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Research Paper

Conservation of World Heritage glacial landscapes in a changing climate: The Swiss Alps Jungfrau-Aletsch case

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A R T I C L E I N F O

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A B S T R A C T

Many glacial landscapes on all continents are inscribed on the World Heritage List. Due to climate change, most of the glaciers are retreating rapidly, thus questioning their Outstanding Universal Value. This paper clarifies what constitutes the heritage values of glacial landscapes and outlines how the heritage values could evolve in a future with less (or without) ice. For two sites in the UNESCO Swiss Alps Jungfrau-Aletsch property (the Great Aletsch Glacier and the Upper Lauterbrunnen Valley), we describe the evolution of the glacial landscape using a Past-Present-Future framework. We then evaluate the present and post-glacial heritage values according to criteria used in the literature on geomorphosites. The results outline two main issues: (1) As glaciers retreat, the geoscientific value will depend more and more on the inherited glacial landforms, such as moraine ridges, which allow the understanding of the Earth and climate history, and less and less on the glacier itself and its dynamics. Their protection is therefore an important issue. (2) The aesthetic value of glacial landscapes could decrease because of the disappearance of the glacier (landscape greying). One possible adaptation could be a shift from glacier tourism, which is mainly oriented towards the contemplation of an aesthetic landscape, to geotourism, where the understanding of landscape evolution is proposed to the public.

1. Introduction

In 2023, 48 out of the 257 natural sites inscribed on the UNESCO World Heritage List contained one or several glaciers within their boundaries (Fig. 1; Bosson, Huss, & Osipova, 2019). In 15 sites, i.e., one third of the total, glaciers were part of the Outstanding Universal Value (OUV) that justifies the recognition as a World Heritage (the OUV is assessed by UNESCO with 10 criteria and the condition of integrity of the site). Apart from Sagarmatha National Park (Nepal) and Khangchendzonga National Park (India), all these 15 sites were meeting the criterion *viii*: “to be outstanding examples representing major stages of the Earth's history, including the record of life, significant on-going geological processes in the development of landforms, or significant geomorphic or physiographic features” (https://whc.unesco.org/en/criteria/; UNESCO World Heritage Convention, 2023). Glacial geomorphology was also a significant part of the OUV of 12 sites and apart from two of them (the West Norwegian Fjords and Yosemite National Park), they are among the 15 sites mentioned above.

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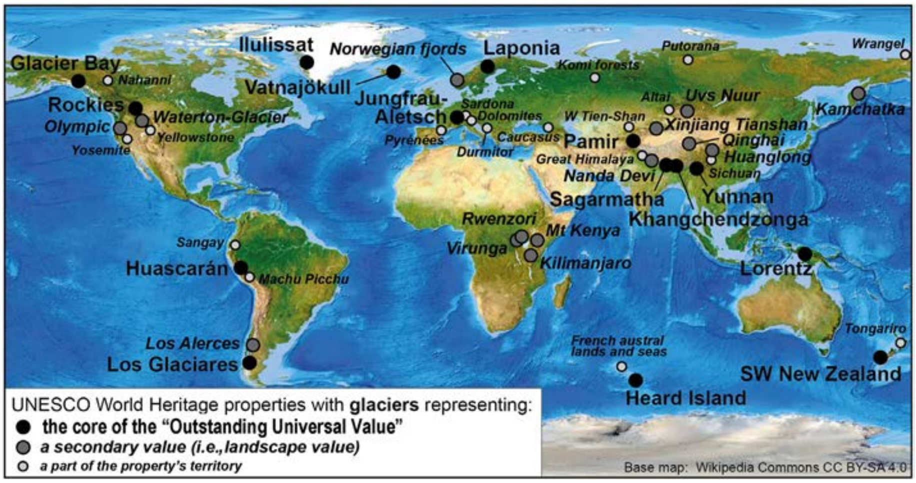

Fig. 1. Glaciers in the UNESCO World Heritage List.

More than three quarters of the 48 sites containing glaciers were also of very high aesthetic value, as they were inscribed under the criterion *vii*: "to contain superlative natural phenomena or areas of exceptional natural beauty and aesthetic importance" (UNESCO World Heritage Convention, 2023). Glaciers were explicitly mentioned as part of the exceptional landscape value of 25 sites, making glaciers a secondary, but relevant, element of the OUV. In 19 sites, glaciers were not mentioned as part of the heritage value.

Observations show clear evidence of a global trend of glacier retreat and mass loss in the last decades (Intergovernmental Panel on Climate Change (IPCC), 2019, 2021; Mannerfelt et al., 2022) and the rates of mass loss since the 1990s are unprecedented since the end of the Little Ice Age (LIA; Zemp et al., 2015). The highest rates of mass loss on the ice surface between 2000 and 2019 were observed in Iceland and in Central Europe (mean elevation change rate of more than -1 m/year), followed by Alaska, New Zealand and the Southern Andes (Hugonnet et al., 2021). Contemporary glacier mass is in disequilibrium with the current climate (Christian, Koutnik, & Roe, 2018) and predictions indicate that about one third of global glacier mass will be lost only in response to past greenhouse gas emissions, without further warming (Marzeion, Kaser, Maussion, & Champollion, 2018). Models estimate that the regions where the ice-covered surfaces are relatively small (Central Europe, Caucasus, Scandinavia, New Zealand, Western Canada and United States) will lose at least half of their present mass by 2100 in the optimistic Representative Concentration Pathways (RCP) 2.6 scenario and nearly all glacier mass (>80%) in the pessimistic RCP 8.5 scenario (Marzeion et al., 2020; IPCC, 2021). According to Rounce et al. (2023), "based on the most recent climate pledges from COP26,[1] global mean temperature is estimated to increase by +2.7 °C (United Nations Environment Programme, 2021), which would result in [...] the near-complete deglaciation of entire regions including Central Europe, Western Canada and United States, and New Zealand" (p.83).

The glaciers located in World Heritage properties are no exception to this trend. According to Bosson, Huss and Osipova (2019), the overall mass loss by 2100 will account for 33% ± 11% (RCP 2.6) to 60% ± 14% (RCP 8.5) of the 2017 volume, and in 8 (RCP 2.6) to 21 (RCP 8.5) sites out of 48, glaciers will disappear. Bosson et al. (2019) suggest that "World Heritage glaciers should be considered as analogs to endangered *umbrella*, *keystone*, and *flagship species*, whose conservation would secure wider environmental and social benefits at global scale" (p.469). But glacier conservation is a very arduous task, as it depends entirely on a global, rapid and massive reduction in greenhouse gas emissions that could bend the curve of climate warming. Direct conservation measures on glaciers, such as covering them with blankets to reduce their ablation (Carver & Tweed, 2021), respond in the short term to local issues such as the protection of skiing infrastructure, but do not give any global and long-term answer for the conservation of glaciers and would certainly compromise the aesthetic value, which is part of the OUV.

The retreat and the disappearance of glaciers have significant implications on several issues: water supply (Huss & Hock, 2018; Immerzeel et al., 2020), water quality and sediment fluxes in glacial watersheds (Milner et al., 2017), frequency and intensity of natural hazards (landslides due to glacial debuttressing, glacier lake outburst floods; Haeberli, Schaub, & Huggel, 2017; Harrison et al., 2018; Veh et al., 2023), implications on global climate and sea level, landscape modifications, aesthetic attractiveness of glacial landscapes (Salim, Ravanel, & Gauchon, 2021), tourism (Salim, Ravanel, Bourdeau, & Deline, 2021) and infrastructure, etc. Ice loss could also reduce or modify the heritage values of the UNESCO World Heritage properties where glaciers are the core of the OUV and even question their inscription on the World Heritage List.

In a future with fewer or without glaciers, at least two components of the OUV of World Heritage glacial landscapes could be affected: the aesthetic value (criterion *vii*), which could be reduced if glaciers disappear, and the geoheritage value (criterion *viii*), which is partly based on current glaciological processes that would no longer exist without ice. The evolution of the characteristics

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[1] COP26 is the 26th Conference of the Parties, which is a United Nations (UN) climate change conference. COP26 was held in Glasgow, Scotland, from November 1 to November 12 of 2021, and was an important milestone in global efforts to tackle climate change.

of World Heritage properties that justify the OUV under criteria *vii* and *viii* (among others) is therefore a major issue. The objective of this paper is to clarify what constitutes the heritage values of glacial landscapes from a geomorphological perspective and to outline how the heritage values could evolve in a future with less (or without) ice. We aim to address the questions of glacial landscape's evolution and conservation with particular attention to the temporal scale imbrication. Two rapidly evolving glacial landscapes located in the Swiss Alps Jungfrau-Aletsch UNESCO World Heritage property will be described as case studies.

