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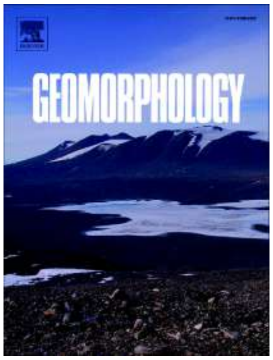

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GEODIVERSITY OF PROGLACIAL AREAS AND IMPLICATIONS FOR GEOSYSTEM SERVICES: A REVIEW

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ABSTRACT – Proglacial areas represent the counterpart of glacial retreat, where a new environmental equilibrium will be reached. During this long and complex stage, which represents the response to ongoing climate change, several abiotic and biotic processes occur in these freshly exposed fragile environments. Proglacial areas, considered as open-air laboratories, have been attracting the attention of scientists recent last decades, and the diversity of their features allows us to classify them based on different aspects (i.e., lithological and structural geodiversity, geomorphodiversity, hydrogeodiversity, pedodiversity) of geodiversity. In this paper, we review the diversity of features of proglacial areas using several examples mainly from the European Alps. The geosystem services (i.e., regulating, supporting, provisioning and cultural) provided by these areas to society are also discussed, revealing the value of these regions as part of geoheritage. As these fragile and vulnerable areas are highly relevant to society, it is important to monitor them, and to set up adequate management strategies, including geoconservation, but also sustainable promotion.

Keywords: proglacial areas, geodiversity, geosystem services, geoheritage

1. Introduction

Climate change is playing an important role in modifications underway in mountain environments, which are now universally recognized as open-air laboratories to study the effects of climate on the relief (Stoffel and Huggel, 2012; Haeberli, 2013; Fort, 2015), on water resources (Beniston and Stoffel, 2014; Welling et al., 2015; IPCC, 2019; Haeberli and Weingartner, 2020), specifically on the cryosphere (Haeberli, 2013; Beniston et al., 2018; Bosson et al., 2019). In the cryosphere, the impact of ongoing climate change is visible in terms of continuous glaciers shrinkage. At the same time, glacier retreat is accompanied by the expansion of areas, known as proglacial areas (*sensu* Schiefer and Gilbert, 2007) or glacier forelands (*sensu* Kinzl, 1932), currently undergoing major adaptation to new conditions. For instance, in the European Alps, one of the regions where this topic studied, glaciers are retreating and proglacial areas are expanding at different local rates (e.g., D'Agata et al., 2020). In general, these changes have been continuous since the end of the Little Ice Age (LIA; 14th century AD - 1850-1860 AD; Ivy-Ochs et al., 2009), except for temporary inversion phases like during the 1920s and the period 1960s-1980s.

Proglacial areas are characterised by the diversification of processes both in space and over time (Gordon, 2018; Chiarle et al., 2021), and become zones suitable for the progressive onset of "non-glacial processes that are directly conditioned by glaciation" (i.e., *paraglacial processes*; Church and Ryder, 1972; Benn and Evans, 1998; Ballantyne, 2002; Mercier, 2008; Zwolińsky et al., 2016). New landforms come to light, and continuously evolve undergoing dismantling due mainly to gravity or water-related paraglacial processes, since not in equilibrium with new environmental conditions. Hence, this assemblage of different landforms is undergoing constant change (Diolaiuti and Smiraglia, 2010; Garavaglia et al., 2010a; Pelfini and Bollati, 2014; Mancini and Lane, 2020; Oliva et al., 2020; Prokop et al., 2021).

This multifaceted variety of landforms and of superficial processes may match the concept of *geodiversity sensu latu* (Dixon, 1996; Gray, 2004) which considers geological (rocks, minerals, fossils), geomorphological (landforms, processes), hydrological (streams, glacier-related river regimes) and soil (post-glacial development) features, and their reciprocal dynamic interactions. Geodiversity in mountain regions in general, is attracting the attention of researchers due to the range of different factors present: variability of elevation, relief, exposure, variety of lithology and structures occurring in narrow spaces, inducing diversification of the local response according to these specific conditions (Gordon, 2018; Carrivick and Tweed, 2021), and making disentangling changes in mountain environments even more challenging (Barsch and Caine, 1984; Brocx and Semeniuk, 2007; Benito-Calvo et al., 2009; Zwoliński, 2009). Barsch and Caine (1984) underlined how in tectonically active mountain regions, the metastable state induces permanent changes in its features, with high sediment yields (Carrivick and Tweed, 2021), and increased fragility and vulnerability towards, respectively, internal and external disturbance (*sensu* Garcìa-Ortiz et al., 2014). The systemic approach to geodiversity proposed by Gray (2004), which accounts for the reciprocal relations between the elements, is particularly effective in proglacial areas, where the interrelations between geomorphic elements and processes are significant. Moreover, according to Zwoliński (2009), the dynamic character of geodiversity over time should be taken into account by analysing its variation.

To go into even more in detail, which is the objective of this review, in proglacial areas, it is possible to detect specific types of geodiversity, for instance, if we consider the bedrock variety (i.e., *geodiversity s.s.*), or the "geodiversity with respect to geomorphology", termed *geomorphodiversity* (i.e., Panizza, 2009; Melelli et al., 2017). Geomorphodiversity is a concept related to space and time, characterised by geomorphological changes from global to regional, to local scale, and bearing the legacy of inherited landforms (Gordon, 2018). This variability is also triggered by microclimate conditions, which are extremely variable in such settings (Golzio et al., 2018), and may influence the space-time trend of climate-related processes. The geomorphodiversity of proglacial areas (e.g., from high latitude to high altitude morphoclimatic contexts; Carrivick and Tweed, 2021) and the changes it undergoes over time, require, for example, constant updating of geomorphological maps, to show the appearance of new forms and the disappearance of others (Ballantyne, 2003). In the same way, one may specifically consider the variety of hydrological elements featuring proglacial areas (i.e., *hydrogeodiversity*; Perotti et al., 2019), or the diversity of soil developing on these new surfaces (i.e., *pedodiversity*; Ibáñez et al., 1995), followed by the colonisation and diversification of species (i.e., *biodiversity*). Indeed, both positive and negative implications for the entire ecosystem (e.g., Viles, 2012; Miller and Lane, 2019; Eichel, 2019; Giaccone et al., 2019), and for the related biotic resources, can also be investigated. Glacier forelands have been considered a special environment within high mountains, where the dynamics of vegetation primary succession following ice retreat can be studied in depth (Erschbamer and Retter, 2004; Pech et al., 2007), to determine variation in biodiversity trends among others (e.g., Swingland, 2001; Pech et al., 2007; Bussard and Giaccone, 2021). Based on all these considerations, the ideal approach to understand changes underway in proglacial areas is at the level of the ecosystem, by investigating abiotic and biotic features, and their interactions (Fox et al., 2020).

During the first years of the 21st century, the concept of ecosystem services, i.e. the values and benefits provided by ecosystems to human beings, was introduced in the frame of the Millennium Ecosystem Assessment (MEA, 2005; Fisher et al., 2009; and later Nature’s contribution to people, Díaz et al., 2018). In this context, ecosystem services were categorised as regulating, supporting, provisioning, and cultural services, and were later specifically applied to abiotic resources (i.e., *geosystem services*; Gray, 2011; Gray et al., 2013).

Since proglacial areas are considered open-air laboratories to investigate geomorphic processes related to deglaciation (Diolaiuti and Smiraglia, 2010; Garavaglia et al., 2010a; Bollati et al., 2018), in some cases they have been proposed as components of geoheritage (*sensu* Brilha, 2016), i.e., geological and geomorphological elements assigned with appropriate scientific, but also aesthetic, cultural and socio-economic values. Indeed, despite the geosystem services they provide to society, they have a proper meaning and a proper intrinsic value (Gray et al., 2013; Gordon, 2018; Fox et al., 2020).

Given these diverse aspects, this review focusses on the geodiversity that characterises proglacial areas, and how all these features make proglacial areas, in addition to their intrinsic value, relevant for the geosystem services they provide. Examples were collected mainly from the European Alps, to show how geosystem services may vary according to the geodiversity s.l. of proglacial areas. The specific aim of the review is to discuss geodiversity s.l. (i.e., bedrock diversity or geodiversity s.s., geomorphodiversity, hydrogeodiversity, soil diversity) in these regions with respect to the related geosystem services, and the associated consequences in terms of geoheritage promotion and conservation.

2. The concept of proglacial areas and their geodiversity

Gordon (2018) provided a rich overview of mountain geodiversity; he included some hints specific to proglacial areas, where landforms, deposits, rates and patterns of landscape change, are obviously diverse (Staines et al., 2015), underlining how the geological and geomorphological processes influence geodiversity in such areas (Barsch and Caine, 1984). Chiarle et al. (2021) provided considerable evidence of how different spatial features of mountain environments (i.e., geodiversity s.l.) affect the response of the Earth's surface to instability processes in diverse regions worldwide. In mountain regions, diverse geological and geomorphological dynamics that affect recently deglaciated areas, interfere each other and are analysed after providing the definition of proglacial area used in this review.

2.1 The definition of proglacial area

The concept of *proglacial area* was introduced by Penck and Bruckner (1909) to identify areas "located close to the ice front of a glacier, ice cap or ice sheet", where the ice-marginal location is a mandatory requirement (Slaymaker, 2011). Later on, the terms *glacier forelands* or *forefields*, were also introduced by other authors (e.g., Kinzl, 1932). The definition of 'proglacial area' is quite intuitive (Slaymaker, 2011), and recently these areas have been broadly accepted as those comprised between the Little Ice Age (LIA) moraines and the current position of the glacier snout (Schiefer and Gilbert, 2007; Zasadni, 2007). In the European Alps, variations in existing glaciers have been analysed in detail (e.g., Ivy-Ochs et al., 2009), especially the transition from the Late Glacial Maximum (Pleistocene glacial stages) to the Holocene. After the LIA, other advancing stages have been recorded, at the beginning of the 20th century and between the 1950s and 1990s, in the Central Italian Alps (Pelfini and Gobbi, 2005; Pelfini et al., 2014; D'Agata et al., 2020), and in the 1920s and in the period 1960s to 1980s, in the Western Italian Alps (Viani et al., 2016). During the first two decades of the 21st century (D'Agata et al., 2020), an increase in the rates of glacier retreat has been observed. Even if an advancing stage analogous to LIA was recorded 2000 years BP in the Central Italian Alps (Orombelli and Pelfini 1985), LIA has been recognised as the reference stage for the Holocene and as a marker for paleoglaciological comparison (Ivy-Ochs et al., 2009), as it is characterised by very sharp geomorphological evidence, and rich iconographic documentation due to the frequent human reporting (e.g., Baroni and Salvatore, 2015; Zumbühl and Nussbaumer, 2018). For these reasons, LIA represents the most obvious recent glacial stage, ideal border of proglacial areas, as defined in the literature. Evidence for more recent advances may thus also be present in proglacial areas.

Proglacial areas are freshly exposed zones, searching for a new equilibrium, and are particularly sensitive to the current variations in climatic conditions (Schiefer and Gilbert, 2007). In these dynamic environments, Slaymaker (2011) underlined how frequently pro-, para- and periglacial concepts are misused. While the term *proglacial* has mainly a spatial meaning, *periglacial* is related to specific morphoclimatic conditions related to the occurrence of permafrost. Moreover, periglacial conditions may feature proglacial contexts and influence their internal dynamics (Reynard et al., 2003; Lugon et al., 2004; Otto and Keuschnig, 2014; Bosson and Lambiel, 2016; Kunz and Kneisel, 2020).

After glacier retreat, the newly exposed surfaces located in a frontal or lateral position with respect to the ice body, need to reach a new equilibrium stage (Hughenholtz et al., 2008). New types of geomorphological processes (and landforms) related to the action of water and gravity on unconsolidated sediments, as well as ice degradation, gradually replace those related to the presence of the ice mass: the resulting transitional conditions are referred to as the *paraglacial stage* (e.g., Ballantyne, 2002; Reynard et al., 2003; Mancini and Lane, 2020; Chiarle et al., 2021). The first definition of *paraglacial* was provided by Church and Ryder (1972) considering both the spatial and temporal meaning of paraglacial-type transformations characterising “non-glacial environments” but that are “conditioned by glaciation”, which is a necessary condition (Mc Coll, 2012). Subsequently, Ballantyne (2002) published a review on paraglacial geomorphology. Finally, Slaymaker (2009) proposed a definition of paraglacial landscape as “a transitional landscape which is in the process of recovering from the disturbance of glaciation”.

To summarise, as per Slaymaker (2009), *proglacial* is a spatial concept, *periglacial* is related to morphoclimatic conditions, while *paraglacial* refers more correctly to a period, a stage, or even more to morphodynamic conditions (as per Heckmann and Morche, 2019).

In this review, all these terms deal with the characterisation of proglacial areas, and the complex changes undergone by such regions could pose the question of the real extent of proglacial areas considering the area of interest of geomorphic (peri- and paraglacial) processes directed towards or starting from these regions. If we consider proglacial areas strictly as the region comprised within LIA moraines and the glacier snout, we can speak about *proglacial areas s.s.*. If we consider the geomorphic processes starting from or reaching these areas, we can speak about *proglacial areas s.l.* or, more properly about *margino-glacial areas*, also beyond the effective borders of the LIA moraines.

This consideration is related to the concept of *sediment connectivity*, which regulates the flux of sediment though single geomorphic regions or through a whole mountain catchment, thereby representing the “degree to which a system facilitates the transfer of water and sediment through itself, through coupling relationships between its components” (sensu Heckmann et al., 2018). Sediment connectivity can be further distinguished as *structural* or *functional*: in this second case, in addition to the physical (structural) linkage, there are processes activating the sediment flux between the landscape units (Heckmann et al., 2018). In Alpine environments, for instance, Reynard et al. (2012) suggested considering the mountain catchments as a whole, applying a holistic approach since cryosphere-hydrosphere-geomorphic dynamics are deeply structurally and functionally connected in space (sensu Heckmann et al., 2018), close to and far from the proglacial areas. This is fundamental when thinking about the regulating, provisioning and cultural geosystem services provided by proglacial areas, the specific object of this review (see 3).

Hence, in this review *proglacial areas s.s.* are those defined by Schiefer and Gilbert, 2007, as bordered by LIA moraines, which, when affected by processes that influence the lateral moraines and rocky slopes connected to the proglacial plain and related sub-landforms, should be named *proglacial areas s.l.*. According to both these meanings, the arrangement of landforms may vary significantly depending on different factors (hydrology, lithology, structures, morphometry) which are analysed in the following paragraphs.

2.2. Types of proglacial areas in relation to glacier categories

Considering the type of glaciers, different kinds of proglacial areas will reflect the variable dynamics of glacier response to climate change.

Zasadni (2007) underlined how the diversity of glaciers responds differently to climate change (i.e., *response time*) according to paleoclimatic conditions, topographic setting, size of the glacier, debris coverage rate, and bedrock features. In general, the morphological and dynamic diversity of the glaciers is related to the morphology of the accumulation basin and to the availability of space for the glacier to flow. Indeed, the local topography may determine differences in hydrological patterns and proglacial features, and, as underlined by Hotaling et al. (2017), in the associated habitats (see 3.2). According to the extension of supraglacial debris coverage, two main categories of glaciers exist, but three kind of proglacial areas may be considered as follows:

i. *Proglacial areas related to debris-free glaciers* – these glaciers are especially affected by a clear retreat occurred since the LIA linked to the increase in global temperature (Oerlemans, 2005; IPCC, 2021). The widening of debris-free glacier forelands is diachronic among different areas according to specific factors. For instance, D’Agata et al. (2020), calculated proglacial areas increased by 16.2 km^2 ($\underline{+}$ 1.3%) between 1954 and 2007, in the Bernina Massif in the Italian Alps, where the authors detected the most powerful change, in terms of rocks and debris exposure, at the snout of the largest glaciers. In these areas, the most intense widening occurred between 1981 and 2003 with a potential volume of newly formed debris (0.006 to 0.012 km^3), prone to erosion and dismantling. The dynamics of debris-free glaciers can generate different types of erosion and deposition processes producing large- and small-scale landforms, depending on the shape of the glacier itself and on the morphology of the surrounding environment. LIA moraines for instance, may entirely be structurally but also functionally disconnected from the lateral valley slopes (e.g., Aurona Glacier, Italian Alps) or they may mantle the slopes (e.g., Mont Miné Glacier, Swiss Alps) favouring connection between the slope and the proglacial plain. Intermediate cases show prevalence of one or the other situation (e.g., Lys Glacier, Italian Alps, Fig. 1a). This variation significantly affects the sediment connectivity pattern between lateral valley slopes and proglacial plain (Cossart and Fort, 2008). Moreover, depending on the type of glacier (e.g., valley, cirque), different kinds of proglacial areas can be recognized. In the European Alps, large valley glaciers usually abandon huge and sharp lateral moraines and relatively flat proglacial plains characterised by consistent amounts of basal till and debris (e.g., Lys Glacier, Italian Alps; Fig. 1a). Whereas, after their retreat and potential disappearance, cirque glaciers left glacial cirques, a bowl-shaped depression, often including areas of exposed bedrock modelled by glacier erosion named *roches moutonnées* (e.g., Bors Glacier, Italian Alps).

ii. *Proglacial areas related to debris-covered glaciers* – this kind of glacier responds differently to global warming, since debris coverage having reached a certain thickness, helps protect ice against ablation (e.g., Brock et al., 2010), as demonstrated by the most important debris covered glacier in the Italian Alps: the Miage Glacier (Fig. 1b). Recent regional scale studies in the Himalayan region, using remote sensing techniques, also demonstrate how this type of glaciers is responding to global warming (Maurer et al., 2019). Instead of presenting relict LIA moraines located far from the current position of the glacier snout, debris covered glaciers are usually characterised by LIA moraines still located close to the glacier snout, and the glaciers are affected by the passage of kinematic waves or by surge episodes, bulging and deflation phases that deeply modify epiglacial and moraine debris (e.g., Miage and Belvedere glaciers, Italian Alps; Pelfini et al., 2007, Haeberli et al., 2002). For instance, surge episodes, like the famous one that occurred in 2001 at the Belvedere Glacier (Italian Alps) (Haeberli et al., 2002), may be followed by a huge lowering of the glacier surface by hundreds to tens of meters, locally, since the morphology but not the volume of the glacier changes, exposing internal flanks of lateral moraines to erosion. The most obvious change in proglacial areas of debris-covered glaciers is hence not their areal variations (e.g., Wigmore and Mark, 2017), but the variation in hydrological processes that characterise glacial lakes and streams in relation to variations in the ice conditions inside the glacier (Garavaglia et al., 2010b; Leonelli et al., 2019).

iii. *Proglacial areas featured by periglacial conditions* - In proglacial areas, periglacial processes may become common (e.g., the occurrence of permafrost from refreezing of former unfrozen glacier beds, preservation of previous subglacial permafrost, burial of dead ice; Otto and Keuschnig, 2014). Interstitial ice can be present within debris bodies, when, for example, dead-ice bodies are buried by sediment. An example of this dynamic can be seen at the Leone Glacier (Italian Alps; Fig. 1c), where a dead-ice body within the border of the LIA moraines has remained isolated, covered by debris, since the middle of 1990s, and in 2022 totally collapsed and created a new proglacial lake. When debris-covered glaciers gradually change into rock glaciers (i.e., *glacier-ice-cored rock glaciers*; Johnson, 1980), typical features of periglacial environments become dominant (Becca Luseney rock glacier, Italian Alps; Fig. 1d). Periglacial-type dynamics related to the presence of permafrost in proglacial areas and the surrounding environments is an important geomorphic agent, which is often disregarded, whose reaction to global warming is frequently delayed and invisible with respect to the response of both debris-free (i) and debris-covered glaciers (ii) (Otto and Keuschnig, 2014).

