)



**Table 1** The attributes considered to discuss the potential of the study site as complex geosite according to Bollati et al. (2017). See also Supplementary Material for the quantitative categorisation

1. Scientific value	2. Additional value	3. Potential for use
1.1 Representativeness of geomorphological processes (including paleogeomorphological features)	2.1 Cultural	3.1 Temporal accessibility
1.2 Representativeness of geological processes	2.2 Aesthetic	3.2 Spatial accessibility
1.3 Educational exemplarity	2.3 Socio-economic	3.3 Visibility
1.4 Site intrinsic geodiversity		3.4 Services
1.5 Geohistorical importance		3.5 Number of tourists
1.6 Ecologic support role		3.6 Sport activities
1.7 Integrity		3.7 Legal constraints
1.8 Rareness		3.8 Use as a geoheritage site
		3.9 Use for interests other than geoheritage
		3.10 Geosites in the surroundings

those reported in Table 1 (for more details, see Bollati et al. 2017). More specifically, within the P. Leysser–Mont Fallère–Becca France slope, four localised sites were identified (1, 2, 3, 4 in Fig. 5), while the other two are multiple scattered geosites (5, 6 in Fig. 5). All the selected spots provide a complete framework of the geomorphological features associated with P. Leysser’s DSGSD. The

assessment criteria derive from a relatively long-lasting procedure addressed to geomorphosites specifically for ranking them through a quantitative methodology based on attributes (Bollati et al. 2017; Bollati and Zerboni 2021). The quantitative procedure was performed according to the numerical values and formula reported entirely in the [Supplementary Material](#).

Some attributes may be discussed first for all the sites: the area is very well studied, contributing to understanding the relationship between human settlements and mass movements (1.5, Table 1). Moreover, the area where almost all the sites are located (all except for the Becca France rock avalanche flowing into a parallel valley) is used by hikers aiming to reach the Mont Fallère mountain hut, representing a potential focal point for promotion activities (all the sites acquired 1/1 for 3.4; all the sites acquired 0.5/1 for 3.6, Table 1). More details are provided in ‘The Plan di Modzon and Verrogne glacial diversion.’ Currently, the number of visitors in the area is a few thousand a year (all the sites acquired 0.5 or 1/1 for 3.6, Table 1), promoted by the occurrence of numerous wooden statues representing animals along the path, with the consequence that the site becomes one of the busiest in the entire Aosta Valley. Additionally, the parallel valley occupied by the Becca France rock avalanche is a touristic area where different opportunities for spending leisure time are available (see ‘Becca France rock avalanche’).

Almost the entire area, except for the lower altitude sites (the sites acquired 1/1 for 3.1, Table 1), can be accessible only from June to the end of October (all the sites acquired 0.5/1 for 3.1, Table 1), due to snow coverage that could impede a favourable view of all the geomorphological elements. As the whole slope is proposed herein as a complex geosite, the presence of more than one geosite increases its potential for use (all the sites acquired 1/1 for 3.10, Table 1). The other attributes, since locally varied, will be mentioned for each single analysed site.

In Table 2, the scores obtained by the sites are reported, with a ranking according to the total score obtained by summing scientific value (1; Table 1), additional values (2; Table 1) and potential for use (3, Table 1).

### The Plan di Modzon and Verrogne Glacial Diversion

The Plan di Modzon is located along the Verrogne Valley (45° 45' 22.9" N, 7° 11' 29.8" E) (1 in Fig. 5), set along the boundary between the continental Gran San Bernardo Nappe and the above oceanic Piedmont Zone (Fig. 6). The deepest unit consists of micaschist, fine-grained gneiss and few metabasic rocks. The highest unit is essentially made up of calcschist with variable carbonate content. The tectonic contact between the two units is marked by tectonic slices of white marble referred to as Mesozoic continental cover. The bedrock is discontinuously hidden by subglacial, ice-marginal and supraglacial sediments deposited by the Verrogne Glacier during the LGM and Lateglacial and by more localised torrential and palustrine sediments (Fig. 7).

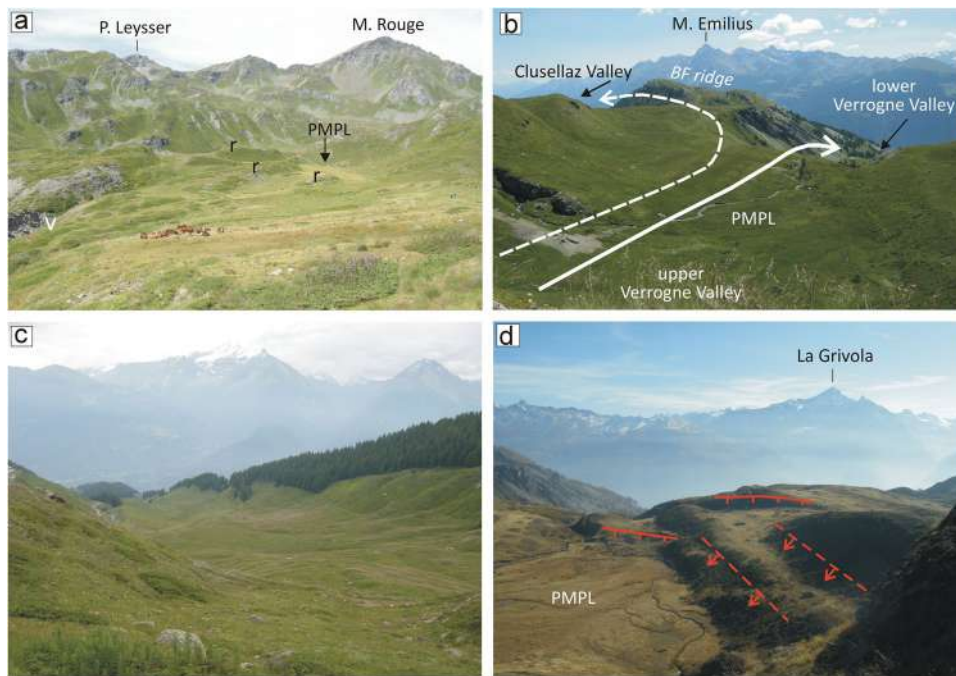
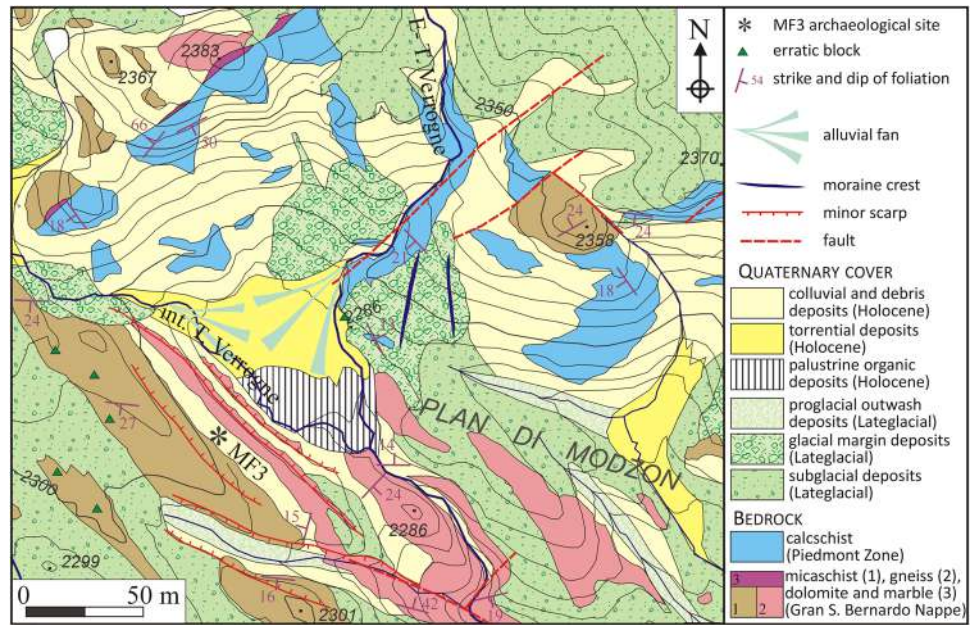
The Plan di Modzon shows a very peculiar morphology in the context of the Aosta Valley (1.8, Tab. 1), consisting of a large flat surface, gently sloping towards the south (5%) and hanging from the main valley through an evident rock threshold (Verdjouan scarp). Moreover, it shows very typical longitudinal rocky rounded reliefs, rough rocky walls and elongated close troughs (0.67/1 for attr. 1.1, Table 1) (Fig. 7a). The Plan di Modzon is also weakly incised by a complex hydrographic network consisting of three main subparallel watercourses (western, intermediate and eastern Verrogne T.). This peculiar morphology is due to the combined action of glacial shaping and DSGSD evolution (Forno et al. 2013, 2014) (1/1 for attr. 1.4, Table 1). In detail, large glacial cirques are preserved at the head of the valley, where ancient glaciers that have now disappeared once fed the Verrogne Glacier. Longitudinal rounded rocky reliefs (5–20 m high) connected to subglacial erosion and widespread sectors with subglacial sediments are visible below, in the Plan di Modzon area, associated with small lateral moraines formed by ice-marginal sediments. This

**Table 2** Numerical scores obtained by the sites ranked according to the total score obtained by summing scientific value (1; Table 1),

additional values (2; Table 1) and potential for use (3; Table 1). The maximum values that can be achieved are indicated in the last row

ID site	Scientific value	Additional value	Global value	Potential for use	Scientific index	Educational index	Total score
3—Becca France rock avalanche	7	2.67	9.67	9.45	0.77	0.81	19.12
5—Badlands scattered geosites	6.84	2	8.84	9.78	0.89	0.76	18.62
1—Plan di Modzon and Verrogne glacial diversion	6.01	3	9.01	9.56	0.55	0.68	18.57
2—Becca France relief and doubled ridges	6.01	2	8.01	8.28	0.78	0.76	16.29
4—Tilted bedrock block geosite	3.67	2	5.67	8.94	0.33	0.81	14.61
6—Calcareous tufa scattered geosites	3.66	1	4.66	7.74	0.44	0.48	12.4
<i>Maximum obtainable value</i>	8	3	11	12	1	1	23

**Fig. 6** The geological map of the Plan di Modzon area with the location of the paleoLake filled by torrential and palustrine deposits (modified from Comina et al. 2015)



**Fig. 7** The peculiar morphology of the Plan di Modzon area. **a** Rounded longitudinal relief (r) linked to glacial shaping separated by gravitational elongated close troughs, cut by the Verrogne T. incision (v). The location of the Plan di Modzon paleoLake (PMPL) is also reported. **b** Low eastern watershed of the high Verrogne Valley linked to the presence of an abandoned previous trend of the Verrogne glacier towards the ESE through the Clusellaz Valley (dashed line). The new trend of the glacier (continuous line) was instead along the lower

Verrogne Valley following the breakthrough of the watershed. The Plan di Modzon paleoLake (PMPL) is a result of glacier-DSGSD interactions. **c** Typical well-preserved glacial landform of the lower Verrogne Valley, shaped by the Verrogne Glacier during the Lateglacial. **d** Graben depression of the filled PMPL formed by the interaction of NNW–SSE minor scarps (lines with arrows) and WSW–ENE counterscarps (lines with teeth) (modified from Comina et al. 2015)

glacial framework suggests a significant shaping carried out by the ancient glacier during the Lateglacial.

