

Review

Geosites and Climate Change—A Review and Conceptual Framework

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Abstract: Geosites are windows into the geological past, which may be recorded in rocks and their properties, the fossil content, and landform produced by processes no longer operating. Since the histories of sedimentation, life, and landscape evolution are to a certain extent controlled by climatic conditions, some geosites may be used as illustrations of various themes linked to the issue of climate change. In this paper, a coherent systematic framework is proposed for how to look at geosites through the lens of climate change. Four major aspects of relevance are recognized: (i) geosites providing evidence of changing climatic conditions in the past; (ii) geosites providing evidence of an environment different than that of today at the place; (iii) geosites providing evidence of extreme weather events; and (iv) dynamic geosites, subject to change as a response to ongoing climate change. The use of geosites to raise awareness and educate the public about climate change faces various interpretation challenges. In particular, linking with ongoing climate change requires caution and balanced presentation as most geosites record changes which occurred without any anthropogenic component. The preferred focus should be on environmental instability in general rather than on any specific reasons for change.

Keywords: geoheritage; climate change; climate record; geo-interpretation; geosite classification



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1. Introduction

Geoheritage usually refers to the part of geodiversity which is considered of particular value and, therefore, should be protected to ensure that it is passed on to the future generations with minimal harm. Thus, whereas geodiversity is an all-inclusive term, denoting the natural range of geological (rocks, minerals, fossils), geomorphological (landforms, topography, physical processes), soil, and hydrological features, including all spatial and functional relationships between them [1], only specific localities (areas, sites) are considered as having the attributes of geoheritage [2]. These are referred to as geosites [3,4]. The reasons behind the value conferred to these selected localities can be different and not mutually exclusive. Scientific value is of primary importance and its recognition emerges from ongoing research performed at these sites, documented in scientific publications [4–7]. Consequently, geosites are windows into the past, informing us about conditions in the interior of the Earth, past marine and terrestrial environments, record of life, and processes shaping the surface of the planet. However, they may also play an important educational role, bringing the geological past to the public and helping us to understand the environment. Although scientific and educational values are closely related, not all scientifically important sites are suitable to develop for educational purposes, as specific site conditions may preclude their use in outdoor teaching (e.g., fragility of the site, difficult access and associated safety issues, remoteness of location, ongoing industrial operations, or simply the clarity of relevant geological features) [4]. Geoheritage sites may also have aesthetic value, which contributes to their appreciation by the general public even if scientific value is ignored, and be associated with biodiversity and cultural heritage values, e.g., [5,8–11].

This general understanding of geosites hides their diversity, which is evident in respect to both size, ranging from single outcrops to large-scale geomorphological units [12,13], the latter best appreciated from designated viewing points [14], and the main theme represented. Perhaps the most comprehensive was the classification by Ruban [15], who followed the classic subdivision of Earth sciences and distinguished as many as twenty-one types: stratigraphic, palaeontological, sedimentary, igneous, metamorphic, mineralogical, economic, geochemical, seismic, structural, palaeogeographical, cosmogenic, geothermal, geocryological, geomorphological, hydrological and hydrogeological, engineering, radio-geological, neotectonic, pedologic (soil), and geohistorical. However, this author was clearly aware himself that more than one theme can be represented at a locality and, indeed, any attempts to rank the themes in order of importance (e.g., main and ancillary themes; see e.g., [16]) are problematic.

An ongoing interest in climate change and its immediate and forecasted long-term effects on the environment allows for an alternative look at the diversity of geosites, from the perspective of climate-related changes in the geological and geomorphological record. This is because various themes highlighted in traditional classifications can be linked to climate change. In addition, looking at geosites through this lens could be particularly useful for the evaluation of the educational aspects of geosites, given the increasing societal awareness of climate change issues and their incorporation into formal and informal education [17–20]. It is also relevant to observe that geoparks, whether associated with the UNESCO Global Geopark Network (UGGp(s) further on) or beyond the network, now have a strong focus on this topic and explore various possibilities to spread the message about climate change [21–23]. As geopark activities are largely based on the network of designated and managed geosites, these are the obvious localities to be used to disseminate knowledge and raise awareness.

Consequently, the principal aim of this paper is to offer a look at geosites from the perspective of climate change and weather-related events. Specifically, the issues presented include the following: (i) the diversity of the record of past and sub-recent climate change at geosites (Sections 2–5); (ii) educational opportunities and challenges (Section 6); and (iii) a proposal for how to relate the focus on climate change to a more traditional thematic classification of geosites (Section 7). The examples chosen to support the presentation are inevitably selective, and it is not implied that they are the best or the only ones of their kind.

2. The Nature of Record of Climate Change—Relevance to Geosites

The evidence of climate change in the geological past is primarily contained in three types of archives, which can be represented as geosites. These are the sedimentary record involving both solid rocks and non-lithified deposits, fossil record contained in these rocks and deposits, and landform record. However, the nature of the record in each archive is also variable, and the ability to read it while visiting a relevant geosite varies widely. In certain cases, the evidence is obvious, even to casual visitors, while in other situations, it may be very subtle or invisible and must be aided by advanced interpretation.