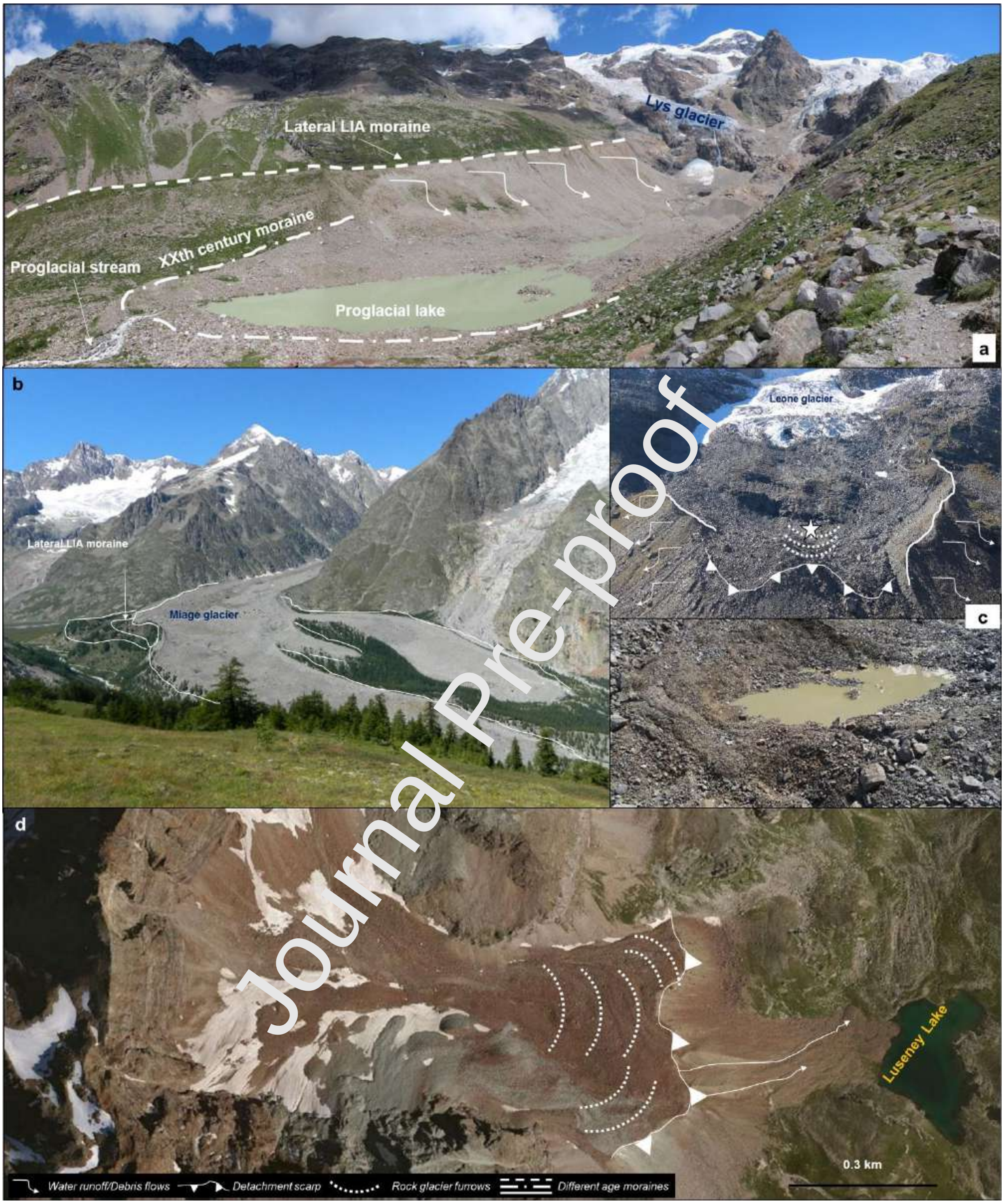

Fig. 1. Different kinds of proglacial areas in debris-free and debris-covered glaciers, or in periglacial conditions: a) Lys Glacier (Italian Alps); b) Miage Glacier (Italian Alps, photo courtesy of D. Zannetti); c) the glacier foreland of the Leone Glacier featuring a dead-ice body covered by debris (white star) (Italian Alps, photo courtesy of A. Pasinetti), collapsed in 2022 and created a proglacial lake (see the frame, corresponding to the white star); d) Becca Luseney rock glacier with visible incisions caused by debris flow affecting the frontal scarp of the rock glacier (Italian Alps, source Aosta Region Webgis).

In figure 2 the examples of glaciers in figure 1 (a, b, c) have been sketched to reveal the different proglacial areas features, as well as the features of surrounding areas (e.g., lateral valley slopes) related to the concept of proglacial areas s.l., as described in detail in the following sections (2.3, 2.4).

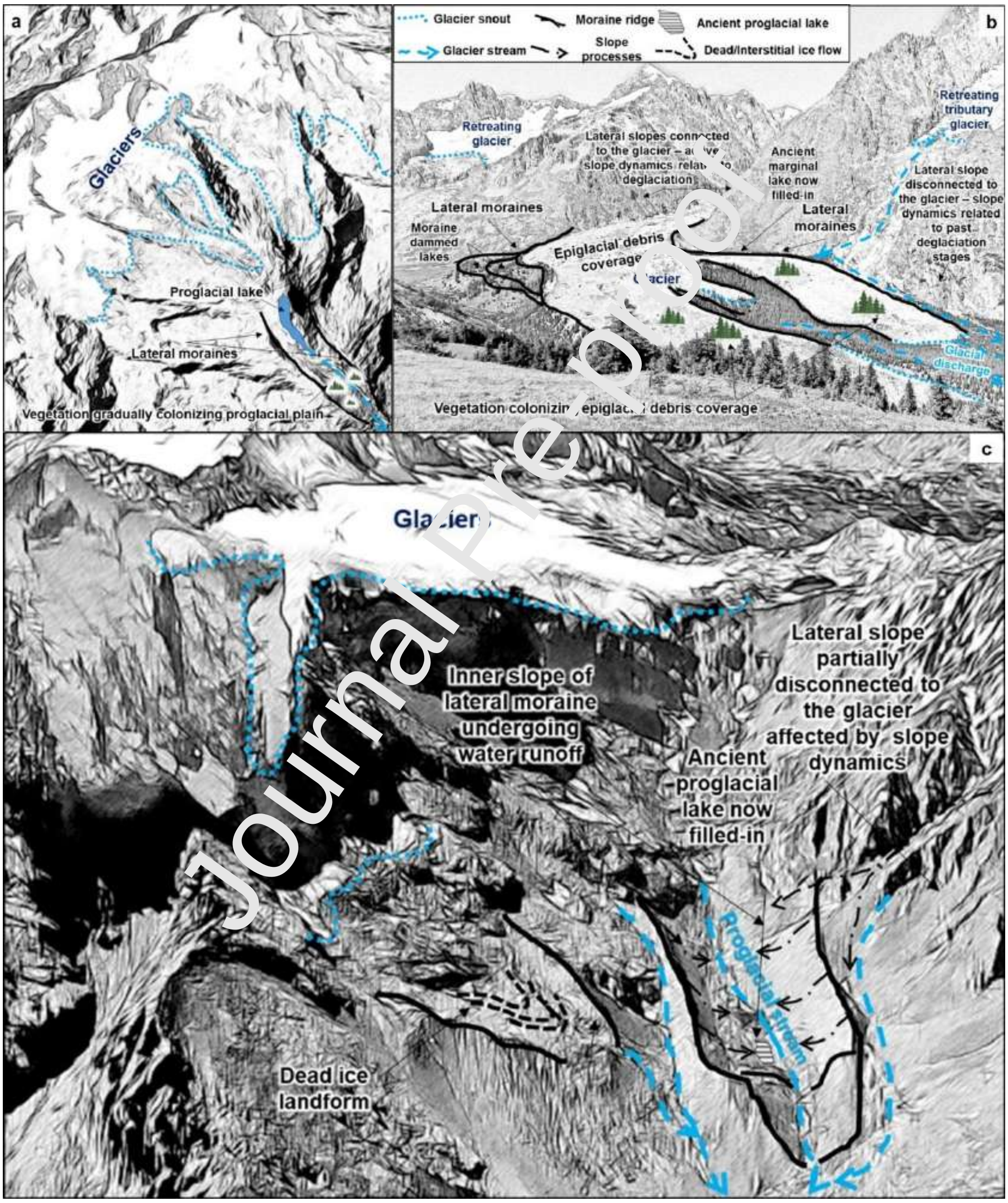

Fig. 2. Sketches of different types of glaciers and related proglacial areas s.l. based on the examples shown in figure 1, and depicting their main traits: a) Debris free glacier with a proglacial area featured by a proglacial lake and LIA moraines mantling the lateral slopes, and vegetation colonising the proglacial plain (Lys glacier-type); b) Debris covered glacier with a deeply vegetated proglacial plain, the glacial snout is still close to the LIA moraine extension (Miage glacier-type); c) Debris free glacier flowing in a structural- controlled valley, with a wide proglacial plain and very clear LIA moraine disconnected from the slopes (Aurona glacier-type), side by side to a

permafrost-dominated proglacial area of a debris free glacier where LIA moraines close a depression with a dead ice body, formerly a glacier snout, now covered by debris (Leone glacier-type), and suddenly collapsed in summer 2022 into a proglacial lake (see figure 1c). The legend of symbol is given in figure b.

Figure 3 gives a classification of *proglacial areas s.l.*, but it should be noted aware the possibile combinations of morphological and morphodynamic traits of proglacial areas are infinite. In all the sketches, the frontal and lateral moraines are intended to be related to the Little Ice Age, according to the definition proposed by Schiefer and Gilbert (2007). Within these moraines, other more recent moraines may be present, but are not depicted to avoid complicating the sketches. It is clear how the concept of *proglacial areas s.l.* (or *margino-glacial areas*) is relevant in relation to connectivity between the geomorphic units involved. More details are provided in the following sections (2.3, 2.4).

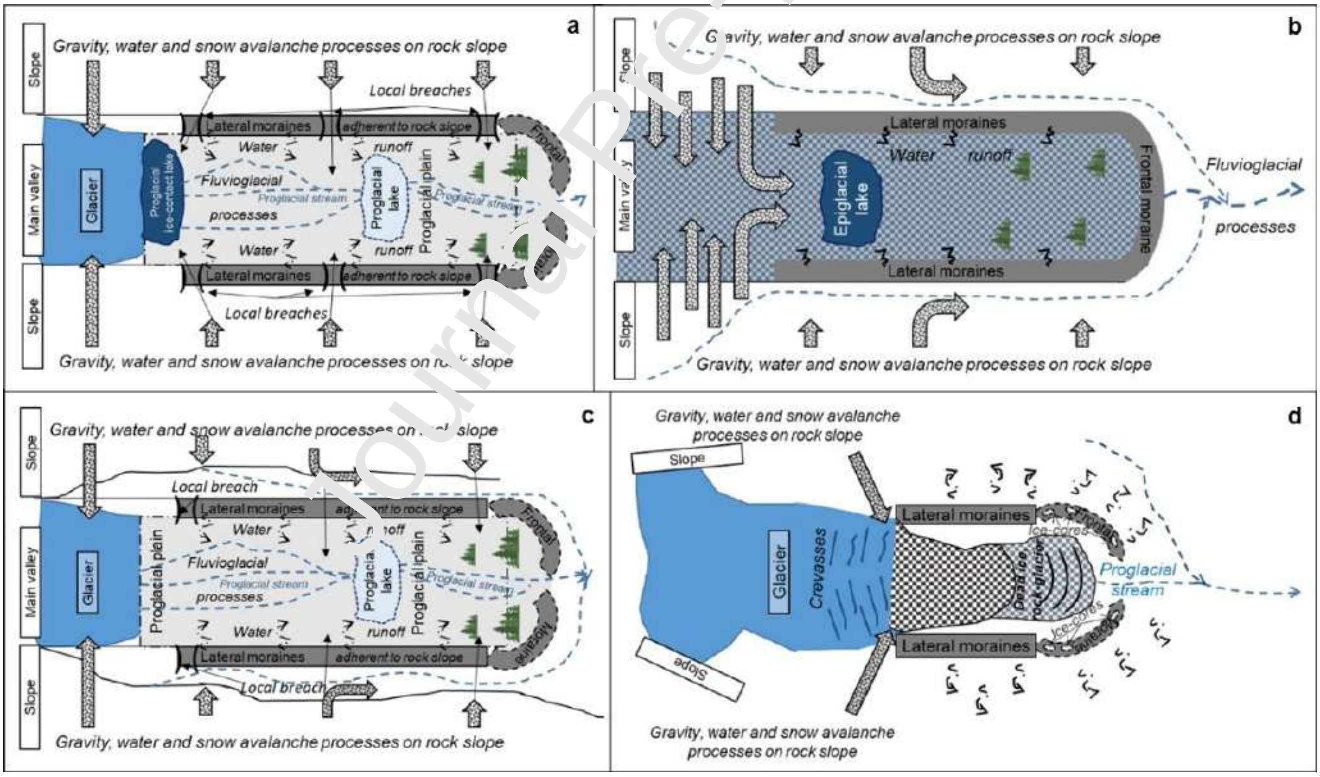

Fig. 3. Different types of proglacial areas (see also figure 1 and 2), showing the main traits of glaciers and proglacial areas s.l.: a) debris free glacier with lateral moraines mainly mantling the lateral valley slopes (Lys-type); b) debris covered glacier debris flows from the lateral valley slope feeding the epiglacial debris coverage (Miage-type); c) debris free glacier with lateral moraines disconnected form the lateral valley slopes with local breach in the lateral moraine (Aurona-type); d) permafrost dominated proglacial area with a dead-ice body, formerly a glacier snout, covered by debris (Leone-type), and potentially evolving with the formation of a proglacial lake (see figure 1c).

2.3. Types of proglacial areas related to bedrock features

As different authors stressed (Ghiselli et al., 2005; Zasadni, 2007; Carrivick and Rushmer, 2009; Frey et al., 2010a; Hotaling et al., 2017; Carrivick and Tweed, 2021), lithology and structural conditions, and related local topography, may affect the glacier flow and the resulting morphology of proglacial areas (overdeepenings, glacial steps and deeply crevassed glaciers). Indeed, glacial and geomorphological dynamics depend strictly, at different spatial scales, on bedrock features (e.g., Ghiselli et al., 2005), as well as on regional tectonic regimes (Carrivick and Tweed, 2021).

Structural features, for instance, influence the morphology of proglacial areas by potentially allowing the creation of overdeepenings that in some cases, may become flat surfaces due to gradual sediment aggradation (Haeberli et al., 2016b). In this case, but also where glacial steps or thresholds transversal to the valleys are present, variation in sediment connectivity conditions may be observed.

In some cases, tectonic contacts, putting different kinds of rocks side by side along valley flanks, may lead to variations in the composition of the debris forming the moraines that are visible in the form of peculiar coloring (Oren Glacier, Italian Alps; Fig. 4a). Beside this aesthetic feature, these structural lines may represent areas of weakness, along which glacial tongues are expected to flow and hence to erode the bedrock more easily (Aurona Glacier, Italian Alps; Fig. 4b).

Differentiation between lithology outcropping along valley slopes, or the exhumation by glacier erosion of different type of rocks, if characterised by different susceptibility to degradation, could evolve into a variable amount of proglacial debris due to selective erosion (Cedec and Gran Zebrù glaciers, Italian Alps; Fig. 4c), again influencing sediment connectivity. This is anyway a questionable relation: some authors distinguish the preconditioning factor of bedrock lithology on sediment export from proglacial areas in the Andes (Harries et al., 2021), while, according to Hinderer et al. (2013), there is no clear correlation between lithology and sediment yield in the European Alps, but rather between sediment fluxes and the percentage of glacier coverage in the basin or catchment relief.

Depending on the lithology, complex landscapes may emerge from the combination of processes related to soluble rocks, like limestone, with glacial processes (i.e., glacio-karst). A relevant example of this mixture is the Tsanfleuron glacio-karstic plateau (Swiss Alps; Fig. 4d), where, according to Schoeneich and Reynard (2021), the proglacial area presents a great variety of glacio-karstic features that are different from older landforms dated back to pre-Holocene times. Moreover, weathering of new exposed rocky surfaces may also reveal complex trends as demonstrated by chemical analyses of water in proglacial streams by Anderson et al. (2000). In general, the gradual exposure of rocks accompayining a glacier’s retreat may increase the lithological geodiversity of proglacial areas.

Fig. 4. Diversity of proglacial areas related to bedrock features: a) structural and lithological diversity reflected in the colour of the lateral moraines at Oren Glacier (Italian Alps, source Google Earth); b) aerial view of the Aurona and Leone glaciers (Italian Alps, photo courtesy of L. Sergio): the Veglia Fault Zone controls the incision operated by the Aurona glacer fault; c) the neighbouring proglacial areas of the Cedec and Gran Zebrù glaciers, visually different in terms of sediment delivery due to variations in lithology and, as a consequence, of slope steepness (Italian Alps, source: Google Earth); d) Tsanfleuron Glacier (Swiss Alps) and glacio-karst diversity. Lithological/tectonic contacts are depicted in red.

2.4 Types of proglacial areas related to geomorphic processes

In general, proglacial areas s.l., here defined as including lateral slopes, previously influenced by the presence of a glacier and lateral moraines, that mantle lateral slopes (structural connection) or that are completely disconnected from them, are undergoing a paraglacial transition from glacier-dominated to hillslope-dominated environments (Carrivick and Tweed 2021). Authors investigating the geomorphological progress of proglacial areas have recently focussed their attention mainly on two kinds of processes: the dismantling of LIA moraines, characterised by unconsolidated sediments and variable features that influence their rates of change, (Fig. 5); and the generation of new rockfalls that affect the bedrock (Fig. 6). Indeed, the two processes may be at least partially related, and combined with other causes (e.g., fluvial undercutting of slopes; Mancini and Lane, 2020), contribute to the relaxation and the removal of support along the flanks of proglacial areas after the glacier retreat (i.e., debutressing; Ballantyne, 2002). Also where glaciers are still present, their down-wasting opens the way for further instabilities to occur as deglaciation proceeds (Blair Jr., 1994; Evans and Clague, 1994; Deline et al., 2015).The debutressing process was discussed, for the first time in the Italian Alps by Panizza (1973), and more recently, was investigated in several case studies of landslides and catastrophic rock failures on both LGM and LIA deglaciated slopes (Mc Coll, 2012; Kos et al., 2016; Cody et al., 2020; Chiarle et al., 2021).

LIA moraines are very impressive and often present a well-preserved shape, characterised by a very sharp relief and a considerable difference in height with respect to surrounding areas (Mortara and Chiarle, 2005; Hugenholtz et al., 2008). The importance of mapping in proglacial areas LIA extension and potential occurrence of ice cores in such moraines has recently been emphasised in the literature (Zanoner et al., 2017; Chandler et al., 2018; Lucchesi et al., 2019), in relation to the resulting on-site and off-site hazards. Along these sediment ridges, water due to rainfall or snow melting, combined with gravity, generates a complex of landforms (i.e., *geomorphodiversity*) with gullies and a pseudo-badland morphology, as well as debris flows and debris sliding (Aurona Glacier, Italian Alps; Fig. 5a1, a2; Mont Minè Glacier, Swiss Alps, Fig. 5b1, b2) (e.g., Curry et al., 2006; Ballantyne, 2002; Schiefer and Gilbert, 2007; Bollati et al., 2017a; Cody et al., 2020; Chiarle et al., 2021). Stages in the change from instable (I-with pervasive gullying on the inner slope), through solifluction dominated slopes (II) towards stabilisation (III) were identified by Eichel et al. (2018), on moraine inner slopes, and recognised in different contexts (e.g., Prokop et al., 2021). Important is their role as complete (Aurona Glacier, Italian Alps) or partial disconnector (Lys Glacier, Italian Alps) between lateral valley slopes and the proglacial plain (Cossart and Fort, 2008).

The paraglacial-type change undergone by such sedimentary unconsolidated sediments that are suitable for reworking, can be very rapid, and the rates of erosion have been quantified in glacier environments at different latitudes, using different morphometric techniques (e.g., Blair Jr, 1994; Palacios et al., 1999; Ballantyne, 2002; Curry et al.; 2006, 2009; Schiefer and Gilbert; 2007; Hughenholtz et al., 2008; Mercier et al., 2009; Laute and Beylich 2014; Bosson et al., 2015; Tonkin et al., 2016; Ravanel et al., 2018; Betz et al., 2019; Williams and Koppes 2019; Mancini and Lane, 2020). In general, higher rates of variations occur near the glacier snout, where deglaciation has started very recently, and rates decrease down-valley (Curry, 1999; Staines et al., 2015; Bollati et al., 2017a), thereby influencing the accumulation rates on the alluvial fan down-valley (Mancini and Lane, 2020). Furthermore, subglacial till, exposed in the proglacial plains, may also be subject to rapid dismantling too (Lane et al., 2017), thereby increasing the delivery of sediment down-valley (e.g., Grand Etrét Glacier, Italian Alps; Gran Zebrù Glacier, Italian Alps, Fig. 4c).