2. Heritage value of glacial landscapes: A temporal scale issue

In a broad sense, a glacial landscape does not necessarily contain ice: It can refer to a region that was once covered by ice, for example, during the Pleistocene, and it is now marked by the legacy of glacial processes, even if there are no longer any active glaciers in the area. In this sense, glacial landscapes without ice are interesting analogues of what the glaciated landscapes of today might look like in the future. However, in this article, we will focus only on active glacial landscape, i.e., with the presence of a glacier and currently experiencing glacial processes. In mountain environments, an active glacial landscape includes the glacier itself, its proglacial margin or glacier foreland, which is generally understood to be the area located between the LIA moraines and the current position of the glacier snout (Bollati et al., 2023), and the surrounding area, potentially including Holocene and Lateglacial moraines and other geomorphological processes and landforms, such as the ones resulting from paraglacial adjustment (Ballantyne, 2002; Cossart, Braucher, Fort, Bourlès, & Carcaillet, 2008; Mercier, 2008), if they are located in the same landscape unit.

Glacial landscapes are made of the imbrication of objective physical elements (ice, crevasses, moraines, U-shaped valleys, cirques, *roches moutonnées*, erratic boulders, etc.) that can be considered as heritage if the values assigned by society or some actors are sufficiently important to justify their preservation and transmission to future generations (Di Méo, 2007). Accordingly, they become heritage through a process of heritage recognition, which depends on the subjective values assigned by different stakeholders over time (Martin, 2013; Portal, 2010; Reynard, Hobléa, Cayla, & Gauchon, 2011). In the case of the sites inscribed on the UNESCO World Heritage List, the OUV is defined according to a catalogue of 10 cultural and natural criteria and has to meet the condition of integrity. Two criteria (*vii* and *viii*, cited above) concern directly the geomorphological characteristics (Table 1; Migoń, 2009, 2018). In the literature on geomorphological heritage, criterion *viii* corresponds to the geoscientific value, considered as a central value that a site must have to be considered a geomorphosite (Grandgirard, 1997; Panizza, 2001; Reynard, 2004; Reynard & Panizza, 2005), and criterion *vii* corresponds to one of the additional values: the aesthetic value (Reynard, 2004, 2005a). Moreover, because of their large size, glacial landscapes belong to the specific category of geomorphosites called geomorphological landscapes (Bussard & Reynard, 2022a; Reynard, 2005a). Because they often combine landforms relating to past climatic conditions (e.g., Lateglacial moraines) remobilised by current active processes (e.g., landslides, gullies, active sandurs), most mountain glacial landscapes relate to the category of evolving passive geomorphosites (Pelfini & Bollati, 2014).

Glacial landscapes are inscribed in a timeline (Table 2): With a combination of traces from the past—moraines, erratic boulders, different types of deposits and erosion landforms, they help to reconstitute the Earth and climate history. They also allow a better understanding of what is going on currently, with active glacial and paraglacial processes that are shaping the landscape today. Together, inherited landforms and current dynamics give a good portrait of the past and present situations. These insights into the past and the present allow possible scenarios for the future to be drawn up.

The heritage values of glacial landscapes are complex to determine, because they depend on a combination of inherited elements, active processes and fast changes. Taken separately, each of these elements can have heritage values: The traces of the

Table 1
Comparison of the criteria used for the selection of the UNESCO World Heritage properties (definition of their Outstanding Universal Value) and for the assessment of the intrinsic value of geomorphosites (after Reynard et al., 2016).

UNESCO	Literature on geomorphosites
Criterion *viii*	Geoscientific or central value
To be outstanding examples representing major stages of the Earth's history, including the record of life, significant on-going geological processes in the development of landforms, or significant geomorphic or physiographic features	Rareness, representativeness, integrity and palaeogeographic interest (i.e., the fact that the site documents an (old or recent) stage of the Earth and climate history)
Criterion *vii*	Aesthetic value (additional value)
To contain superlative natural phenomena or areas of exceptional natural beauty and aesthetic importance	The presence of viewpoints and the colour contrasts, vertical development and space structuration by the geomorphosite
Criteria *ix* and *x*	Ecological value (additional value)
To be outstanding examples representing significant on-going ecological and biological processes […]	The impacts of the geomorphological context on the development of specific species or habitats
To contain the most important and significant natural habitats for in-*situ* conservation of biological diversity […]	
Criteria *i*, *ii*, *iii*, *iv*, *v* and *vi*	Cultural value (additional value)
To represent a masterpiece of human creative genius	Religious importance, historical importance, artistic and literature importance, economic importance, and geohistorical importance
To exhibit an important interchange of human values, over a span of time or within a cultural area of the world, on developments in architecture or technology, monumental arts, town-planning or landscape design […]	

Table 2
Characteristics of glacial landscapes, with inherited landforms, current geomorphological processes and future changes.

Time scale	Characteristics
Past	The presence of traces of past glacial stages and inherited geomorphological landforms, such as moraine ridges, erratic boulders, former river beds, proglacial lakes, *roches moutonnées*, glacial potholes, eskers, kames and kettles, drumlins, etc.
Present	The current dynamics of glaciers (thermal regime, mass balance, geometry, surface deformations, velocity, equilibrium line, glacier hydrology, etc.) and the current dynamics of paraglacial processes (Ballantyne, 2002; Cossart et al., 2008; Mercier, 2008), such as the effects of glacial debuttressing (large-scale rock mass deformation, rockfalls, rockslides, rock avalanches) and the reworking of sediments in glacier forelands
Future	The future evolution of glacial landscapes is uncertain, but strong trends (glacier retreat, landscape greening, increase in slope instabilities, development of new lakes, etc.) allow us to anticipate some of the changes and to imagine how glacial landscapes might evolve. Glacier landscapes are a strong symbol of landscape evolution related to climate change

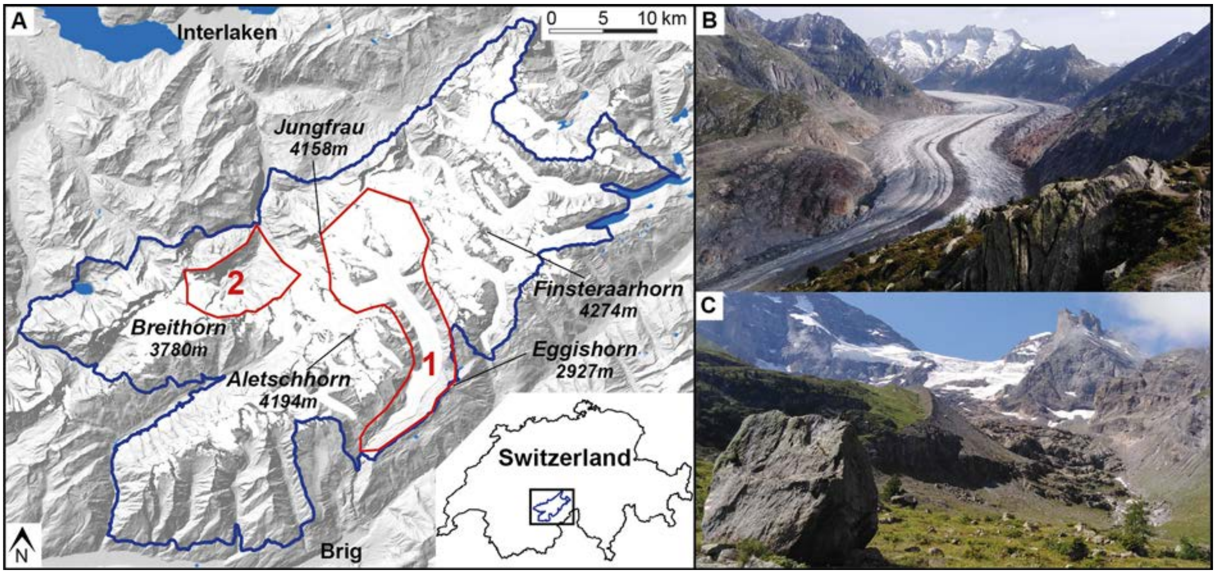


Fig. 2. A. Location of Swiss Alps Jungfrau-Aletsch UNESCO World Heritage property (in blue) and the two study sites (in red): Great Aletsch Glacier (1) and Upper Lauterbrunnen Valley (2). B. Great Aletsch Glacier. C. Upper Lauterbrunnen Valley.
Source: Digital Elevation Model (DEM) by author, based on DEM from © Swisstopo, 2020; photos by Jonathan Bussard, 2021.

past provide information on the evolution of the landscape and the climate; the present characteristics allow a better understanding of the active processes that shape the landscape; and the indications of the future have a strong symbolic value as they visibly illustrate the impact of climate change on the landscape. Taken together, the different elements of the past, present and future are of additional interest as they allow to understand and illustrate the combination of landforms and processes in their spatial and temporal dimensions. In this respect, evolving geomorphosites are of particular interest, although to our knowledge, issues of combining temporal scales in geomorphological landscapes have been little described so far, apart from the influence of past and present surface processes on geodiversity (Gordon, 2018; Thomas, 2012) and the consideration of these dynamic processes as part of the geoheritage values in mountain environments (Migoń, Kasprzak, & Woo, 2019).

3. Material and methods

3.1. Study area

Two glacial landscapes in the UNESCO Swiss Alps Jungfrau-Aletsch (Switzerland) were studied (Fig. 2): the Great Aletsch Glacier and the Upper Lauterbrunnen Valley. These two sites are interesting because they are particularly representative of active glacial landscapes and are well documented by numerous previous studies.