Rough, rocky walls of various heights (5–30 m) are also evident in the upper Verrogne Valley. Their overall curved pattern in a plan, with prevailing NE–SW, E–W and WNW–ESE trends and essentially without traces of subglacial erosion, suggests that these landforms can be referred to as DSGSD minor scarps.

Elongated close troughs (10–30 m deep) hosting small lakes, still present or filled by sediments, are also observed in the upper Verrogne Valley, connected with dislocation of minor scarps and counterscarps and/or opening trenches. Narrow longitudinal depressions (up to over 40 m deep) are bounded by rough longitudinal reliefs where the bedrock widely crops out. These landforms, without associated glacial evidence, can be referred to as DSGSD trenches and are only partly reused by the watercourses located on the valley floor (Fig. 7a; Forno et al. 2013, 2014).

Gravitational morpho-structures (scarps and trenches) usually cut glacial landforms, suggesting that this DSGSD essentially evolved during the Holocene. The involvement of some of these gravitational structures in glacial shaping suggests that some of them are partly synchronous with Lateglacial episodes of withdrawal (Comina et al. 2015).

This enlarged valley-floor stretch also preserves the evidence of a remarkable glacial diversion phenomenon regarding the Verrogne Glacier, triggered by the interaction between glacial and gravitative shaping (Forno et al. 2013). In detail, this glacier flowed along the Clusellaz Valley during the LGM (26–19 ka BP) and subsequently changed its trend, shaping the lower Verrogne Valley during the Lateglacial (19–11.7 ka BP). This reconstruction is suggested by the following elements. The upper Verrogne Valley shows a very low eastern watershed and is almost continuous with the adjoining wide current head of the Clusellaz Valley (Figs. 7b and 10a). This evidence suggests that the Verrogne Glacier previously flowed towards the ESE through the Clusellaz Valley. Subsequently, the Verrogne Glacier erosion broke down the rocky divide weakened by the DSGSD and started to flow towards the SSE, shaping the lower valley (Fig. 7b).

In addition, the morphology of the high Clusellaz Valley, with a large distribution and extent of subglacial cover, subglacial erosional reliefs and ice-marginal sediments with related moraines, suggests a link with a larger Verrogne Glacier during the LGM (Forno et al. 2013, 2014). The well-preserved (1/1 for attr. 1.7, Table 1) and smaller glacial landforms of the lower Verrogne Valley, with associated subglacial sediments and local ice-marginal sediments forming moraines, instead suggest a narrower Verrogne Glacier during the Lateglacial (Fig. 7c).

Therefore, the Verrogne Glacier before (LGM) flowed through the Clusellaz Valley and subsequently (Lateglacial) took a new path towards the SSE, forming the present

low valley (Fig. 7c). This evolution is likely favoured by NNW–SSE and/or N–S open fractures diffusely observed along the BF ridge and by scarps along which the glacier forms a U-shaped valley (the current lower Verrogne Valley). Subsequently, the Verrogne glacier deepened the valley floor by a few tens of metres in the Plan di Modzon area, shaping the current very low watershed between the Verrogne and Clusellaz valleys. The low Verrogne Valley also shows evidence of sin-glacial to postglacial gravitational deformation due to the DSGSD activity.

Some close depressions filled with peat are locally present in the valley floor of the high Verrogne Valley, forming flat surfaces. In detail, three depressions near the Mont Fallère Hut (Crotte Basse and two other unnamed) are aligned with the Lago delle Rane according to an ENE–WSW trench. These peat bogs, during rainy seasons, can appear as small ephemeral lakes, and their survival is directly related to the lack of a tributary.

Their filling is particularly significant because it represents a lithostratigraphic, biostratigraphic and climatostratigraphic record of the Lateglacial and Holocene evolution of a high-elevation area (0.67/1 for attr. 1.1; Table 1). A succession of lacustrine–palustrine sediments was sampled by wells in the Crotte Basse peat bog. This research provided information for the reconstruction of the vegetation from the last part of the Lateglacial to the Present, proving an early stage of vegetation development (before the Holocene) and the subsequent expansion of forest growing well above its present-day altitudinal ranges (Pini et al. 2011, 2017) (*‘Calcareous tufa scattered geosites’*) (0.67/1 for attr. 1.6; Table 1).

A large, filled lake (Plan di Modzon paleoLake) is hosted in an elongated NW–SE close depression with flat morphology, bordered both upstream by rounded rocky reliefs (30 m high) and downstream by a low rocky threshold (10 m high) (Fig. 6). Only the southern sector of the depression preserves the typical horizontal lacustrine morphology and shows peat sediments at the top, while the wider northern sector is also filled by torrential sediments, forming two alluvial fans.

Several scientific studies have been developed in the area (0.67/1 for attr. 1.5, Table 1). Combined electric resistivity tomography (ERT) and geological surveys evidenced that the Plan di Modzon preserves an overdeepened trough shaped by the Verrogne Glacier in the bedrock, subsequently displaced by a set of gravitational morpho-structures (Comina et al. 2015; Forno et al. 2017). These structures, connected to the evolution of WNW–ESE minor scarps and NNW–SSE counterscarps, formed a graben that lowered the lake sector with respect to its threshold, creating a close depression in which a lake developed, now filled by sediments (Fig. 7d). The geoelectric surveys also showed some elongated bands of loosened rocks dipping ENE and WSW, suggesting the presence of sliding surfaces that may be related to the major

and antithetic fractures cropping out in the Plan di Modzon area. Geophysical cross-sections through the filled lake also highlighted the presence of buried trenches defined by scarp and counterscarp settings. Three different bodies hosted in the glacial overdeepened depression are suggested by shallow low-resistivity layers of sediments (referred to as subglacial, lacustrine and palustrine) that overlay a higher-resistivity bedrock. The highly consolidated subglacial sediments observed in the surrounding sectors essentially consist of angular clasts mixed with a sandy–silty matrix. The lacustrine body likely consists of laminated silty sands and subordinate gravelly sands with planar bedding. The palustrine body, cropping out in the southern sector of the lake, is instead composed of black silty sediments rich in organic matter and plant remains (peat).

This overdeepened glacial trough was shaped during the LGM and Lateglacial, while lacustrine-palustrine filling formed after glacier withdrawal during the Lateglacial and Holocene. The reported sedimentary succession shows an overall thickness of from 5 m to approximately 15 m, with values increasing from the lake edges to its inner sector.

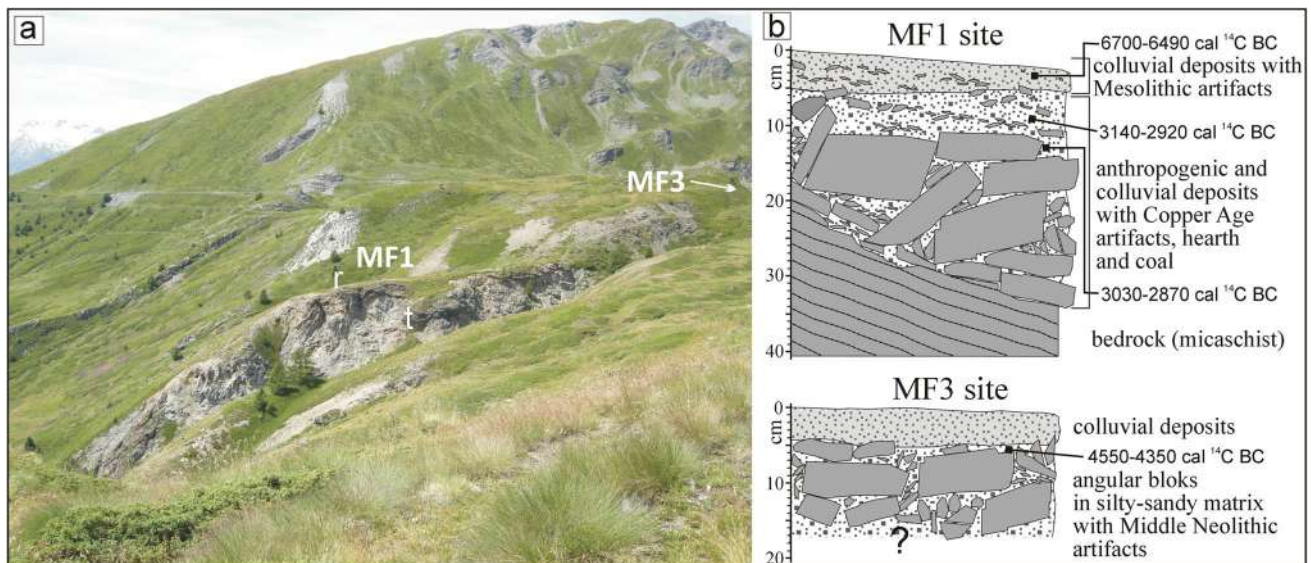
Naine archaeological sites (MF1 to MF9) have recently been found between 2242 and 2292 m a.s.l. in the Plan di Modzon surroundings on an area of approximately 0.2 km<sup>2</sup> (Fig. 8), including ones investigated by systematic excavation (MF1 and MF3) (Guerreschi et al. 2010, 2017; Forno et al. 2013, 2014) (1/1 for attr. 2.1, Table 1). The MF1 site is located along the Verdjouan scarp on the summit of a NW–SE ridge (2242 m a.s.l.), which is very gently sloping (5%) and overlooks the 25–40-m-deep eastern T. Verrogne incision, through a very abrupt rocky scarp (Fig. 8a). This

scarp is developed along a longitudinal trench linked to the Pointe Leysser DSGSD (t in Fig. 8a), in which the eastern T. Verrogne currently flows. In detail, the summit ridge is eroded into the bedrock (micaschist), dipping 25–30° towards the south. The rounded morphology of the ridge, except for the scarp along the eastern T. Verrogne, is related to subglacial abrasion.

Decimetric angular elements of micaschist, characterised by prevailing horizontal arrangement, lie on the bedrock, suggesting that some clasts have been placed by ancient human activity. This carryover was designed to create a horizontal plane for the settlement, containing copper age artefacts, a hearth and charcoal fragments. The ensemble of archaeological evidence and radiocarbon dating allows us to report this layer to the Copper Age (Fig. 8b).

A thin cover of prevalent yellowish-brown (10 YR 4/4) sandy–silty sediments lies on the carryover deposits, with some centimetric subangular to subrounded clasts (micaschist). These fine sediments were likely derived from the anthropogenic reworking of the subglacial sediments as suggested by their texture and yellowish-brown colour, similar to the subglacial cover cropping out in the surrounding area.