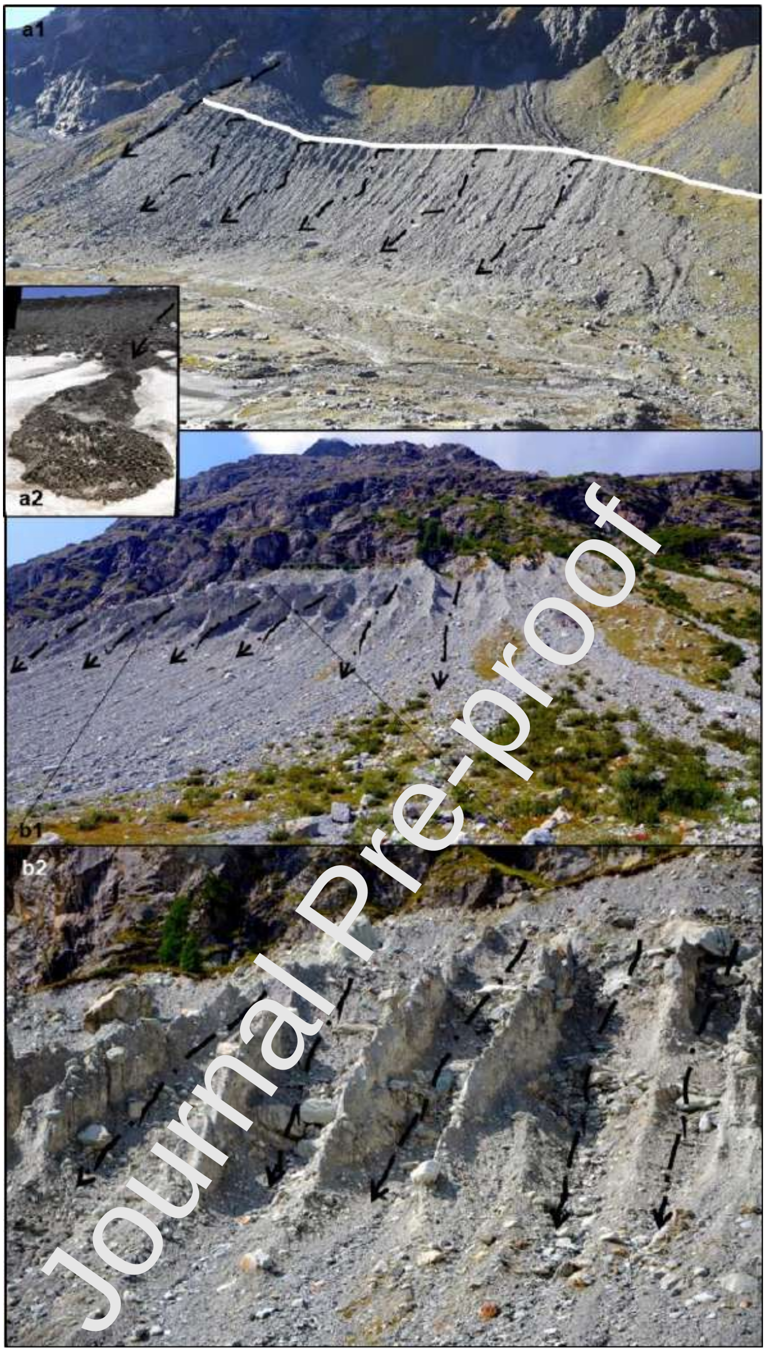

Fig. 5. Examples of water runoff related landforms developing after glacier retreat in proglacial areas on lateral LIA moraines: a) one of the two spectacular lateral LIA moraines (white ridge) of the Aurona Glacier (Italian Alps), disconnected from the slope at the rear; the moraine is subject to water runoff, causing a typical pseudo badland morphology (a1), and earth- and debris- flows (a2; on the opposite moraine) (Stage I; Eichel et al., 2018). At the upvalley origin of the moraine, debris flows may activate on the rear slope and by-pass the moraine ridge to reach the proglacial plain. A debris slide is also indicated on the right (line of white triangles) (Stage II; Eichel et al., 2018); b) b1- lateral LIA moraine of the Mont Miné Glacier (Swiss Alps), an example of a sediment-mantled slope undergoing water runoff, causing a typical pseudo badland morphology, a detail is reported in b2. Black arrows indicate the occurrence of gullying or debris flow.

Co-evolution of permafrost (and related landforms such as rock glaciers, protalus ramparts and push-moraines) and glacial processes (and related landforms) is particularly complex along some high-altitude proglacial margins, where periglacial and glacial phases have alternated during the Holocene (Reynard et al., 2003; Lugon et al., 2004; Bosson et al., 2015; Capt et al., 2016; Bosson and Lambiel, 2016; Ravanel et al., 2018). Due to terrain warming, permafrost-related dynamics also play an important role in inducing and accelerating instability in rock slopes (Deline et al., 2015), ice-cored moraines, and sediment-mantled slopes (Ravanel et al., 2018; Chiarle et al., 2007; Deline et al., 2015; Tonkin et al., 2016; Betz et al., 2019; Viani et al., 2020a), favouring sediment transfer (Kummert and Delaloye, 2018; Kummert et al., 2018). This role has been demonstrated (e.g., Trajo Glacier, Italian Alps; Chicco et al., 2020; Mount Blanc Massif; Deline et al., 2015), but is not always straightforward. For instance, at the Thurwieser peak, a rock avalanche occurred in 2004, partly covering the Zebrù Glacier, and deeply impacting the proglacial area, the channel networks and also the path to reach the infrastructures in the area, was only hypothesized but not demonstrated to be caused by melting permafrost.

In this scenario, different types of instabilities can occur after glacier retreat including rock avalanches (e.g., Kos et al., 2016), debris flows (e.g., Cody et al., 2020), complex movements (Blair Jr., 1994), as well as large and relatively slow deformation (Hugenholtz et al., 2008), depending on the local conditions at the site (Hugenholtz et al., 2008). Chiarle et al. (2021) showed that different precipitation trends can cause variable responses, specifically in the recurrence of landslides, in different mountain regions of the Earth, introducing yet other regulating factors for the dynamics affecting proglacial areas.

Globally, the complex dynamics on debris or bedrock lateral slopes are relevant in terms of geomorphodiversity (articulated patterns of landforms), specifically also with respect to the sediment connectivity trend.

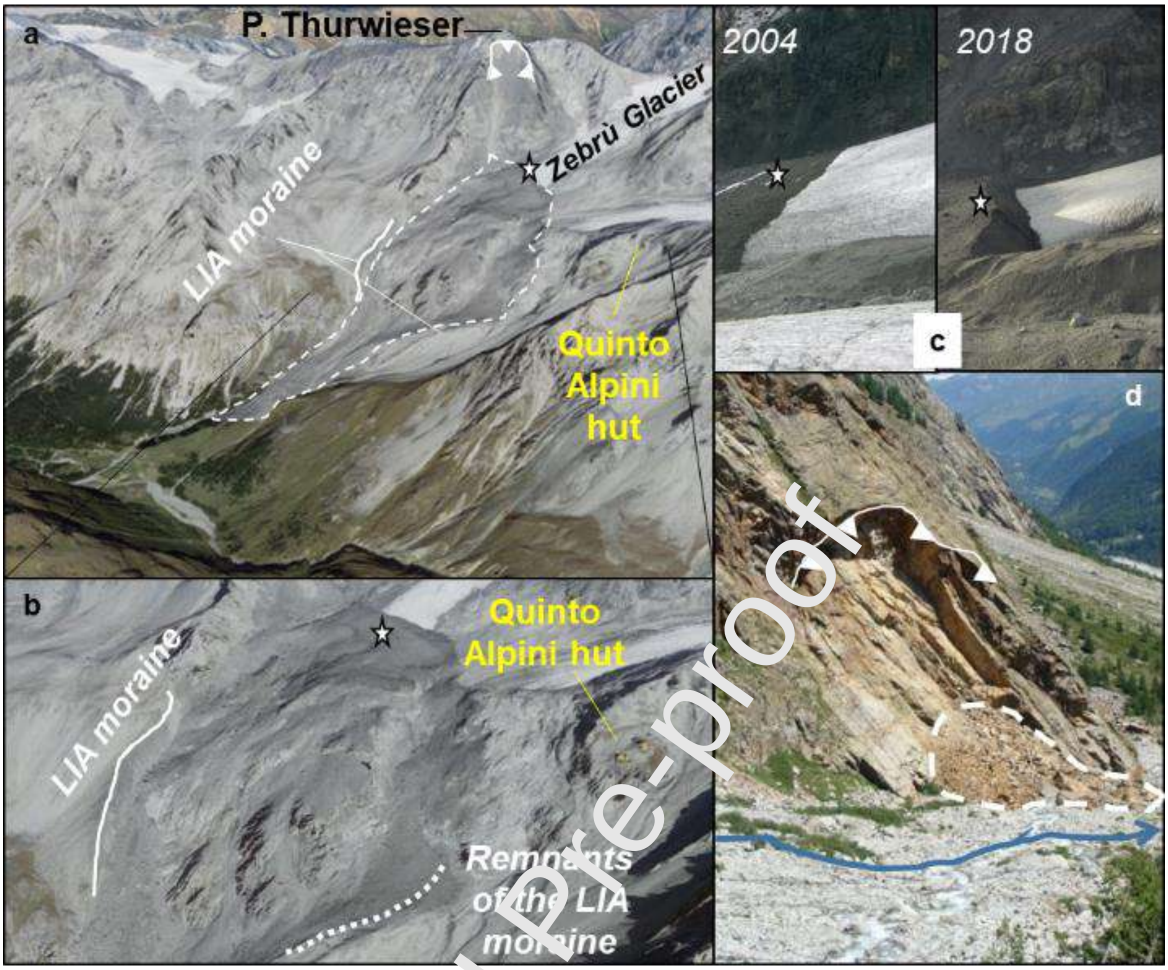

Fig. 6. Examples of gravity-related landforms developing after glacier retreat in proglacial areas: a) the rock avalanche at Thurwieser peak (Italian Alps), which in 2004, destroyed part of the path to the Quinto Alpini hut, partly covering the Zebrù Glacier and completely modifying its proglacial area (b), with visual effects in terms of differential ablation of the glacier (c; 2018 photo courtesy of G. Cola); d) one of rockfalls occurring on the southern side of the Mont Blanc, along the left flank of the Miage Glacier (Italian Alps). In the figures, the lines of white triangles mark the limits of the detachment zone.

3. Application of the geosystem services approach to proglacial areas

As underlined by Barsch and Caine (1984) mountains and their relief have always been important to human use of Earth. Gordon (2018) depicted how mountains contribute to the ecosystem services from different points of view. Mountains are relevant regions because they were calculated to provide support to 10-20% of the population, indirectly affecting the life of half humankind (Gordon, 2018 and references therein). Proglacial areas are a sub-system of the mountain environment, with their own peculiarities. All geological, geomorphological, hydrological, pedological and biological features of proglacial areas converge well in the geosystem services approach derived for geodiversity by Gray et al. (2013) (i.e., *geosystem services*). As also underlined by Mitchell et al. (2013), both structural and functional variations in sediment connectivity could become of paramount importance for ecosystem services in such environments.

The 25 geosystem services recognized by Gray et al. (2013), starting from the MEA, can be classified in 4 categories (*regulating, supporting, provisioning and cultural*) (Fig. 7). More recently, Fox et al. (2020) proposed a *Geo_Eco Services Framework*, underlining the importance of distinguishing between: i) theoretical biosystem services (biological structures and processes); ii) ecosystem services (biophysical structures and processes); iii) geosystem services (geodiversity structures and processes). The first and third categories are really distinct and should be considered at the same level, while the second one derives from the overlapping of the other two, with a variable prevalence of one over the other. Especially in the last case (iii), services may be delivered by geodiversity independently from their link with the biological component, that could be interpreted as the intrinsic value to geodiversity mentioned previously (Gray et al., 2013; Gordon, 2018). Clarifying these concepts is important for the management of geodiversity, also because of the non-renewable nature on a human time scale of the majority of georesources (Fox et al., 2020), especially when dealing with fragile areas (Mengist et al., 2020) which is the case of glacier forelands.

More recently, a new concept has begun taking hold: the *Essential Variables of Geodiversity* (EVGs; Schrodt et al., 2019): these are abiotic state and process variables linked to geology-geomorphology-soils-hydrology, and which are accompanied by Climate, Biodiversity and Ocean Variables. They represent the bridge between scientific investigations to assess global changes and policy makers, with the aim of encouraging the latter to undertake initiatives for geodiversity management.

A more in-depth assessment of proglacial areas, one of the first attempts to map geosystem services in proglacial areas, was recently undertaken by Tognetto et al. (2021). Starting from a geomorphological map, these authors drew a thematic chart, showing the two-way connection between natural and human modified landscapes.

Figure 7 is a sketch of the geosystem services approach applied to glacier forelands, which is discussed through examples in the following sections (3.1, 3.2, 3.3, 3.4). It is important to underline how families of services are reciprocally linked and some features can be discussed in more than one category (see 4). This aspect was also highlighted by Mengist et al. (2020), who regret the lack of specific studies that explore the interrelations among the different categories of services in mountain regions. These authors also underline the role of humans in affecting ecosystem services, whose effects, in proglacial areas, despite being remote, could have extreme impacts. According to Mengist et al. (2020), among the services in mountainous areas, as well as in proglacial areas, those that provide support and cultural services are the least evaluated, whereas they should acquire importance as well as regulating and provisioning services.

All geosystem services are discussed relative to the diversity of proglacial areas s.l.. Indeed, variations in landform assemblages and environmental properties (e.g., sediment connectivity) may affect the various kinds of geosystem services differently, especially regulating services (Mitchell et al., 2013), becoming pivotal with respect to societal benefits (Carrivick and Tweed, 2021). In this sense, although regulating, provisioning and cultural geosystem services provided by proglacial areas can also be analysed off-site, supporting ones should be more properly considered locally (on-site effect).

Moreover, as changes undergone by proglacial areas are tightly linked with the glaciers s.s., all the considerations can be inferred to also be deeply connected: glaciers (i.e., geoheritage sites according to Pelfini and Smiraglia, 2003) and their forelands act as a complex system that cannot be split. The gradual conquest of new areas by fresh geomorphic and hydrological processes, soils and new vegetation is accompanied by a migration from the geosystem services provided by glaciers to those provided by these new environmental features.

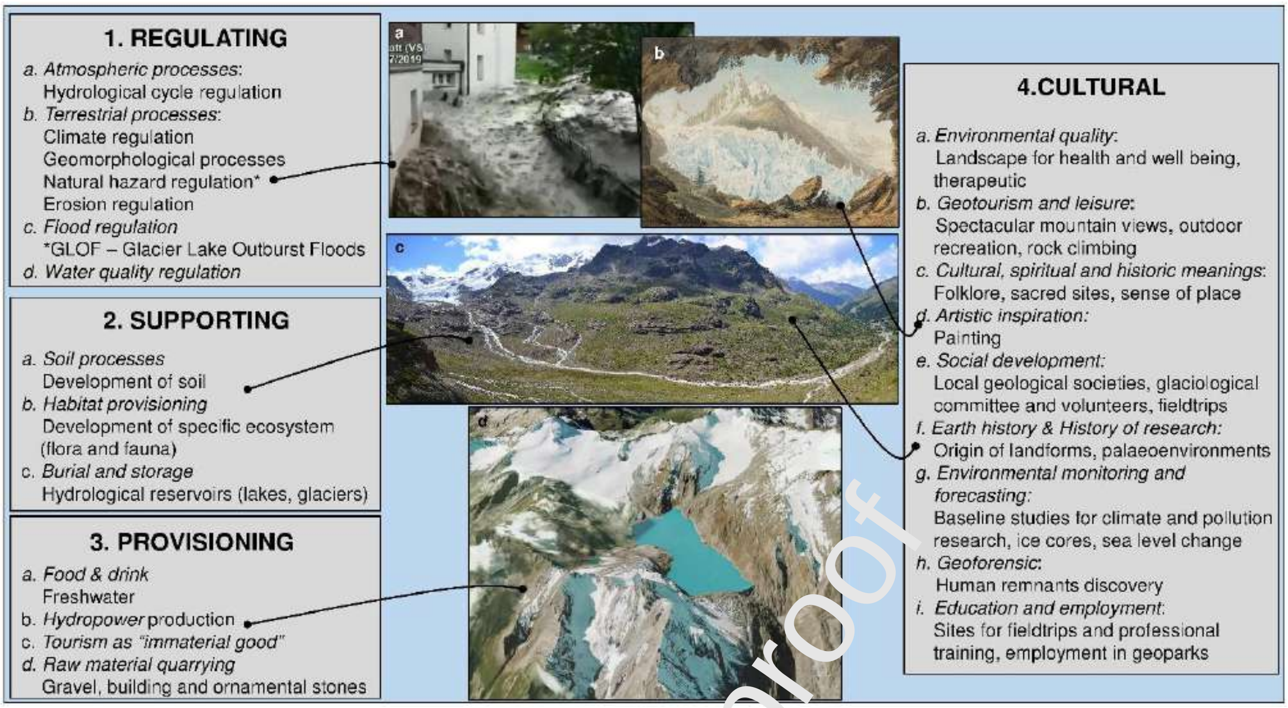

Fig. 7. Geosystem services provided by geodiversity of proglacial areas s.l.: a) the Glacier Lake Outburst Flood that hit Zermatt in July 2019 (source https://youtu.be/lhGWdWH6-n8); b) the painting by Jean-Antoine Linck,View of the Glacier des Bois and the Needles of Charmoz from the arch, called the Cap, 1799 (source: meisterdrucke.it); c) soil and vegetation development following deglaciation along the Forni Glacier Valley (Italian Alps); d) the Sabbione Glacier proglacial lake (Italian Alps) dammed for hydropower production and an attractive tourist destination (source: Google Earth 3D).

3.1. Regulating services

Regulating services are usually linked to atmospheric and terrestrial processes, flood and water quality regulation (Fig. 7). By virtue of geodiversity s.l. of proglacial environments, the behaviour of the systems can vary significantly, thereby also altering regulation of both on-site and off-site effects.

Considering the atmospheric processes, the articulated morphology of mountain reliefs creates very complex meteorological circulation (Golzio et al., 2018; Gordon, 2018), introducing marked variability of the response to climate-related processes and the intensification of extreme events (e.g., Palomo, 2017). These meteorological patterns combined with the geodiversity of glaciers and proglacial areas, make hazard detection quite challenging, with a potential differentiation of risk scenarios (Evans and Clague, 1994; Beniston and Stoffel 2014; Hughenholtz et al., 2008; Purdie et al., 2015; Williams and Koppes, 2019), for which risk mitigation strategies are required (e.g., drainage of water, early warning systems based on real-time glacier monitoring, Lindner et al., 2020).

The main element we are used to think about when dealing with areas undergoing deglaciation is probably water in its different states (as ice and flowing): as a resource (see 3.3), stored in glaciers and ideally slowly released due to ice melt (Carrivick and Tweed, 2021). Geodiversity plays a key role in regulating processes in proglacial areas also linked to the presence of debris-free and debris-covered glaciers that display different dynamics (see 2.2). Indeed, an indirect regulating service related to different rates of deglaciation is the positive feedback between disappearing glaciers and climate change (Gordon, 2018): the more ice melts, the bigger the decrease in the albedo and the higher the increase in solar radiation absorption, leading to a rise in terrain temperature that favours the amplification of climate warming and, in turn, increases ice melt (i.e., positive feedback) (Carrivick and Tweed, 2021).

Another relevant hydrological feature in proglacial areas is represented by the different kinds of glacial lakes (i.e., *hydrogeodiversity*). Lakes are very variable elements that characterise glacier forelands, depending on the regional and local topography of surrounding environments (Tweed and Carrivick, 2015), and different classifications have been proposed (Tweed and Carrivick, 2015; Viani et al., 2016). Based on their position in the glacier system these include proglacial lakes and ice-marginal lakes (Fig. 8a), located in front of or in the proglacial plain s.l.; supraglacial lakes, located on the glacier surface (Fig. 8b, c); subglacial lakes or englacial lakes, respectively situated at the base or inside the glacier body. The three last categories are also relevant for proglacial dynamics regulating the water flow.