The UNESCO Swiss Alps Jungfrau-Aletsch property covers 824 km^2 of a mountainous area belonging to the Aare Massif, dominated by nine summits of more than 4,000 m a.s.l., including Finsteraarhorn (4,274 m a.s.l), Aletschhorn (4,193 m a.s.l.) and Jungfrau (4,158 m a.s.l.). Mainly made of autochthonous crystalline rocks and marginally by sedimentary rocks (Labhart, 2007), especially Upper Jurassic limestone (Zumbühl, Nussbaumer, & Wipf, 2021), partly covered by Quaternary deposits (Holzhauser, 2021), the site contains numerous glaciers, which together form the largest continuous ice surface in the Alps. The biggest of them, the Great Aletsch Glacier, was the longest (20.5 km from Jungfraujoch) and largest (78.5 km^2) glacier in the European Alps in 2017 (GLAMOS, 2022). In December 2001, the Jungfrau-Aletsch region was the first natural site in the Alps to be inscribed on the World Heritage List, for three different reasons (UNESCO, 2001, p. 50):

(1) This site is "of significant scientific interest in the context of glacial history and ongoing processes, particularly related to climate change" (criterion *viii*).
(2) With "a wide range of alpine and sub-alpine habitats [and] superb examples of ecological succession," this site offers a particularly good illustration of the effects of climate change, "as reflected in the varying rates of retreat of the different glaciers, in turn providing new substrates for ongoing ecological succession" (criterion *ix*).
(3) The "impressive landscape […] globally recognised as one of the most spectacular mountain regions to visit […] has played an important role in European literature, art, mountaineering and alpine tourism" (criterion *vii*).

Originally covering an area of 539 km^2, the site was extended by 285 km^2 in 2007 (IUCN, 2007). The perimeter of the UNESCO property excludes the surrounding villages and tourist resorts and the vast majority of tourist and ski infrastructure.

3.2. Methodology

Temporal scale issues in geomorphosites studies may be addressed through the Past-Present-Future (PPF) framework, commonly used in physical geography (e.g., Goudie, 2019; Nesje, Bakke, Dahl, Lie, & Matthews, 2008). In the context of geoheritage interpretation and conservation, Martini (2012) and Martini, Zhang, Gu, and Li (2013) suggested to apply the PPF framework to improve interpretation in geoparks. "PPF concept […] is based on the systematic use, in Geoparks [*sic*], of interpretative supports which could present, on each site open to visitors, three superimposed images of the locality corresponding to its present situation, its origin and genesis and its future evolutions" (Martini et al., 2013, p. 4). Applied to the evaluation of the heritage values of evolving geomorphosites such as glacial landscapes, the PPF framework is particularly useful in drawing attention to the future evolution—a parameter that is usually not considered.

Two glacial landscapes located in the Swiss Alps were selected as case studies and are described below. For each site, we first examined the characteristics of the glacial landscape through the PPF framework (such as what is shown in Table 2). The descriptions were based on the literature and field observations. Simplified geomorphological maps were produced for each site. In a second step, we assessed the present heritage values of each site from a geomorphological point of view, using the criteria proposed by Reynard, Perret, Bussard, Grangier, and Martin (2016) for the assessment of their geoscientific and additional values. The geoscientific value was assessed quantitatively using four classical criteria (Grandgirard, 1997; Mucivuna, Reynard, & Garcia, 2019), rated from 0 to 1: integrity, representativeness, rarity, paleogeographic interest. The palaeogeographical interest referred to the importance of the site for the understanding of the Earth or climate history (Reynard, Fontana, Kozlik, & Scapozza, 2007). Three additional values were evaluated qualitatively: the aesthetic, cultural and ecological values. For the latter, we focused especially on the impact of geomorphological landforms and processes on the richness and rarity of plant species (Bussard & Giaccone, 2021). After evaluating the present heritage values of inherited and active landforms, we examined how future changes in the glacial landscape might affect the heritage values in the future. This was intended to provide arguments for answering the question of the evolution of the heritage values of glacier sites inscribed on the UNESCO World Heritage List. However, we did not propose an assessment of the heritage values as they might have been assessed in the past, and this would require positioning ourselves in the scientific and social context of the chosen period, which was beyond the scope of this study.

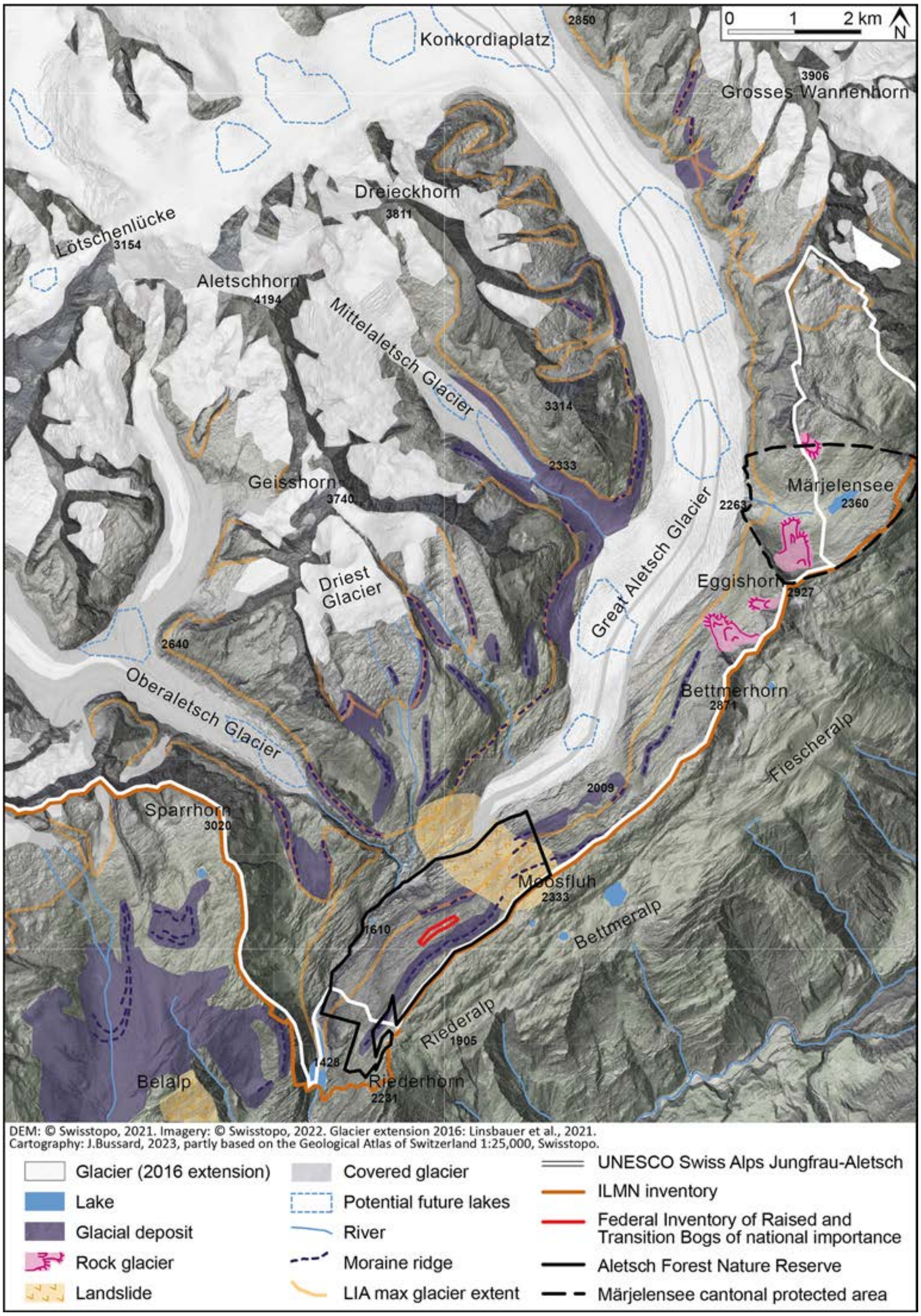
4. Results

4.1. Great Aletsch Glacier: Past-Present-Future analysis

4.1.1. Past

Past extensions of the Great Aletsch Glacier have left many traces in the landscape (Figs. 3 and 4). The presence of numerous *roches moutonnées* and a rounded topography around the Lake Märjelen and on the ridge between Hohbalm (below Bettmerhorn), Moosfluh and Riederfurka is the result of glacier erosion during the Pleistocene. The trimline is visible in many places, separating the sharp rock faces of the nunataks and the smoother shaped areas that were covered with ice during the Last Glacial Maximum (24.0 ± 1.1 ka BP), when the Great Aletsch Glacier and other glaciers of the Rhone Valley reached the Swiss Plateau near Wangen an der Aare (Ivy-Ochs, Hippe, & Schlüchter, 2021; Schlüchter, Akçar, & Ivy-Ochs, 2021). A moraine ridge from the Lateglacial (11.2 ± 1.0 ka BP, Egesen stadium during the Younger Dryas) stretches along the left bank of the glacier, with some interruptions, below the Bettmerhorn, Moosfluh and Riederfurka, between 1,950 m a.s.l. and 2,250 m a.s.l. (Holzhauser, 2021; Ivy-Ochs et al., 2009; Kelly, Kubik, Von Blanckenburg, & Schlüchter, 2004).