The sequence is covered at the top by two sandy–silty colluvial layers of brown colour (7.5 YR 4/4); the lower part is derived from reworking of the local subglacial cover, and the upper part is derived from the weathered bedrock. The latter contains Mesolithic artefacts (approximately 3000 hyaline quartz artefacts and a few flint manufacturing residues of the Mesolithic age). The retouched artefacts (94) indicate a probable Sauveterrian phase. Some double backs, backs and cutting and triangular artefacts are the most



**Fig. 8** a The location of the MF1 archaeological site on a rounded ridge (r) of glacial shaping cut by a scarp along a gravitational trench (t). b Stratigraphic reconstruction of MF1 and MF3 archaeological sites (modified from Forno et al. 2013, 2014)

indicative. The age of 6700–6490 cal BC on charcoal dates these remains. The association of these reworked artefacts with colluvial sediments, superimposed above more recent remains, suggests their secondary arrangement was caused by limited reworking by runoff, forming an example of a reversed archaeological sequence.

Site MF3 is instead located in a N–S trending weak counterslope depression (less than 1 m deep), stretched in the N–S direction and perched approximately 10 m on the wide Plan di Modzon paleoLake (Fig. 6). At this site, erratic boulders lie on the bedrock and are covered by yellowish-brown silty–sandy colluvial sediments, coming from the reworking of the glacial deposits. The colluvial body, partially filling the described depression, contains several artefacts of rock crystals (hyaline quartz) referred to as the Middle Neolithic.

Ancient human settlements were favoured by the morphological features of Plan di Modzon, characterised by an overall flat surface and an unusually wide (due to the connection of the two Verrogne and Clusellaz valley floors), facing south, directly hanging on the Dora Baltea incision and devoid of environmental hazards. These features were considered by prehistoric man favourable for settlement in a high mountain environment characterised by excellent visibility, near the upper tree limit (Pini et al. 2011) and rich in water (Forno et al. 2013). Moreover, the Plan di Modzon, despite being significantly hanging with respect to the valley floor of the Dora Baltea that develops at 700 m a.s.l., connects with the latter through the relatively shallow slope of the P. Leysser DSGSD, which makes the area directly accessible from the main valley. The articulated morphology of this area also promoted ambush hunting by ancient men.

Finally, the lack of an evident eastern watershed associated with the southern exposure of the Plan di Modzon surface also favours prolonged insolation.

In summary, this complex site shows evidence of different processes over time (1/1 for attr. 1.4, Table 1) and the related landforms are well preserved and representative (i.e. 0.67/1 for attr. 1.1; 1/1 for attr. 1.7 and 1.8, Table 1). Moreover, geomorphological features have influenced vegetation dynamics through time (0.67/1 for attr. 1.6; Table 1). Hence, site 1 alone could be enough to justify promotion as well as conservation of its scientific value. In addition, the site also features a geoarchaeological value (1/1 for attr. 2.1, Table 1). Moreover, the area is characterised by the presence of wooden statues that recall a high number of tourists (1/1 for attr. 3.5; Table 1).

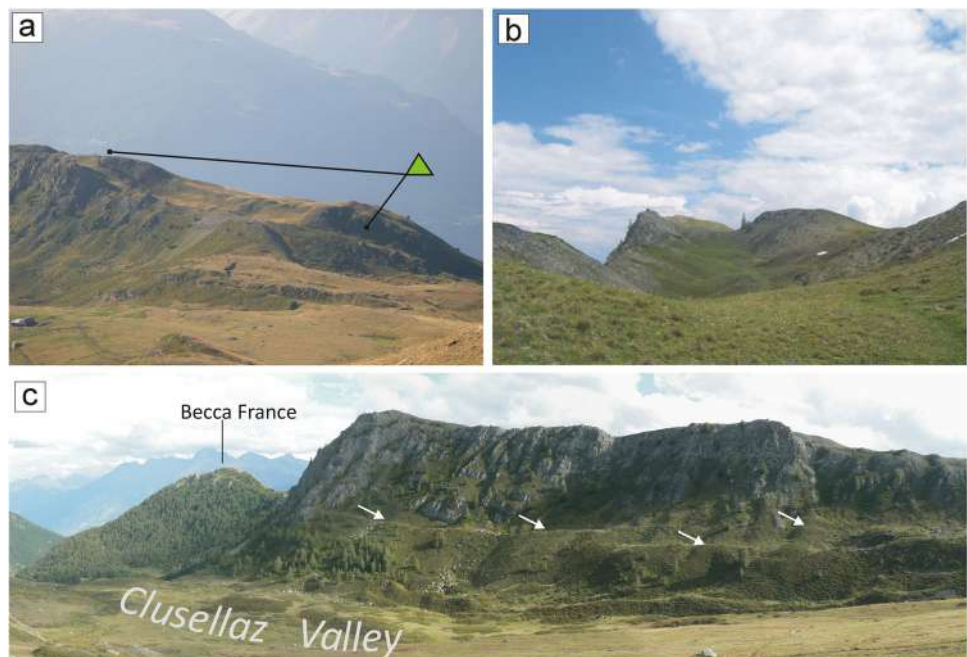
An asphalted road allows buses to reach Vetan Dessus (a large parking area) from Saint-Pierre via Saint-Nicolas (16 km). Plan di Modzon (2270–2300 m a.s.l.) and Mont Fallère Hut (2380 m a.s.l.) are easily reachable on foot from Vetan Dessus (1768 m a.s.l.) via a 5-km-long dirt road or more briefly via the path of wooden statues with a vertical gain of 600 m.

Globally, the site obtained a total score of 18.57 over 23 (Table 2).

### Becca France Relief and Doubled Ridges

Becca France (45° 44' 53.7" N, 7° 13' 08.7" E) (2 in Fig. 5) is an emerging relief located on the southern slope of Mont Fallère (3061 m a.s.l.), which appears separated from the

**Fig. 9** Wide WNW–ESE doubled Becca France ridge. **a** View from the M. Fallère Hut with the dendrogeomorphology sampling sites (green triangle). **b** Doubled watershed in the western stretch of the ridge. **c** Counterslope ledge (white arrows) on the northern side of the Becca France ridge in the Clusellaz Valley



wide Clusellaz Valley. It, therefore, forms the panoramic watershed between the Dora Baltea and upper Clusellaz valleys (Fig. 9a) (i.e. 1/1 for attr. 2.2, 3.3; Table 1).

The Becca France relief is made up of two overlapping tectonic units related to the Piedmont Zone and bounded by a tectonic contact. The lower unit consists of a calcschist with very thick and continuous prasinite and paragneiss bodies. The upper tectonic unit, in which the Becca France watershed is shaped, essentially consists of calcschist with variable carbonate content.

Calcschist, characterised by an average dip of 30° towards the south, discontinuously crops out along the ridge summit and forms high rocky walls overhanging the Clusellaz Valley. The ridge is also cut by diffuse open fractures, N–S striking and both E and W dipping. The bedrock is discontinuously covered essentially by debris deposits that also partially fill the ridge depressions, while glacial deposits were not found on the summit but only on the slopes.

The Becca France watershed shows a typical morphology, forming a WNW–ESE elongated ridge that is perched on the northern side of the Aosta Valley suggesting that it is a geosite due to its representativeness and educational exemplarity (1/1 for attr. 1.1; 1.3; 1.7; Table 1). It shows, in detail, a complex morphological ridge profile characterised by an unnamed rounded summit at an altitude of 2348 m a.s.l. and a very sharp peak at 2312 m (Becca France), separated by a much lower saddle at 2227 m (Forno et al. 2012).

The Becca France ridge is abruptly interrupted, on its eastern edge, by the wide detachment niche hanging on the lower Clusellaz Valley, which fed a catastrophic historical landslide (see ‘Becca France rock avalanche’). The overall morphology is particularly spectacular due to a strong contrast between an SSW less-sloping grassy side and an NNW rocky subvertical slope, both sharply cut off by the detachment scarp (1/1 for attr. 2.2; Table 1).

The presence of relief on a mountain side with the same trend, sharply separated from the main watershed, represents a rarity (1.8; Table 1) in the whole Aosta Valley. It represents a remarkable viewpoint on the southern reliefs of the Aosta Valley (Mont Emilius, Mont Grivola, Mont Rutor) and consists of a spectacular landform clearly visible from the surrounding mountains (Pointe Leysser, Mont Rouge, Mont Vertosan, Mont Fallère, Pointe de Chaligne) (1/1 for attr. 2.2, 3.3; Table 1).

Becca France also very clearly shows a set of WNW–ESE doubled ridges on the top that are characterised by a total length of 1.8 kms, an average width of 50 m and a depth of 25 m (Forno et al. 2012). These doubled ridges, very close to Fallère Hut (Fig. 9a), are the largest ones in the Aosta Valley and among the most remarkable in the Alps (1/1 for attr. 1.1; Table 1) (Figs. 9b and 10b). A short, doubled ridge is also observed at the P. Leysser summit, located according to the same alignment as the Becca France doubled ridge

(Fig. 10c). Doubled ridges are a significant geomorphological effect of DSGSD gravitational activity located near the watershed, usually representing its clearest evidence. These doubled ridges are among the most significant morphostructures of the Pointe Leysser DSGSD.

Moreover, a noticeable southward-dipping sliding surface has been identified on the northern slope of the Becca France relief at 2220–2230 m (Fig. 9c). It consists of a continuous low-angle counterscarp forming a 500-m-long ledge, separating differently fractured calcschist walls and can be considered a structurally low sliding surface of the DSGSD (Forno et al. 2012).

