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Article

Geosites in the *Gole della Breggia* Geopark, Ticino, Southern Switzerland

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Abstract: This work is aimed at showcasing one of the most engaging geoparks in Europe, the *Gole della Breggia* Geopark. By following its geotrail, the visitors can observe a great deal of features that encompass a wide variety of sedimentary, stratigraphic, tectonic and paleogeographic processes. Its contents are valorized by a comprehensive geotrail that encompasses 23 geostops, enriched with explanatory panels, which enable viewers to gain an overall picture of the complex processes that led to the present-day configuration of the outcrops encountered in the Geopark. We have selected five significative outcrops, which we have regarded as fully-fledged geosites, and which encompass the whole 170-million-year interval, from Early Jurassic to Late Miocene times, during which the rocks of the Geopark were deposited and deformed. We have performed an assessment of the five geosites, using the most common criteria that can be applied for geosite evaluation. The result of the assessment show that the most valuable geosite is the Lombardian *Maiolica*, highly representative of a pelagic limestone, which is rich in fossil contents, marked by integrity, scientific interest and has a major educational value. All geosites, thanks to a QR code added to each figure along the text, can be viewed as Virtual Geosites (VGs), integrated by 360° videos.

Keywords: geosites; geoheritage; sedimentary rocks; Breggia; educational; Virtual Reality

1. Introduction

1.1. The main definitions

Geoheritage, which incorporates aspects of geodiversity, has been documented by a great deal of papers over the last 20 years [e.g., 1–9]. It has major scientific, cultural, and educational relevance and these qualities make it worth of popularization in Earth Science museums [10–13], and of protection in geoparks [14–23]; moreover, geoheritage can be crucial for geotouristic purposes [24–35]. Safeguarding geoheritage also means preserving specific geomorphological and geological features, which are named geosites. These are natural elements that reflect the geological heritage of a place [36–39] and are marked by a number of values. They can have paleontological [40], petrological, volcanic [41–43], tectonic [44,45] mineralogical [46], stratigraphic, igneous [47], climate-related, paleogeographic, petrographic [48] and sedimentary relevance. They can also be non-natural features, like road cuttings, industrial archaeology quarries and museum collections. In a recent paper [49] it has been underscored that the definition of a geosite has to be considered equivalent to a major outreach effort, which should be based on an in-depth knowledge of the geological meaning

of the geosite itself. It goes without saying that geosites can also be geomorphological elements, which compose geomorpho-diversity [50] and, therefore, are known as geomorphosites [51].

1.2. *The fundamentals of geosite assessment*

Over the last couple of decades, a great number of authors have attempted to assess the quality of geosites, both in a qualitative and a quantitative way. This assessment has been made by employing a range of criteria. One of the most used criterium is the scientific relevance of a geosite, known as “scientific value” [52]; this, in turn, is composed of four sub-criteria, which are integrity, representativeness, rarity [53,54] and how much a given geosite has been the subject of scientific publications. As pertains to representativeness, this regards how much a geosite is exemplary if we consider the extent of the natural processes that occurred there. Rarity, on the other hand, expresses how a geosite is uncommon at the local, regional or worldwide level. Along with the scientific value, there are other values that are called “additional values” [55,56] and can become subject to assessment. These additional values are ecological, cultural, aesthetic, educational, and economic. The most relevant is the educational value [57], which reflects the combination of the didactic potential of the geosite (pertaining to how well the lay public can grasp the meaning of its features) with its accessibility, safety, as well as its possible usefulness for educational purposes—for example in terms of the possibility to organize guided tours to access and view the geosites.