2.1. Rocks

The sedimentary record encompasses all those cases where a change in the lithology or specific properties of the rock within a stratigraphic profile can be linked with climate change. Thus, this archive is restricted to sedimentary rocks and unconsolidated deposits, although if the metamorphism of primary sedimentary rock was weak (low-grade), deciphering primary environments may also be possible. Relating to the thematic classification of geosites [15], climate change can be recorded by stratigraphic, sedimentary, palaeogeographical, and pedological sites. Obviously, the evidence of climate change arises from the parallel examination of at least two adjacent rock units, where each needs to be interpreted in terms of the environment at the time of deposition, or the comparison of climatic conditions at that time with the contemporary ones.

The signal of change may be of variable nature. The most evident and easiest to recognize in the outcrop is lithological change, which is the replacement of one rock type by another. The change can be gradual, indicating slow climatic evolution, or abrupt, associated with a brief period of transition from one type of climate to another. The latter also includes stratigraphic gaps. More subtle are variations included within one general type of lithology, such as changing grain size, petrological composition, or an increase/decrease in bedding density (Figure 1a). A valuable source of information, increasingly explored nowadays in research, are the geochemical characteristics of sedimentary successions, although the educational potential of this kind of evidence is limited by the fact that geochemical change usually remains invisible to the observer. Likewise, the fossil record, examined in more detail in the next section, may not be obvious to the observer in the field.



Figure 1. Climate change context at sites of geoscientific interest. (a) Succession of sedimentary rocks of Triassic age in East Devon (England) indicates generally warm and dry climate at the time of deposition and frequent changes in local environmental conditions; (b) clay-rich weathering mantles in the Ardennes (Belgium) testify to much more efficient weathering in the geological past, when climate was warmer; (c) fossilized tree trunks of Lower Miocene age provide record of humid subtropical environments, Lesvos Island (Greece); (d) blockfields at low altitudes in Central Europe are inherited from periglacial conditions of the Pleistocene, Ralsko (Czechia) (all photos by P. Migoń).

Besides the rocks themselves, two more types of records can be interpreted in terms of past climatic conditions and, by implication, of climate change. First, these are the effects of weathering and pedogenesis, producing weathering horizons (saprolites) and relict soils, which also indicate the position of the land surface in the past. The accumulated knowledge now allows us to link specific types of saprolites with specific climatic conditions (Figure 1b), and the relationships between soil types and the environment are also generally well recognized [24–27]. For example, the occurrence of ferrallitic weathering horizons, typical for warm and humid climates (tropical), in high latitudes provides a clear record of major environmental change [28,29]. The second type includes various deformation structures in sediments, whose occurrence shows that the environment changed. Among

them are those indicating the presence of permafrost and increasing aridity (e.g., desiccation cracks, surface crusts) [26,30,31].

An important observation here is that interpreting the rock record in terms of climate change requires caution, as certain sedimentary and post-sedimentary features may have more than one origin, whereas other rock and weathering mantle properties may not be related to climatic effects at all [26,31,32]. For example, the fining of grain size in a clastic sedimentary succession can be caused by the decreasing ability of fluvial systems to transport larger clasts due to climate desiccation but may also indicate decreasing relief in the source area due to the long-term denudation or exhaustion of the sediment source. For more recent times, distinguishing between natural climate change and anthropogenic disturbance at a catchment scale as a reason for lithological change is a persistent problem [33,34]. Frequent lithological changes, especially in fluvial successions, may also indicate the occurrence of extreme atmospheric events (i.e., “accidents”) rather than any directional climate change, although one may also argue that this is a valuable record of climate instability.

2.2. Fossils

The fossil record is intimately associated with the rock record and fits palaeontological sites recognized in [15]. Therefore, it also shares several characteristics with the former, such as the necessity to examine a sedimentary succession in order to first recognize faunal or floral change and then to connect it with climate change. Similarly to the rock record, considerable caution is required at the interpretation stage as changes in biota may also have different reasons, not necessarily related to climate. Moreover, many palaeontological geosites are windows into rather brief intervals of the geological past, and to appreciate past climate change, one needs to connect various localities over a larger area, which together illustrate a longer period and the trajectory of climate change. Nonetheless, a simple comparison of fossil assemblages from a snapshot captured in the geological record with the present-day environment may also be very instructive. Cave localities hosting bone findings of Pleistocene mammals (e.g., cave bear, woolly rhinoceros, sabretooth tiger) are relevant examples [35–37].

The nature of the fossil record is diverse, reflecting the variety of life forms and their ability to survive in the fossil state in a particular geological environment. Thus, it ranges from rarely found complete skeletons of vertebrates to tiny specimens recognizable only under a microscope. Rocks containing fossils occur in various contexts, both in natural outcrops and quarries. Working quarries are usually the most suitable places to follow the fossil record since the progress of exploitation uncovers more and more fossiliferous beds, creating room for new discoveries. However, this advantageous situation for research is disadvantageous for geoeducation and geotourism due to access restrictions. Whatever the context of a site, the fossil record is typically poorly visible at the outcrop scale, and only rarely, well-preserved fossils protrude from the rock face and survive. Therefore, fossil sites *in situ* generally require considerable interpretation efforts to show the geological record and its implications in an engaging way [38,39]. Many are aided by life-size models of extinct animals. Indoor exhibitions appear to offer more opportunities, especially if modern technologies are implemented to recreate ancient environments and their changes through time. Having said that, one should mention a number of localities, where the fossil record is successfully presented in an outdoor setting. These include, for instance, several localities in the Lesvos Island UGGp [40] (Figure 1c) or the ichnofossils in Naturtejo UGGp in Portugal [41].