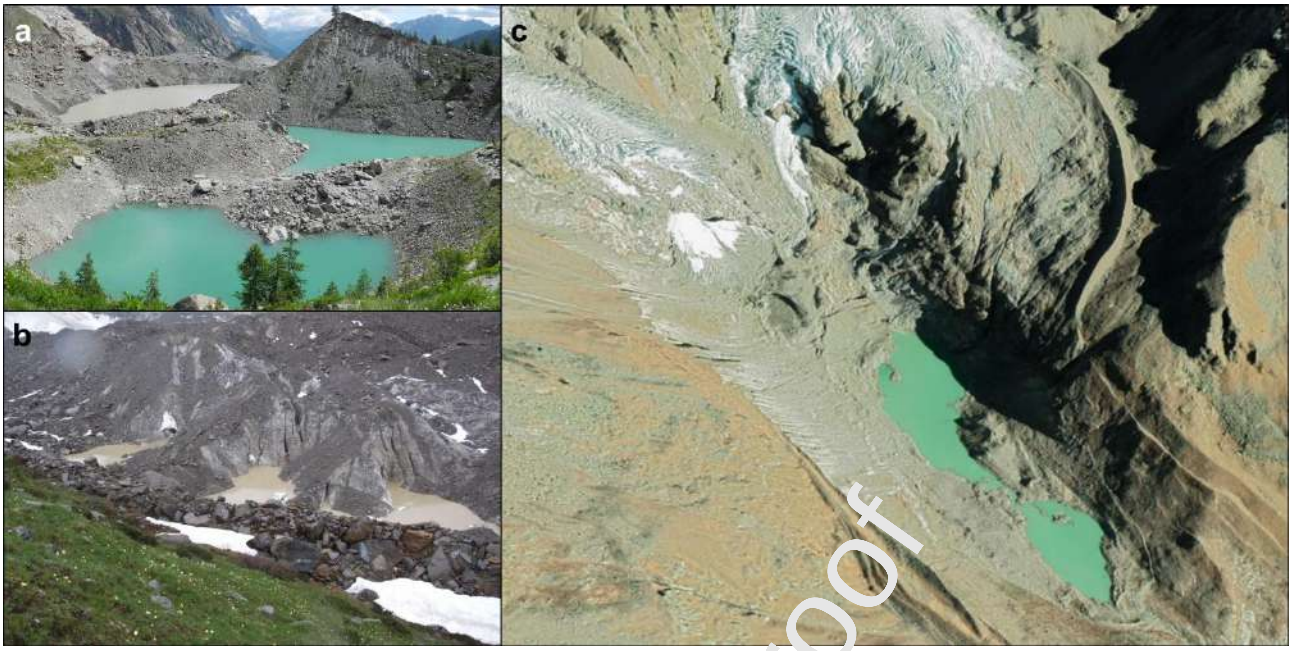

Fig. 8. 3D or 2D views of types of glacial lakes with respect to their position in relation the glacier: a) ice-marginal lake located within a moraine amphitheatre (Miage Glacier, Western Italian Alps, photo courtesy of A. Franchino, 2019, see a field view in Fig. 1b); b) supraglacial lakes on debris-covered glacier (Belvedere Glacier, Italian Alps, 2021); c) supraglacial lake formed on dead-ice detached from the Lys Glacier and now transformed into a proglacial lake (Italian Alps, source Google Earth 3D) (see a field view in Fig. 1a).

Glacial lakes are also classified according to their origin and the kind of dam that allows retaining water, a feature used to model Glacier Lake Outburst Floods (GLOFs) that could occur in the catchment. Lakes may be impounded by moraine/debris, like the huge moraines formed during the LIA at Lake Locce (Italian Alps; Fig. 9d), or at the Lago Blu (Blue Lake) at the Verra Grande Glacier (Italian Alps; Pelfini, 1999). They can also be dammed by a bedrock threshold, like in glacial overdeepening (Fig. 9b, c, e). In this case they fill depressions in the glacier bed that are modelled by the erosive action of the glaciers (Haeberli et al., 2016b): an exemplary case is that of the Tzére Glacier (Italian Alps; Fig. 9e). Carrivick and Tweed (2013) added to this category, lakes dammed by a landslide, a process that affects proglacial areas as described in section 2.4, and being an element that is considered relevant in terms of sediment disconnectivity along mountain streams in general (Korup, 2005; Carrivick and Tweed, 2021). Finally, supraglacial lakes, but also proglacial lakes, can be dammed by ice (Fig. 8 b, c); in the second case it is often dead-ice. In figure 9 (b, c) the coexistence of different kinds of impounding is particularly clear.

Hydrogeodiversity of glacier forelands and its influence on the related regulating geosystem services could hence be relevant.

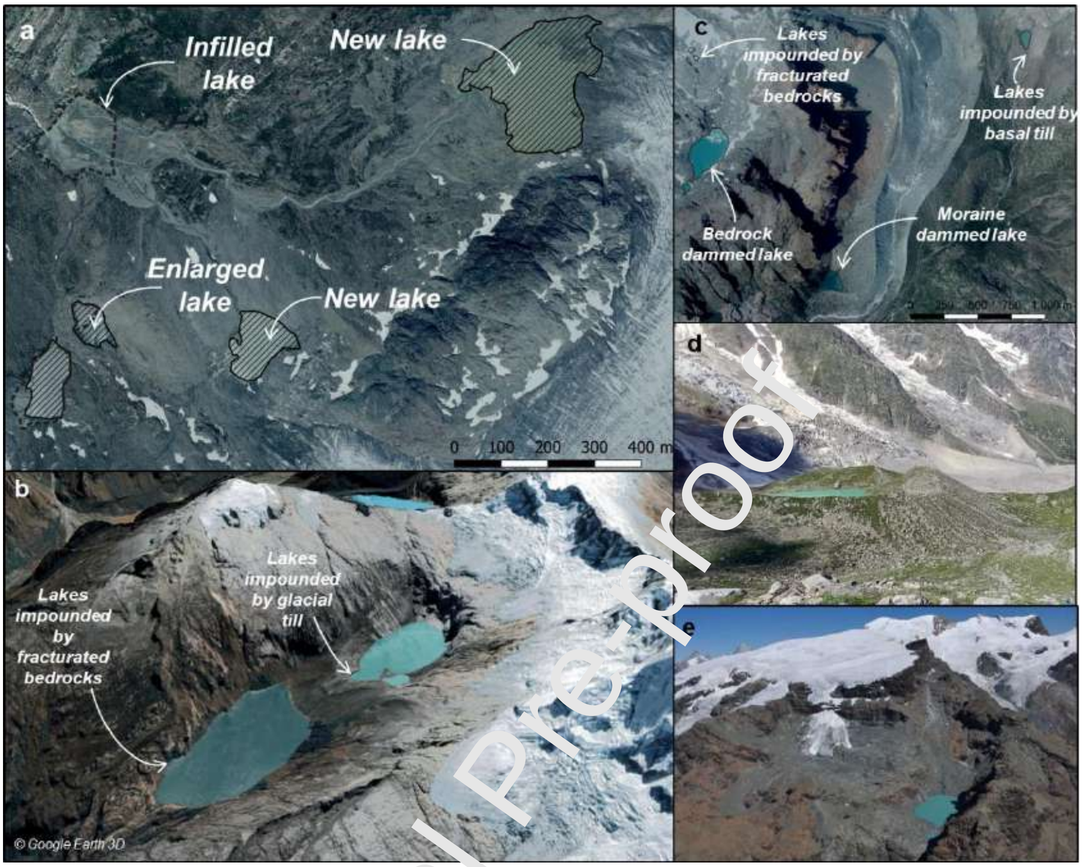

Fig. 9. 3D or 2D views of glacial lakes classified according to the type of dam: a) processes of infilling, expansion and formation of new lakes at Rutor Glacier (Italian Alps) (orthophoto 2012, source Italian National Geoportal); b) longitudinal sequence of lakes impounded by glacial till and fractured rock at the Hualcan Glacier district (Cordillera Blanca, Perù; source Google Earth 3D); c) series of lakes impounded by basal till and fractured rock, bedrock and moraine dam at Ayas Valley glaciers (Italian Alps); d) proglacial lake dammed by the moraine system, in the picture the artificial drainage cut for regulating the lake level is visible on the left lateral moraine (Locce North Glacier, Italian Alps); e) proglacial lake in bedrock overdeepening (Tzére Glacier, Italian Alps, photo courtesy of Società Meteorologica Italiana, 2012).

Significant geomorphological changes (disappearance, expansion/shrinkage) in the existing lakes that reflect climatic fluctuations and environmental changes, may occur over time (Gardelle et al., 2011; Salerno et al., 2014, 2016; Zhang et al., 2017). The progressive glacier retreat is also followed by an even increasing number of new glacier lakes if the conditions are favourable (Paul et al. 2007; Linsbauer et al., 2009; Carrivick and Tweed, 2013; Mergili et al., 2013; Emmer at al., 2014; Viani et al., 2016; Buckel et al., 2018). The formation of new lakes is well documented in the main high mountain areas of the world (Stokes et al., 2007; Frey et al., 2010b; Salerno et al., 2012, 2014, 2016; Viani et al., 2016; 2020b; Zhang et al., 2017; Buckel et al., 2018; Drenkhan et al., 2018), and testifies to a temporal trend in hydrogeodiversity and related regulating services, as clearly visible at Rutor Glacier (Italian Alps) (Fig. 9a), but may also pose threats to society (Maurer et al., 2019).

According to Tweed and Carrivick (2015), one of the regulating effects of (pro)glacial lakes is related to climate, which can be influenced directly or indirectly by their presence, also because responsible for positive feedback with the calving process.

A relevant aspect concerns the role of water in regulating the dynamics of natural hazards on-site within the proglacial area, but also off-site, far from glacier forelands (Evans and Clague, 1994; Chiarle et al., 2007; Cossart and Fort, 2008; Carrivick and Heckmann, 2017). This kind of issue can be driven by local bedrock conditions, geomorphological features, but also by extreme meteorological events, currently undergoing intensification due to climate change (Chiarle et al., 2021), and especially affecting certain morphoclimatic contexts (e.g., the Himalayan monsoon region, Wulf et al., 2012). The potential risks associated with lakes (e.g., outbursts and severe flooding; Allen et al., 2009; Worni et al., 2013; Emmer et al., 2015; 2016) may vary significantly depending on geodiversity, and may indeed be involved in regulating the entire hydrological cycle. In an articulated relief with a complex glacial structure, all the categories of glacial lakes described above may provoke GLOFs, more or less reliably forecast (i.e., through modelling of the potential occurrence of breaches in the ice or debris barrier retaining the water).

On-site risk scenarios may become reality due to the presence of vulnerable elements, mainly people visiting glacier forelands (Evans and Clague, 1994; Brandolini and Pelfini, 2010; Purdie et al., 2015). In a very recent review concerning the response of glacier tourism to climate change (Salim et al., 2021a), several strategies to address specific difficulties are examined and discussed (see 3.3.)

On-site risk scenarios associated with the presence of lakes may occur when a proglacial lake is influenced by anomalous waves caused by debris, rocks or ice falling into the water basin (Carrivick and Tweed, 2021). One well-known such event occurred when a large wave caused by an abnormally large block faling into the lake hit some tourists located along the shores of the

Miage Lake (Italian Alps, Fig. 10a) in the summer 1996, involving about a dozen of tourists including children (Tinti et al., 1999).

Concerning off-site risk scenarios, in some cases proglacial areas may act as temporary storage for sediment, and is then suddenly released during catastrophic events like rock avalanches. An example occurred at the Thurwieser peak (Fig. 6), where the proglacial area of the Zebrù Glacier was infilled with sediment, and the channel network as well as the LIA moraine system, was deeply modified by the landslide (Frattini et al., 2016). Moreover, unconsolidated sediments undergoing re-equilibrium may have implications for densely inhabited areas down-valley due to the potential intense delivery of sediments during paroxysmal episodes as GLOFs, as a result of moraine breaching (Chiarle et al., 2007; Westoby et al., 2014; Carrivick and Heckmann, 2017; Carrivick and Tweed, 2021). High magnitude debris flows, accompanied by moraine breaching, can cause deep scars in landscapes (Bollati et al., 2019), and destroy even more vulnerable elements in their path (Chiarle et al., 2007).

Figure 10 shows some examples of GLOF processes, and of evidence in the landscape. In Zermatt (Swiss Alps; Fig. 10b), a sudden flood, due to the unexpected drainage of a meltwater pocket occurred in August 2019. Despite hitting the village, there were no casualties on that occasion. In other conditions this could have been the case, if actions (e.g., drainage of water at the Plaine Morte Glacier, Swiss Alps; Fig. 10g) had not been planned. Some cases in the Italian Alps or in the French Alps had been tackled before the GLOFs provoked serious casualties: the Ephemeral Lake at the Belvedere Glacier, the Gran Croux Glacier Lake, the Tête Rousse Glacier endoglacial lake, and the Rochemelon Glacier ice-contact lake (Vincent et al., 2010; 2012). They are located in highly touristic areas, and were artificially drained to help control sudden natural discharge. In particular contexts like Iceland (e.g., Eyjfjallajökul Glacier; Fig. 10c), the presence of volcanoes (i.e., particular category of mountain; Gordon, 2018) creates even more dynamic ice melt and GLOFs. In this case, GLOFs (i.e., *jökulhlaup*), are characterised by particularly high energy volcanogenic glacier-outburst floods (Everest et al., 2017). The peculiar geological context (i.e., geodiversity), in such cases has a significant influence on the regulating services.

As illustrated above, LIA moraines and proglacial lakes may represent elements of sediment disconnectivity along the hydrographic network, creating complex relations between glaciers - proglacial areas - downvalley routes in terms of erosion rates and ice mass lost, with positive feedback processes (Carrivick and Tweed, 2013; Staines et al., 2015; Tweed and Carrivick, 2015).

Paroxysmal events, for instance GLOFs, may represent interference in the regular trend of sediment connectivity. According to Cavalli et al. (2019), local conditions, that can be highly complex in glacier forelands (Harbor and Warburton, 1993; Williams and Koppes, 2019; Antoniazza and Lane, 2021), could significantly affect the functional and longitudinal connectivity between geomorphic elements (see also Mancini and Lane, 2020, Buter et al., 2020), creating a situation of empowered or slowed down connectivity (i.e., hypertrophic sediment stores; Bosson et al., 2015; Messenzehl et al., 2014; Bollati and Cavalli, 2021). According to Mancini and Lane (2020), proglacial areas are complex multiscale systems where subsystems respond differently, and are able to provide secondary peaks in the paraglacial exhaustion model as proposed by Ballantyne (2002).

In general, as underlined by Carrivick and Tweed (2021), the impacts of deglaciation on sediment yields in different kinds of glaciated/undergoing deglaciation catchments may have important repercussions for nutrient cycling, carbon fluxes and natural resources management. Artificial regulation of sediment delivery or storage along streams, for instance to prevent infilling of dams, may occur. Indeed, it could also pose problems for water resources management (see 3.3), requiring specifically designed infrastructures (dams, weirs) depending on the specific features of the proglacial areas, in order to protect these important assets (Carrivick and Tweed, 2021). In some cases, actions are taken that deeply modify the physical landscape, like in the case of the Zmutt Glacier foreland in the Swiss Alps (Fig. 12b). Another crucial point concerns the precautions that need to be taken concerning the concentration and transfer of pollutants through deglaciation water (Carrivick and Tweed, 2021).

Regulating effects, which may have an influence very far from proglacial areas, may include sea level rise due to ice melt, which could lead to the progressive drowning of coastlines (Haeberli and Weingartner, 2020).

Another aspect of regulating services is linked to the soil in proglacial areas. Soils surely have the most obvious role of supporting life (see 3.2), but also provide a series of regulating ecosystem services, which were recently analysed in Alpine regions by Geitner et al. (2019), and in Himalayan regions by Prokop et al. (2021). These regulating services concern regulation of nutrient cycles, water filtration and purification, regulation of water retention and surface runoff, regulation of local and global climate. The different environmental conditions in proglacial areas indeed favour the gradual development of soil according to different space and time patterns (i.e., chronosequences, see 3.2; e.g., Temme, 2019). The onset of different geomorphological processes along the slopes (i.e., geomorphodiversity) following soil stabilisation (e.g., surface erosion) may disturb soil development (Masseroli et al., 2020), generating different trajectories of change in proglacial areas: the greater the disturbance, the less the differentiation between soils (convergence of soil properties), the smaller the disturbance, the greater the differentiation (divergence of soil properties) (Temme et al., 2015; Prokop et al., 2021), which is then reflected in soil regulating services (Prokop et al., 2021).

By considering all these aspects, hydrogeodiversity, coupled with a variety of geological, geomorphological and pedological features (i.e., geo- and pedodiversity s.l.), is a key factor in the regulating process in glacier forelands (e.g., Prokop et al., 2021). Investigating regulating services from a holistic point of view of the whole hydrographic basin, may also represent an opportunity related to geoheritage and Earth Sciences dissemination (see 3.4), linking headwater resources to alluvial plains, from high to low altitudes, thus providing a general view of the entire hydrological cycle (Testa et al., 2019).

Fig. 10. Regulating geosystem services of proglacial areas: a) Calving resulted in a tsunami that hit tourists on the shores of the glacial lake in 1996 at Miage Glacier (Western Italian Alps; source https://youtu.be/P2WsNI1fn-M); b)Triftbach stream undergoing flooding due to sudden drainage of a glacial pocket provoking a GLOF verified on 24th of July, 2019 (Zermatt, Swiss Alps; source https://youtu.be/lhGWdWH6-n8); c) Jökulhlaup linked to volcanic activity occurred in 2010 at the Eyjfjallajokul Glacier (Iceland; source https://youtu.be/il2WSmXa4CA); d) Signs of the GLOF after the 2015 earthquake that shook the area of the Dig Tsho Glacier (Everest Massif, photo courtesy of R. Bell); e) A breach in the right lateral moraine (picture taken in 1996) at the Kumbu Glacier (North-Eastern Nepal); f) GLOFs at Lake Locce occurred in 1970,1978,1979 progressively enlarged the breach in the lateral right moraine Belvedere Glacier (Italian Alps); g) artificial tunnels in the Plaine Morte Glacier (Swiss Alps) created to drain the glacier meltwater that could cause disastrous floods downvalley (source swissinfo.ch).

3.2. Supporting services

Supporting services of proglacial areas are mainly linked to soil development, habitat provisioning, burial and storage function (Fig. 7). Within high mountain areas, glacier forelands have been considered a particular biological environment (Erschbamer and Retter, 2004; Pech et al., 2007). Geodiversity has been proven to have a strong influence on biological variety (i.e., *biodiversity*; Swingland, 2001; Bussard and Giaccone, 2021). Mengist et al. (2020) underlined how mountainous areas are hot spots of half of the global biodiversity, including the occurrence of several endemic species. In particular, the expansion of proglacial areas may expose new bare surface prone to pedogenesis (e.g., Egli et al., 2006), which can be progressively colonised by vegetation (e.g., McCarthy and Luckman, 1993). As underlined by Eichel (2019) citing Jochimsen (1962), "a glacier foreland is not a desert". In any case, biological features may not have an easy life, since they could be disturbed by the intensification of geomorphic processes that affect glacier forelands (Pirola et al., 2005; Garavaglia et al., 2010b; Hart et al., 2010; Capps et al., 2011; Leonelli et al., 2019).

The response of ecosystems in proglacial areas is regulated by geomorphodiversity and water features that characterise glacier forelands (see 3.1), with feedback (Eichel, 2019). As indicated by Carrivick and Tweed (2021), sediment flux in the proglacial area, which is generally regulated by sediment connectivity, may affect the ecological equilibrium in water environments not only on the continent, but also along the sea shore. According to a detailed study by Hotaling et al. (2017), mountain glaciers and proglacial ecosystems are characterised by a diverse microbial ecology featuring the different parts of the system that exchange materials (i.e., supraglacial, englacial, subglacial and proglacial streams or forefields), resulting from the diversity of physical properties of glaciers and related forelands. According to these authors, hydrogeodiversity exerts strong control over geomorphology and ecology, also in terms of connections along the waterways (see also Carrivick and Tweed, 2021). Proglacial lakes, for example, have been recognized to be of environmental relevance for high mountain biodiversity (e.g., Čiamporová-Zaťovičová and Čiampor, 2017), like in the case of the Goletta Glacier lake (Italian Alps), as a supporting habitat for microorganisms (Fig. 11a) (Peter and Sommaruga, 2016; Hotaling et al., 2017; Tiberti et al., 2019). Considering the specific role of proglacial lakes as elements of disconnection (not only with respect to sediment delivery; Carrivick and Tweed, 2021), Tweed and Carrivick (2015) highlight their role in influencing colonisation by both humans and animals.

The dynamics of proglacial areas, including the variations discussed above and the related sediment connectivity issues, have important effects on the development of the soil (Seijmonsbergen et al., 2019), which in turn plays a supporting role in habitat provision and biodiversity (Geitner et al., 2019).

Even if the importance of soil diversity, generally defined as the variation of soil properties (usually characterised by soil classes) within an area has been demonstrated (Ibáñez et al., 1995; Mc Bratney, 1995; Mc Bratney and Minasny, 2007; Costantini et al., 2013), it is rarely considered in geodiversity studies (Ibáñez et al., 2019). In proglacial areas in particular, where “the most evident soil changes in the Alps will occur” (Egli et al., 2006), retreating glaciers progressively expose fresh rock to surface conditions. These environments, thus offer an excellent opportunity to study the evolution of soil over time. Starting from the concept of substituting space for time, it is possible to observe how time influences pedogenic processes through the study of a *chronosequence* (i.e., a group of related soils that differ, one from the other, primarily as a result of differences in time as a soil-forming factor, Glossary of Soil Science Terms, https://www.soils.org/publications/soils-glossary#).

Considering that proglacial areas s.s. are those included within the LIA edges, in the European Alps, the oldest post-LIA soils are typically less than 180 years old and hence the most common soils are skeletic, hyperskeletic or humiskeletic Leptosols and Regosols (Temme, 2019), but in some case studies, for example, in the Morteratsch Glacier foreland, Fluvisols and Cambisols have also occasionally been found (e.g., Fig. 11b, Morterasch Glacier, Swiss Alps; Egli et al., 2006), while developed Cambisols and Podzols are found outside LIA borders (Egli et al., 2001; Temme et al., 2016).