2. Overview of the *Gole della Breggia* Geopark

In southern Ticino (Switzerland), the Breggia River valley shows one of the most representative stratigraphic series of the southern Alps. These outcrops represent an exceptional document, which illustrates the sedimentary processes that took place in an overall time interval of about 100 million years, between Early Jurassic and the Late Cretaceous. However, considering the more recent rocks (from the Messinian to the Quaternary) in the Park, the time interval represented here spans from the Jurassic to the present day. Due to its completeness, this cross-section is unique in the entire alpine Arc (Figure 1). It testifies to the evolution of sedimentation and tectonics in the Southern Alps from Early-Jurassic times onwards, from the early deposition of the *Moltrasio* Limestone and *Domario* Limestone both cropping out in the Geopark, to the successive sedimentation of the *Morbio* Limestone, the *Rosso Ammonitico Lombardo*, and the Limestones and Marls with Pelagic Bivalves. All these formations were laid down on the floor of the Tethys ocean, which had been opening up since 180 million years ago [58], separating the Eurasian Plate from the African plate; later on, the Tethys continued spreading and deepening until 140 million years ago, reaching a maximum width of about 800 km [58]. This ocean became the site of deposition of deep-sea sediments known as *Radiolarites* (almost entirely siliceous), the Rosso ad Aptici Formation and the Lombardian *Maiolica* (*Late Jurassic-Early Cretaceous*), the latter marking the beginning of a new geological period. All the above sedimentary units are represented in beautiful outcrops along the Park’s geotrail.