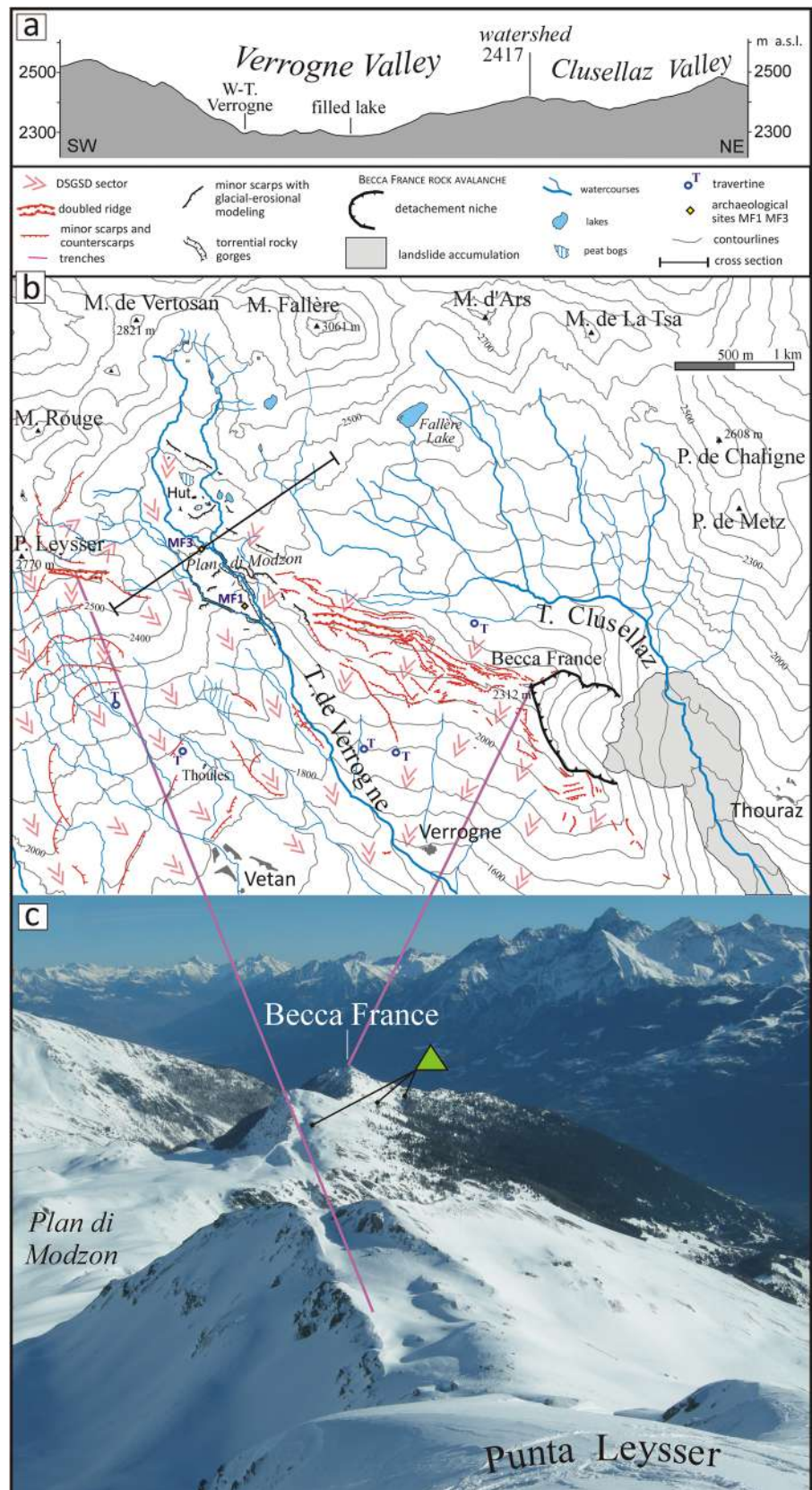
The Becca France doubled ridges seem like wide valleys, but, unlike them, these landforms are without a watercourse and show an anomalous location in the relief top, with a trend parallel to the watershed. These landforms are particularly evident in the springtime, concentrating and preserving the snow cover over time. Water infiltration, as a result of precipitation and snow melt gathered in these depressions, triggered the formation of the large landslide (see ‘Becca France rock avalanche’).

The support and/or disturbance with respect to the biological features could be considered relevant at this site (0.67/1 for attr. 1.6; Table 1). According to a recent dendrogeomorphological analysis performed on trees of *Larix decidua* Mill. growing along trenches and scarps located on the Becca France ridge, the main indicators used in similar contexts (i.e. reaction wood and traumatic resin ducts; Stoffel and Corona 2014; Šilhán 2020) revealed a differentiation of processes from W towards E (Fig. 11). While compression wood is detected mainly in trees growing on the extensional trenches in the western sector of the ridge, traumatic resin ducts are present on trees located under the Becca France top in the eastern sector, where the relief energy is greater and debris fall occurs. This underlined how strict the relationship is between the biotic and abiotic components of the environment, conferring to such sites an ecological support role. This latter, as indicated in the literature, should be counted within the scientific feature of a geosite (Bollati et al. 2015).

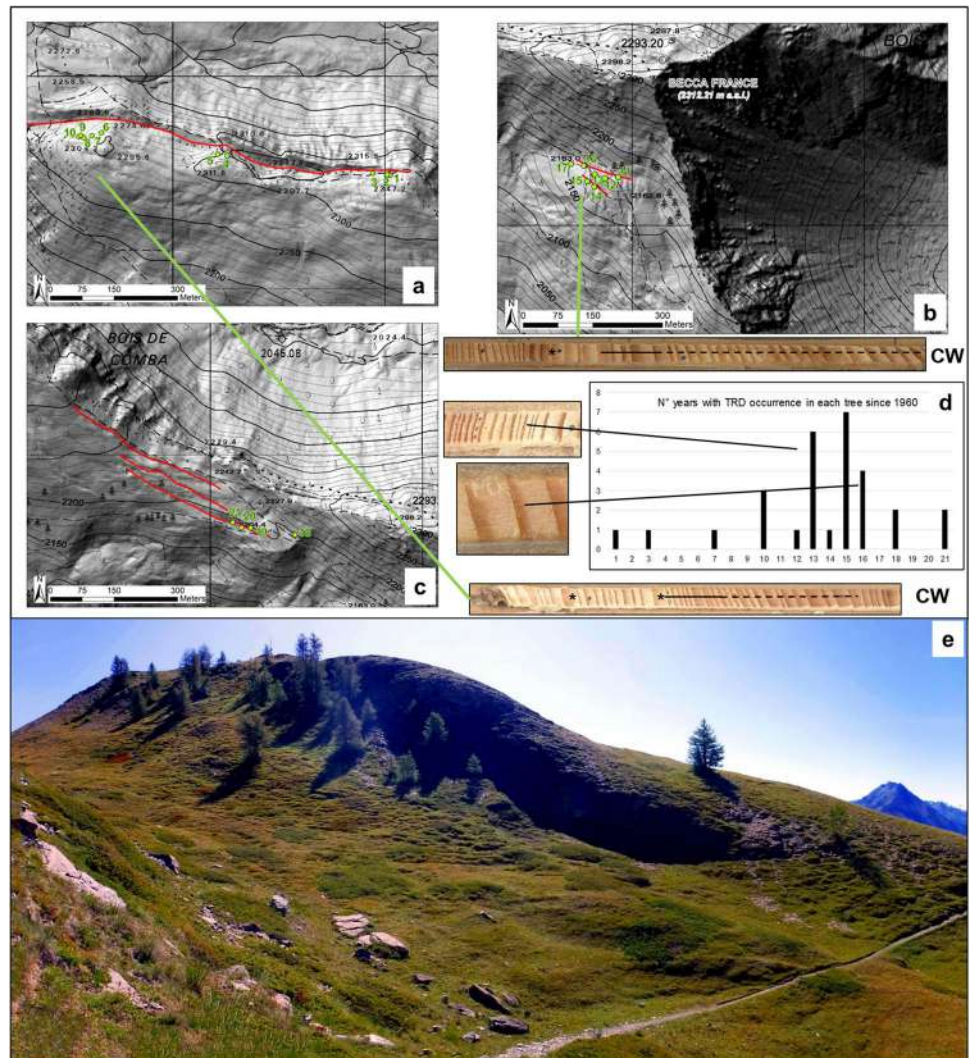
In summary, site 2 is characterised by the representativeness of geomorphological processes (1/1 for attr. 1.1, Table 1), integrity (1/1 for attr. 1.7, Table 1), and rareness (1/1 for attr. 1.8, Table 1). Moreover, the scientific value (6.01/8 for attr. 1, Table 1) is enriched by the ecological support role (0.67/1 for attr. 1.6, Table 1) when vegetation clearly responds to the different solicitations received by the different processes affecting the Becca France ridge: extensional stress detected by compression wood (Fig. 11a, b, d), debris and rock falls testified by traumatic resin ducts (TRDs) (Fig. 11c, d). Concerning additional values, the aesthetic value is evident (1/1 for attr. 2.2, Table 1) and connected with the visibility of the peak and ridges far from the area (1/1 for attr. 3.3, Table 1).



**Fig. 10** Map of the Mont Fallère southern slope, comprising the Clusellaz and Verrogne valleys (modified from Forno et al. 2016). **a** Topographic cross-section of the Plan di Modzon and the Clusellaz valley head. **b** Gravitational morpho-structures and archaeological sites (MF1 and MF3) recognised in the Plan di Modzon and Becca France geosites. **c** Winter view of the two main stretches of the doubled watershed ridge (Becca France and Pointe Leysser) crossed by the new trend of the Verrogne Valley where the Plan di Modzon area develops (modified from Forno et al. 2014), with the dendrogeomorphology sampling sites (green triangle)



**Fig. 11** Dendrogeomorphological indicator analysis at site 2, showing the location of sampled trees with respect to the double ridge crest of Becca France (a–c). Moving from the area along the double ridge crest (a, c) to the Becca France southern slope (b), the occurrence of some of the indicators (d compression wood and traumatic resin ducts-TRD) differently affect tree rings of *Larix decidua* (Mill.). e View of the field of the tree group of (a)



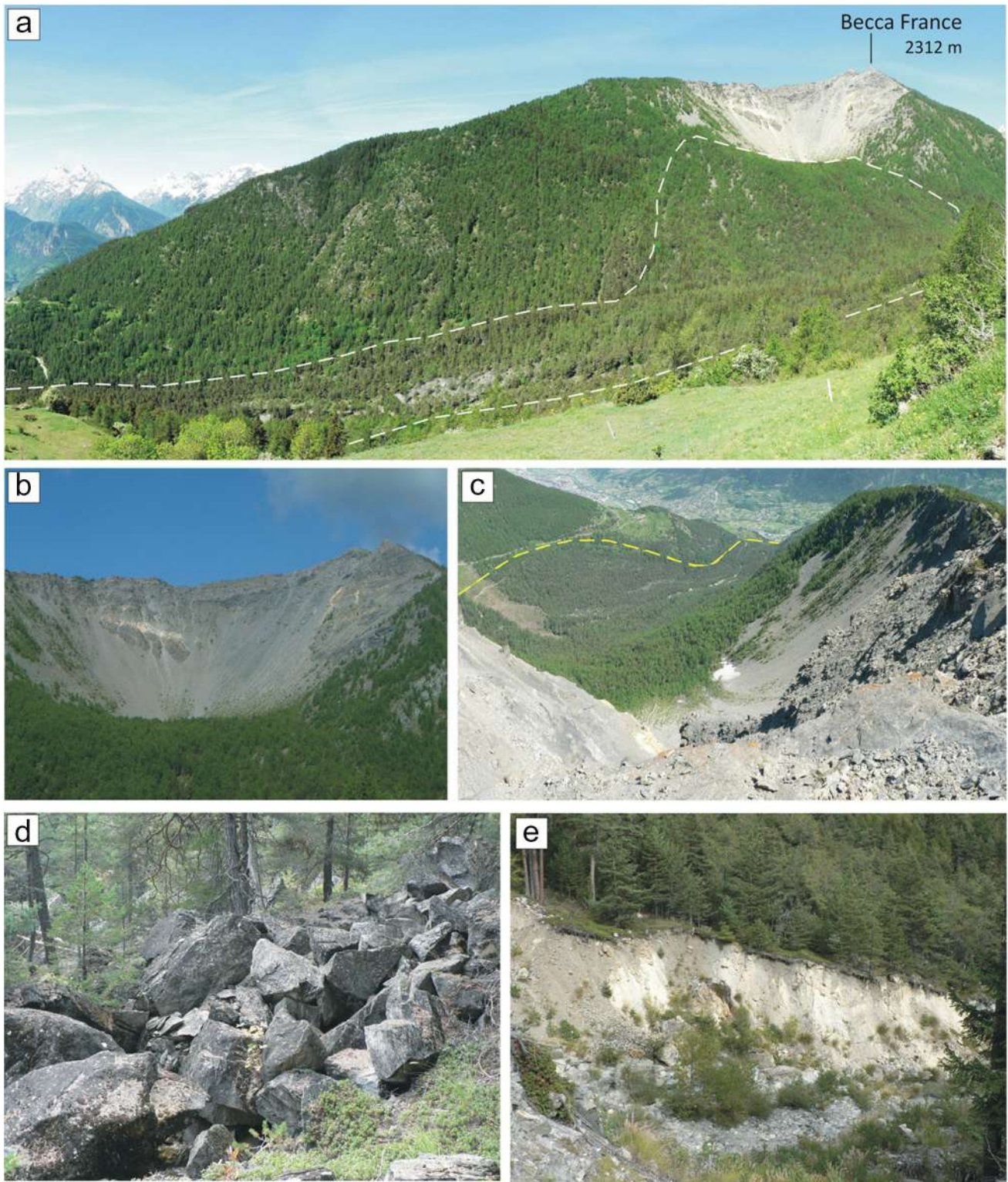
The total score obtained is 16.29 over 23 (Table 2), where the lowering is mainly due to the spatial accessibility to the site through a path locally exposed. Indeed, the Becca France ridge (2312 m a.s.l.) is accessible on foot from the Mont Fallère Hut via a 1.5-km mountain path or directly from Vetan by a 9-km-long loop hike. Another 2 km are needed to proceed along the doubled ridge up to the easy Becca France peak (2312 m a.s.l.).