However, studies carried out in the proglacial areas show that the soil of these environments is influenced by the occurrence of geomorphological processes and that the geomorphic history, combined with the time factor, can determine an increment in soil variability (i.e., convergence and divergence of soil properties; Temme and Lange, 2014; Temme, 2019; Prokop et al., 2021;

Masseroli et al., 2022). Indeed, geomorphic processes (e.g., snow avalanches, debris flows, fluvioglacial processes), causing differences in soil stoniness, in the fine earth fraction and organic matter, may lead to different rates of soil formation and development (Pirola et al., 2005; Temme and Lange, 2014; Temme, 2019, Masseroli et al., 2022).

Temme et al. (2016) found that terrain parameters (e.g., slope steepness, aspect), representing processes of erosion and deposition, also have a significant influence on soil development. For example, in the proglacial area of the Gepatsch Glacier (Austrian Alps), soils affected by erosion had a higher pH and low organic matter contents, indicative of reset of soil development, confirming the role of geomorphic variables (Temme et al., 2016). In the Morteratsch Glacier foreland, Egli et al. (2006) found several types of soil of about the same age, underlining how the relatively slight topographic differences (e.g., slope, exposure and landform) within a glacier foreland can play a major role in determining soil properties.

The presence of different types of soil with different properties, determines the differentiation of the ecosystem services that soil can offer, as these services depend on their properties and interactions (Adhikari and Hartemink, 2016).

Soil formation also favours colonisation by organisms, even if according to relatively recent studies, these aspects have not yet been sufficiently investigated (Bradley et al., 2014; Hotaling et al., 2017). The first organisms to establish in these areas are usually microbes, able to undertake engineering actions on deglaciated terrains: a specific term is also used in the literature: *microbial geomorphology* (Viles, 2012, Miller and Lane, 2019).

Specific chronosequences of bacterial and fungal communities have recently been analyzed (Franzetti et al., 2020). Arthropod species are among the most widely studied organisms in changing proglacial areas, and are able to adapt to glacier foreland conditions. Some authors studied these dynamics in detail, especially in ground beetles (family: Carabidae, order: Coleoptera) that are among the pioneer species to colonise such environments (e.g., Gereben-Krenn et al., 2011; Gobbi et al., 2006).

Soil and bacterial and fungal communities are thus tightly linked to the development of vegetation development in proglacial areas. Mainetti et al. (2021) underlined the importance of the reciprocal feedback also between soil and vegetation: in initial stages, the vegetation plays a key role in soil formation and development, while, after soil establishment, in terms of nutrient supply and functionality, the passage between pioneer to alpine grasslands species becomes straightforward. The spatial variability of the development of proglacial soils, particularly during early stages, could hence also be relevant for biodiversity regulation, but, on the other hand, it is itself influenced by biodiversity (Burga et al., 2010; D'Amico et al., 2014; Temme, 2019). For example, in the Lys Glacier foreland (Fig. 1a, 2a, 3a, 8c), the presence of both subalpine and alpine habitats made it possible to study how different types of vegetation cover can influence soil characteristics. Under subalpine grazed grassland, a Haplic Cambisol (Dystric) formed over a period of 130 years, while above the timberline, the same taxonomic level was reached in 260 years. However, only below the timberline and under a quasi-climax Larch–*Rhododendron* forest was it possible to observe the podzolisation processes, whose rapid onset compared to other proglacial chronosequences in the Alps, seems to be more driven by vegetation properties than by specific climatic conditions. This underlines the importance of pedoclimatic and vegetation spatial variability in driving the direction of pedogenetic processes (D'Amico et al., 2014).

Concerning the shift in vegetation species, several authors (e.g., Matthews, 1992; Miller and Lane, 2019) identified the following sequence of species colonisation: *pioneer species*, *early-successional stage species*, *intermediate-successional stage species*, *late-successional tree species* and *shade-tolerant plants*. Eichel (2019) conferred average time intervals to the first four stages following deglaciation, valid for mid-latitude environments (i.e., 0-15 years, 15-40 years, 40-80 years, > 80-100 years). In particular, the first signs of herbaceous vegetation have already been observed after 1 year in the Italian Alps (Cannone et al., 2008). In general, a subtle shift in species composition within alpine plant communities takes place (Keller et al., 2005). After the first pioneer stage, in glacier forelands, the progressive establishment of vegetation until the appearance of arboreal species, has been observed and studied. In general, to reach the same stage of vegetation found in areas outside LIA borders, may require from decades to centuries (Eichel, 2019), or even millennia.

Like the soil, the dynamic proglacial environment disturbs the establishment of vegetation (e.g., Pirola et al., 2005; Garavaglia et al., 2010b; Eichel, 2019), but on the contrary, vegetation may play an active role in stabilizing such terrains (e.g., Miller and Lane, 2019; Eichel, 2019). Vegetation settlement following deglaciation is directly linked to time, soil grain size and soil moisture content, as well as snowmelt, topography and geomorphic disturbances (Matthews and Whittaker, 1987; Pirola et al., 2005; Moreau et al., 2008; Burga et al., 2010; Garavaglia et al., 2010b; Eichel, 2019; Giaccone et al., 2019). Using remote sensing validated through fieldwork, Lambert et al. (2020) assessed spatial and temporal changes in land cover, including in vegetation, in sample glacier forelands, linking the different dynamics with the different topography and geology related characteristics of proglacial areas. Reciprocal adaptation was found to occur at multiple spatial scales (Graae et al., 2018). D'Amico et al. (2017) investigated the dependence of vegetation typology on lithological composition in glacier forelands, focusing on serpentinites: aspects that linked biodiversity to lithological diversity and its variation according to glacier retreat (see 2.3). Giaccone et al. (2019; 2021) introduced morphodynamics as a variable in regression models able to explain species cover and species richness in alpine environments, studying, among others, a geomorphological system in a proglacial area.

Fig. 11. Supporting geosystem services of proglacial areas: a) Goletta Lake supporting habitat for microorganisms at the Goletta Glacier (Italian Alps; source Google Earth); b) the proglacial area of the Morterasch Glacier (Swiss Alps) where soil chronosequences were investigated by Egli et al. (2006) (source Google Earth 3D); c) vegetation colonising the proglacial area of the Ventina Glacier (Italian Alps); d) vegetation colonising the proglacial area of the Forni Glacier (Italian Alps); e) vegetation in the proglacial area of the Miage debris covered Glacier (left) and along the border of a marginal ice cliff (right) (Italian Alps).

Worthy of note is the fact that different vegetation dynamics have been observed in the case of debris-free or debris-covered glaciers.

The proglacial area of a debris-covered glacier (proglacial area of type ii, section 2.2) is more stable in terms of width, and vegetation colonises as far as the supraglacial debris environments, considered as a potential refuge (e.g., Pelfini et al., 2007; Caccianiga et al., 2011; Pelfini et al., 2012; Pelfini and Leonelli, 2014; Vezzola et al., 2016), and where an increasing trend of supraglacial vegetation growth has been recorded (e.g., Italian Alps, Pelfini and Leonelli, 2014) (Fig. 11e). While vegetation in front of the glacier snout may record fluvioglacial processes (Garavaglia et al., 2010b), on supraglacial debris, it is a sort of data logger of glacier movements (e.g., Leonelli and Pelfini, 2013). Other iconic situations exist all over the world, such as the Fairweather and Malaspina glaciers (Fickert et al., 2007), where a permanent forest grows on the glacier.

Concerning the occurrence of rock glaciers or permafrost – related landforms in proglacial areas (proglacial area of type iii, section 2.2), Brighenti et al. (2021) recently reviewed the role of rock glaciers, belonging to the group defined by the authors as the *cold rocky landforms*, as climate refugia for terrestrial and aquatic biodiversity. Due to the higher resistance to climate warming of such landforms in relation to their cool wetland environments, they act as alternative hosts for endangered species that in the nearby regions may be threatened by worsening environmental conditions.

In the case of a gradually retreating debris free glacier (proglacial area of type i, section 2.2), space is available for the gradual development of soil and for colonisation by vegetation, like for example, in the Italian Alps, in the Ventina (Fig. 11c) or Forni (Fig. 11d) proglacial areas where studies were perfomed on the time required for colonisation after deglaciation (Garbarino et al., 2010; Garavaglia et al., 2010a). In this context, arboreal colonisation took a specific time, defined *ecesi time* (*sensu* Mc Carthy and Luckman, 1993). Garavaglia et al (2010a) and Garbarino et al. (2010) summarised the results of several studies conducted around the world, using data on the *ecesi time* at regional scale: 6-30 years (Coleman Glacier, Mount Baker, USA; Heikkinen, 1984), 10-20 years (Canadian Cordillera; Mc Carthy and Luckman, 1993), 10-30 years (Morteratsch Glacier, Swiss Alps; Burga et al., 2010), 14-34 years (Ventina Glacier, Italian Alps; Garbarino et al., 2010) and 25-52 years (Forni Glacier, Italian Alps; Garavaglia et al., 2010a). The period between the deglaciation of surfaces and the establishment of arboreal vegetation can be extremely variable as a function of active geomorphological processes, which may interfere with this age-trend (e.g., Pirola et al., 2005), and of the climate and meteorological conditions (Koch and Kilian, 2005), which are particularly variable in mountain environments (e.g., Gordon, 2018; Golzio et al., 2019).

Like for soils, Miller and Lane (2019) underlined that using the age-trend approach, if considered alone i.e. without external constraints (geomorphological processes), can be unrealistic (i.e., *Interaction-based models*; Clements, 1928). Garbarino et al. (2010) and Eichel (2019), among others, suggested that a pure terrain age approach versus ages should not ignore disturbances caused by environmental factors (i.e., *Geoecological models*; Matthews, 1992). Hence, geodiversity, and in particular geomorphodiversity, as well as microclimate variations (i.e., environmental disturbance factors) can affect vegetation "chronosequence" trends (Andreis et al., 2001; Eichel, 2019).

The complex feedback between vegetation and geomorphological processes in proglacial areas can be summarised as proposed by different authors (Eichel et al. 2018; Miller and Lane, 2019; Eichel, 2019). Proglacial areas can be defined as *biogeomorphic environments* (*sensu* Corenblit et al., 2015), and a model considering the abiotic disturbance of vegetation succession and its potential as engineer species (e.g., *Dryas octopetala*), focusing on LIA moraine dynamics, was developed and subsequently improved by different authors (Gurnell et al. 2000; Corenblit et al., 2007; Eichel et al. 2018; Miller and Lane, 2019). This model can be integrated in the stages of development of lateral moraines described by Eichel et al., 2018) (see 2.4), and works as follows: *geomorphic phase* (abiotic factors completely dominant); *pioneer phase* (biotic factors present but dominated by abiotic factors); *biogeomorphic phase* (abiotic and biotic factors of relatively equal importance) and *ecological phase* (biotic factors dominant) (Miller and Lane, 2019). Sediment connectivity play a key role in this complex framework. The sequences described, which are regulated by longitudinal connectivity, can be disrupted when lateral connectivity is high, favouring mass wasting from the slopes towards the glaciofluvial plain (Gurnell et al., 2000).

Finally, the burial and storage functions are included among the supporting services provided by proglacial areas (Fig. 7). In this view, they can be seen as expressing the potential of these areas to store water and debris (see 3.3), as occurs, in the case of the Zmutt Glacier, even if human-driven (Fig. 12b), or in relation to catastrophic events (e.g., Thurwieser rock avalanche; Fig. 6).

3.3. Provisioning services

Proglacial areas are not always easily accessible areas, even though they ensure a series of provisioning ecosystem services (Fig. 7). These services are mainly linked to water supply (e.g., Liniger et al., 1998; Maurer et al., 2019) and tourism (e.g., Welling et al., 2015). Whereas hydropower production and the role as water reservoir are material services, tourism is an “immaterial” service, which is usually only included among cultural services (Gray et al., 2013). As it provides economic income to local communities, here it is also listed among provisioning services. This feature is described in more detail in the section on cultural services (see 3.4) and is a clear example of a transversal type of ecosystem service (see 4).

From a hydrological point of view, mountain environments in general are referred to as “water towers” which ensure 95% of the water provisioning of a catchment (Liniger et al., 1998). Water provisioning is related to seasonal melting of ice in glaciers, and of subsurface ice as mountain permafrost, of which the latter is an only recently investigated source (Haeberli and Weingartner, 2020). Moreover, the passage of water through proglacial areas, that act as a sort of by-pass towards down-valley, may be regulated by connectivity conditions, as discussed in detail above. The role of glaciers in water provisioning is particularly important when seasonal snow melting has run out, corresponding to the potentially the driest period of the year (Haeberli and Weingartner, 2020), or in dryer climates (Maurer et al., 2019; Grima and Campos, 2020). In these climatic conditions, specific measures are need to slow down the forecasted decrease in water (Grima and Campos, 2020). Hence, considering water production, storage and drainage towards low elevation areas, combined with the rapid increase in the demand of the population for water (Haeberli and Weingartner, 2020), the variations in glaciers accompanied by the expansion of proglacial areas worries scientists as well as society (Beniston et al., 2011; Beniston and Stoffel, 2014; Palomo, 2017; Huss and Hock, 2018). Despite the fact some authors underline the temporary benefit, to be considered on a short-time scale, from the current increase in glacier water runoff in terms of current water supply and hydropower production (Thorsteinsson et al., 2013; Gordon, 2018), the supporting effect of glaciers in summer runoff discussed above must seriously be taken into account (Haeberli and Weingartner, 2020). Moreover, exploitation of the water resource and the hydropower production have to face the problem of increasingly extreme events affecting certain climatic contexts, which will surely in a deterioration of their quality due to increasing solid discharge (Wulf et al., 2012; Schwanghart et al., 2016), as mentioned in relation to sediment connectivity (see 2.4; 3.1). Provisioning services may be deeply disturbed as a result.

Concerning proglacial lakes, as depicted above in terms of regulating services (see 3.1), they may represent risks, but also opportunities (Haeberli et al., 2016a), as they have a strong socio-environmental value, recently quantified by Viani et al. (2022) using a dedicated approach. These opportunities are related to the hydropower production and the role of proglacial lakes as water reservoirs, as well as their potential in terms of tourism (Terrier et al., 2011; Drenkhan et al., 2019). An interesting example is the Sabbione Glacier in the Italian Alps (Fig. 12a), where the hydropower plant was built in the first half of the XX century to supply electricity to the northern Piedmont area. At the same time, the Sabbione Glacier has become a very attractive tourist destination.

Fig. 12. Provisioning geosystem services offered by proglacial areas: a) exploitation of glacier melt water for hydroelectricity production and the renowned tourist destination, Sabbione Glacier (Italian Alps); b) Zmutt Glacier (Swiss Alps) with the artificial basins created to trap sediment before reaching artificial reservoirs located downvalley (source Public Commons Wikimedia); c) Locce Lake, Belvedere Glacier district with the drainage duct used to reduce the risk of GLOFs (Italian Alps, photo courtesy of A. Tamburini); d) snow-avalanche defences constructed to protect a ski resort in the proglacial area of the Montabel and Cherillon glaciers (Italian Alps, source Google Earth); e, f) Belvedere debris covered glacier (Italian Alps, photo courtesy of A. Tamburini) general view on the right, and impact of the development of the ski resort, on the left (source Google Earth); the position of Lake Locce (c) is indicated by the black line.

Exploiting provisioning services, be they material, like water resources (Fig. 12b), or immaterial like tourism (Fig. 12d, e, f) can, in certain cases, be responsible for significant human impacts in proglacial areas. On the other hand, the existence of risks can discourage exploitation of resources or travel to tourist destinations in such environments (Purdie et al., 2015) (see 3.1). In parallel with the transformation of the physical landscape, i.e. the creation of new landforms and the dismantling of old ones, that may reduce the attractiveness of the view (Diolaiuti and Smiraglia, 2010), indeed, the location of mountaineering huts (Blair Jr., 1994), alpine routes (Mourey and Ravanel, 2017; Palomo, 2017; Ritter et al., 2012; Watson and King, 2018; Mourey et al., 2019) or thematic itineraries like glaciological trails (Garavaglia and Pelfini, 2011; Comitato Glaciologico Italiano, 2017; Salim et al., 2021b) (see 3.4), are undergoing continuous changes, thus encouraging local stakeholders to run to keep up with changing landscapes and risk scenarios (Pelfini et al., 2009; Beniston and Stoffel, 2014; Pröbstl-Haider et al., 2016, Carrivick and Tweed, 2021). For instance, ongoing slope instabilities, involving paroxysmal events like the 2019 rockfall, have been threatening both the site itself and path leading to the Mutthornhűtte (Tschingel; Swiss Alps), and continuous GPS monitoring has become necessary. Changing mountaineering routes in high mountains is accompanied by an increase in objective hazards, dangers, technical difficulties and commitment, lengthening of the itinerary and of the trails to reach glacier snouts, and an increase in the effort required to climb it (Watson and King, 2018). In some cases, routes of high cultural value for alpine history have been completely destroyed (Thurwieser rock avalanche; Frattini et al., 2016; Fig. 6a, b, c; *Bonatti route* on the Petit Dru, Mount Blanc Massif, Western Alps, Mourey et al., 2019) (see 3.4).

Risks disseminating from proglacial areas can be managed through mitigation measures like lake drainage in cases like GLOFs, (Fig. 12c; f), or for snow avalanches, the building of defences at ski resorts like the famous Breuil Cervinia (Fig. 12d). The hazard deriving from excessive sedimentation rate in dams can be mitigated using extraction techniques that have a deep impact on the landscape (Zmutt Glacier; Fig. 12b): this may represent an opportunity when the extracted material is used as a georesource and could thus be considered as a second positive benefit and a real provisioning service. In this sense, especially where glaciers retreated a long time ago (i.e., LGM), but also in recent proglacial areas s.s., the quarrying of erratic boulders for building and ornamental stones, has been not regulated for centuries, threatening the survival of such important evidence of the history of the Earth (see 3.4; 4), as has occurred in many regions in the Alps (e.g., Italian Prealps) (Reynard, 2004, Motta and Motta, 2007).

3.4. Cultural services

Cultural ecosystem services are the most diversified but also the easiest to grasp, and include environmental quality, (geo)tourism and leisure, cultural, spiritual and historical meanings, artistic inspiration, social development (again tourism), Earth history & history of research, environmental monitoring and forecasting, as well as geoforensic issues (Fig. 7).

Since the end of the LIA, the exploration of proglacial areas by scientists has enabled the detection of areas that are the most suitable for use as open-air laboratories to understand the effects of deglaciation on the natural environment by the scientific community, but also by the general public (i.e., glaciological trails; Cayla, 2009; Garavaglia et al., 2012; Bollati et al., 2018; Fig. 13a, c, d). Historical glaciological trails have been gradually refurbished as cultural resources (in the European Alps Comitato Glaciologico Italiano, 2017; Salim et al., 2021b), also enriched with the help of new technologies, as game applications for kids (e.g., Pelfini et al., 2016), or immersive reality (e.g., Diolaiuti et al., 2022). Moreover, as access to proglacial areas is sometimes difficult, the participatory approach involving the collection of scientific data by mountaineering communities (e.g., Alpine clubs) is a desirable practice (Watson and King, 2018), helping scientists by periodically collecting data. These experiements have already been shown to be successful (e.g., Italian Alps, Pelfini and Leonelli, 2014; Cordillera Blanca, Carey et al., 2016). Participatory approaches can also be used to test peoples' perception of how climate change affects proglacial environments (Moreau, 2010; Garavaglia et al., 2012), while taking particular care to base activities on the specificity of each area (Garavaglia et al., 2012). Again concerning vegetation, this feature can enrich the educational content of thematic trails in glacial and proglacial environments, linking the cultural and supporting service (e.g., Pelfini et al., 2009; Garavaglia and Pelfini, 2011; see 4). Field trips to proglacial areas, which often require professional support, could become a cultural resource for local communities. Indeed, such activities may both create a provisioning service for local professionals (provisioning service), and contribute to social development, (cultural service).

Field trips also exploit the effect of landscape for well-being (Palomo, 2017) thanks to the beauty of glaciers viewed from proglacial areas, as well as that of proglacial lakes, which hence represent a psychological resource (Purdie et al., 2015). Considering the well-being to be procured in proglacial areas, outdoor activities, like hiking, alpinism and climbing, are among the preferred activities in glacier forelands. For example, climbing is common on erratic boulders in some locations in the Italian Alps (proglacial areas of the Belvedere and Brenva glaciers), and has additional cultural relevance linked to the value of erratic boulders as geohistorical evidence of past glacial stages (Reynard, 2004; Motta and Motta, 2007).