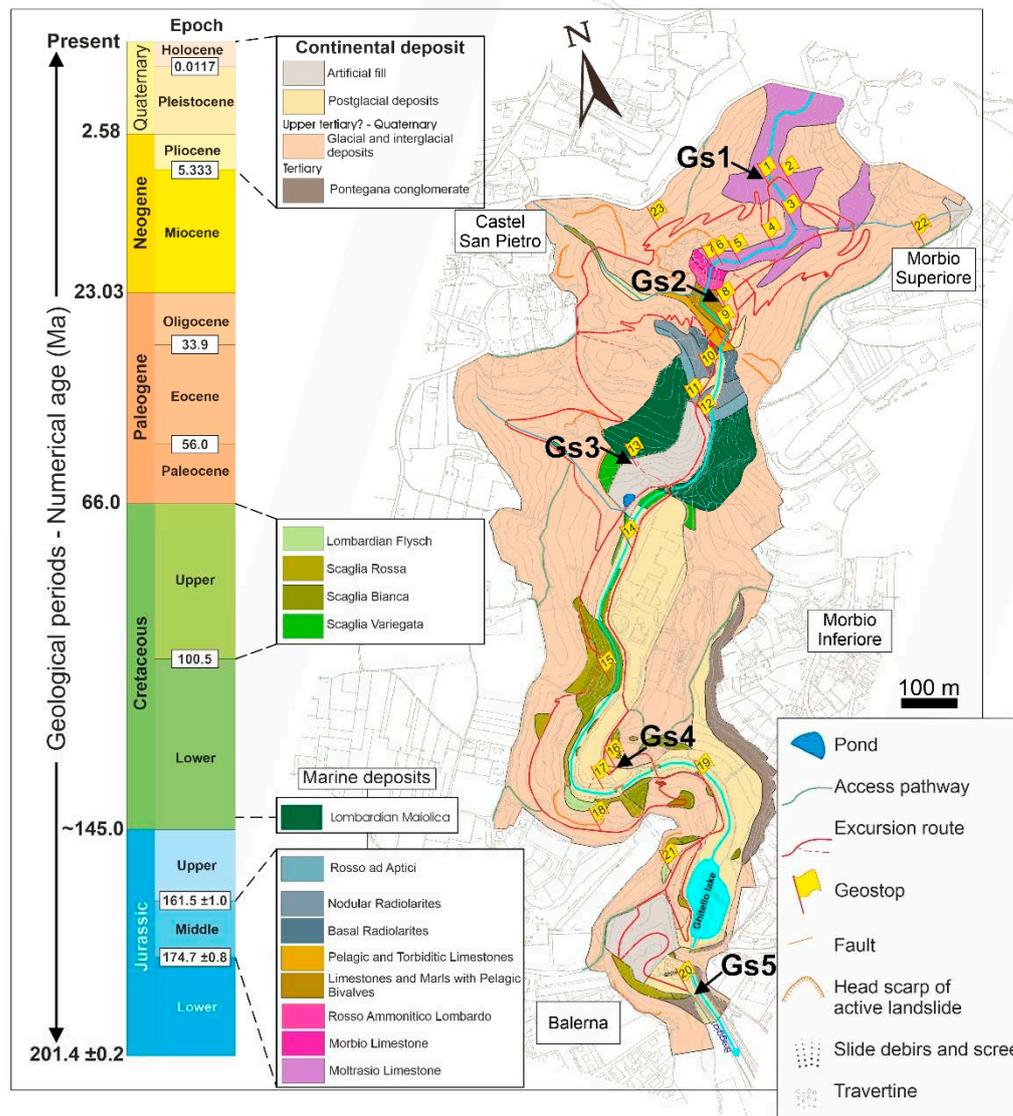


Figure 1. The Parco della Breggia geotrail. Modified after [58]. Geological time scale is from International Commission on Stratigraphy (<https://stratigraphy.org/chart>).

Then, about 130-120 million years ago, the opening of the South Atlantic forced the African plate to rotate anticlockwise towards the European plate, generating the first compressive movements [58]. The ocean started to be consumed and marine, terrigenous deposits became widespread. In the Gole della Breggia Geopark, this paleogeographic evolution is recorded in the formations known as *Scaglia* and *Flysch*, dating back to the Cenomanian. The collision between the two plates took place slightly after 65 million years ago, in Early Tertiary times [59]. At the very beginning of the Tertiary, during the early formation of the Alps, movements along a major transform fault, the Insubric Line [60], had the effect of separating the Alps from the Southern Alps. Mountain building processes reached their climax in the mesoalpine phase (45-30 million year ago) and in the successive neoalpine phase (30-0 million years ago). After the climax of the orogenic phases, the orogen has been subject to intensive erosion, and this is reflected in the youngest rocks of the Geopark, the *Pontegana* Conglomerate, a terrigenous deposit of Messinian age [61,62], made of repeated accumulations of debris and mud flows in a subaerial environment. The latest event in the long geological history of this Geopark took place during the most recent glacial age, in the Quaternary, with the deposition of new conglomerates

that form the highest terraces in the Park area, and are easily recognized for their composition, made of a mixture of dominant sedimentary rocks and a minor amount of detritus with common metamorphic pebbles and metric blocks (erratic blocks), abandoned by a tongue of the Adda glacier during its last maximum expansion [63].

3. Geosite description

The fruition of the geological heritage of the whole Geopark is made easier by a geotrail that features 23 geostops, all enriched with explanatory panels (Figures 1 and 2).



Figure 2. The first of 23 explanatory panels that enable visitors to gain a comprehensive picture of the geological contents of the Geopark. There is also a geoguide, both in Italian and English, which provides visitors with an overall view of the geological history that is beautifully represented here [58].

It would be impossible to document all the stops that compose the geological itinerary of the Geopark: therefore, we have chosen five stops belonging to the geotrail, which correspond to five geosites that have been firstly described based on [58] and then assessed using the most common criteria for geosite evaluation. Then, the geosites have been turned into Virtual Outcrops (VOs) and finally into Virtual Geosites (VGs); as detailed in recent papers [64,65], the creation of VOs, i.e. 3D models of outcrops, is made of two main phases: (i) collecting images by means of Unmanned Aerial Vehicles (UAVs); (ii) processing of the collected images through Agisoft Metashape (<http://www.agisoft.com/>, (accessed on 20 July 2023), a commercial Structure from Motion software. VOs can be accessed by users virtually, in the form of VGs. In the present paper, VGs are available by clicking on QR Codes embedded in the figures; moreover, they are accessible at <https://geovires.unimib.it/geotrail/>.

3.1. Geosite 1. The Moltrasio Limestone and a tectonic structure

This geosite shows the *Moltrasio* Limestone beds that dip towards the southwest [58]. This formation is a light grey, bedded limestone, with marly intercalations rich in muscovite and siliciclastic materials, dating back to the Early Jurassic, a time when sedimentation was taking place in a context of rifting and breakup of the Pangea supercontinent. This geosite allows to observe a phenomenon which testifies to the dynamicity of the Earth's crust. The rocks are, in fact, cut by a fault (normal fault). This tectonic structure makes it clear that the succession of strata is not simply fractured: the separate parts moved in relation to each other [58].