### Becca France Rock Avalanche

The Becca France landslide is a 2.2-km<sup>2</sup>-wide geosite comprising the detachment scarp (45° 44' 45.1" N, 7° 13' 19.4" E) and the accumulation (45° 44' 36.6" N, 7° 14' 14.7" E) of a large historical landslide (3 in Fig. 5). This landslide fell in the lower Clusellaz Valley from the eastern slope of the Becca France ridge, deformed by the Pointe Leysser DSGSD (Forno et al. 2004, 2012; Polino

et al. 2015a, 2015b) (Fig. 12). This event is reported in the local historical literature as it destroyed the populous village of Thora (120 or 545 victims according to different sources) at dawn on 6th July 1564, resulting in the worst natural disaster in the Aosta Valley Region (references in Bollati 1988, and in Caniggia et al. 1999). Due to the deep interference with the human settlements in the area, the site may be considered featured by a cultural value (1/1 for attr. 2.1; Table 1).

The detachment scarp is shaped on the east-facing right side of the Clusellaz Valley and cuts the eastern edge of the doubled Becca France ridge (2312 m a.s.l.). It corresponds to an arched steep scarp showing a strong cirque-like morphology (Turnbull and Davies 2006), which is remarkable for its width (approximately 850 m), height (more than 500 m) and lack of vegetation cover (Fig. 12a, b) (1/1 for attr. 1.1; Table 1). Two calcschist units (Lower and Upper Tectono-metamorphic Units of the Aouilletta Unit) well



**Fig. 12** The Becca France landslide. **a** General view of the lower Clusellaz Valley with the detachment scarp and the landslide accumulation (white dashed line) forming longitudinal ridges. **b** The detachment niche with the white-yellow layer of cargneule and gypsum and the doubled ridge at the summit. **c** Panorama from the landslide crown towards the Clusellaz valley bottom. The yellow dashed line

marks the landslide extent on the left side of the valley approximately 800 m below the crown of the detachment scarp. **d** Detail of the blocky facies of the landslide accumulation. **e** Cargneule layer pinched in the landslide body cropping out along the Clusellaz T. incision

outcrop in the scarp, the lower one with prasinite, separated by the upper one consisting of only calcschist, by a tectonic contact underlain by cargneule and gypsum (Fig. 12b), making the site also representative of the geological features (1/1 for attr. 1.2; Table 1). The extended arched Becca France detachment scarp, clearly recognisable at a distance (1/1 for attr. 3.3; Table 1), strongly characterises the panorama from the middle Aosta Valley, for its yellowish and white stripes of cargneule and gypsum, in addition to its large dimensions and typical morphology.

The Becca France landslide event was triggered by the bedrock slackening connected to the Pointe Leysser DSGSD, but the detachment occurred from a marginal sector of the DSGSD, where the bedrock is not entirely crushed and a high-energy relief is preserved (Fig. 12c). The landslide accumulation shows a wide extent (1.26 km<sup>2</sup>), a maximum thickness of 20 m probed by a geophysical cross-section (Deparis 2007) and a consequently estimated volume of 15–25 million m<sup>3</sup>. Its magnitude and *H/L* ratio of 0.36 (total fall height *H* = 1500 m, related to the maximum runout distance *L* = 4150 m) and a run-up of 80 m on the opposite side of the valley agree with the values required for rock avalanches (Forno et al. 2012). Rock avalanches are catastrophic rock-fall events characterised by great size (> 10<sup>6</sup> m<sup>3</sup>), high speed (100–250 km h<sup>-1</sup>) and long-transport distance (*H/L* < 1), involving rapid runout and emplacement of crushed, pulverised and dry rock for distances of several km (Hewitt et al. 2008).

Most of the valley floor (3.3 km of a total length of 4 km and between 1605 and 800 m a.s.l.) is filled by the landslide accumulation, essentially formed by large angular boulders (from metric to over 200 m<sup>3</sup> in size) mixed with minor clasts and subordinate sandy–silty matrix (Fig. 12d). This accumulation is arranged into several ridges aligned parallel to the Clusellaz Valley, up to 10 m high and some hundreds of metres long, with different petrographic compositions (Fig. 13). The Becca France landslide is, therefore, a rather rare example of a rock avalanche with longitudinal ridges (similar to lateral moraines), according to the few cases reported in the literature: Flims in the Swiss Alps (Abele 1997), Mutzogata in the eastern Pamir (Fort and Peulvast 1995), Ghoro Choh I in the Karakoram (Hewitt et al. 2008) and Slide Lake in Montana (Butler et al. 1986) (1/1 for attr. 1.8; Table 1). The Becca France rock avalanche had a caroming flow, as documented for the Pandemonium Creek rock avalanche in British Columbia (Evans et al. 1989). The subsequent wave-like movement down the valley produced the emplacement of alternating ridges of debris on the opposite valley sides. Prasinite and prasinite-gneiss blocks constitute the external ridges and the entire distal sector below 1300 m a.s.l. Calcschist, graphitic calcschist and marble schist clasts instead constitute the internal-proximal ridges. All these lithologies are mixed in some intermediate ridges. The two

compositional sectors of the landslide body are separated by a gently dipping and metric-thick tabular body of crushed and pulverised cargneule that outcrops along the Clusellaz T. incision (Fig. 12e). The neatly distributed lithological composition of the Becca France accumulation, which preserves the complex stratigraphic sequence cropping out in the niche, is a remarkable example of ‘remnant stratigraphy’ (Heim 1932) (1/1 for attr. 1.2; Table 1) (Fig. 13). The landslide accumulation area is clearly distinguishable also thanks to the dark green colour of the larch and pine wood that covers it (*Larix decidua* and *Pinus nigra*), since it differs from the pine-free woods of the adjacent sectors (0.67 for attr. 1.6; Table 1).

The Becca France rock avalanche is listed among the six geosites of the Aosta Valley Region, adding the value deriving from its use as a geoheritage site to this landmark (1/1 for attr. 3.8; Table 1). In addition to having a cultural value (1/1 for attr. 2.1, Table 1) linked to the human settlements deeply impacted by the rock avalanche, it is characterised by the representativeness of geological features (1/1 for attr. 1.2; Table 1) and rareness (1/1 for attr. 1.8; Table 1). It is also featured by an aesthetic value (1/1 for attr. 2.2; Table 1) and high visibility (1/1 for attr. 3.3; Table 1).

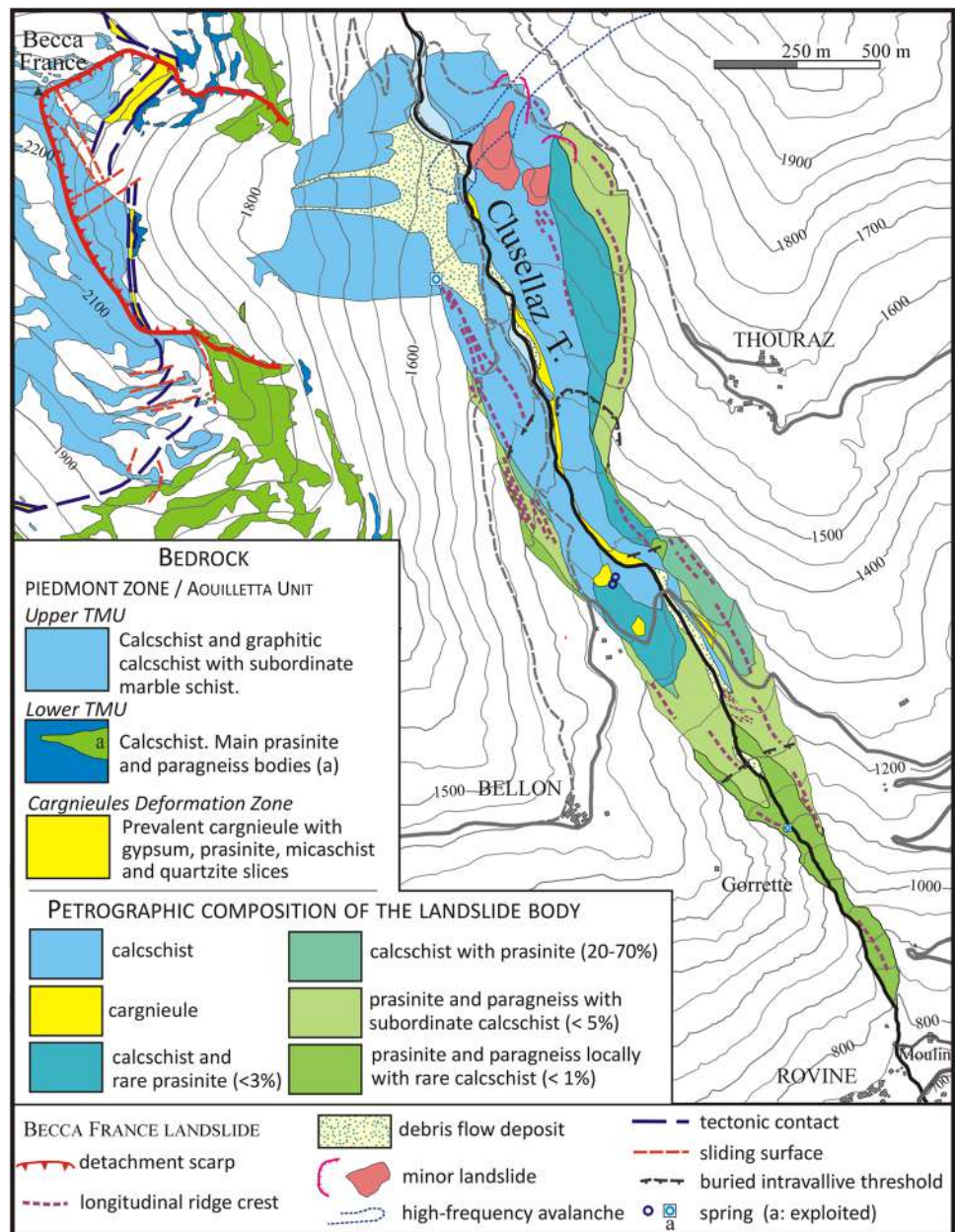
The niche-accumulation system can be admired from the Thouraz viewpoint at 1630 m a.s.l., which can be reached by an asphalted road (barely accessible by minibus) going up from Sarre (630 m a.s.l.). A large picnic area is located in the middle of the landslide accumulation at 1340 m a.s.l., at the point where it is crossed by the nice road Ville sur Sarre-Bellon. From here, a dirt road climbs the accumulation up to Thouraz.