From the artistic point of view, glaciers and surrounding areas were frequently the object of attention during the Romanticism Period and some mountains are considered sacred places (Palomo, 2017; Gordon, 2018). In glacier forelands, especially during the LIA, in certain conditions, religious processions (Fig. 13e) were organized to pray to God to halt a glacier advance or prevent another type of geomorphological hazard, like at the Aurona Glacier (Italian Alps). At the Rutor Glacier (Italian Alps), Santa Margherita lake was source of several GLOFs between 1430 AD and 1864 AD causing both damage and deaths. These events led people build a chapel in 1937 to ensure protection of the area (Viani et al., 2022). Other examples related to geomorphic disasters in proglacial areas, that led ton deaths, are the commemoration of the Mattmark tragedy (1965, Allalin Glacier, Swiss Alps), and the chapel built to recall the rock-ice avalanche of the Becca di Luseney (1952; Valpelline, Italian Alps). The human perception of natural risk underlines the interdependence of regulatory and cultural services (see 4). In the present period of glacier retreat initiatives have been also used to commemorate disappearing or ‘dead’ (i.e., extinct) glaciers, and to raise awareness among the general public of climate change responsible for their disappearance (Fig. 13g). Some examples are the *Requiem for a glacier* celebration (http://paulwalde.com/projects/requiem-for-a-glacier/), the *L’adieu des glaciers* exhibition (https://www.fortedibard.it/mostre/ladieu-des-glaciers-monte-rosa-ricerca-fotografica-e-scientifica/), or the *Carovana dei ghiacciai* organized by an Italian Environmental Association in collaboration with the Italian Glaciological Committee in the last 3 years.

In general, alpinists cannot be fully aware of all the new hazards involving recently deglaciated areas (discussed in section 3.3) that raise safety issues (Pröbstl-Haider et al., 2016). These conditions further underline the importance of cultural services, informing society about natural hazards and the influence of climate change (Pelfini et al., 2009; Prosser et al., 2010; Pelfini and Bollati, 2014; Gordon, 2018), the need to start raising people's awareness already at school (Bollati et al., 2013; Pelfini et al., 2016). In this sense, proglacial areas, and mountain environments in general, represent a good opportunity, also linked to the geohistorical service offered by mountains, in turn linked to the importance of such sites in reconstructing the history of the Earth (Gordon, 2018). Due to deglaciation, previously buried bedrock features (i.e., lithology and structures), could provide new key information on the geological evolution of the area (see 2.1). A highly significant discovery was made in a study of recently ice-freed rocky outcrops in southwest Greenland, where Nutman et al. (2016) reported evidence of ancient life in 3.700-Myr-old metacarbonate rocks, whereas previous studies dated the oldest evidence of life in rocks back to 3.480 Myr. Deglaciation could also enable retrieval of evidence of past human life (i.e., geoforensic applications), as already occurred in the Italian Alps where the Ötzi Man was discovered (Fig. 13f; Kutschera and Rom, 2000), and where First World War remnants are gradually coming to light (Fig. 13h). Human migration habits could be investigated, and, as suggested by Tweed and Carrivick (2015), the presence of proglacial lakes may have favoured migration since a supply of water and the easiness of routes encouraged human exploration (see 3.2, 3.3). Although not common in the proglacial areas, buried soils can increase soil diversity of these areas, which, in turn, can provide information on past environmental conditions and on the geomorphic processes that affected the areas prior to the LIA (Hart et al., 2010). For instance, in the study by Mahaney et al. (2011) in the Schwarzensteinkees, Hornkees and Waxeckkees forelands (Austrian Alps), the presence of buried remnants of pre-LIA soils suggests pedogenic weathering in tills that most probably took place during an earlier phase of Neoglaciation (pre-LIA). These soils showed a convoluted character, indicating either cryoturbation or pushing by moraines during the LIA. More recently, the discovery of paleosols as precious remnants, made it possible to confirm the presence of conditions favouring pedogenesis on the Stolenberg Plateau (Italian Alps) already since 22.000–21.000 yr BP, labelling the area as a Lateglacial Nunatak representing one of the first documented relict non-glacial surfaces in the high-elevated European Alps (Pintaldi et al., 2021).

Fig. 13. Cultural geosystem services provided by proglacial areas: a) Interpretative panel at the lake site of the Bessanese Glacier (Italian Alps); b) Boat trip to watch glacier calving at the Perito Moreno Glacier (Argentinian Ande; source https://youtu.be/SUDkbpVdf5E; c) Field trip for members of the Italian Alpine Club along the proglacial area of the Forni Glacier (Italian Alps); d) scientific meeting in the field for members of the Italian Glaciological Committee (Miage Glacier, Italian Alps), e) religious procession at the Mittelberg Glacier (Austrian Alps) to slow down the glacier advance (drawing by H. Wieland, 1898); f) Val Senales Glacier (Italian Alps) where Ötzi remnants were retrieved (source https://youtu.be/d2n_3Ya3wHs); g) Okjokull Glacier (Iceland) where a commemoration plaque was set up during the funeral held for the glacier in summer 2019; h) Ortles Cevedale Massif (Italian Alps) and the First World War remnants (source https://youtu.be/N2SuJTchxYg).

4. The correlation linking geodiversity, geosystem services and geoheritage

Mountain regions are significantly diverse and, to summarize, at least two forms of geodiversity extrinsic (between different mountain regions) and intrinsic (within the same mountain area/region) (*sensu* Panizza, 2009) can be identified. In both cases, the analysis and comparison of results among the elements can be challenging due to the complexity of their dynamics (Barsch and Caine, 1984). The geodiversity of proglacial areas has emerged in relation with variability of relief and slope aspect, bedrock outcrops and degradation, genesis and development of landforms due to different kinds of processes, and pedological processes that are interrelated with biological elements. Hence, the system comprised by glaciers and their related forelands is complex and intrinsically diverse, including articulated interactions (i.e., intrinsic geodiversity; Panizza, 2009). Moreover, according to Zasadni (2007), glacier forelands are "clearly different from the surrounding areas in respect to geomorphic setting, pedological characteristics, floristic succession and the degree of weathering" (i.e., extrinsic geodiversity; Panizza, 2009). What emerges from the cases presented here, is that these regions can be defined as geodiversity hotspots (sensu Bétard and Peulvast, 2019): "the richest – or "geodiverse" – and most endangered areas of a given territory or geographical zone at a chosen scale (regional, national, continental or global)".

As shown in section 3, several geosystem services are provided by proglacial areas s.l., and they are tightly linked with the different kinds of diversity discussed throughout this text (bedrock diversity, geomorphodiversity, hydrogeodiversity, pedodiversity). These diversities have different weights when it comes to influencing the families of geosystem services (Table 1). Hydrogeodiversity emerges as the most influential, followed by geomorphodiversity.

Geosystem services	*Regulating*	*Supporting*	*Provisioning*	*Cultural*
Type of diversity				
Bedrock diversity	X	X	X	X
Hydrogeodiversity	XXX	XX	XXX	XX
Geomorphodiversity	XXX	XX	XX	XX
Pedodiversity	XX	XXX	X	X

Table 1 Weight of diversity types in proglacial areas in influencing geosystem services. The number of crosses (1 to 3) represents a qualitative degree of influence.

According to several authors (e.g., Schiefer and Gilbert, 2007; Staines et al., 2015; Carrivick and Heckmann, 2017; Bollati et al., 2018), proglacial areas are natural open-air laboratories where the investigation of geomorphic dynamics is ideal for different reasons, among others, the scarce vegetation cover, and the highly textured nature of recent glacial deposits. These areas are thus potentially complex landforms/landscapes in evolution (Lane et al., 2017; Harbor and Warburton, 1993; Coratza et al., 2021), where it is possible to detect geodiversity or geoheritage sites (*sensu* Brilha, 2016), characterised by scientific and other values (aesthetic, cultural and socio-economic), as well as a potential for relevant use (Bollati et al., 2017b).

Considering the dynamic geodiversity approach proposed by Zwoliński (2009), and according to the classification proposed by Prosser et al. (2010) for geoheritage sites, proglacial areas can be labelled *active process sites*, specifically distinguished by "their unique characteristics in terms of their likely responses to climate change". Following the classification proposed by Pelfini and Bollati (2014), proglacial geomorphological systems are also potentially complex active or evolving passive sites of geomorphological interest, have previously undergone glacial processes, and are currently mainly affected by gravity- and water-related processes. Prosser et al. (2010) called for maintaining the capacity of active processes to evolve naturally at these both active and evolving sites.

These complex geodiversity hotspots (*sensu* Bétard and Peulvast, 2019), provide geosystem services that can be translated into the attributes usually used to assess geoheritage sites (i.e., Grandgirard, 1999; Pelfini and Smiraglia, 2003; Brilha, 2016; Bollati et al., 2017b; Reynard and Coratza, 2016). Since several methodologies are used to assess geoheritage sites (Brilha, 2016), the one used in this discussion is that of Bollati et al. (2017b), who defined the values based on a literature analysis. These values (*scientific value, additional values* and the *potential for use*) are used to define their relationships with geosystem services (see section 3), as depicted in figure 14.

The *scientific value* of proglacial areas is comparable with the intrinsic value identified for mountain regions in general by Gordon (2018). It is also linked to the importance of such areas for monitoring the effects of climate change on the relief and on the evolution of the bedrock (i.e., regulating and cultural services; Fig. 14). As also outlined by Carrivick and Heckmann (2017), and stated above, proglacial areas demonstrated to be key sites are of high educational value (Garavaglia and Pelfini, 2011; Bollati et al., 2013) for the investigation of active geomorphological processes that can be mapped and quantified over short period (i.e., 3.1; 3.4; Fig. 14). Carrivick and Tweed (2016) also underlined the scientific importance of the roles of glacial lakes and paleolakes, among others, as current and paleo environmental indicators, and several are also examples of soils featuring such areas (see 3.4).

Among scientific value criteria, the *intrinsic geodiversity* of proglacial areas has been demonstrated to be high, as well as *rare*, also because, in some cases, particular geomorphological and hydrodynamic processes favour the growth of specific biological features (see 3.2; Fig. 14). Indeed, the *ecologic support role* (Pelfini and Gobbi, 2005; Garavaglia et al., 2010a; Pelfini et al., 2010; Bollati et al., 2015; Bussard and Giaccone, 2021) is also important (see 3.2). However, the *integrity* of glacier forelands could rather be deeply mined by internal or external processes, be they natural (see 3.1; Fig. 14) or, even if limited, of human origin (see 3.3; 3.4; Fig. 14)

Additional values of geoheritage sites are related to *cultural* aspects connected to immaterial cultural services (e.g., tourism, knowledge), and to the association of sites with cultural assets like human settlements (Fig. 14). Additional values include the *aesthetics* of the landscape, which is also classified among cultural geosystem services (Fig. 14). Aesthetic value is related to the beauty of the landscape, often associated to glacier morphologies, contrasted colouring, and the endemic species that colonise these areas. *Socio-economic* opportunities are classified as additional values of geoheritage sites, and, in proglacial areas, have been described mainly as provisioning geosystem services (e.g., supplying water and earth materials, opportunities for tourism; Fig. 14; Viani et al., 2022).

The *potential for use* is linked with opportunities for geotourism. The *spatial* and *temporal accessibility* of sites, depending on relief and (active) geomorphological processes (see 3.1; Fig. 14), may raise issues since glacier forelands are often remote areas, reached after several hours of walking and requiring good physical condition, thereby limiting the number of tourists. For the same reason, the remoteness of services related to the shape of the relief (see 3.1; Fig. 14) represents a limitation to the potential use of such areas. Also possibly related natural hazards may raise some concerns (Bollati et al., 2013; 2015; Purdie et al., 2015). Further, if proglacial areas are located in protected areas, appropriate behaviour is required of those who enter them, to ensure conservation of geodiversity and biodiversity (see 3.2; Fig. 14). From a positive point of view, *sport activities* (hiking, alpinism, climbing) aimed at well-being (see 3.4; Fig. 14), are favoured, making it possible to visit amazing landscapes, while bearing in mind ongoing changes to access routes (Mourey et al., 2019; Watson and King, 2018). The *visibility* of glacier forelands is thus linked to their aesthetic value (see 3.4; Fig. 14), favoured by the scarcity of arboreal vegetation and human impact. Finally, if the glacier forelands are connected along glaciological and/or multidisciplinary trails linking other geoheritage sites in the surrounding, the potential for use increases, along with that of cultural services (Fig. 14).

Hence, although these areas may be considered as complex and valuable geoheritage sites, the balance between scientific/educational value and risk scenarios may be very delicate, and requires detailed analysis before projects are made concrete (Pelfini and Bollati, 2014). In such cases, or when proglacial areas are very remote (see *potential for use*), virtual tools are a valid alternative to promote the richness of these areas, as already demonstrated in several situations (e.g., in the French Alps, Ravanel et al., 2014; Iceland, Pasquarè Mariotto and Bonali, 2021; Italian Alps, Diolaiuti et al., 2022).

Figure 14, summarises all the illustrated mutual relations among the geosystem services (regulating, supporting, provisioning and cultural) and the attributes used for the definition and assessment geoheritage sites (scientific value, additional values, potential for use).

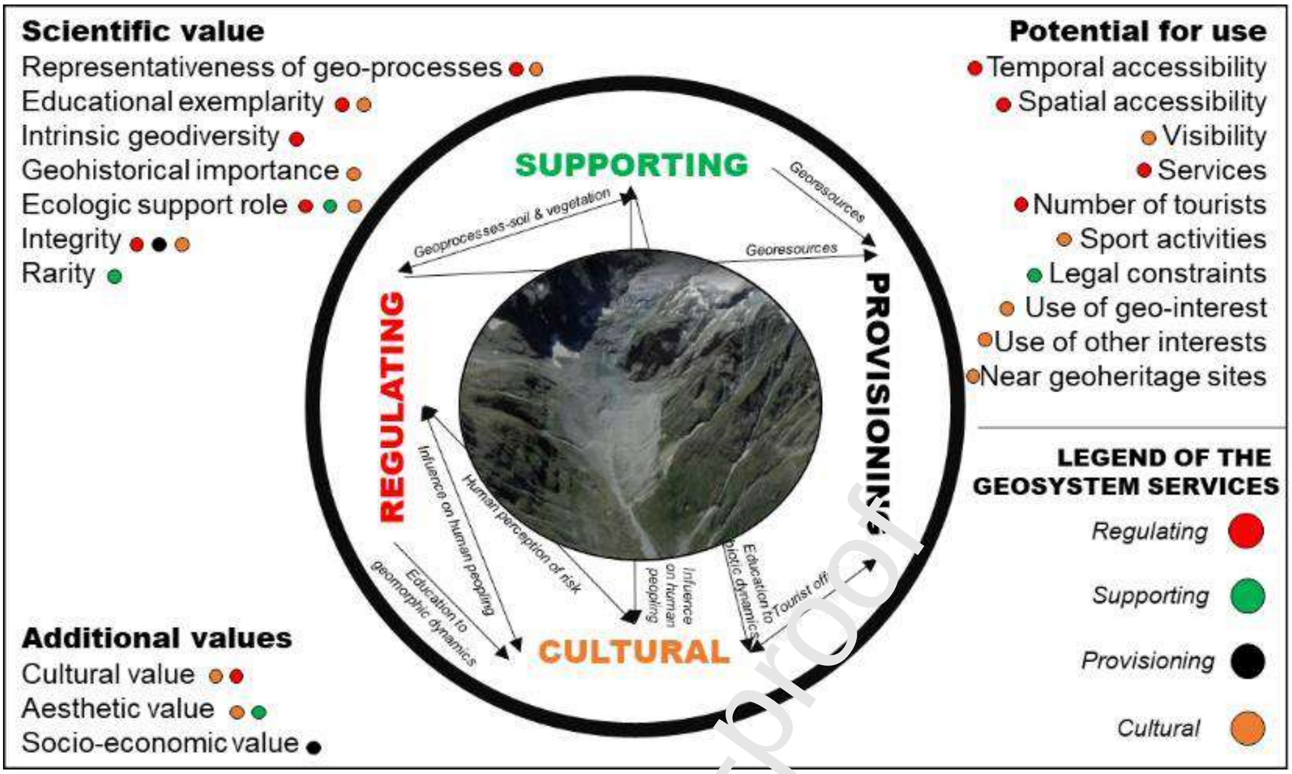

Fig. 14. Ecosystem services provided by the geodiversity of proglacial areas, their interrelationships and their relationships with the attributes used to assess the value of the geoheritage sites. The latter were modified from Bollati et al. (2017b). In the central circle the Mont Miné Glacier foreland, Swiss Alps (source Google Earth 3D).

5. Concluding remarks

While glaciers have been defined as vanishing geoheritage sites (Diolaiuti and Smiraglia 2010; Bosson et al., 2019), proglacial areas are currently evolving complex geoheritage sites, characterised by significant geodiversity s.l., extremely dynamic in space and time (Zwolińsky, 2009; Diolaiuti and Smiraglia, 2010; Garavaglia et al., 2010a). These dynamics and evolution trends require continous monitoring and careful management (Prosser et al., 2010; Pelfini and Bollati, 2014). Glacier forelands are both fragile and vulnerable (i.e., geodiversity hot spots *sensu* Bétard and Peulvast, 2019), and should be studied using a holistic approach combining different types (abiotic and biotic) of indicators (Seijmonsbergen et al., 2019). This review highlights a need to continue investigating these highly sensitive proglacial systems (i.e., landscape sensitivity *sensu* Brunsden, 2001), according to the progressive variations in the factors that regulate the response of proglacial systems to resisting and disturbing forces. These forces may in fact affect the geosystem services provided by proglacial areas (see section 3; Fig. 7 and 14), as well as their intrinsic value, scientific, additional and potential for use as elements of geoheritage (see section 4; Pelfini and Bollati, 2014; Bollati et al., 2017b; Gordon, 2018).

To go into a little more detail, since proglacial areas probably represent geodiversity hotspots, in the framework of the potential natural and human-derived degradation of such regions, their sensitivity should be assessed by developing specific degradation indexes, of which some examples are available in the literature for both geodiversity or geoheritage sites (e.g., *Threat Index* by Bétard and Peulvast, 2019; *Degradation Risk Index*, by Selmi et al., 2022). When this is achieved, glacial, paraglacial and periglacial dynamics should be even more investigated, long with the response of the biological compartment of the ecosystems, including the often neglected pedological interface (Bradley et al., 2014; Hotaling et al., 2017). Multi-temporal mapping to monitor changes in glacier forelands (as depicted by Ballantyne, 2003) could become a more frequent practice, since the resulting thematic maps could also be used for territorial planning (Coratza et al., 2021).

According to Palomo (2017), overlooked topics include analysis of the effects of variation in geosystem services on local communities, from which emerges the need for involving them in studying the impacts of glacial and proglacial dynamics. This could suggest the need to boost participatory approaches aimed at studying high mountain environments related to deglaciation (Pelfini and Leonelli, 2014; Carey et al., 2016; Watson and King, 2018).

Studies of low latitude proglacial systems are also urgently needed (Palomo, 2017; Grima and Campos, 2020; Azzoni et al., 2017; 2022; Baldasso et al., 2019), as climate change may seriously compromise such morphoclimatic environments in the near future.

In conclusion, due to the climate-related processes (in some cases triggered by human intervention) that affect these vulnerable and fragile geodiversity hotspots, which are part of our cultural heritage (i.e., geoheritage), even more attention is called for in the framework of geoconservation and management strategies (Prosser et al., 2010), starting from a geosystem services approach (Mengist et al., 2020).