The formation of faults represents a rigid and fragile response of the rock to the pressure to which it is subject. It is not by chance that, along faults, great amounts of energy are discharged in the form of earthquakes [58].

By clicking on the QR codes in Figure 3, it is possible to have access to both the Virtual Geosite and a 360° video, uploaded on Youtube.

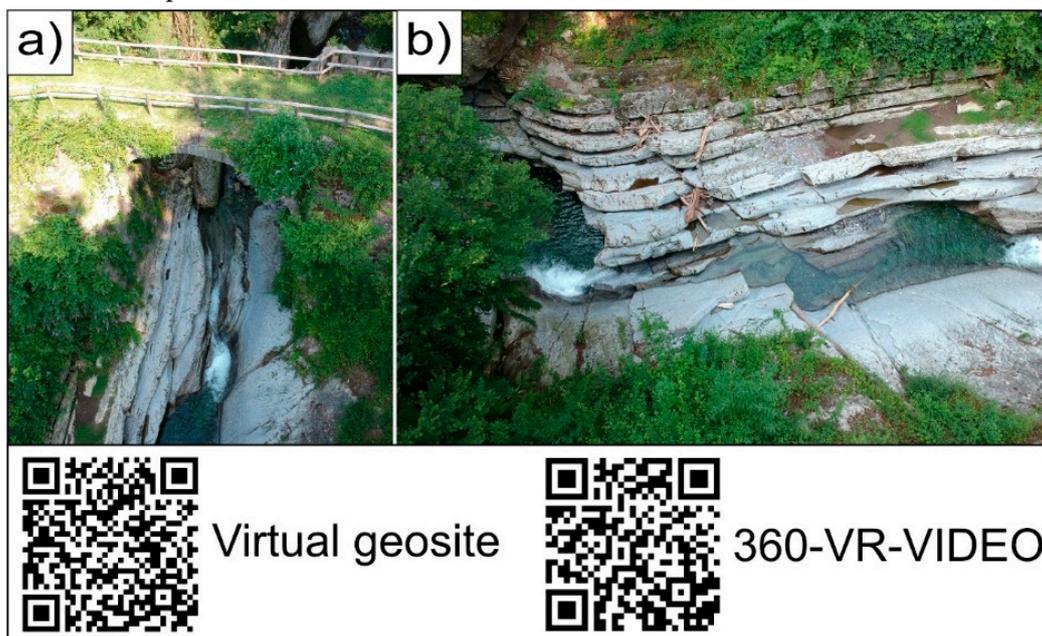


Figure 3. a) Drone-captured image of the *Moltrasio* limestone; b) UAV-collected photographs of the fault dissecting the layers of the *Moltrasio*. The two QR codes enable viewers to access the Virtual Geosite and a 360° video.

3.2. *Pelagic limestones and a peculiar gravitative event*

The rocks that compose this geosite [58] are from the Lower to Middle Jurassic. This formation, named “Limestones and Marls with Pelagic Bivalves”, consists of well-stratified, white to pinkish limestones. Ammonites are abundant; however, the name of this formation refers to different organisms, already visible by means of the hand lens, but which can be better examined under the microscope. In fact, making their appearance in great abundance, are very fine shells of bivalves (lamellibranches). Almost as if to compensate for a size of barely 2-3 mm, their number is often so high as to make up the entire rock [58]. Another particularity of Geosite 2 is surely the phenomenon that can be observed in Figure 4: It is a synsedimentary event that took place in the depths of the ocean, while the sediment was being deposited. Along an irregular slope, a pack of strata broke loose and dragged down by its own weight, continued to slide downwards. The strata were already well compacted but had not yet become rigid rock. They folded and buckled and in some places were caused to break. This is a process known as a submarine slump (“slumping”, “gravity fold”). Following this event, the regular deposition of sediment continued, forming undisturbed parallel strata [58].