In the complex, the site obtained a total score of 19.12 over 23 (Table 2), the maximum obtained among the evaluated sites.

### Tilted Bedrock Block Geosite

Back-tilting is one of the more usual processes of a DSGSD (Forno et al. 2016). It consists of vast bedrock slabs gravitationally displaced on listric sliding surfaces outcropping as DSGSD scarps. Tilted blocks are integers (1/1 for attr. 1.7; Table 1) and widespread on the whole Pointe Leysser DSGSD, but they are particularly developed around the top of the most deformed central sector in the Vetan area (4 in Fig. 5) (i.e. 1/1 for attr. 1.1; Table 1), where the alpine pasture cover and absence of trees allow excellent visibility (1/1 for attr. 3.3; Table 1). East of Vetan Dessus, a 16-ha-wide tilted slab forms the pastures between Chatelanaz and Pesse Dètot at 1925–1960 m a.s.l. (Fig. 14). It has a prismatic shape with an N10E–S10W-trending 700-m-long axis and a gently (approximately 20°) upslope-dipping topographic surface. The landscape deriving is aesthetically valued (1/1 for attr. 2.2; Table 1).

**Fig. 13** Geological map of the Becca France landslide. The petrographic composition of the blocks in different sectors of the accumulation reflects the composition of the rocks cropping out in the detachment scarp, also preserving their stratigraphic order



The sliding surface is part of the gravitational scarp system at the head of the DSGSD (Fig. 4b). Filled trenches and scarps mildly divide the tilted slab into three minor blocks. This startling gravitational landform is visible in panoramic view (1/1 for attr. 3.3; Table 1) from the dirt road that joins Vetan with Fallère Hut at 2100–2200 m a.s.l. From here, the tilted block can be recognised as the lower slab of a former subglacially shaped wide terrace that was displaced into various slabs by the DSGSD. In summary, this site is relevant for the visibility and representatives of the geomorphological and geological features (1/1 for attr. 1.1; 3.3; Table 1).

This site obtained a total score of 14.61 over 23 (Table 2), a relatively low score mainly due to the quite low scientific value (3.67/8 for attr. 1; Table 1).

### Badlands Scattered Geosites

Eight potential sites were selected among the numerous badlands-like areas of the Pointe Leysser DSGSD, three of which have strong morphological evidence (1/1 for attr. 2.2; 3.3; Table 1) and large extent (5a–c in Fig. 5), while five are minor sites, anyway interesting for the representativeness of the geomorphological process and their educational



**Fig. 14** Panoramic view of the wide tilted bedrock block west of Vetan (view towards SSW), without bedrock outcrops

exemplarity (1/1 for attr. 1.1; 1.3; Table 1) (5d–h in Fig. 5). They are quite different types of badlands, enhancing the site's intrinsic geodiversity (1.4; Table 1). These badlands are confined within the sides of glacial (i.e. the Gaboé and the Verrogne tributary valleys) or torrential (i.e. the Meod T. and the Isolettaz T.) grooves developed into longitudinal trenches. They are polychromatic unvegetated landforms carved directly in the fractured bedrock and/or in gravitative and glaciogenic deposits arranged in very complex stratigraphic relationships (Fig. 15), most connected to former small tributary glaciers flowing down the valley slope and coeval with the DSGSD spread out during the Lateglacial.

At most sites (5a–d and 5 g in Fig. 5), the badlands are shaped by the very fractured bedrock tilted and collapsed along a DSGSD sliding surface system, which is also locally displaced by glaciotectonics.

Two main badland areas are hosted at the western edge of the DSGSD in two stretches of the Gaboé T. deep incision at very different elevations (5a and 5b). Leytanettaz badlands (5a in Fig. 5; Fig. 15a), in the upper stretch of the Gaboé

incision, are the widest (0.14 km<sup>2</sup>) and the most complete landforms (1/1 for attr. 1.7; Table 1) as they are characterised by widespread erosional forms carved both into the crushed bedrock and into the Quaternary cover made of subglacial and ice-marginal deposits of the Gaboé Glacier, according to their petrographic composition (marble, prasinite and serpentinite).

Fossaz badlands (5b in Fig. 5) are a 0.08-km<sup>2</sup>-wide area with a high density of gullies and the presence of earth pyramids (Fig. 15b). They are regionally well known as they are surprising, visible and integer landforms close to the Saint-Nicolas centre (1/1 for attr. 1.1; 1.7; 3.3; Table 1). These badlands are carved into a 700-m-long and 30–35-m-high succession of proglacial lacustrine (10 m of visible thickness), subglacial (15–18-m-thick lodgement till) and cemented ice-marginal sediments (6 m thick) (Forno et al. 2020). The lacustrine deposits, cropping out at the base of the badland distal sector, show sandy-gravel texture and planar bedding. They were deposited in an ice-marginal lake dammed by the Dora Baltea Glacier but

infilled by proglacial fan-delta sand and gravel fed by the Gaboé Glacier according to their almost monotonous lithological composition (calcschist). The overlying subglacial sediments are particularly interesting because they show anomalous features (scarcity of matrix, coarse texture of the matrix, greater abundance of angular clasts, absence of faceted, polished and striated pebbles, low degree of overconsolidation, greater permeability and consequent local carbonate cementation). Their features are connected to a supply by a small glacier coming down from a catchment totally comprised of the Pointe Leysser DSGSD, in which the very fractured bedrock produces a high number of small rocky angular fragments (Forno et al. 2020). The ice-marginal sediments visible at the top, in the proximal (upper) sector of badlands, crop out on the inner flank of a frontal moraine that separates the Fossaz village from the Gaboé T. incision.

Wide badlands near Chantel village (5c in Fig. 5), with an extent of 0.056 km<sup>2</sup>, exposed on the left side of the Isolettaz T. incision, were already reported in the Regional Geological Guides (Carraro in Dal Piaz 1992). These badlands are shaped by a thick body of subglacial sediments (lodgement till) cropping out in the upper stretch (Fig. 15c), made of overconsolidated, matrix-supported, silty-sandy massive deposits with faceted, smoothed and striated pebbles, while the crushed bedrock prevails downstream in the middle-lower stretch. The lithological composition of subglacial sediment clasts (dark grey marble, white-veined marble and prasinite, with subordinate Gran San Bernardo gneiss, lacking many lithologies from the main valley and rare serpentinite clasts interpreted as reworked from former subglacial deposits of the Dora Baltea Glacier) indicates a deposition by the tributary Verrogne Glacier. The current location of this till body far from the Verrogne Valley suggests that it is part of a rock block shifted to the south by sliding phenomena along the DSGSD scarps.

Moreover, the erosional history of the Leytanettaz (6a) and Chantel (6c) gully systems was studied by means of dendrogeomorphological analysis (Bollati et al. 2019b), which detected erosion rates higher than those affecting similar landforms not related to DSGSD. As for site 2 (Fig. 5), here, it could be considered relevant to the ecological support role in terms of influence on vegetation growing along specific features of the investigated DSGSD (0.67/1 for attr. 1.6; Table 1).

Three small (0.4–1.1 ha) badland areas are also reported in the T. Meod incision. An outcrop of crushed bedrock is visible in the lower stretch of the Meod badlands (5d in Fig. 5), consisting of impure marble with a green prasinite layer. This bedrock shows a group of boulder-capped earth pinnacles interpreted as remnants of infill debris deposits (Fig. 15d). The typical blue-grey Vulmian badlands (5e in Fig. 5) visible in the middle stretch of the Meod T. incision extend on subglacial sediments (Fig. 15e). Finally, the

upper Meod T. badlands (5f in Fig. 5) consists of a 1.1-ha-wide area exposed at the incision head along the path to the Mont Fallère Hut, where complex stratigraphic contacts between subglacial sediments and subglacial trench-infill deposits can be observed.

Another site above the Or mountain pasture (5g in Fig. 5) is characterised by a wide incipient badland area carved on the southern side of the Becca France ridge (Fig. 15e). These poorly developed landforms represent an area of strong sheet erosion involving a very fractured and loosened, but not crushed, bedrock (calcschist), which is affected by a set of gravitational minor scarps.

A last significant badland area extends near Montoverto north of Villeneuve, also clearly visible from the state road above the bridge on the Dora Baltea R. (5h in Fig. 5). These and other erosional landforms scattered on the distal slope of the DSGSD are characterised by a 1–3-m-thick debris-colluvial cover overlying the loosened bedrock.

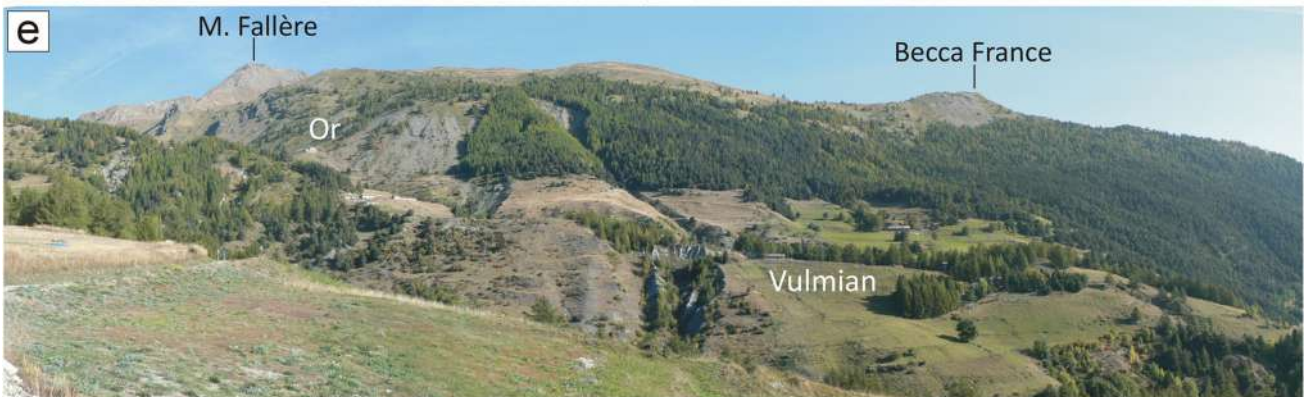
The most evident feature regarding this kind of site is its intrinsic geodiversity (1/1 for attr. 1.4; Table 1), where the same process of erosion affects different deposits and rocks, locally generating very integer landforms (1/1 for attr. 1.7; Table 1), which allows us to reconstruct the geomorphological evolution of an area (1/1 for attr. 1.1; Table 1). Their educational exemplarity is also high (1.3, Table 1) and even more concerning the scientific value, the ecological support role (1.6; Table 1) is revealed by the specific analyses performed on vegetation. Undebatable is their aesthetic value (1/1 for attr. 2.2; Table 1), augmented also by their visibility (1/1 for attr. 3.3, Table 1). One of them (Fossaz) is already inserted into the regional inventory of geosites of the Aosta Valley (1/1 for attr. 3.8; Table 1). Indeed, the viewpoints of Fossaz (close to the village) and in front of Chantel (1.5-km-long flat dirt road) are equipped with explanatory panels.