The history of the Great Aletsch Glacier during the last 3,500 years has been reconstructed on the basis of different clues (Holzhauser, 2009; Holzhauser, Magny, & Zumbühl, 2005). Fossil larch woods were found in the glacier forefield and dated with radiocarbon or dendrochronological methods, showing a maximum extension of the glacier around 813–600 BCE and three climate optimums in the late Bronze Age (1350–1250 BCE), between Iron Age and Roman Age (200 BCE-50 CE) and in the Middle Ages (800–1300 CE), during which the glacier reached its present extent or even a smaller size than today. Dendrochronological dating allowed the identification of three successive glacial maxima during the LIA: the 1370s, the 1670s and 1859/60 (Holzhauser, 2009; Holzhauser et al., 2005). Glacier advances during the LIA are confirmed by written historical sources, such



DEM: © Swisstopo, 2021. Imagery: © Swisstopo, 2022. Glacier extension 2016: Linsbauer et al., 2021.
Cartography: J.Bussard, 2023, partly based on the Geological Atlas of Switzerland 1:25,000, Swisstopo.

Fig. 3. Geomorphological map of the Great Aletsch Glacier area and location of the protected areas.
Note: LIA: Little Ice Age. ILMN inventory: Federal Inventory of Landscapes and Natural Monuments of national importance (Linsbauer et al., 2021).

as documents reporting the use of pastures accessible only when the Upper Aletsch Glacier was filling the Upper Aletsch Gorge (Holzhauser & Zumbühl, 1999), by old maps, plans or paintings (Zumbühl & Holzhauser, 2007) and by field evidence.

The glacier length has been measured yearly since 1882 and the tongue has retreated about 3.5 km from the end of the LIA to 2021 (GLAMOS, 2022). As a result of this retreat, the Märjelen Lake (see Holzhauser, 2021; Fig. 4B) disappeared. This paraglacial lake, which reached a depth of up to 78.55 m in 1878 (Lütschg, 1915), was famous for its icebergs and blue water, but also generated fear due to its unpredictable and frequent water outburst floods (Albrecht, 1999; Holzhauser, 2021). The LIA maximum extent of the glacier is still clearly visible in the landscape today, with differences in vegetation cover (Fig. 4A): Green pastures

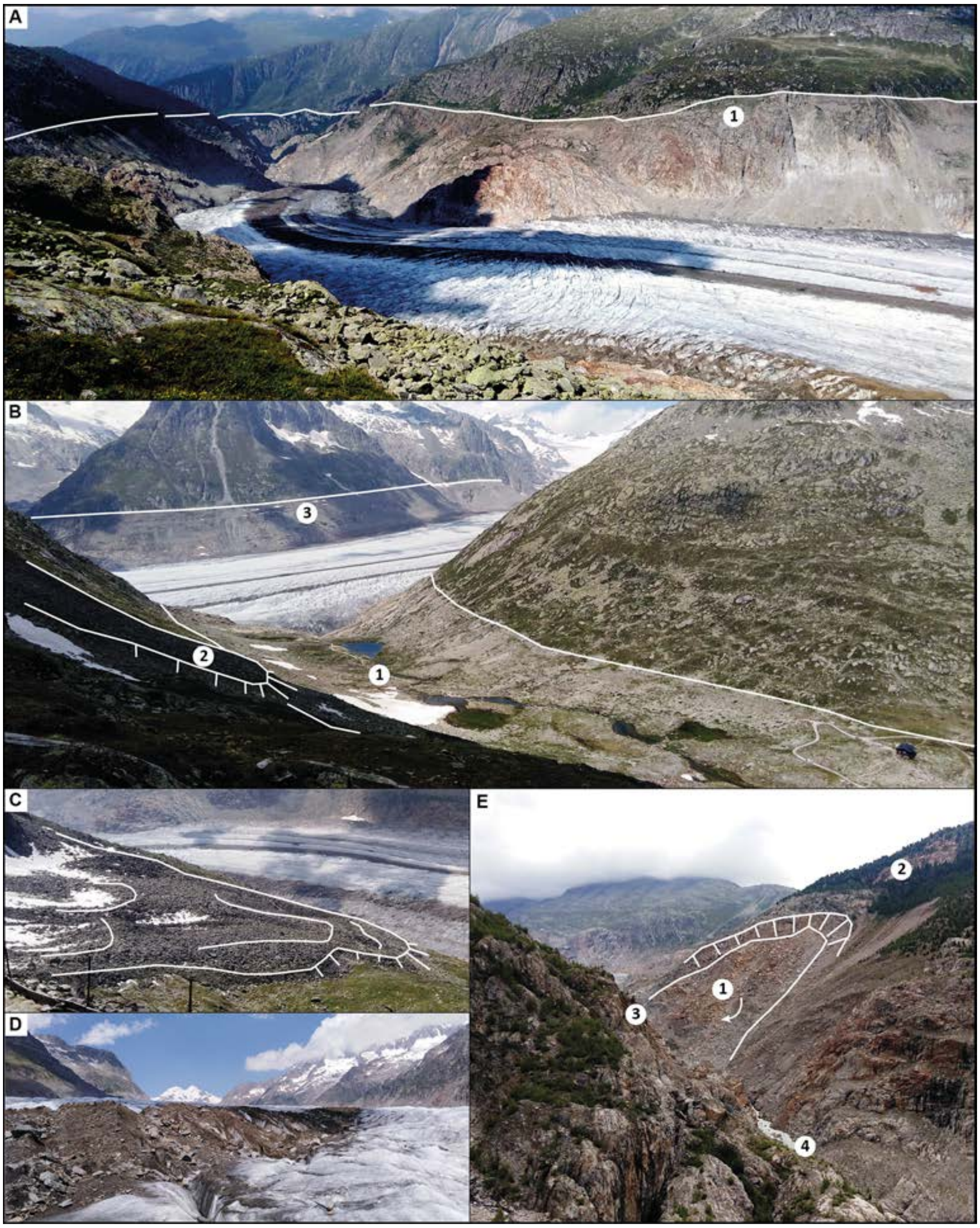


Fig. 4. A. Snout of the Great Aletsch Glacier. The white line indicates its maximum LIA position, highlighted by contrasts of colours and vegetation (1). B. The former Märjelen Lake (1) with its maximum extension. A rock glacier (2) and the LIA limits of the Great Aletsch Glacier (3) are also visible. C. Grosses Gufer Rock Glacier. D. A medial moraine of the Great Aletsch Glacier. E. Moosfluh instability, with zones affected by rotational sliding (1) and by toppling movement (2) after the retreat of the glacier (3). Basal erosion by the Massa River (4) could cause a renewed acceleration of the entire landslide.
Photos: Jonathan Bussard, 2021.

that once were above the maximum ice level of the LIA stand in sharp contrast to the greyish, almost bare land that was covered by the glacier. In addition, parts of LIA lateral moraine ridges are preserved on each side of the glacier tongue. Downstream of the current glacier front, a nature reserve was created in 1933 on the initiative of the nature conservation organisation Pro Natura to protect the Aletsch Forest (Gerber, 2004), where pioneer species such as larch and birch colonize the surface left free by the glacier retreat.

4.1.2. Present

The Great Aletsch Glacier is a typical temperate valley glacier with several large medial moraines (Fig. 4D). The four tributaries of the main glacier tongue are converging in Konkordiaplatz (2,650–2,700 m a.s.l.). At this location, the bedrock topography is heavily overdeepened and the maximum ice thickness has been estimated from seismic investigations to be 890 m

(Thyssen & Ahmad, 1969), and this was confirmed by Hock, Iken, and Wangler (1999), who found a maximum thickness of 905 m in a borehole dug in 1990. With a volume of 15 km^3, the Great Aletsch Glacier alone accounts for about 20% of the total volume of all Swiss glaciers (Farinotti, Huss, Bauder, & Funk, 2009). The dynamics of the largest glacier in the Alps has been the subject of numerous measurements and research activities (Holzhauser, 2009). For instance, mass balance measurements started in the 1910s and represent the longest direct measurements of mass balance worldwide (Huss & Bauder, 2009).

Apart from the glacier itself, various surface processes of para- and periglacial environments are worth mentioning. On the north-eastern slopes of the Eggishorn and Bettmerhorn, several active rock glaciers indicate the presence of discontinuous permafrost at an altitude of between 2,300 m a.s.l. and 2,700 m a.s.l. The largest of them, called Grosses Gufer Rock Glacier (Fig. 4C), was described and its velocity was measured already in the 1960s (Barsch, 1977; Messerli & Zurbuchen, 1968). It is monitored by the Swiss Permafrost Monitoring Network (2016, 2019, 2022). The maximum surface velocity measured in the 1960s was 60–75 cm/year (Messerli & Zurbuchen, 1968), whereas today it is several metres per year in the lower part (Université de Fribourg, 2022). The rock glacier overruns the Lateglacial left moraine of the Aletsch Glacier and its front currently reaches the LIA moraine (Holzhauser, 2021).