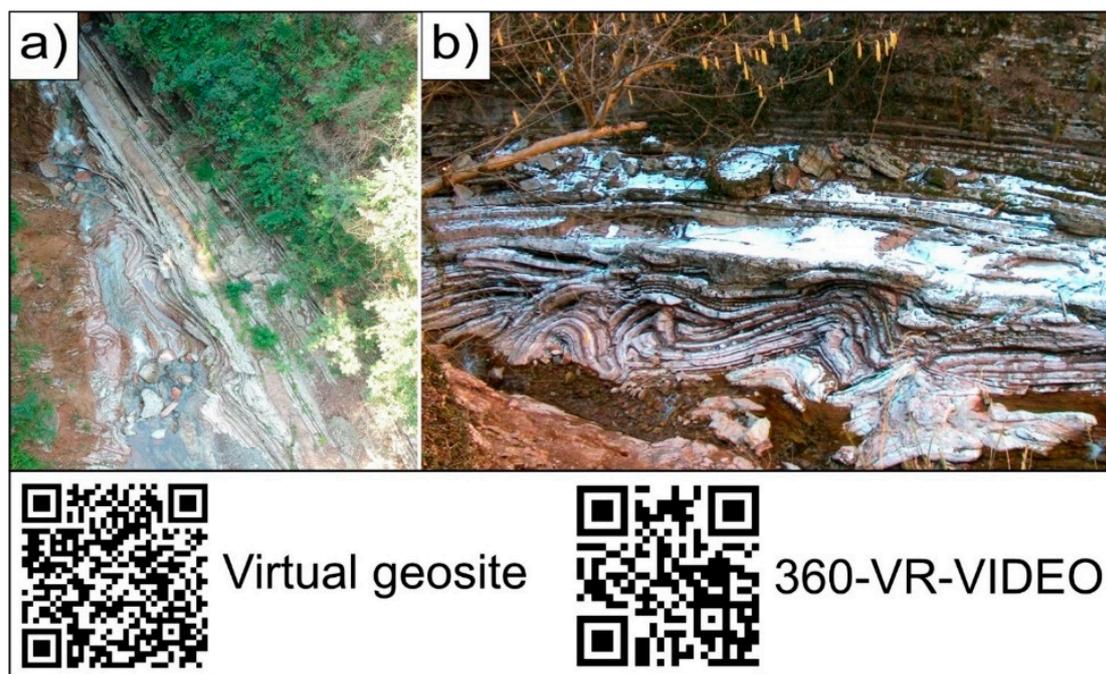


Figure 4. a) UAV-captured image of the slump in the pelagic limestones. b) Photograph taken at closer distance, where the process leading to the slump can be observed. In the lower hand side of the image, it is worth observing the folding and partial fracturing of the strata involved, originally in a plastic state. Above the folds, the strata resume their regularity, indicating a return to normality on the seafloor. The two QR codes enable viewers to access the Virtual Geosite and a 360° video.

3.3. Geosite 3. *The Lombardian Maiolica: from the depths of the Alpine Tethys*

The Lombardian *Maiolica* in the *Gole della Breggia* Geopark is a 130 m-thick sequence [58] composed of white, decimetric strata of fine-grained, micritic limestone, dipping 70° to the south, with typical conchoidal fracturing, containing dark chert nodules and layers [66-69]. They can contain a great abundance of aptici, calcareous plates in the form of tiny shields that might have had the function of protecting the ammonites from predators. Belemnite rostra can be present as well. At the base of the sequence (Figure 5a), rocks almost white in colour reflect the purity of their composition; the percentage of calcium carbonate can reach 95% permitting in the last century an intense use of this resource for the industry of concrete [70]. The Lombardian *Maiolica* (Upper Jurassic-Lower Cretaceous) was originally an ooze that “rained” slowly onto the deep seafloor of the Alpine Tethys, enveloping it in a white blanket; so slowly that 1000 years of life in the ancient ocean are compressed today into 6 mm of rock. This mud consisted in skeletons of single-cell organisms, whose abundance became “explosive” during the transition between the Jurassic and the Cretaceous: coccolithophorids [58]. These are planktonic algae which exist today in oceans all over the world. Possessing chlorophyll and therefore capable of photosynthesis, they are fundamental to produce oxygen and are found at the base of the food chain. Their cell walls, globular in form and of a gelatinous consistency, are covered with calcareous plates, elliptic or circular, which form a sort of “armour”: coccoliths. These are transformed immediately into sediment, either when the algae die, and the “armour” disintegrates or as undigested waste once the algae have been eaten [58]. Within the last 20 meters of the Lombardian *Maiolica*, dating back to around 125 million years ago, and intercalated between the regular strata of limestone, there are layers of dark shales, 20 cm in thickness (Figure 5b).