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Declaration of interests

☒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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Highlights

- Proglacial areas are featured by a great geodiversity
- Geodiversity of proglacial areas depends on water, rocks, landforms and soils
- Geodiversity influences biodiversity in proglacial areas
- Proglacial areas provide geosystem services in virtue of their geodiversity
- Proglacial areas are geoheritage elements to be preserved and promoted

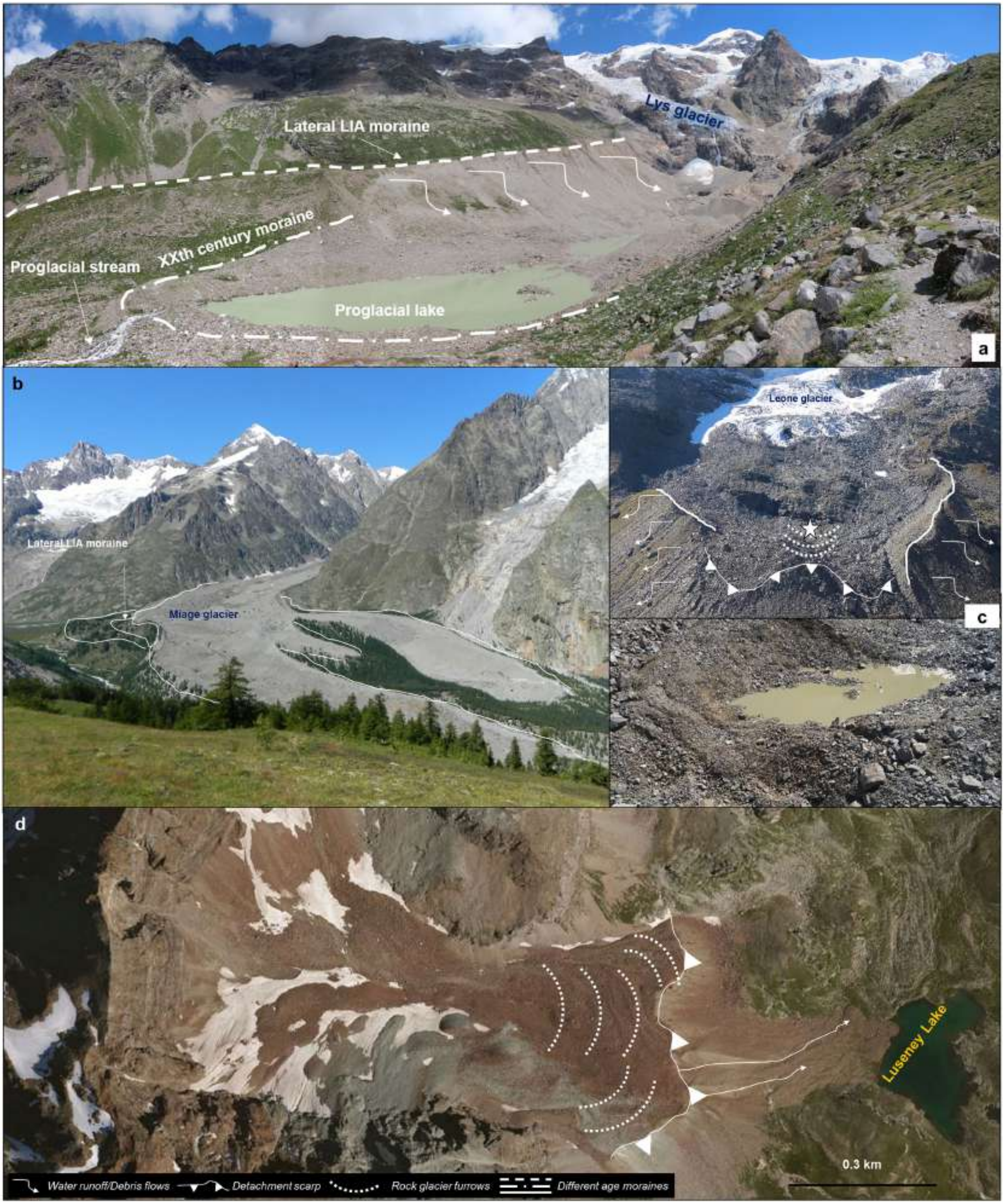

Lateral LIA moraine
Lys glacier
XXth century moraine
Proglacial stream
Proglacial lake
a
b
Lateral LIA moraine
Miage glacier
Leone glacier
c
d
Luseney Lake
0.3 km
Water runoff/Debris flows
Detachment scarp
Rock glacier furrows
Different age moraines

Figure 1

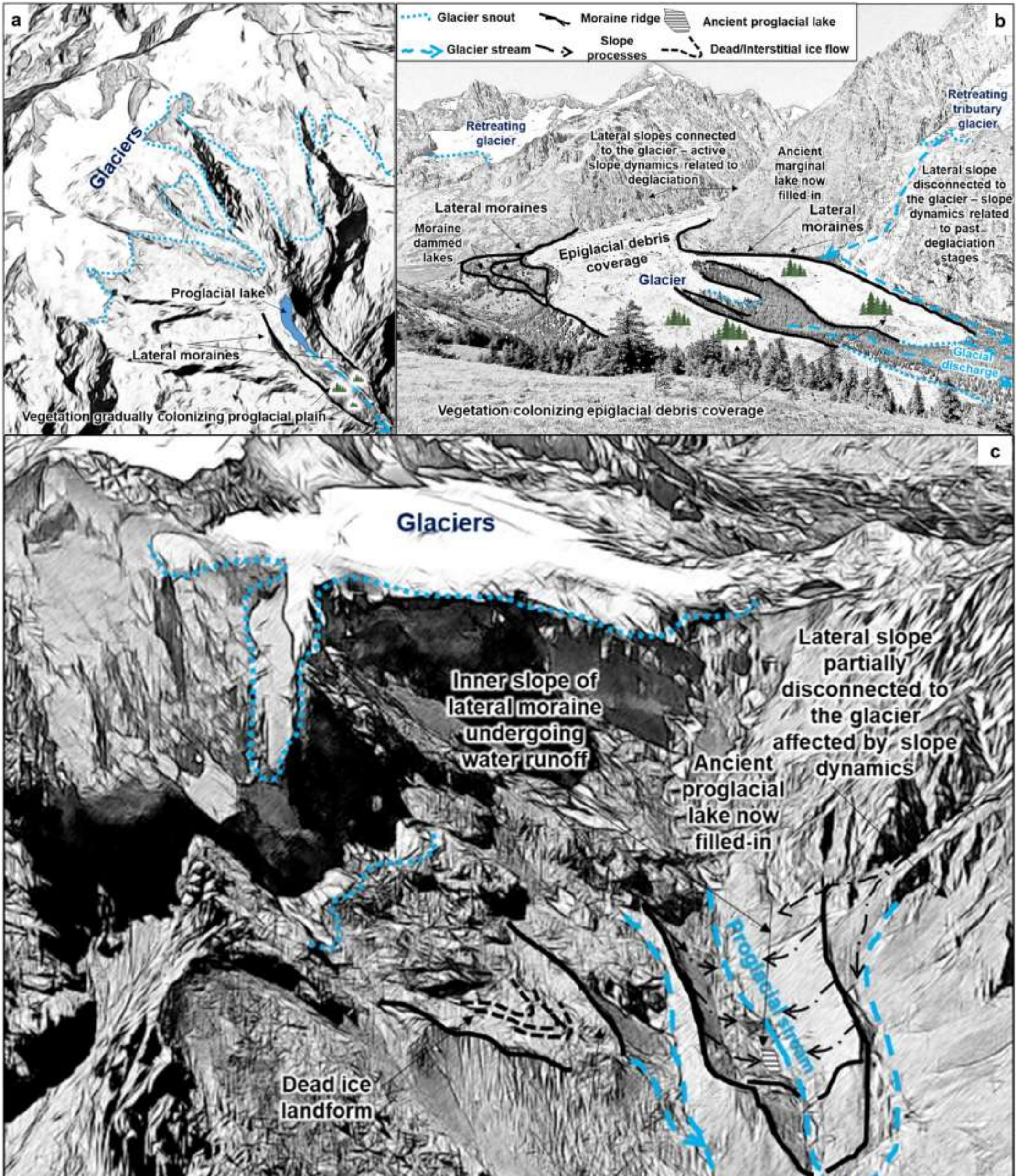

a
Glaciers
Proglacial lake
Lateral moraines
Vegetation gradually colonizing proglacial plain
Glacier snout
Moraine ridge
Ancient proglacial lake
Glacier stream
Slope processes
Dead/Interstitial ice flow
b
Retreating glacier
Lateral slopes connected to the glacier – active slope dynamics related to deglaciation
Ancient marginal lake now filled-in
Retreating tributary glacier
Lateral slope disconnected to the glacier – slope dynamics related to past deglaciation stages
Lateral moraines
Moraine dammed lakes
Epiglacial debris coverage
Glacier
Lateral moraines
Glacial discharge
Vegetation colonizing epiglacial debris coverage
c
Glaciers
Inner slope of lateral moraine undergoing water runoff
Lateral slope partially disconnected to the glacier affected by slope dynamics
Ancient proglacial lake now filled-in
Proglacial stream
Dead ice landform

Figure 2

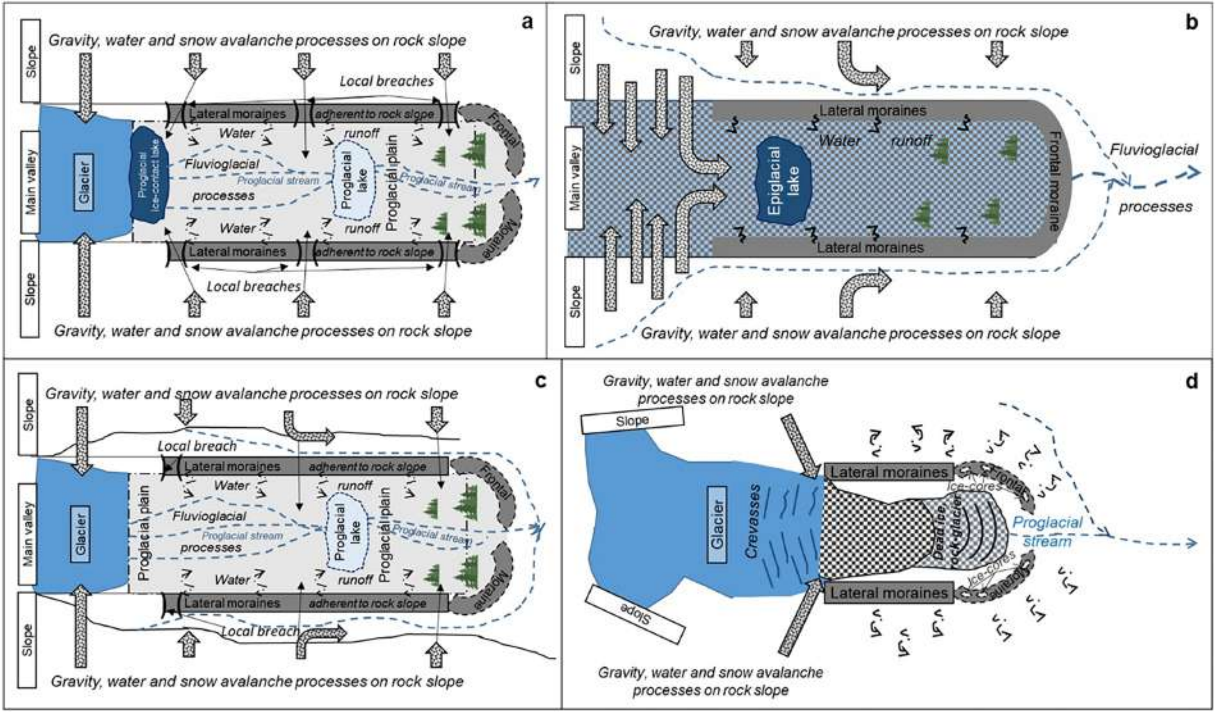

a
Gravity, water and snow avalanche processes on rock slope
Slope
Main valley
Slope
Glacier
Proglacial ice-contact lake
Local breaches
Lateral moraines
adherent to rock slope
Water
runoff
Fluvioglacial
Proglacial stream
processes
Proglacial lake
Proglacial plain
Frontal
Moraine
b
Fluvioglacial
processes
Epiglacial lake
Frontal moraine
c
Local breach
Proglacial plain
d
Crevasses
Dead ice
rock-glacier
Ice-cores
Proglacial stream

Figure 3

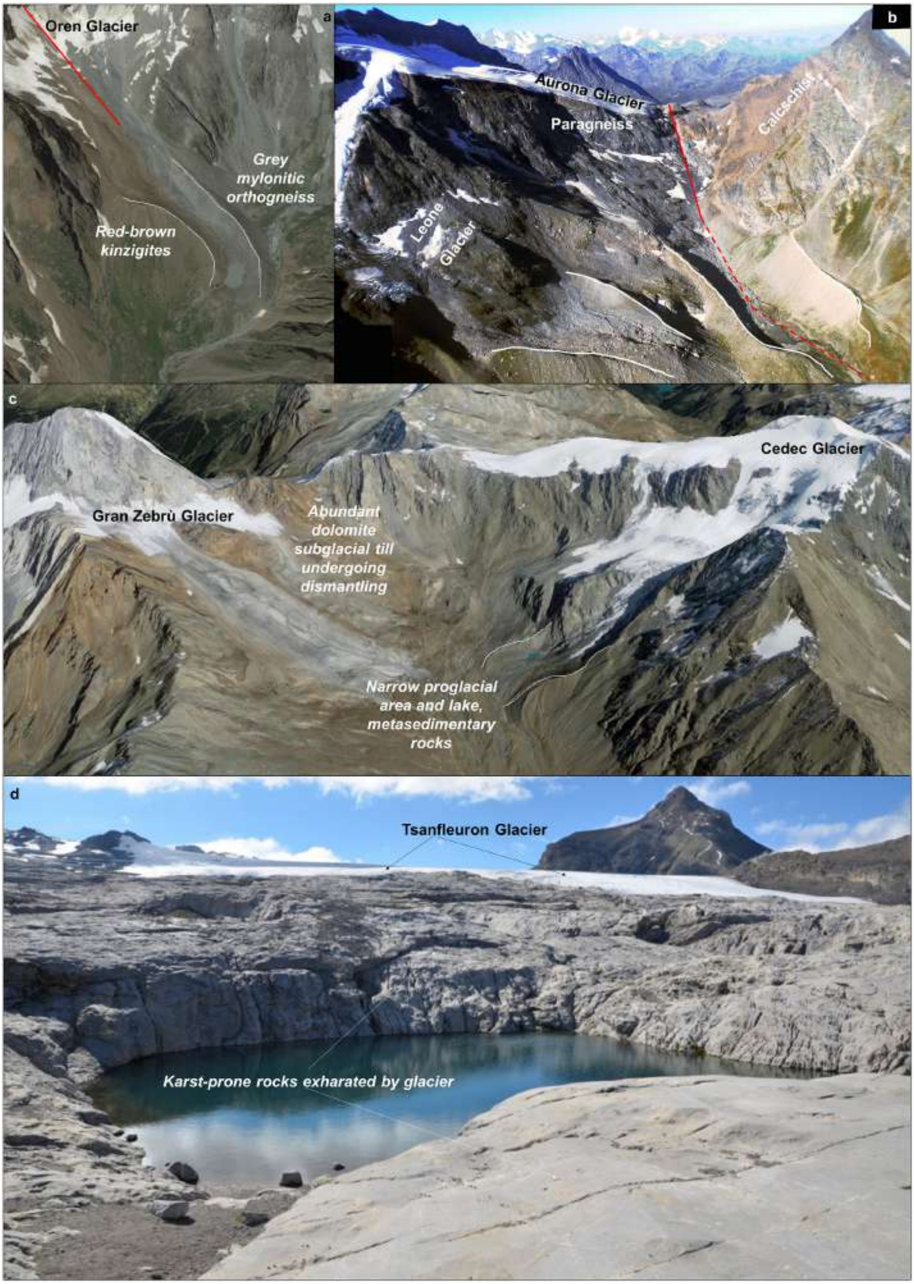

a
Oren Glacier
Grey mylonitic orthogneiss
Red-brown kinzigites
b
Aurona Glacier
Paragneiss
Calcschist
Leone Glacier
c
Gran Zebrù Glacier
Abundant dolomite subglacial till undergoing dismantling
Cedec Glacier
Narrow proglacial area and lake, metasedimentary rocks
d
Tsanfleuron Glacier
Karst-prone rocks exharated by glacier

Figure 4

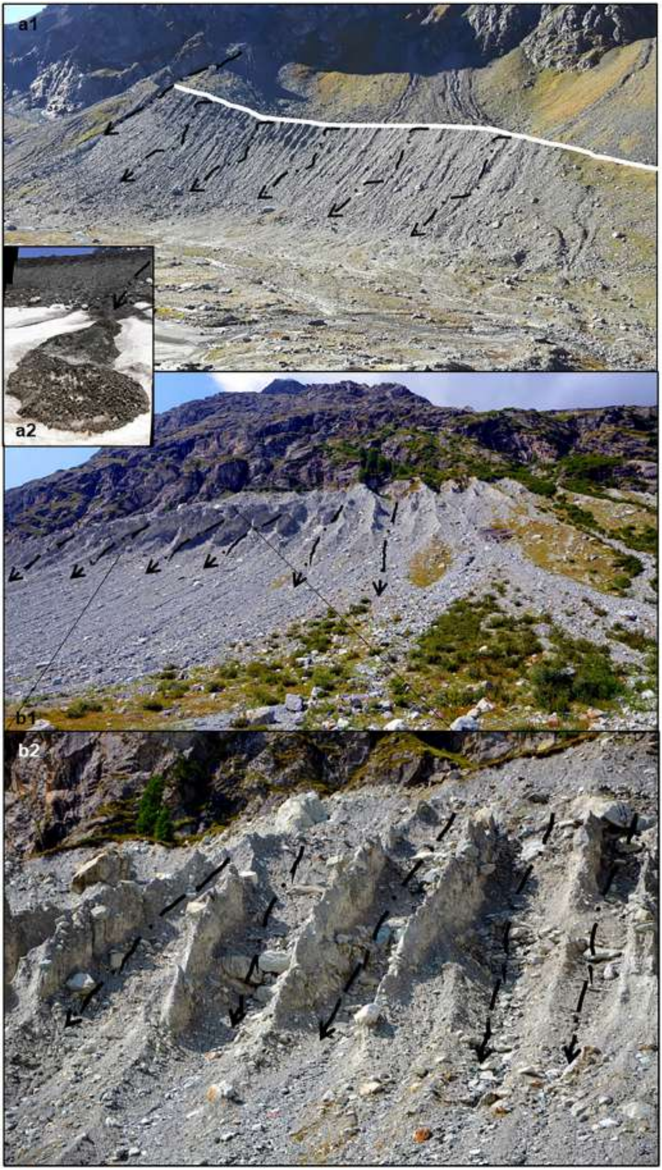


Figure 5

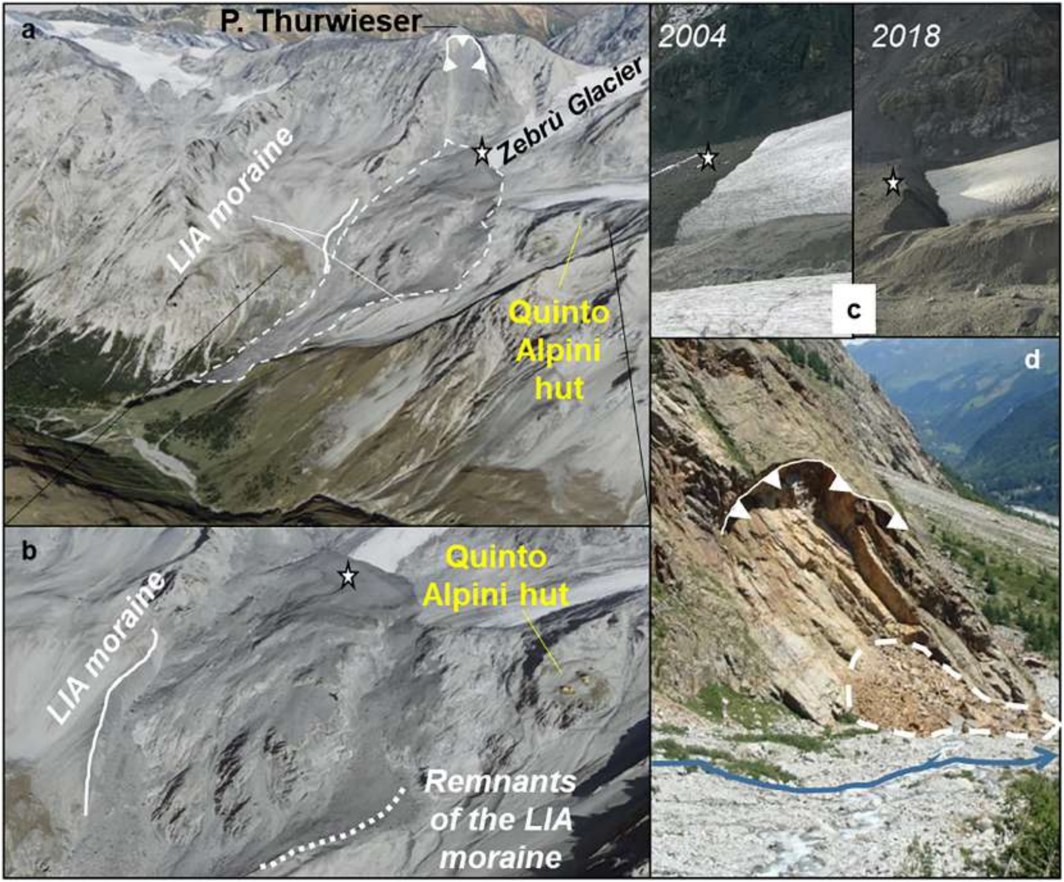

a
P. Thurwieser
Zebrù Glacier
LIA moraine
Quinto Alpini hut
b
LIA moraine
Quinto Alpini hut
Remnants of the LIA moraine
2004
2018
c
d