2.3. Landforms

Most exogenic geomorphological processes are controlled by climatic conditions, and hence, landforms resulting from these processes bear an imprint of these conditions too [42]. However, some landforms are particularly distinctive for specific climates and constitute a record that can be interpreted in terms of climate change. This is specifically true for

extreme climatic conditions such as very cold, where glaciers and frozen ground develop, or hyperarid, where wind erosion and deposition is pervasive. The respective landforms, such as glacial erosional and depositional features, landforms associated with permafrost and its decay (e.g., blockfields, rock glaciers, patterned ground, pingos and pingo remnants; Figure 1d), yardangs, and dunes, if present in areas not subject to extreme cold or dryness today, provide clear evidence that a major climate change has occurred. On the other hand, contemporary arid areas may host landforms formed in more humid conditions, examples being lake basins and associated lake terraces, certain fluvial landforms, and karstic features. Other landforms illustrate climate change in an indirect way. Among them are those associated with global sea-level changes, themselves related to the glacial–interglacial cycles during the Quaternary, such as raised marine platforms and beaches, relict sea cliffs, submerged river valleys (rias), or cut-off marine embayments. Sequences of river terraces and alluvial fans may also indirectly record climate variability, although—as in the previously presented types of records—reasons for their origin may be different and reside in tectonic rather climatic history. There are also landforms which originate in response to extreme, instantaneous events or during relatively brief periods of environmental (including climatic) instability and are therefore also indicators of climatic disturbances. These include landslides, in many areas demonstrated to be associated with more humid intervals [43], gullies, and badlands [44,45]. The value of landforms as evidence of climate change is considerably enhanced if their ages (or lifetimes) can be established, but numerous dating techniques applicable to deposits building the landforms and exposed rock surfaces provide opportunities to constrain the timing of landform origin [46].

The landform record of climate change may be more or less evident visually and, hence, suitable to develop interpretation. It is usually far more clear in high mountains, above the treeline, where glacial and periglacial landforms are very clear. Likewise, the evidence is easier to recognize in arid and semiarid regions, where the concealment of landforms by vegetation is limited. This is not the case in humid areas, where the expansion of plant cover limits panoramic views and hides diagnostic landform shapes. A relevant example is provided by late Pleistocene dune fields in central Poland, formed under cold periglacial climate but entirely overgrown by forest stands today [47,48]. Their patterns are clear on digital terrain models but are impossible to appreciate from the ground perspective.

3. Geosites Evidencing Climates of the Past

The key role of geosites is to reveal evidence of processes which shaped or continue to shape the surface and the interior of the Earth. Thus, by implication, they also help to appreciate factors controlling the very occurrence of these processes, their spatial patterns, and rates. Among these factors are climatic conditions, and hence, the interpretation at some geosites may also include issues relevant to climate and climate change. Two kinds of geosites may be distinguished in this context and these will be discussed in the following sub-sections. These are localities which themselves contain the record of changing climates and those which include specific geological or geomorphological features formed in climatic conditions different from the contemporary ones in the given region. Therefore, a comparison with the current environment will point to a major climate change.

3.1. Climate Change Recorded at a Geosite

Bedrock and sediment outcrops are among the most common geosites. Their primary role is to show the lithological diversity of an area, and many are relatively small, exposing just one rock type, formed in a specific moment within the geological timescale. However, some outcrops of sedimentary rocks can be large enough to cover a longer time interval, within which the evidence of climate change can be demonstrated. The more complex a sedimentary succession is, the more multifaceted the climatic history inferred could be.

Outcrop geosites in loess terrains, although not very conspicuous at first sight, are among the most instructive in this respect. If loess deposition took place semi-continuously at a given site throughout the Quaternary (or its part), it results in a stacked sequence

of loess layers from different time intervals. However, dust transport and deposition were generally associated with cold periods, whereas climate warming during interglacials/interstadials resulted in the development of soil upon the loess substrate. In this way, loess/soil sequences formed, and these are among the best terrestrial archives of climate change. From a geoeducational perspective, it is particularly important that fossil soils are clearly differentiated from the parent loess not affected by pedogenesis by their darker colour; hence, they are relatively easy to recognize in the outcrop. There may also be climate-related changing properties of the loess beds themselves, but these normally cannot be recognized in the field, although may be highlighted in interpretation materials. Some loess sections also include post-depositional deformation structures, formed in response to climatic conditions. These include ice-wedge casts, which provide evidence of permafrost and seasonal thaw of the active layer. An additional value of some loess outcrop geosites resides in the association with archaeological findings. Examples of loess outcrops as geosites come from several Central European countries (Figure 2), including southern Moravia in Czechia, with famous localities at Červený kopec in Brno [49] and Dolní Věstonice [50], Willendorf and other sites along the Danube in Lower Austria [51], and several places in Vojvodina, northern Serbia [52,53]. The Po Plain in northern Italy offers further examples of loess/paleosoil sequences which have the potential to be geosites, used for educational purposes [54].