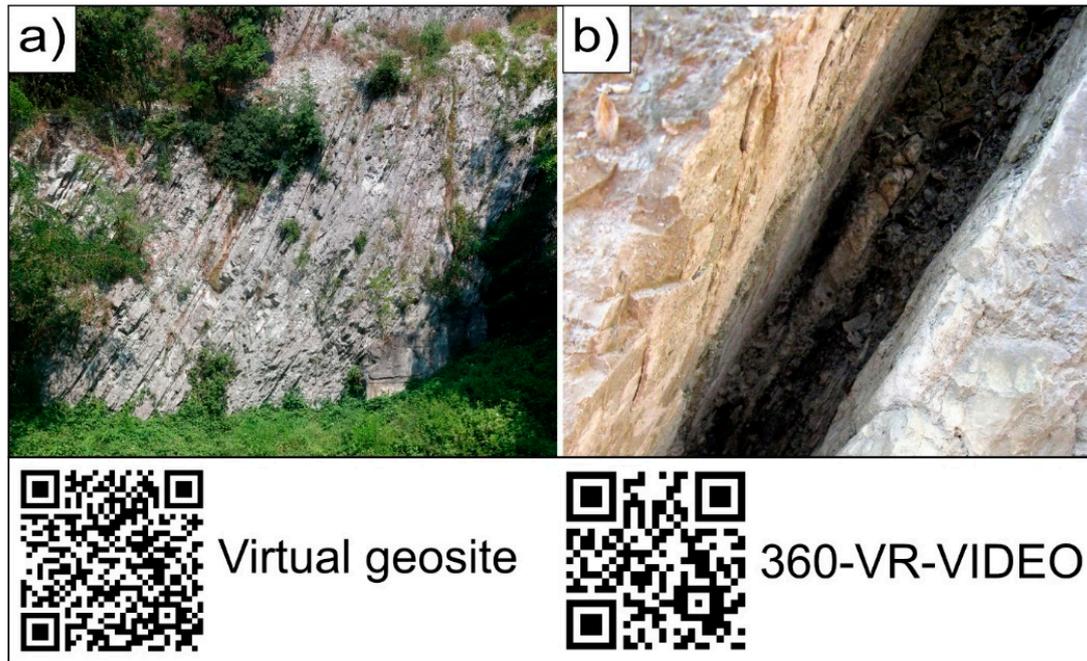


Figure 5. a) Drone-captured picture of the steeply-dipping strata of the Lombardian *Maiolica*; b) detail of a dark, bituminous layer intercalated between the white strata of the Lombardian *Maiolica*. The two QR codes enable viewers to access the Virtual Geosite and a 360° video.

These dark layers are slightly bituminous, due to a moderate content of organic material (up to 4% of its weight), originating from vegetal and animal decomposition. It needs to be taken into account that they reflect particularly hot, humid climatic periods (“greenhouse effect” conditions), with a resulting increase in the development of organisms, especially vegetal ones [58]. Organic material derived from their remains then collected on the ocean floor in conditions in which there was a lack or scarcity of the oxygen that would have enabled their preservation. According to some theories, it was the decomposition of the abundant accumulation of organic material that consumed the oxygen. Besides, the existence of a stagnant seafloor is also confirmed by the stratification of these layers, which is uniformly flat and thin. This suggests that the seafloor was not only undisturbed by the effects of marine currents but was also insufficiently oxygenated to sustain the life of sediment “feeders” (e.g. worms and crustaceans) [58].