All the panoramic viewpoints in the badlands can be easily reached on foot via dirt roads and/or paths. In particular, the Leytanettaz badlands can be observed from the mountain path that connects Gerbore village (1638 m a.s.l.) to the small Mont-Joux Lake (1894 m a.s.l.) upstream to Vens.

Globally, the site obtained a total score of 18.62 over 23 (Table 2).

### Calcareous Tufa Scattered Geosites

Some locally developed calcareous tufa outcrops, with extents between 0.1–0.2 ha, are located at short distances from each other upstream of Vetan village (Polino et al. 2015a, 2015b) (6 in Fig. 5). They are typically confined at the outlet of torrential incisions that intersect some DSGSD minor scarps, where they form 2- to 4-m-thick bodies hanging 2–15 m above the riverbeds.





◀**Fig. 15** General view over some of the badland-like areas distributed on the Pointe Leysser DSGSD: **a** Leytanettaz (Saint Nicolas in Bollati et al. 2019b), **b** Fossaz, **c** Chantel (Rumiod in Bollati et al. 2019b), **d** Meod and **e** Or and Vulmian badlands

The best outcrop (Chatelanaz calcareous tufa, Fig. 16a) is located northwest of Vetan at the outlet of a deep incision of the Vetan T. (Fig. 16b), where 3.5 m-thick well-stratified yellowish calcareous tufa covers 2.5 thick dark-greyish debris flow sediments (0.67/1 for attr. 1.2; Table 1). Both units show inclined bedding dips of 30–35° to the SE (Forno et al. 2016). A similar succession is visible downstream at the village's upper edge (Vetan Dessus calcareous tufa), where the same creek cuts another DSGSD minor scarp. Here the tufa bodies are perched on the right side of the incision up to 15 m above the valley floor and form a bulging tabular wall with a waterfall (Fig. 16c). A third site is located along the Isolettaz T. incision (Thoule calcareous tufa, Fig. 16d), where a tufa slab has been tilted by recent DSGSD activity.

Tufa is rich in wood, cone and needle imprints of *Pinus cembra* (Pini et al. 2011). Tree imprints (trunks and branches) have up to decimetric sizes, visible as large voids derived from the decomposition of all the organic matter, with the exception of rare, preserved charcoal remains. Their setting and lithofacies agree with a fluvial environment. Phytoclastic and phytohermal calcareous tufa prevails, although lithoclastic tufa made of angular pebbles of calcschist and impure marble are present at the bottom and (locally) at the top of the sequences. Rounded speleothems are abundant in the voids. Subordinately, massive strata of stromatolitic and microhermal facies are interbedded (Fig. 16e).

Radiocarbon dating of the Chatelanaz tufa (9.1–5.8 ka cal BP) (Pini et al. 2011) proves sedimentation starting from the Boreal (9.5–8.5 ka cal BP) and Atlantic (8.5–5.8 ka cal BP). The tufa spread out at high quote (1800–2000 m a.s.l.) was coeval with the rise of the forest up to the maximum treeline elevation at 8.5–6 ka BP, when a *Pinus cembra*-dominated forest, with minor *Abies alba* and *Picea abies*, occurred up to 2365 m, as proven by palynological analysis and radiocarbon dating of the Crotte Basse peat bog in the Verrogne Valley (Pini et al. 2017; Badino et al. 2012; [The Plan di Modzon and Verrogne glacial diversion](#)). The underlying debris flow probably formed during the Lateglacial when the DSGSD longitudinal trenches and minor scarps had already largely developed. Their burial by calcareous tufa during the first half of the Holocene preserved these ancient debris flow deposits from the subsequent torrential erosion that terraced the sequence.

Calcareous tufa observed at Vetan, together with maximum treeline elevation and glacier withdrawal attested by the Crotte Basse and the Rutor mire sequences, respectively, are the main evidence of the Holocene *optimum climaticum* in the Aosta Valley (Pini et al. 2011).

The Vetan Dessus tufa outcrop is by far the easiest geosite to reach in the whole Pointe Leysser DSGSD, as it is visible directly from the car park. The other two outcrops are located within 30 min on foot from there.

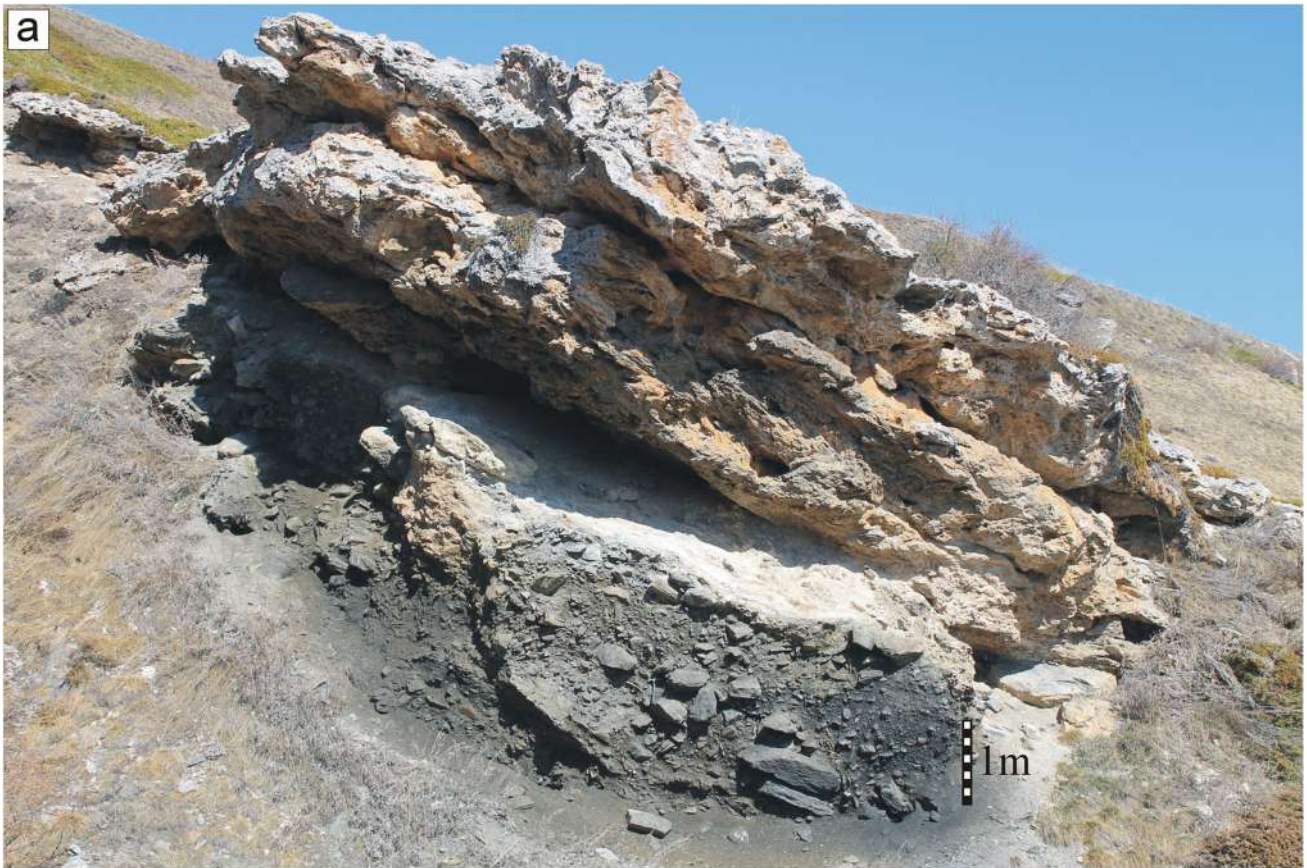
This is the site less valued than all the others (12.4 over 23, Table 2).

## Discussion and Conclusion

The usual approach to a geosite, especially within geosite inventories, is related to a primary interest (e.g. stratigraphic, geomorphological, petrographic, paleontological) that is described in detail, sometimes accompanied by secondary interests that are usually only listed (e.g. for Italy, Giovagnoli 2017). The concurrence of more than one primary geofeature is rarely considered.

As mentioned above, the investigated slope is not listed in the Italian Inventory of Geosites. Instead, the Geosites Inventory of the Aosta Valley region (<https://www.regione.vda.it/territorio/territorio/geositi/>) includes two sites on the investigated slope: the Becca France (or Thouraz) landslide (3 in Fig. 5) and the Saint Nicolas badlands (5b in Fig. 5).

The investigated slope is herein proposed as a *complex geosite*: it is a meaningful example of a very large gravitative phenomenon showing significant geomorphological evidence, as visible from the viewpoint of Point de la Pierre, located on the opposite flank of the Aosta Valley (Fig. 17). Moreover, six exemplary features have been recognised (Fig. 5), each representing a single element of a DSGSD or an element whose evolution is strictly related to DSGSD dynamics. All the proposed sites contribute to the reconstruction of the articulated evolution related to the presence of a DSGSD (e.g. Bollati et al. 2019b; Forno et al. 2013, 2014, 2016 in this case of Pointe Leysser). The different detected sites, as described in the previous paragraphs, are featured by the attributes of scientific and additional values, as well as the potential for use (Bollati et al. 2017). In Fig. 18, all the detected values are qualitatively summarised, while they are reported as numerical values in Table 2. It is worth emphasising that the two most valued sites (3, Becca France rock avalanche; 5, Badlands scattered geosites) are those included in the Geosites Inventory of the Aosta Valley region, as mentioned above. Quantitative evaluations represent a useful tool at least under two points of view: (i) if one has to compare sites within a study area, to decide to which site addresses, for instance, economic resources for promotion (Bollati et al. 2017); and (ii) when one is looking for comparison, evaluating sites located outside the study area, but comparable for geological and geomorphological genesis (e.g. Bollati and Zerboni 2021). What could also be quantified in the future, in the view of geoconservation versus promotion, is the potential of degradation of each



◀**Fig. 16** Calcareous tufa outcrops at the head of the most deformed central sector of the Pointe Leysser DSGSD, near Chatelanaz at the outlet of the Vetan T. incision (a, b), at Vetan Dessus (c) and at Thoule (d). Local stromatolytic structure and rounded morphology in the vacuolar tufa at Thoule (e)

site, according to a quantitative methodology, as recently proposed in the literature (e.g. Selmi et al. 2022).