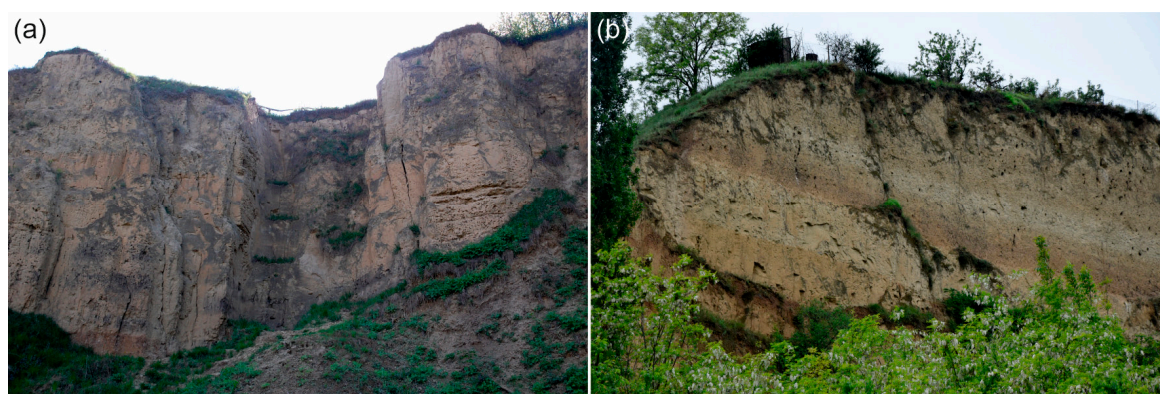


Figure 2. Thick successions of alternating loess layers and ancient soils (paleosoils) constitute the most complete terrestrial record of climate change during the Pleistocene. (a) Dolní Věstonice (Czechia); (b) Stari Slankamen (northern Serbia) (all photos by P. Migoń).

Similar records can be read from outcrops of older rocks. For example, Newsome and Ladd [55] showed a relevant example from Western Australia (Coalseam Reserve), where an outcrop in Permian sedimentary rocks documents a transition from a glacial environment to a cool temperate swamp, where coal seams originated, whereas after a stratigraphic gap, a transition from humid temperate to more arid conditions can be followed.

Evidence of past climate change can also be deciphered from landform analysis, and panoramic viewpoints (viewing geosites) play a special role here [14], allowing the visitors to see various landforms in a context and the spatial relationships between them. High-mountain settings provide relevant examples, where one can see sequences of glacial landforms, with multiple moraine ridges indicating phases of glacial advances and retreats, developed in response to climatic oscillations during the Pleistocene [56–58]. High mountains and deep canyons also offer an opportunity to see thick vertical successions of sedimentary rocks exposed within steep valley sides, not uncommonly on a kilometre scale, with evident lithological changes that may signify major environmental, climate-driven changes (e.g., in the Grand Canyon of the Colorado River [59]). However, in subdued landscapes, landform patterns may also show considerable climatic shifts in the past. A good case is the northern, lowland part of Tierra del Fuego in Argentina, where an extensive plain is punctuated by numerous desiccated lake basins, some with several former lake

floor levels, surrounded by hills built of sand deflated from the dried lakes during periods of increasing aridity. Together, they provide a valuable record of wet/dry climate oscillations during the Pleistocene [60,61]. Seasonal lake basins in the western United States, with their staircases of lake terraces indicating higher lake stands in the past, provide similar examples [62–64]. As in many other cases, adequate interpretation facilities are essential to help landform recognition, which is not easily attempted by an untrained eye.

3.2. Evidence of Environments Different Than the Contemporary Ones

Each sedimentary rock, weathering layer, and tract of relief is formed under some sort of climatic conditions, and these may have left distinctive signatures, giving an identity to a geosite. As only a minority of designated geosites illustrates the present-day environmental conditions, many of the remaining ones can be used to emphasize that the environmental conditions were once different.

3.2.1. Individual Geosites

Some geosites offer particularly striking examples. The Giant's Causeway in Northern Ireland is most known for impressive outcrops of columnar basalt of early Palaeocene age exposed on the shore platforms and within high cliffs, but another geologically significant component is the interbasaltic bed (IB), exposed within the cliff and separating two major lava flows [65]. It is very easy to recognize due to its distinctive reddish colour, so different from dark basalt above and below (Figure 3a). The IB is a weathering horizon, formed over a relatively brief period of less than 1 Ma, and its lithological and geochemical characteristics point to a very efficient weathering system, likened to tropical/subtropical ferallitic weathering, not possible under the contemporary humid cool temperate climate [29]. Thus, the IB witnesses the climatic optimum at the Mesozoic/Cenozoic transition. A similar direct link to ancient environments different than the present-day one can be explored at geosites exposing reef limestones, whose very existence points to warm climate at the time of coral reef growth [66].

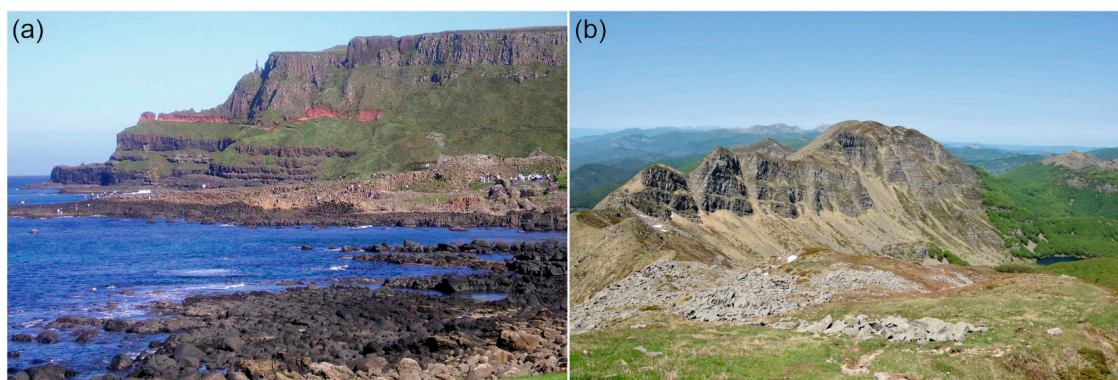


Figure 3. Examples of geosites evidencing different environmental conditions in the past. (a) Red interbasaltic bed between two thick lava flows is a weathering mantle, developed quickly during a geologically brief interval separating two phases of volcanic activity in the Paleocene, Causeway Coast (Northern Ireland); (b) inherited glacial landforms (cirques, moraines, lake basins) in the northern Apennines (Italy), where current climatic conditions do not allow for glaciation (all photos by P. Migoñ).