As a consequence of glacial debuttressing, at least four landslides have been identified on both sides of the Aletsch Glacier (Kos et al., 2016; Truttmann, Herwegh, Schreurs, Ebert, & Hardmeier, 2021). The largest one affects the valley flank between Moosfluh and the glacier front (Fig. 4E), where pre-existing deformation structures such as shear zones and joints related to tectonic processes favoured a toppling movement (Glueer, Loew, & Manconi, 2020; Truttmann et al., 2021). In autumn 2016, when the glacier reached a critical level (the valley bottom became almost ice-free), this large rock mass movement accelerated dramatically, with surface velocity passing from maximum values of 0.2 cm/day up to 80 cm/day (Manconi, Kourkouli, Caduff, Strozzi, & Loew, 2018), and the lower part of the slope was affected by a rotational sliding (Glueer, Loew, Manconi, & Aaron, 2019). In 2017, the landslide activity decreased significantly, but the erosion of the base of the slope could cause a renewed acceleration of the entire landslide, with a potential catastrophic failure of a large rock volume (Truttmann et al., 2021).

4.1.3. Future

The most important and visible changes in the future glacial landscape are the spectacular retreat of the glaciers as a result of climate warming, the associated landscape greying and the landscape greening induced by the increased vegetation productivity (Rumpf et al., 2022). Detailed models have confirmed with high confidence that the Great Aletsch Glacier (the largest and longest glacier in the European Alps) will lose at least half of its volume and length by 2100 under scenario RCP 2.6 and will almost completely disappear under scenario 8.5 (Jouvet & Huss, 2019; Jouvet, Huss, Funk, & Blatter, 2011). As shown by Haeberli, Schleiss, Linsbauer, Künzler, and Bütler (2012); Haeberli, Bütler, Huggel, and Schleiss (2013); Haeberli et al. (2016) and Linsbauer, Paul, and Haeberli (2012), new lakes will fill the overdeepenings of the glacier bed after the ice melts. These new lakes are an attractive element in the landscape left by the glaciers retreat and provide opportunities for water supply and hydropower production. According to Ehrbar (2018) and Ehrbar et al. (2018), the Great Aletsch Glacier is part of the five best-rated sites in Switzerland for potential future hydropower plants, and Oberaletsch was inscribed in 2021 on a list of 15 promising hydropower projects prepared by a round table of different stakeholders led by the Federal Department of the Environment, Transport, Energy and Communications (DETEC, 2021). Today, to preserve the sites of national importance, the municipalities of Naters and Riederalp receive financial compensation for not using hydroelectric power in Oberaletsch (Art. 22, al. 3 of Federal Law on the Use of Water Power), but this could be questioned. The lifetime of the potential reservoirs is, however, reduced by sedimentation (Perera, Williams, & Smakhtin, 2023), as shown by the example of the existing Gebidem Reservoir, located downstream of the Aletsch Glacier and which could be filled within only 20–30 years (Ehrbar, Schmocker, Vetsch, & Boes, 2018). The development of new lakes will also induce risks related to landslides or rock/ice avalanches into the lake, generating lake outburst floods; the risk is exacerbated by the degradation of permafrost on the surrounding slopes and by glacial debuttressing (Cathala, Magnin, Linsbauer, & Haeberli, 2021; Haeberli et al., 2013, 2017). This shows that the landscape changes induced by global warming do not only impact the aesthetic qualities of glacial landscapes—which are globally reduced due to the disappearance of glaciers and related landscape greying —but also question the possible future uses of these landscapes, with increased slope instabilities in deglaciated areas and potential conflicts between electricity production, tourism and nature protection.

4.2. Great Aletsch Glacier: Heritage values

The Aletsch Glacier landscape has a high geoscientific value (0.88 out of 1) due to its exceptional representation of a valley glacier system and is of remarkable paleogeographic interest (Table 3). In addition to the landforms themselves, the current dynamics of the glacier and the para- and periglacial processes are particularly relevant for the geoscientific value of the site. The aesthetic value is exceptional, with the glacier as the central element of the landscape's attractiveness. The ecological value, characterised by interesting ecological successions in the glacier forefield that became ice-free since the end of the Little Ice Age, is also of high interest. This is in line with UNESCO's evaluation of the site's OUV, which is based on three criteria *vii*, *viii* and *ix* (defined above).

4.2.1. Future heritage values

The geoscientific value could decrease because of the disappearance of the glacier and its dynamics (loss of representativeness) and a possible decrease in integrity, if the space exposed by the glacier retreat was used for the construction of hydropower plants or other infrastructure (Table 4). The palaeogeographical interest would remain very high if the traces of the past were not

Table 3
Evaluation of the heritage values of the Great Aletsch Glacier landscape.

Geoscientific value		0.88
Integrity	The Great Aletsch Glacier landscape is well preserved, apart from the impacts of global warming. The infrastructure of the Aletsch Arena ski area (cable cars, ski lifts, etc.) is located on the south-eastern slope of the Eggishorn–Bettmerhorn–Riederhorn ridge, and therefore has no impact on the glacier and its LIA glacier forefield. The Gebidem Dam is located in the Massa Gorge and is invisible from the glacier viewpoints. A hiking trail follows a Lateglacial moraine, but mainly within the Aletsch Forest Nature Reserve. The only noticeable infrastructure is the small Märjelen Reservoir, which occupies the highest section of the former Märjelen Lake	0.75
Representativeness	Exceptional representation of a valley glacier system, including the glacier itself, some small lateral moraine ridges, many landforms of glacier erosion and numerous para- and periglacial processes which make it very representative	1.00
Rarity	Many glaciers exist in the Alps and particularly in the Swiss Alps, but the dimensions of the Great Aletsch Glacier are unique at the Alpine scale	0.75
Paleogeographic interest	The history of the Aletsch Glacier during the last 3,500 years has been reconstructed with field evidence, dating of fossil trees, and written historical sources. It constitutes a reference site, and therefore has a very high paleogeographic interest	1.00
Additional values		
Aesthetic value	Exceptional diversity of colours, contrasts and landforms, with the presence of the emblematic largest glacier in the Alps. The Aletsch glacier landscape is a tourist attraction since the 19th century (Albrecht, 1999). Its aesthetic value is particularly high	
Cultural value	Two examples illustrate the fearful relationship that local people had with the glaciers: (1) The lake outburst floods caused by the sudden emptying of Lake Märjelen have given rise to the legend of the "Rollibock," a feared supernatural being living in the Great Aletsch Glacier whose anger could trigger these floods (Albrecht, 1999). (2) During the LIA, the advance of the Aletsch and Oberaletsch glaciers threatened the Aletschji alpine pasture. To ward off the ice, processions were held since 1653 and two wooden crosses were erected in 1818 (Holzhauser, 2009). These crosses were not destroyed by the glaciers and still exist today. The Villa Cassel, located in Riederfurka, is a historic Victorian building (1902), which was the summer residence of the English banker Ernest Cassel. It is listed in the Swiss Inventory of Cultural Property of national and regional importance (PCP Inventory). It is a remarkable example of Belle Epoque summer tourism and is now an interpretation centre belonging to the environmental association Pro Natura, which manages the Aletsch Forest Nature Reserve	
Ecological value	A remarkable ecological succession exists in the Aletsch Forest: The upper part reaches the tree line while the lower part is colonising areas that were covered by the glacier until the end of the LIA. The glacier retreat offers new habitats for pioneer species	

destroyed. A good protection of the site would ensure the preservation of a geoscientific value of 0.81 (out of 1). As a consequence of the glacier retreat, the aesthetic value could decrease, but this decrease would be partly compensated by the emergence of new natural lakes (Fig. 3). The ecological value could increase significantly, with the colonisation of deglaciated lands by pioneer species and the increased vegetation productivity. In general, the site would retain exceptional heritage values, unless the integrity of the site is diminished by the construction of hydropower plants or other infrastructure such as photovoltaic and wind power plants, cable cars or ski slopes, which would also have an impact on the aesthetic and ecological values.