Figure 6

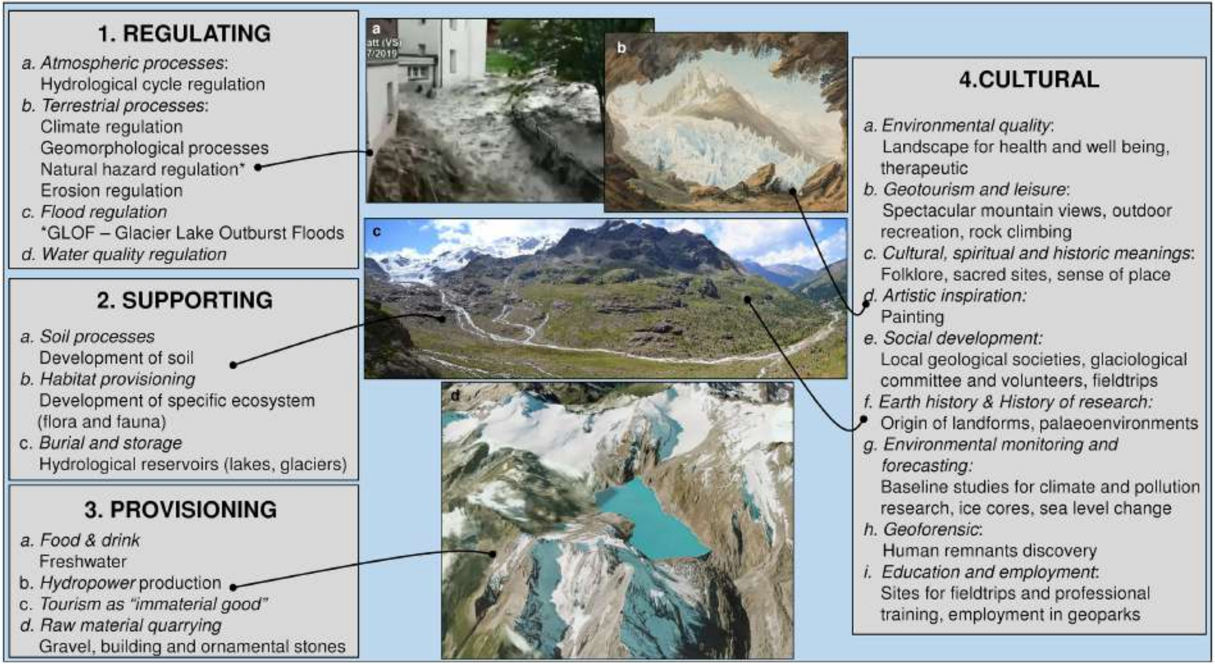

1. REGULATING
a. Atmospheric processes:
Hydrological cycle regulation
b. Terrestrial processes:
Climate regulation
Geomorphological processes
Natural hazard regulation*
Erosion regulation
c. Flood regulation
*GLOF – Glacier Lake Outburst Floods
d. Water quality regulation
2. SUPPORTING
a. Soil processes
Development of soil
b. Habitat provisioning
Development of specific ecosystem
(flora and fauna)
c. Burial and storage
Hydrological reservoirs (lakes, glaciers)
3. PROVISIONING
a. Food & drink
Freshwater
b. Hydropower production
c. Tourism as "immaterial good"
d. Raw material quarrying
Gravel, building and ornamental stones
a
att (VS)
7/2019
b
c
d
4.CULTURAL
a. Environmental quality:
Landscape for health and well being, therapeutic
b. Geotourism and leisure:
Spectacular mountain views, outdoor recreation, rock climbing
c. Cultural, spiritual and historic meanings:
Folklore, sacred sites, sense of place
d. Artistic inspiration:
Painting
e. Social development:
Local geological societies, glaciological committee and volunteers, fieldtrips
f. Earth history & History of research:
Origin of landforms, palaeoenvironments
g. Environmental monitoring and forecasting:
Baseline studies for climate and pollution research, ice cores, sea level change
h. Geoforensic:
Human remnants discovery
i. Education and employment:
Sites for fieldtrips and professional training, employment in geoparks

Figure 7

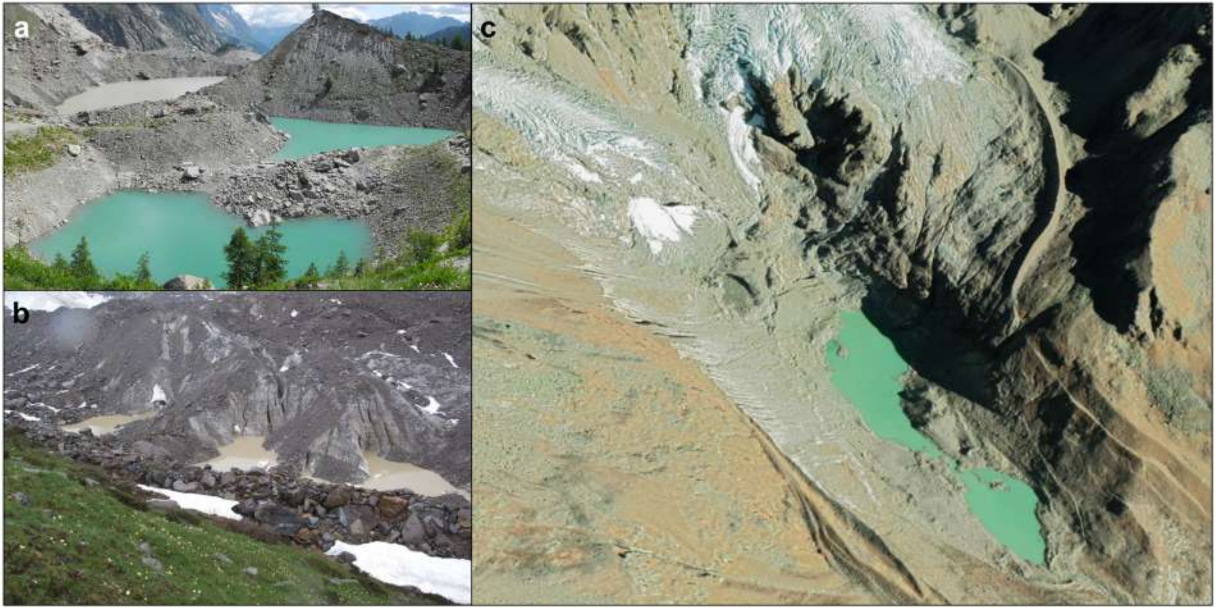


Figure 8

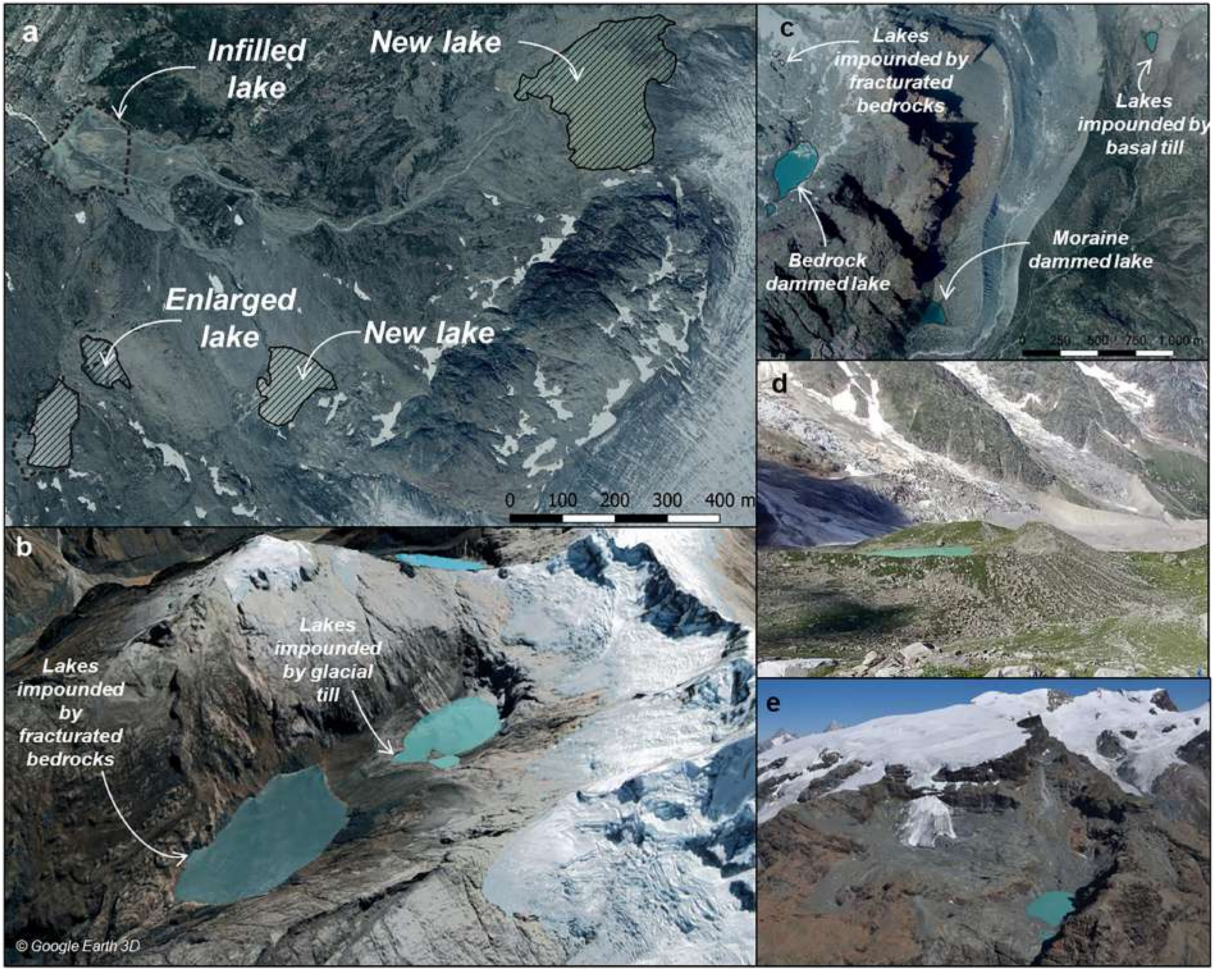

a
Infilled lake
New lake
Enlarged lake
New lake
0 100 200 300 400 m
b
Lakes impounded by fracturated bedrocks
Lakes impounded by glacial till
© Google Earth 3D
c
Lakes impounded by fracturated bedrocks
Lakes impounded by basal till
Bedrock dammed lake
Moraine dammed lake
0 250 500 750 1,000 m
d
e

Figure 9


TRAGEDIA GHIACCIAIO MIAGE
a
RAIDUE
Tg2
0:14 / 1:11
b
V•A
0:00 / 0:29
Glacial outburst flood at Eyjafjallajokull volcano, Iceland
c
John Seach
0:04 / 0:13
d
e
f
g
SWI

Figure 10

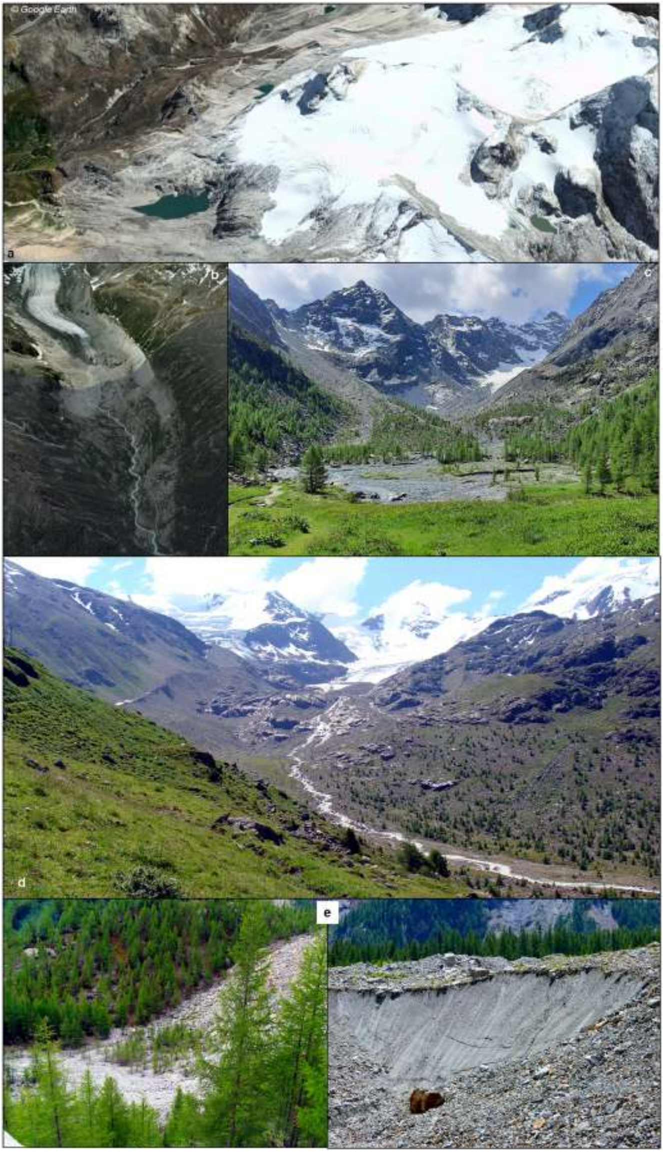
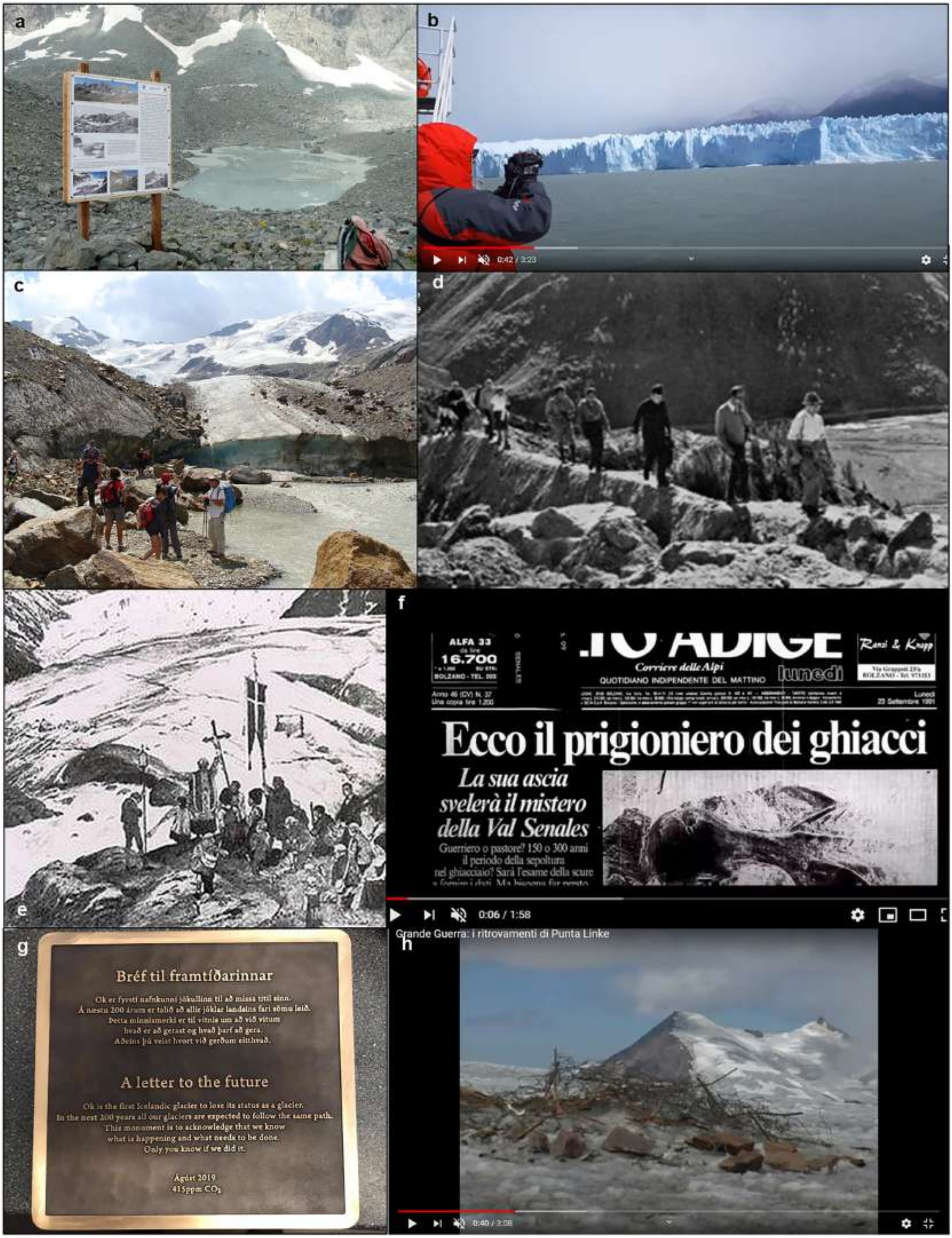


Figure 11

Figure 12



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Ecco il prigioniero dei ghiacci

La sua ascia svelerà il mistero della Val Senales

Guerriero o pastore? 150 o 300 anni il periodo della sepoltura nel ghiacciaio? Sarà l'esame della scure a fornire i dati. Ma bisogna far presto

Bréf til framtíðarinnar

Ok er fyrsti nafnkunni jökullinn til að missa titil sinn.
Á næstu 200 árum er talið að allir jöklar landsins fari sömu leið.
Þetta minnismerki er til vitnis um að við vitum
hvað er að gerast og hvað þarf að gera.
Aðeins þú veist hvort við gerðum eitthvað.

A letter to the future

Ok is the first Icelandic glacier to lose its status as a glacier.
In the next 200 years all our glaciers are expected to follow the same path.
This monument is to acknowledge that we know
what is happening and what needs to be done.
Only you know if we did it.

Ágúst 2019
415ppm CO_2

Figure 13

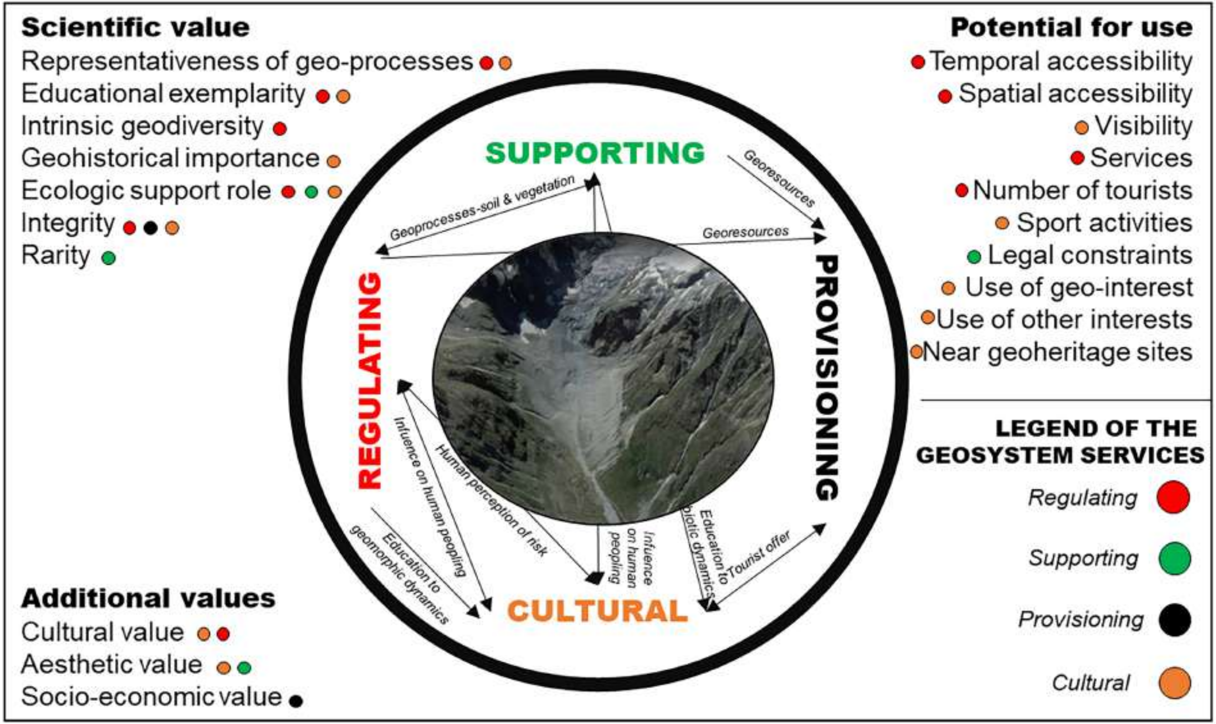
Scientific value
Representativeness of geo-processes
Educational exemplarity
Intrinsic geodiversity
Geohistorical importance
Ecologic support role
Integrity
Rarity
Potential for use
Temporal accessibility
Spatial accessibility
Visibility
Services
Number of tourists
Sport activities
Legal constraints
Use of geo-interest
Use of other interests
Near geoheritage sites
SUPPORTING
Geoprocesses-soil & vegetation
Georesources
Georesources
REGULATING
PROVISIONING
Infuence on human peopling
Human perception of risk
Education to geomorphic dynamics
Infuence on human peopling
Education to biotic dynamics
Tourist offer
CULTURAL
LEGEND OF THE GEOSYSTEM SERVICES
Regulating
Supporting
Provisioning
Cultural
Additional values
Cultural value
Aesthetic value
Socio-economic value

Figure 14