The Lesvos Island UGGp in Greece includes several localities where petrified (silicified) wood is exposed, uncovered from beneath pyroclastic deposits of Miocene age [40]. Remarkably preserved, many in living position, these tree remnants offer an insight into subtropical environments of the Lower Miocene (c. 22–17 Ma ago), dominated by mixed forest communities, with predecessors of sequoias, pine, cypress, laurel, and many other broadleaved species. This reconstructed Miocene environment remains in stark contrast

to the present-day, semiarid Mediterranean climate, with significant water deficit in summer. A window into the subtropical lake environment of the Middle Eocene is offered by the Messel Pit geosite in Germany, with its numerous fossils preserved in oil shales [67], whereas cave geosites with abundant finds of cold-climate fauna inform us about dissimilar climates during glacial intervals of the Pleistocene [68].

The lowlands of northern Poland and northern Germany, currently in the temperate climate with significant Atlantic influences, owe much of their contemporary topography to processes of glacial erosion and deposition during the last glaciation, between ~23 and 15 ka, effected by the Scandinavian ice sheet. A growing interest in geoheritage and geotourism has recently led to the recognition of a number of potential geosites thematically related to glacial geology and geomorphology, including moraine hills, eskers, fields of erratic boulders, kettle holes, and viewing points over tunnel valleys, ice-marginal valleys, and lake basins [69–72]. Thus, they imply major climatic changes that occurred over a geologically very short timescale, and if aided by engaging interpretation, they may become powerful tools to inform us about drastic environmental shifts. In a similar way, landforms associated with past mountain glaciers, no longer existent because of climate warming in the Holocene, are clear testaments to major environmental changes (Figure 3b).

3.2.2. Multiple Geosites—A Journey through Time

The proximity of several geosites exposing rock and/or the landform record from different slices of geological time offers further opportunities to explore the issue of climate change in the past. The Muskau Arch UGGp at the German/Polish border promotes itself by the phrase “a landscape shaped by warm and cold climates”, which alludes to two main geological components of the territory. These are lignite beds of Miocene age, along with adjacent quartz sands and clays, and Pleistocene glacial, outwash, and aeolian deposits, respectively [73,74]. Both can be seen in outcrops in the close vicinity, but the very presence of lignite at the surface is the result of considerable glaciectonic deformations that occurred during the Elsterian glaciation, more than 400 ka ago, moving deeply buried Miocene beds up to the surface. Thus, geosites in the geopark not only illustrate that the climate changed but show profound consequences of this change, such as much easier access to mineral resources.

In the nearby Land of Extinct Volcanoes UGGp, a similar journey through time can be designed, capitalizing on the existence of rock series from the Cambrian to the Quaternary. However, another option is to use adjacent geosites to emphasize the regional diversity of landscape changes due to climate shifts. Although part of the area was reached by the Scandinavian ice sheet during the Elsterian glaciation, for most of the time, the region was shaped by periglacial processes, which left an impressive and varied legacy [75,76]. The Pleistocene inheritance includes angular blockfields on outcrops of resistant volcanic rocks [77], rock cliffs on greenstones [78], solifluction sheets [79], glacial outwash deposits in the low-lying part of the region [80], and loess covers [81], all accessible as geosites.

Another example comes from the vicinity of the city of Brno in Czechia, which is typified by extremely varied geology spanning the period from the Precambrian up to recent and geomorphological complexity [82]. Within a radius of 25 km, one can visit outcrops of terrestrial and shallow marine rocks, whose properties clearly show that the climate underwent major changes even though the general location remained the same (Figure 4). The journey would start from the conglomerates of Devonian age, indicating the existence of semiarid mountains, through coal-bearing beds of the Carboniferous formed in warm and humid swampy conditions, Permian terrestrial sedimentary rocks signifying the return to aridity, Jurassic to early Cretaceous kaolinic clay infills of deep karstic depressions, evidencing a humid and warm environment, to the Cretaceous sandstones laid down during a marine transgression associated with the global climatic optimum. The rock record of the Cenozoic is less impressive visually, but the Quaternary climate shifts are illustrated by loess/paleosol sections (see Section 3.1).



Figure 4. Geosites providing windows into different intervals of geological history in the vicinity of the city of Brno (SE Czechia). (a) Conglomerates of Babi lom testify to arid climate in the Devonian; (b) clayey, kaolinite-rich infills of ancient karst depressions in Rudice in the Moravian Karst are of Early Cretaceous age and formed under warm and humid climate; (c) Cretaceous shallow marine deposits at Malý Chlum are linked with global sea-level rise at the time of climatic optimum; (d) outcrop of Pleistocene loess with associated paleosoils at Červený kopec in Brno (all photos by P. Migoń).