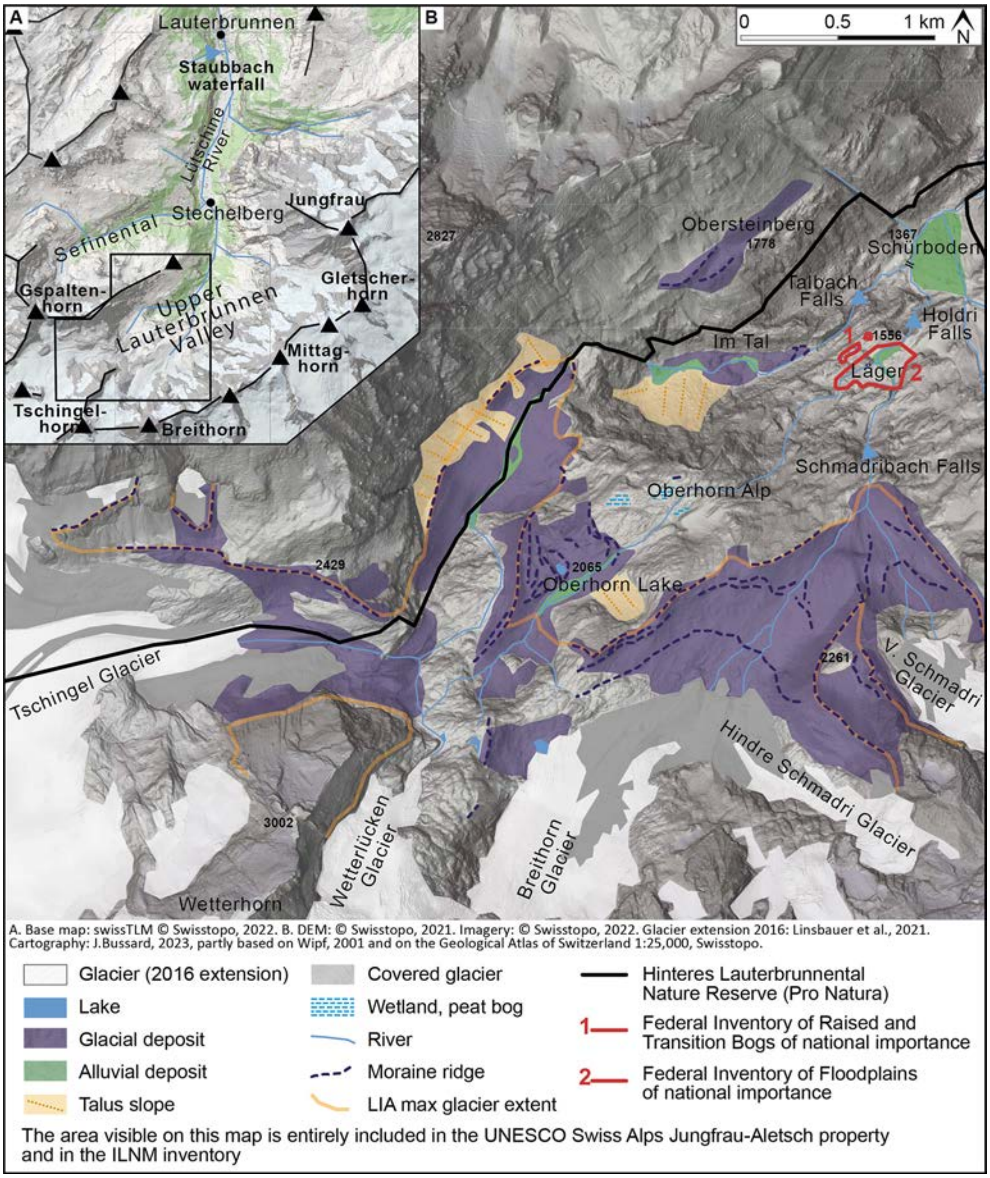
4.3. Upper Lauterbrunnen Valley: Past-Present-Future analysis

4.3.1. Past

The Lauterbrunnen Valley (Fig. 5A) can be divided into three parts, each of which is interesting in terms of geomorphological heritage. The downstream section, between the villages of Stechelberg and Lauterbrunnen, is a very spectacular example of a U-shaped valley, with a flat bottom surrounded on either side by walls of massive Upper Jurassic limestone, from which numerous waterfalls flow (Reynard, 2005b). This Pleistocene glacial landscape, and particularly the Staubbach Waterfall, was a major site for

Table 4
Heritage values of the Great Aletsch Glacier landscape in a post-glacial future.

Geoscientific value		0.5–0.81
Integrity	Climate change will continue to significantly modify the landscape, but as these changes are natural phenomena, the integrity will not change (in this case: 0.75). The possible construction of new infrastructure in the proglacial margin (especially hydropower plants, but it could also be other energy production installations, cable cars and others) could affect the integrity (in this case: 0.25)	0.25–0.75
Representativeness	The post-glacial morphology could remain very representative of an alpine valley, with new lakes, glacial deposits, and para- and periglacial processes. However, the representativeness of the glacier itself and its dynamics would be lost	0.75
Rarity	Post-glacial evolution of a valley of this size (>20 km long) could be rare at the Alpine scale and could show rare interactions between postglacial slope movement processes, permafrost degradation and emergence of new lakes	0.75
Paleogeographic interest	The site would retain the high palaeogeographical interest due to the abundance of the traces of the past that it contains, unless the latter were destroyed by anthropic activity (in this case: 0.25)	0.25–1.00
Additional values		
Aesthetic value	The aesthetic value could decrease as a result of the disappearance of the glacier (landscape greying). However, the presence of new lakes in a grandiose mountain landscape would keep the aesthetic value relatively high	
Cultural value	Showing melting glaciers or post-glacial landscapes could have an artistic and symbolic importance	
Ecological value	With the rise in altitude of the forest limit, the increased vegetation productivity and the colonisation of deglaciated lands by pioneer species, the ecological value could increase. Water availability at the end of the summer could be a constraint	



A. Base map: swissTLM © Swisstopo, 2022. B. DEM: © Swisstopo, 2021. Imagery: © Swisstopo, 2022. Glacier extension 2016: Linsbauer et al., 2021. Cartography: J.Bussard, 2023, partly based on Wipf, 2001 and on the Geological Atlas of Switzerland 1:25,000, Swisstopo.

The area visible on this map is entirely included in the UNESCO Swiss Alps Jungfrau-Aletsch property and in the ILNM inventory

Fig. 5. A. Sketch map of the Lauterbrunnen Valley. The dark polygon indicates the location of the geomorphological map. B. Geomorphological map of the Upper Lauterbrunnen Valley and location of the protected areas (Linsbauer et al., 2021).
Note: LIA: Little Ice Age. ILMN inventory: Federal Inventory of Landscapes and Natural Monuments of national importance.

early tourism in the Alps in the Romantic period (Reichler, 2002) and a source of inspiration for several renown writers and artists (e.g., Goethe, Tolkien, Wolf, etc.). However, this part of the valley is located outside of the active glacial landscape. Above Stechelberg, the valley splits in two. To the west, the Sefinental is a narrow, hanging valley (which we will not describe here). South of Stechelberg, the Upper Lauterbrunnen Valley (Fig. 5B) opens into a cirque whose rim is formed by peaks over 3,500 m in altitude (Fig. 5A). These peaks, from east to west, include the Jungfrau (4,158 m), Gletscherhorn (3,982 m), Mittaghorn (3,896 m), Breithorn (3,780 m) and Tschingelhorn (3,557 m). On this north-facing slope are numerous small cirque glaciers. The two largest are the Breithorn and Tschingel glaciers, which have formed numerous moraine ridges of great scientific interest. This remarkable glacial heritage is described in more detail here.

The glacial history of the Upper Lauterbrunnen Valley has been studied in detail by Wipf (2001) using a combination of dating methods. The oldest moraine ridges in the area date from the Lateglacial and are found near Obersteinberg and Im Tal (Fig. 5B). During the Holocene, the advances of the Tschingel Glacier created a very interesting imbrication of moraine ridges around the Oberhorn Lake (Fig. 6A and 5C), which allow a detailed reconstruction of the glacial fluctuations. Close to Oberhornalp (2,030 m a.s.l.), not far from the outermost Holocene moraine ridge, small peat bogs surrounded by *roches moutonnées* have been dated by radiocarbon analysis to about 10,390 years BP (Wipf, 2001), indicating that moraines in the plain of Lake Oberhorn

Fig. 6. A. Oberhorn Lake Holocene moraine complex (1) and LIA moraine (2) of the Tschingel Glacier. Jungfrau is in the background. B. Schmadribach Waterfall (1) and a floodplain of national importance near Läger (2). C. Lake Oberhorn (1) and a moraine dating from about 3,330 years BP (2). Wetterlücken Glacier is in the background (3). D. LIA moraine (1) and proglacial margin (2) of the Tschingel Glacier.
Photos: Jonathan Bussard, 2021.

are all of Holocene age. The maximum Holocene extensions of the Tschingel Glacier, which formed the outermost moraine ridges, date from around 4,475 years BP and around 3,340 years BP. Several other phases of considerable advance were registered around the Oberhorn Lake until the last one at the end of LIA, in 1850 (Wipf, 2001). The LIA moraines of the Tschingel, Breithorn and Schmadri glaciers are well marked (Fig. 6D). The landscape evolution of the area during the Holocene has also been documented by pedological analysis (see Egli, Fitze, & Mirabella, 2001; Egli & Mirabella, 2001).

This glacial landscape was depicted by painters in the 18th and 19th centuries, who were mainly interested in the Schmadribach Waterfall (Fig. 6B) with Breithorn and Schmadri glaciers in the background. For example, oil paintings by Caspar Wolf from around 1774 show the front of the coalescing Breithorn and Schmardi glaciers reaching the top of the Schmadribach Waterfall (Wipf, 2001; Zumbühl et al., 2021). When Johann Wolfgang Goethe visited the Upper Lauterbrunnen Valley in 1779, he described the Schmadribach Waterfall as flowing directly from the glacier. The glaciers close to their LIA maximum extension were captured in Samuel Birmann's watercolours in the 1820s (Wipf, 2001; Zumbühl et al., 2021).

The change in length of the Tschingel Glacier has been measured occasionally since 1893 and annually since 1962 (GLAMOS, 2022). These measurements show a significant glacier retreat (-359 m between 1893 and 2021 for the Tschingel Glacier), interrupted by minor advances or stagnations in 1920/30 and 1970/80. Small moraine deposits, particularly visible in the Breithorn proglacial margin, are evidence of these small advances. Rapid glacier retreat of Wetterlücken Glacier is monitored photographically since 2010 (Zumbühl et al., 2021).