In particular, the investigated slope shows some of the most iconic geomorphological features related to a DSGSD context of the whole Aosta Valley (i.e. at the regional scale), and an intrinsic geodiversity (sensu Panizza 2009), considering both the lithological and morphological elements, where the low human frequentation, even if relevant, for example, concerning the archaeological witnesses, allows us to see integer and rare geological and geomorphological features. The same geomorphological context featured by one of the most relevant DSGSDs of the Italian Alps favoured the settlement of the prehistoric populations, conferring to the place a high cultural value (Forno et al. 2013, 2014). As a whole, the complex geosite presents all three typical features described before for geomorphosites (Coratza and Hoblèa 2018): multiscalarity, aesthetic value and dynamism, which are even more multifaceted for the specific case.

The necessity to act at the slope scale rather than at the single-site scale emerges, and in the study case, it should be suggested to include the entire slope both in the regional and national inventories of geosites, pushing for considering complex geosites as elements of these geoheritage lists. As suggested by Migoń and Różycka (2021) working on a complex morphostructure in Central Europe, it is important to consider geoheritage at the landscape scale and only successively focus on individual geosites (i.e. rocky outcrops or small-scale landforms). Indeed, these latter alone *may not be sufficient to tell the story*. In the specific case of the Pointe Leysser–Becca France slope, the DSGSD was demonstrated to influence the dynamics of every single site described here in different ways, further reinforcing the necessity of a landscape-scale approach (Wang 2015; Bollati et al. 2019a; Stanczyk et al. 2019).

Once recognised as a complex geosite, the crucial point regards its promotion and enhancement. If the approach of the presented analysis is from the local-site scale to the slope scale, one of the possibilities to allow visitors to understand the site could be starting from a general overview on the slope to discover the single sites characterising the slope.

The two options proposed for this specific case could be as follows:

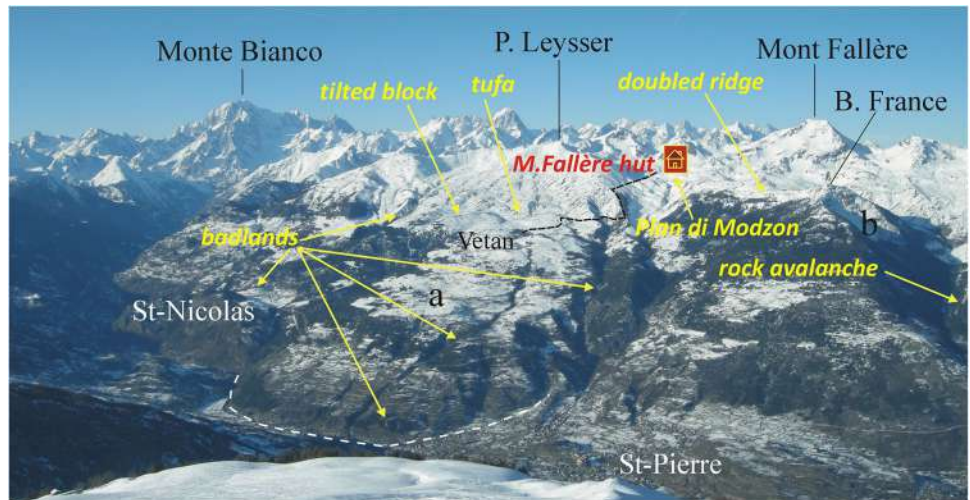
- i) The use of a multimedia platform (e.g. an app), remotely showing the complex geosites as a whole, with further insights into the single features of the slope. It is a quite

widespread approach at the regional scale (e.g. Perotti et al. 2020) and allows a high degree of freedom to move from one site to another. Remote views using, for example, a specific browser such as Google Earth could be a potential option (Migoń and Różycka 2021). This activity could be used as a preparatory for exploring the single sites located within the slope through dedicated field trips, undoubtedly enriching the virtual experience (see point ii).

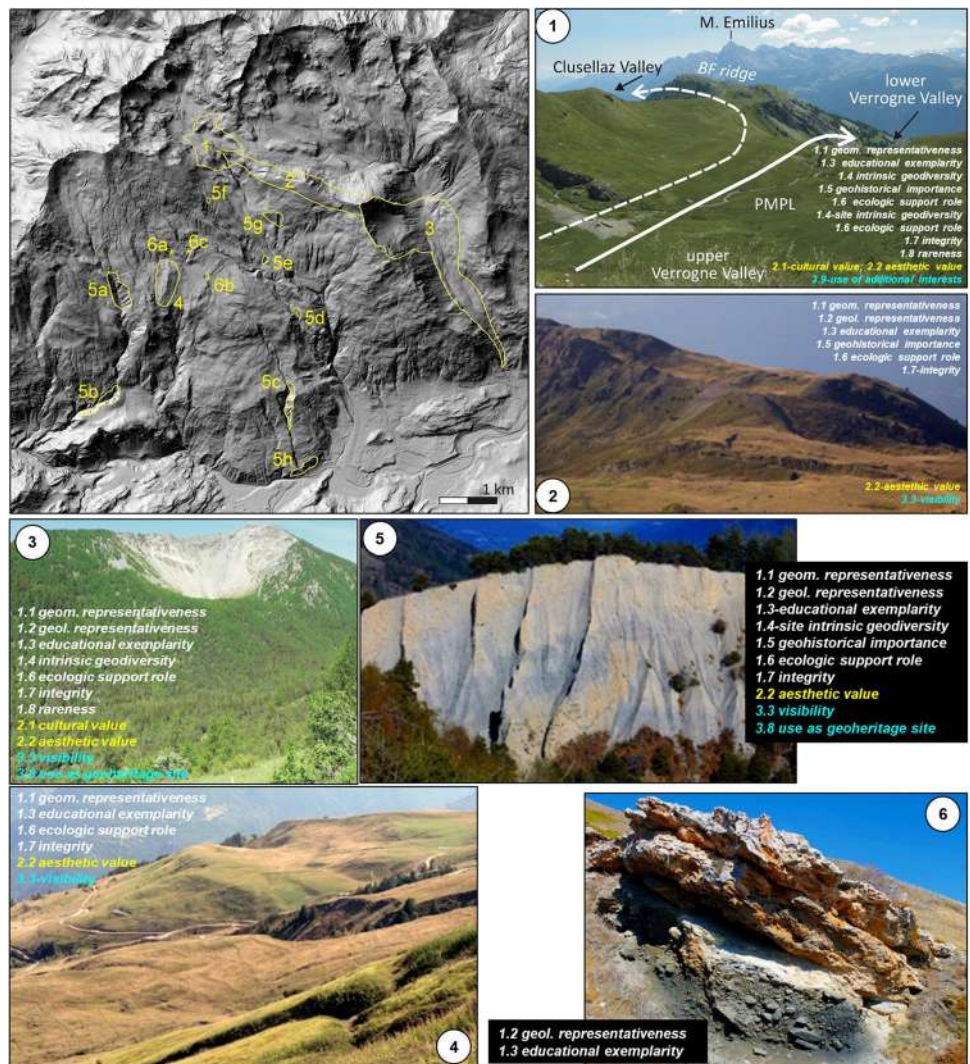
- ii) Another option is the promotion of the geosite on the field, at first from a dedicated *viewpoint geosite* (sensu Migoń and Pijet-Migoń 2017). In this specific case, the best view of the slope in its complex is from the opposite side of the Dora Baltea valley at Pointe de la Pierre (Fig. 17). The positioning at the viewpoint of interpretive tools (e.g. panels with landscape interpretation, Fig. 18) could stimulate curiosity in the visitors, who could later plan a visit to the slope to see each or some of the single sites. In such a case, the problem related to geoheritage spots that are not connected to each other emerges through a simple and relatively short trail (Migoń and Różycka 2021), limiting the option of creating itineraries for all the targets in the audience, which represents a good opportunity to integrate more than one topic, specifically regarding gravity-related features and bedrock (e.g. Tognaccini 2019; Bollati et al. 2019a). In this specific case, for example, several sites are visible along a dirt road leading to the Mont Fallère mountain hut located in Plan di Modzon, which is close to private cars. A solution could be the planning of organised field trips through authorised car access along the road or the planning of individual and autonomous field trips on foot, supported by leaflets or multimedia materials previously downloaded from the web. This option may be planned over at least two days using the Mont Fallère mountain hut as a base location.

The integration of both proposals (i and ii) could represent a successful strategy for enhancing such a valuable but complex geological context. The second one, even if trickier from the logistic point of view, could favour the local economy by increasing the number of visitors in the area. All these considerations should be made in relation to the dynamic conditions of the presented areas. In the framework of dynamic geosites, indeed, as already mentioned in ‘Introduction,’ the tricky point regards the safety fruition of active geofeatures. In these contexts, the safety conditions to visit them should be mandatorily observed (Pelfini et al. 2009). Moreover, where no indications are provided on the territory, they should be included in the planning of both physical and virtual promotion proposals.

**Fig. 17** Winter landscape of the Pointe Leysser DSGSD (a), showing a convex toe advancing on the Dora Baltea valley floor (dashed white line). The extended detachment niche (b) of the Becca France landslide is visible at the far right (view towards the NW from the Pointe de La Pierre summit, a potential viewpoint geosite sensu Migoñ and Pijet-Migoñ (2017)



**Fig. 18** Summary of the single sites with the related geoheritage attributes, contributing to the assessment of the Pointe Leysser-Becca France slope as a complex geosite. White are the attributes conferring a scientific value to the site, yellow ones are those related to the additional values and light blue ones concur with the potential for use (see Table 1). The circled numbers refer to the various geosites as reported in Fig. 5 and along the text. The attributes associated with each site are those peculiar and obtaining a medium to high score; ones that are very high but that characterise all the sites are not listed



Another significant aspect related to complex geosites is how to communicate the effective border of these geoheritage elements for management purposes (i.e. promotion, geoconservation, territorial planning). Coratza et al. (2021) proposed a strategy to depict the boundaries of geomorphosites on geomorphological maps edited by the National Geological Survey (i.e. ISPRA—<https://www.isprambiente.gov.it/it/pubblicazioni/periodici-tecnici/i-quaderni-serie-iii-del-sgi/quad13settembre2020.pdf>) by means of golden borders around the selected landforms. This procedure is particularly meaningful in a case such as a study area, underlining once more the special attention devoted to such complex landscape features, not only for promotion but also for geoconservation and territorial planning in general.

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**Availability of Data and Material (Data Transparency)** Data are available upon request.

**Code Availability** Corel Draw 9.0 (licensed to F. Gianotti), Windendro 2017 (Regent Instruments), TSAP Win 4.81 (Rinntech) (licensed to the University of Milan).

## Declarations

**Conflicts of Interest** The authors declare no conflict of interest.

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