Looking at geosites through the lens of climate change can also be accomplished by combining real and virtual tours. Lozar et al. [83] proposed an itinerary in the Piemonte region of NW Italy, which shows evidence of major environmental changes at the time of the Messinian Crisis in the Mediterranean realm, around 6 million years ago. It combines natural outcrops and quarries, not all easily accessible and feasible to be developed for on-site interpretation.

4. Evidence of Extreme Atmospheric Events

Geosites also help to better understand the role of extreme atmospheric events and their role in shaping the landscape. The evidence is occasionally preserved in the rock record, for example, poorly sorted boulder-rich insets within otherwise much finer clastic successions (sandstones, mudstones) are usually interpreted as debris-flow deposits, which in turn are typically triggered by high-intensity rainfall. Easier to show are the consequences of extreme weather conditions in geomorphological systems, where major landform changes and reorganizations can occur within very short time intervals. Morino et al. [43] have recently presented landslide terrains as potential geosites, pointing out various educational benefits emerging from their interpretation, including an opportunity to link the topic with climate change. One example is the historical landslide in Bardo (SW Poland), which occurred on 24 August 1598 and was triggered by a combination of prolonged heavy rainfall and simultaneous fluvial undercutting of the slope during flooding conditions. It left clear geomorphic evidence consisting of a head scarp, hummocky depositional area, and steep toe and caused river channel shift away from the

footslope [84]. Being easily accessible, it is an ideal geosite but yet to be developed in terms of interpretation facilities.

Other potential geosites of this kind are landforms produced by debris flows (torrential fans, boulder piles, levee-lined furrows) and river avulsions (abandoned channels, oxbow lakes). The efficacy of singular atmospheric events may also be discussed in respect to gullies and their networks. They are generally considered as a cumulative result of many runoff erosion episodes, but there are examples of large gullies produced or significantly expanded during specific cloudburst events [85,86]. Some currently forested gullies within former (medieval) agricultural land in Central Germany are also suspected to have been formed very quickly, perhaps in response to catastrophic rainfall [87], and if developed into sites of geoheritage/geodiversity interest, they would illustrate the theme of weather impacts on landforms as well.

The evidence of extreme hydrometeorological events may also be recorded by the so-called cultural geomorphosites, where linkages between geomorphology and cultural heritage are particularly strong and evident [88,89]. They may include historical buildings damaged or destroyed by natural processes of excessive flood-related sedimentation, river bank undercutting, or coastal erosion. Figure 5 shows two relevant examples. One is a medieval chapel in Grünsfeld, central Germany, once built on the level of the floodplain and now half-buried by c. 5 m of alluvial deposits [90] (Figure 5a). The second example shows the ruins of a medieval church in Trzęsacz on the Polish Baltic coast, built in the 15th century at some distance from the contemporaneous cliff line, perhaps 300–500 m, and now standing in a ruined state at the cliff edge (Figure 5b). Its current position is a testament to the power of sea storms, which shaped the coast over the last few centuries, causing incremental cliff retreat [91,92]. Old buildings buried in the sand of coastal mobile dunes, such as the one in Skagen, Denmark, show another face of extreme weather conditions at the coast.



Figure 5. Evidence of extreme atmospheric events affecting historical building and objects of cultural heritage. (a) Chapel in Grünsfeld (central Germany) was built on a floodplain, but is now located several metres below the ground level in the vicinity due to many episodes of flood deposition and floodplain build-up over centuries; (b) cliff undercutting by severe storms caused its considerable retreat since late medieval times and, finally, nearly complete destruction of a late 15th century church in Trzęsacz (NW Poland) (all photos by P. Migoń).

5. Geosites and Ongoing Climate Change

Geoheritage is implicitly mainly about the past, and geomorphic features emerging in the most recent period (c. 100 years from now), such as landforms produced by mass movements (landslides, debris flow-related features) and karstic (e.g., collapse sinkholes) or fluvial processes, are rarely considered from the perspective of geosites, geoeducation, and geoconservation. Moreover, wherever they interfere with an established land use, communication network, or safety regulations, they become quickly obliterated unless they

are very large. The landform record of environmental change in European high mountains since the end of the Little Ice Age (c. end of the 19th century) is an exception, appearing in focus in some Alpine countries [56,93,94]. The recent study about the retreat of the Aletsch glacier in Switzerland [95] is a pioneering work which is likely to inspire similar studies elsewhere. The locality today is mainly appreciated for the glacier itself and its dynamics, but its ongoing retreat will likely shift attention to inherited glacial landforms (moraines), which will become the main resource to develop interpretation focused on rapid climate change and its effects. Specific localities best suited to appreciate the changes are panoramic viewing points, and similar spots may be found all across the Alps (Figure 6). Similar changes are recorded at high latitudes where shrinking glaciers are common, and some glacier fronts, recognized as geosites, are promoted as the most suitable locations to learn about climate change and its consequences. A good example is the Sólheimajökull glacier in the Katla UGGp, easily accessible and highly dynamic [96] (Figure 7).