4.3.2. Present

The retreat of the glaciers in the Upper Lauterbrunnen Valley has been continuous since the 1990s and experienced periods of acceleration. For example, the length of the Tschingel Glacier decreased by 91 m in just 4 years between 2009 and 2013 (GLAMOS, 2022). Most glacier tongues are covered with sediment at their terminus. When the ice melts, these sediments are deposited in large proglacial margins, where sometimes small lakes are formed, such as at the front of the Breithorn and Tschingel glaciers. The amount of water and sediments made available by the retreating glaciers favours strong alluvial dynamics, exacerbated by the position of the valley on the northern slope of the Bernese Alps, the region with the highest rainfall in Switzerland (>2000 mm/year). The alluvial dynamics are reflected by the presence of braided rivers (e.g., the Läger alluvial zone of national importance or the Im Tal area), strong sediment transfer and triggering of debris flows, especially in the gully formed by the Inner Schwandbach, whose deposits form the alluvial fan close to the Schürboden Alp. In winter, the same gully is favourable for avalanches, which can destroy the bridge over the Lütschine at Schürboden. Important runoff feeds impressive waterfalls, in particular the Schmardibach, the Hödri and the Talbach waterfalls, which are attractions for hikers.

4.3.3. Future

As elsewhere in the Alps, climate warming and glacier retreat are leading landscape greening: The upper limit of the forest is rising, vegetation productivity is intensifying and the areas freed from ice are being colonized by pioneer species. The new proglacial lakes appearing in glacial overdeepenings after the ice melts, which are small in this area, will quickly be filled with sediment. If the glaciers disappear, the hydrological regime of the Lütschine River will change from glacial regime, with high water in July and August, to nival regime, with high water during the snowmelt season in May and June. Extensive permafrost is very likely to cover most of the northern slopes of the Mittaghorn-Breithorn-Tschingelhorn above about 2,600 m. In the coming decades, degradation of permafrost and freeze-thaw processes will increase slope instability in the higher parts of the valley, thus possibly leading to the triggering of rock mass movements, rockfalls and landslides.

Almost the entire Upper Lauterbrunnen Valley is a nature reserve, created in 1947 by the Swiss League for the Protection of Nature (Pro Natura) and extended in 1954. At that time, a hotel and a tourist centre were proposed near the Oberhorn Lake, with a ski lift or cable car; there were also projects for a dam and a tunnel to divert the water of the Lütschine Basin into the adjacent valley (Bopp, 1956). In 1960, the government of the Canton of Berne decided to protect the whole Upper Lauterbrunnen Valley as a cantonal nature reserve. This ensures a long-term protection of the area, and the construction of new infrastructure is unlikely in the next decades.

4.4. Upper Lauterbrunnen Valley: Heritage values

The particularly high geoscientific value of this glacial landscape (0.94 out of 1, Table 5) is highlighted by the very high paleogeographic interest of the Holocene moraine complex around the Oberhorn Lake. The integrity of this site, which has been a nature reserve for 75 years, and its representativeness of glacial geomorphology also contribute to the high geoscientific value. Several additional values are worth mentioning: high but not exceptional aesthetic value, the importance of artistic production in the 18th and 19th centuries and high ecological value. As for the Aletsch Glacier landscape, the heritage values described here are in line with UNESCO's evaluation of the site's OUV.

4.4.1. Future heritage values

The heritage values of the Upper Lauterbrunnen Valley would be affected more by poor management of the nature reserve than by the disappearance of the glaciers (Table 6). Indeed, the geoscientific value is high due to the existence of rare and valuable, but fragile, inherited landforms located around the Lake Oberhorn. These peat bogs and Holocene moraines could be threatened by human activities, but are not affected by glacier retreat. The role of the nature reserve in maintaining a high geoscientific value is therefore central. Concerning additional values, only the aesthetic value could be slightly reduced, as the glaciers provide a colour contrast. The cultural value will not be affected by the ice melting and some pioneer species could benefit from the glacier retreat, leading to an increase in ecological value.

5. Discussion

The analysis of the evolution of the heritage values of glacial landscapes illustrates an important point: As glaciers retreat, their geoscientific value will depend more and more on the inherited glacial landforms, and less and less on the glacier itself and its dynamics. This is particularly true for the Great Aletsch Glacier, whose significance as an outstanding example of a valley glacier will be diminished by the disappearance of the ice, even if this process can be recognized among the "ongoing glaciological/geomorphological and ecological processes (criteria *viii* and *ix*) of which the property provides an outstanding example" (IUCN, 2007). The Upper Lauterbrunnen Valley would be less affected, as glaciers are of secondary importance in terms of geoscientific

Table 5
Evaluation of the heritage values of the Upper Lauterbrunnen Valley.

Geoscientific value		0.94
Integrity	Protected since 1947 as a nature reserve, this site is very well preserved, apart from the impacts of global warming. The moraine complex around Oberhorn Lake is intact	1.00
Representativeness	This site is very representative of glacial geomorphology, with interesting morainic constructions at the front of the Tschingel and Breithorn glaciers, and of the braided morphology of the mountain torrents, with strong dynamics and large quantities of sediments transported by the river	1.00
Rarity	Many alpine valleys have similar geomorphology in their upper parts, but the well-preserved imbrication of Holocene moraines around Oberhorn Lake is rare	0.75
Paleogeographic interest	The Holocene history of the Tschingel Glacier is quite well known, thanks to the presence of several moraine ridges and peat bogs that have been dated. This site has therefore a high paleogeographic interest	1.00
Additional values		
Aesthetic value	The glacial landscape of the Upper Lauterbrunnen Valley is one of contrasts, with steep rock faces, cirque glaciers, proglacial margins with gentle slopes, forested areas, waterfalls and alpine meadows. The landscape is dominated by greens and greys as there is no significant lake and the glaciers are distant, on the upper slopes. The aesthetic value is high, but not exceptional compared to other landscapes in the UNESCO Swiss Alps Jungfrau-Aletsch property	
Cultural value	As other places in the Bernese Oberland, the Upper Lauterbrunnen Valley was visited by many renown artists since the 18th century (the painters Caspar Wolf, Joseph Anton Koch, Gabriel Ludwig and Matthias Gabriel Lory, Samuel Birmann, Ludwig Richter and Alexandre Calame [Wipf, 2001]; the writer Johann Wolfgang Goethe)	
Ecological value	The main rocks in the Upper Lauterbrunnen Valley are migmatites from the Aare crystalline massif, but sedimentary rocks (mainly limestone) from the Helvetic Nappes are present in the north and west of the valley, especially around the upper part of the Tschingel Glacier. The moraines of the glacier are therefore mainly composed of basic rocks (limestone) deposited on an acid basement of polished migmatites. This creates a variety of habitats (basic/acidic, dry/wet), which favours the diversity of plant species. In addition, the areas left free by glacier retreat and the alluvial floodplains are suitable for the presence of pioneer species	

value. However, the paleogeographic interest of these sites, which is particularly high and represents a central element of the current heritage value, could be maintained as long as the inherited glacial landforms are well protected. The preservation of the integrity of the most important moraine ridges and other evidence (peat bogs, fossil organic matter, lacustrine deposits, etc.) for the reconstruction of glacial evolution depends very much on the protection measures and their effectiveness. Inherited glacial landforms are indeed non-renewable and could be damaged or destroyed by the construction of energy production installations, tourist infrastructure or over-intensive use.

Overall, the preservation of the geoscientific value of the two studied glacial landscapes depends more on protection measures than on the effects of climate change. In this sense, the case of the Upper Lauterbrunnen Valley is less worrying, as it is almost entirely within a nature reserve. Although the geomorphological features are not explicitly mentioned in the official decision to create the nature reserve (State Council of the Canton of Berne, 21 July 1960), the uses are strongly restricted and only limited damage could occur in the case of poor management of the protected area. In contrast, the vast majority of the Great Aletsch Glacier landscape is protected only by its inclusion in the Federal Inventory of Landscapes and Natural Monuments of national importance (ILNM inventory; Art. 5 Federal Act on the Protection of Nature and Cultural Heritage [NCHA]), with the exception of areas protected by cantonal decree (the Aletsch Forest Nature Reserve and the Märjelen area) and a small area (4.7 ha) of raised bogs of national importance, which is strictly protected (Art. 78, al. 5 of the Swiss Federal Constitution). The ILNM inventory aims to preserve the richness of the Swiss landscapes in the long term and takes into account the presence of remarkable

Table 6
Heritage values of the Upper Lauterbrunnen Valley in a post-glacier future.

Geoscientific value		0.75–0.94
Integrity	As the protection status of the site is very high (nature reserve), it should remain intact. However, some valuable inherited landforms are fragile (peat bogs, moraine ridges) and could be damaged if the nature reserve is not well managed (in this case: 0.75)	0.75–1.00
Representativeness	The glacial heritage and torrential dynamics will persist in a post-glacial future, even if the hydrological regime becomes nival instead of glacial. As the representativeness of this site is not directly linked to the glaciers themselves, it will not be affected by their disappearance	1.00
Rarity	As the rarity of this site does not depend on the presence of glaciers, but depend on a distinctive Holocene glacial geomorphology, it will not be affected by their disappearance. However, damage to the fragile inherited landforms could reduce the rarity of the site (in this case: 0.5)	0.5–0.75
Paleogeographic interest	The paleogeographic interest will remain very high or could even increase if new glacial stages are recorded by new moraine ridges or by fluvial or lacustrine deposits. But it could also decrease if some fragile inherited landforms are damaged (in this case: 0.75)	0.75–1.00
Additional values		
Aesthetic value	The presence of glaciers is not central to the present aesthetic value of the site. Their disappearance would therefore have little effect on the colour contrasts, and most of the aesthetic characteristics of the landscape should remain	
Cultural value	The cultural value will not be affected by the glacier retreat	
Ecological value	The ecological value could increase, with more space available for pioneer species in the areas left free by the glaciers	

geomorphological landforms (Federal Office for the Environment, 2022). In the Great Aletsch Glacier area, the objectives of the inventory are among others to preserve the richness of geomorphological landforms and geological formations and to maintain the dynamics of the landscape-forming processes, in particular the natural dynamics and geomorphology of the floodplains, alluvial plains and glacier forelands, as well as the habitats shaped by them. However, the protection status of ILMN sites is not very strong, as serious alterations to the sites may be permitted if they are justified by an interest of national importance that overrides the interest in protecting the site (Art. 6, al. 2 on the NCHA). In particular, installations for the use of renewable energies, especially accumulation power plants of a certain size and importance, are of national interest (Art. 12 of Energy Act), and recent debates in the Swiss parliament could lead to a reduction in nature and landscape protection in order to ease electricity production from renewable energies (Jerjen, 2022). If the construction of new tourist infrastructure in the ILMN perimeter is unlikely, that of electricity production is not excluded and could significantly alter the heritage values of the site. The construction of dams in preserved natural areas led to numerous historical environmental controversies (e.g., in the glacier-carved Hetch Hetchy Valley, United States, where a dam was built after several years of intense debate; Righter, 2005). Despite the difficulties in finding compromises between nature conservation and hydropower production, dam construction has entered a new period of growth on a global scale since the end of the 2000s (Zarfl, Lumsdon, Berlekamp, Tydecks, & Tockner, 2015), with the idea that hydropower production is sustainable because it does not emit greenhouse gases (Flaminio, Piégay, & Le Lay, 2021). In this context, it is not certain that protecting geoheritage will become a priority.

The effects of climate change may reduce the aesthetic value of glacial landscapes, as the loss of ice volume, the debris cover of glacier tongues and their greyish appearance are often perceived negatively (Salim, Ravanel, & Gauchon, 2021). In the case of Aletsch, the glacier is a central element of the landscape and its disappearance could compromise its inscription on the World Heritage List under the criterion *vii* (exceptional natural beauty). However, in a post-glacial future, the reduced attractiveness of the landscape resulting from ice loss could be mitigated by the appearance of new natural lakes, which are potentially attractive elements, and by the presence of spectacular inherited glacial geomorphology. Examples of World Heritage properties without active glaciers (or very small ones), where the presence of large formerly glaciated valleys with many glacial landforms and deposits is central and most valued, are Yosemite National Park (United States), the West Norwegian Fjords (Norway) and the Pyrénées-Mont Perdu (France and Spain). Apart from the issue of heritage recognition, the disappearance of glaciers is likely to be a problem for the value of glacial landscapes as a tourist resource (Salim, Ravanel, Bourdeau, & Deline, 2021). One possible adaptation could be a shift from glacier tourism, which is mainly oriented towards the contemplation of an aesthetic landscape, to geotourism, where the understanding of landscape evolution is proposed to the public (Bussard, Salim, & Welling, 2021; Salim, 2023). Indeed, glacial retreat and related peri- and paraglacial processes provide remarkable, very visible examples of the impacts of ongoing climate change on mountain environments. The development of geo-interpretation products that allow visitors to understand the scientific interest of glacial landscapes and their evolution is therefore fundamental to renewing their tourist value (Nesur, Salim, Girault, & Ravanel, 2022), but only half of the 33 existing offers in the Swiss Alps Jungfrau-Aletsch property succeed in demonstrating the geoscientific interest of the sites presented (Bussard & Reynard, 2022b).

Finally, the retreat of glaciers could be positive for biodiversity, as pioneer species can benefit from the space freed up by the ice to develop (Burga et al., 2010; Erschbamer, Niederfriniger Schlag, & Winkler, 2008; Fickert & Grüninger, 2018; Garavaglia, Pelfini, & Bollati, 2010). The ecological value of glacial landscapes should therefore be maintained and could even increase in some cases. The inscription of the Swiss Alps Jungfrau-Aletsch on the World Heritage List under the criterion *ix* should not be questioned.

In general, the use of the Past-Present-Future framework—a model originally intended for interpretation—is useful for describing evolving geomorphological landscapes at three time steps. However, it does not reflect the rate of change between two time steps and does not indicate whether the changes are linear or not. It is reasonable to assume that most changes in glacial landscapes are not linear in time: They depend on the rate of change of external factors (climate and human activities), which is not linear, especially at the local level, and on the response of the physical system to these impulses, which may vary in space and time depending on the sensitivity of the landscape to change (Brunsden & Thornes, 1979; Thomas & Allison, 1993). For example, glacier retreat, slope instabilities or periglacial processes have periods of acceleration and periods of stagnation; at fine scales, landforms and processes are not necessarily evolving at the same time depending on their location, orientation or other local conditions; potential new uses of glacial landscapes may occur suddenly (e.g., in the case of the construction of industrial or tourist facilities); high magnitude-low frequency events can cause punctual but very significant disturbances, etc. It would therefore be interesting to refine the methodology so that the description of changes better reflects a dynamic evolution over time.

6. Conclusion

The significant changes affecting active glacial landscapes inscribed on the UNESCO World Heritage List could compromise some of their heritage values. This is particularly the case for the aesthetic value, which could be diminished by the landscape greying due to glacial retreat, and for the geoscientific value, which could be reduced (probably non-linearly over time) by the disappearance of the glaciers and their dynamics. In this article, we have described the evolution of two glacial landscapes located in the UNESCO Swiss Alps Jungfrau-Aletsch property following a Past-Present-Future framework. This analysis showed the richness of the inherited glacial landforms and the variety of active geomorphological processes in the two study sites. In addition to glacier retreat and the associated landscape greying, the future landscape could be characterized by the appearance of new lakes in glacial overdeepenings, increased slope instabilities due to glacial debuttressing and permafrost degradation, landscape greening due to increased vegetation productivity, changes in hydrological regimes and possible construction of new infrastructure in ice-free areas, such as hydro, wind or solar power plants or new tourism infrastructure.

Based on these descriptions, we have estimated how the heritage values of the two glacial landscapes studied might evolve in a post-glacial future. It is likely that the retreat or disappearance of the glaciers will only partly reduce the high geoscientific value of the two sites, which are characterized by a very high palaeogeographical interest (the inherited glacial landforms around the Great Aletsch Glacier and Lake Oberhorn have allowed the reconstruction of Holocene glacial stages). We have also shown that the inherited landforms of high palaeogeographical interest and the para- and periglacial processes that develop in post-glacier conditions are likely to gain interest, while the dynamics of the glacier itself, which is an important part of the current geoscientific value, will decline and even be lost when the glacier disappears. As the inherited landforms can be fragile, are non-renewable and will become more central to the heritage value, their protection is an issue. The proglacial margins are attractive for new uses, such as power generation and tourism, which could threaten the integrity of the geomorphological landforms. In the case of the Swiss Alps, the protection status of the sites inscribed in the Federal Inventory of Landscapes and Natural Monuments of national importance may not be sufficient to ensure that the high geoscientific value of the glacial landscapes is maintained.

The rapid evolution of glacial landscapes opens the discussion on the protection of evolving geoheritage sites. The use of the Past-Present-Future framework for the description of glacial landscapes and the evaluation of their heritage values through time is useful to obtain a precise view of the actual temporal scale imbrication that characterizes a site. In addition, this analytical framework allows for a better understanding of how the heritage values (and in particular the OUV of World Heritage sites) might change in the future. Anticipating these changes could help to adapt the management of glacial landscapes, and in particular the objectives and location of protected areas, which are often not designed to evolve with changes in the landscape and do not always provide sufficient protection for the most valuable inherited geomorphological landforms.

We believe that there is potential for further research on the evolution of the geoheritage values over time and on the combination of landforms and processes in their spatial and temporal dimensions. It would be interesting to continue the discussion started on glacial landscapes for other types of evolving geoheritage sites, such as coastal, fluvial or periglacial environments. We suggest that in certain cases, the changes themselves and their timing may be of heritage interest. Discussions are therefore needed on how to assess the heritage values of ongoing processes.

Credit author statement

Jonathan Bussard: Conceptualisation, Methodology, Fieldwork, Data curation, Writing. **Emmanuel Reynard:** Supervision, Writing, Reviewing.

Ethical statement

The authors confirm that no ethical issues are linked to this manuscript and the underlying study.

Declaration of Competing Interest

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

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