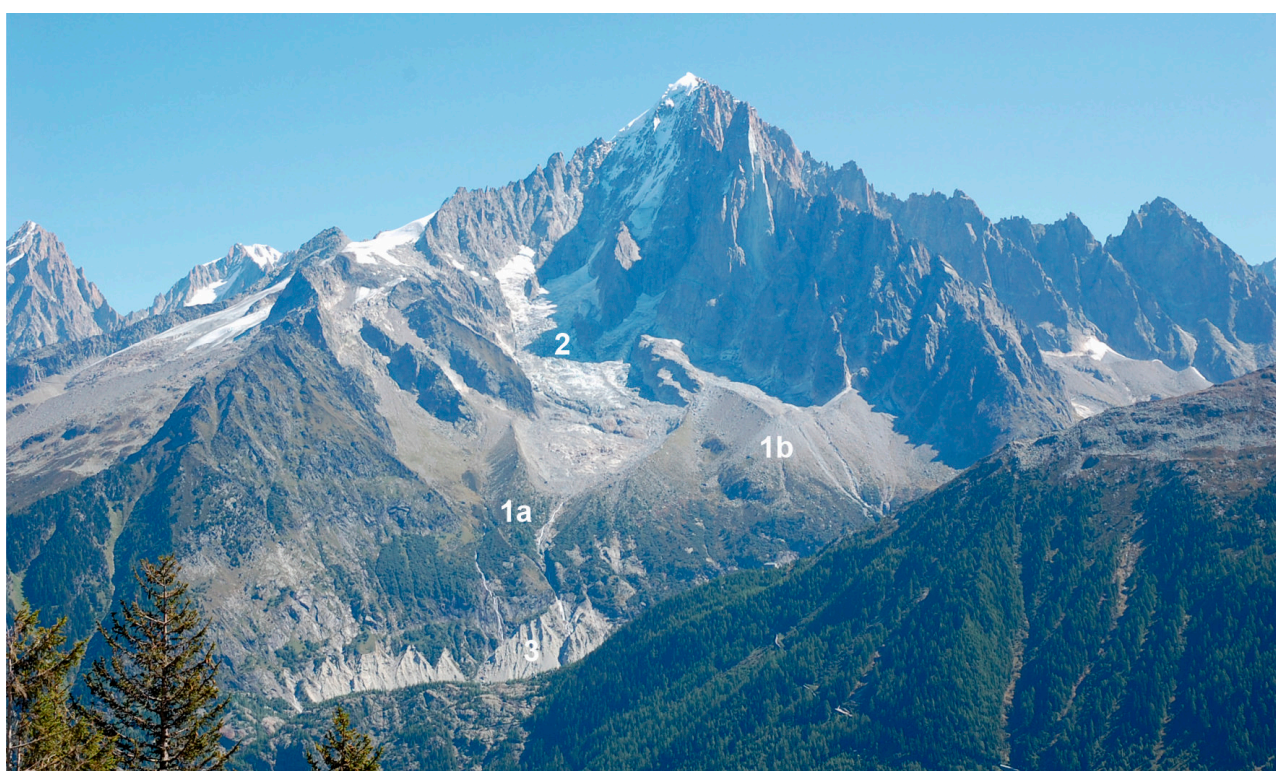


Figure 6. High-mountain Alpine landscape near Chamonix (France) records dynamic changes related to ongoing warming since the Little Ice Age. Annotations: 1a, b—arcuate moraine ridges testify to past extent of small glaciers; 2—decaying small glacier, destined to disappear completely; 3—eroded lateral moraines of a shrinking glacier in the main valley (photo by P. Migoń).

Different scenarios of climate change predict an increased frequency of extreme atmospheric events [97,98], and it is conceivable that they will affect geosites, especially those located in exposed, vulnerable settings. These localities will become “dynamic geo(morpho)sites”, changing fast and destined to disappear [56]. However, before they do this, they can play an important educational role, informing us about ongoing environmental changes, including those caused by or clearly related to climate change. A recent example of a geosite that vanished apparently in relation to the increased storminess of the Mediterranean Sea is the famous sea arch of Azure Window in Gozo (Maltese Archipelago), which collapsed without a trace in 2019 [99]. Nevertheless, the locality still hosts valuable geoheritage elements (sea cliffs, collapse dolines, some partly submerged, sea tunnels, karren fields) [100], and one might argue that from an educational perspective the disappearance of the Azure Window actually enhanced the site, adding an exciting

theme of sudden landscape change, whereas the development of virtual reality may help to “recreate” the lost arch for visitors. In fact, coastal geosites may become particularly vulnerable given both the sea-level rise and anticipated more frequent storms [101,102]. To ensure their survival, special conservation measures may be needed, e.g., at soft cliffs [7], but one probably needs to accept that some are destined to disappear.



Figure 7. Sólheimajökull glacier in the Katla UNESCO Global Geopark in Iceland, as many others in the world, is subject to fast decay and thinning but, being easily accessible, is widely used in outdoor education about climate change (photo by P. Migoń).

6. Interpretation Challenges

The role of successful interpretation in spreading the message in geoeeducation has been repeatedly emphasized, and various requirements have been discussed by various authors [103–107]. Having a clear objective is a prerequisite, followed by the selection of educational means adjusted to the target groups, whose backgrounds and expectations may be very different. Examples provided in this paper demonstrate that many geosites convey the message that climate has always been subject to change and that the nature of this change can be deciphered from the rock record and the landform record. Moreover, some geosites teach us that besides gradual change recognized at the scale of thousands to millions of years there occur short-term, almost instantaneous climatic events (weather events) capable of drastically changing the environment.

The first challenge here is that the link between the rock/landform record and climate change interpretation is in most cases not obvious, especially for casual visitors, and their learning experience must be facilitated by engaging interpretation. Interpretation panels are a minimum, but they need special design to be effective [108,109], relating what can be seen at a geosite (e.g., layered stratigraphic succession, specific rock and sediment structures, panoramic landscapes) to the unseen different environment(s) of the past. Annotations, photographs from analogous contemporary environments (if applicable), artwork (drawings, possibly using the same landscape background but filled with different details), and links to augmented reality are among the means to enhance the panel’s content. Some of these solutions are simple, such as annotations, and others require more effort

and skills and may be more costly (e.g., preparation of artwork). Different computer-aided solutions (voice recording, complex animations) would be more advanced [110–113], but effective connection at a site could be a problem. Technical problems may be easier to overcome if an interpretation centre is located at a geosite, with all facilities available to visitors, but this occurs in the minority of cases. A very effective approach is through guided tours, allowing for better interaction between the visitors and the interpreter (providing adequate interpersonal skills of the latter), but this is again possible at a limited number of geosites and not all the time. However, certain geosites of particularly high scientific value and vulnerable to damage are only accessible in this way.

Geosites illustrating the geological and/or geomorphological record of climate change also offer an opportunity to learn how scientists work and how they assemble evidence. This is because messages such as that “these lithological changes indicate climate change” or “this group of landforms formed under different climate than today” broaden the knowledge but do not necessarily facilitate a better understanding. A logical follow-up question is then “but how do we know [that this rock change is due to climate change]?”, and this can be answered by presenting selected, relevant principles of scientific reasoning and techniques of analytical research. It may not be possible on a single panel, without risking overloading its content, but a separate panel can be an option, as can a QR link. Certainly, guides and educators should be able to address these issues during outdoor lessons and tours, regardless of whether such questions are asked by the participants or not.

Another issue worth discussing is the relationship between climate change evidenced at geosites and the ongoing concern with the climate change on Earth, most likely heavily influenced by the human impact on the environment, especially in the last two centuries. For example, UNESCO Global Geoparks are expected to include the climate change agenda in their educational programmes, following the framework of the UN Sustainable Development Goals [114], with the aim to raise awareness of this critical issue among society. However, as most geosites are windows into the geological past, the changes they bear a record of occurred without any anthropogenic intervention, so making a direct link is not feasible, and actually, the key message may be misinterpreted and the importance of the current climate change downgraded or even questioned. Therefore, interpretation programmes at such geosites should be carefully designed, with the preferred focus on environmental instability in general and over various timescales, as an inherent feature of an environmental system, rather than on any specific reasons of change. Nevertheless, geosites (particularly geomorphosites) located in high-mountain areas experiencing the rapid withdrawal of glaciers and permafrost decay, in high-latitude areas facing similar environmental change, and along exposed coastlines are well suited to be used in thematic conjunction with the current climate change discussion.

7. Conclusions—A Synthesis

There are evident links between geosites, understood as the most valuable elements of geoheritage and most suitable to support outdoor geoeducation, and climatic changes. Many record the change in climatic conditions directly, showing a succession of rocks, sediments, or landforms developed in response to environmental change, whereas others demonstrate that conditions at a given place were different in the past than they are today. The relevance is not limited to the distant geological past. Many geosites, particularly geomorphosites, show an ongoing change exposing a recently ice-freed terrain, decaying permafrost, or highly dynamic coastline. As such, they may be explored for geoeducational opportunities with the focus on climate change, although a convincing link cannot be made everywhere between a change that occurred in the past and the current climate change debate. Moreover, the interpretative content is of critical importance, as the evidence of changing environments is not necessarily obvious at a geosite, especially for visitors with less background in geosciences (and these clearly form a majority). Whereas traditional means can still be successfully used, and may be the only feasible solutions in specific

places, opportunities offered by modern computer-aided technologies can revolutionize interpretation in this specific context.

Table 1 attempts to summarize the discussion and identifies four main types of geosites from the perspective of climate change and weather-related events. It also relates these types to the perhaps most elaborate thematic classification of geosites offered in [15], pointing out the diverse suitability of different types of geosites for this specific theme. Some geosites have no link to climate change at all, whereas others are much more relevant. Stratigraphic, sedimentary, and palaeogeographical sites are the most suitable to inform us about the distant geological past, even going back to the Palaeozoic and possibly beyond, whereas geomorphological sites reveal climate change in the more recent epochs, particularly in the late Quaternary, and have great potential to help raise awareness about the ongoing change.

Table 1. Geosite classification matrix from the perspective of recording climate change and in relation to the main themes as defined in [15].

Geosite Thematic Classification [15]	Climate-Related Issues at Geosites			
	Evidence of Climate Change	Evidence of a Different Environment	Evidence of Extreme Weather	Evidence of Ongoing Change
Stratigraphic	X	X		
Palaeontological	X	X		
Sedimentary	X	X	X	
Igneous				
Metamorphic				
Mineralogical				
Economic				
Geochemical	X	X		
Seismic				
Structural				
Palaeogeographical	X	X		
Cosmogenic				
Geothermal				
Geocryological		X		X
Geomorphological	X	X	X	X
Hydrological				
Engineering				
Radiogeological				
Neotectonic				
Pedologic (soil)	X	X		
Geohistorical				

In a number of cases, this ongoing change makes geosites more vulnerable to destruction due to either increasing geomorphic instability or via vegetation growth, which requires the implementation of special management strategies to ensure their survival [7,56,115–117], but also offers further opportunities for outdoor education. However, the same ongoing change may reduce the use of specific areas, adversely affecting the safety of visitors due to the increasing environmental dynamics [56,118].

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