3.4. Geosite 4. A fold records mountain building processes leading to the formation of the Alps

This geosite is represented by a spectacular outcrop of the *Scaglia Bianca* (Lower Cretaceous). This formation is made of marly limestones and white/grey marls [58]. Intercalations of clays and bituminous marls can also be noticed. The presence of the *Scaglia Bianca* marks the moment in geological time, when there was a tectonic inversion, from a rifting kinematics (which led to the fragmentation of Pangea and the formation of the Tethys) to a converging tectonic regime that eventually led to the formation of the Alps [68,69]. Testifying to this transition, in the Geopark a spectacular example of a tectonic fold can be observed (Figure 6). The fold was generated by the pressure due to the converging motion of Africa against Europe, a process which, millions of years later, ended up in their collision. This anticlinal fold is therefore directly linked to the movements that led to the formation of the Alps. A distinction needs to be pointed out, between structures of this kind, which originated after the formation of the rock, and the so-called gravity folds (Figure 4), created during the period in which sediment was being deposited. The origin of the former can be attributed to the horizontal compression between tectonic plates, whereas that of the latter to the weight of the layers sliding down submarine slopes [58].

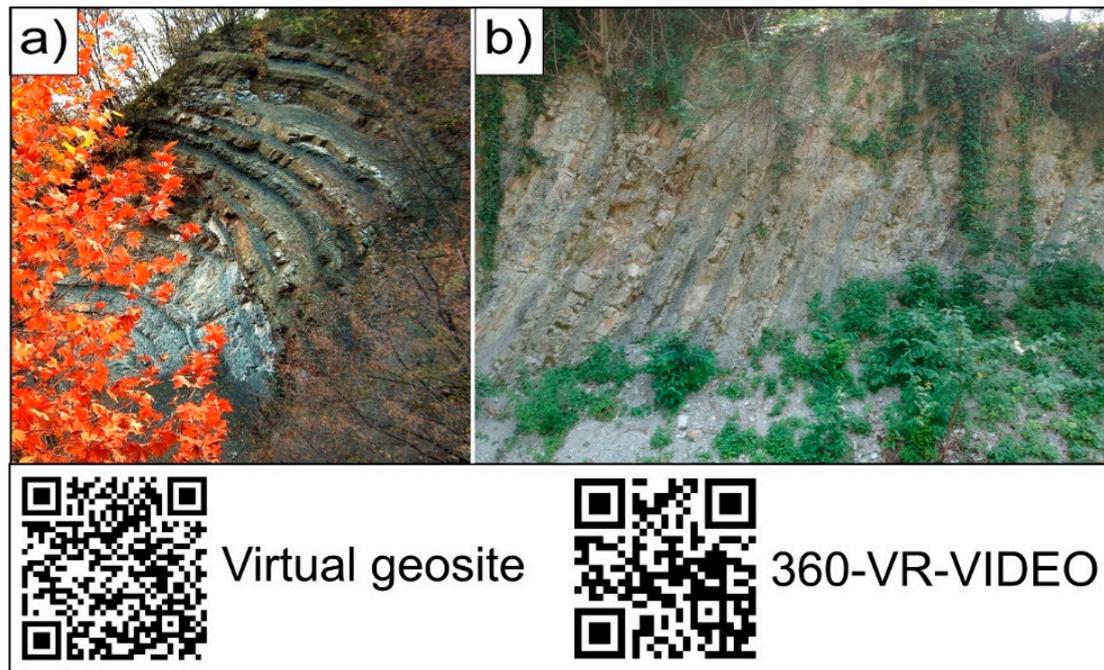


Figure 6. a) The layers of *Scaglia Bianca* deformed by the fold; b) detail of steeply-dipping strata of the *Scaglia Bianca*. The two QR codes enable viewers to access the Virtual Geosite and a 360° video.

Folding in the strata was certainly favored by the characteristics of this rock. It is worth noting that it was originally a clayey mud which is now hardened. In addition, the *Scaglia Bianca* is also subdivided into alternated very soft marl and harder marly limestone. The former is deformed easily, while the latter remains in relief on the surface and highlights the fold like the “layers” of an onion [58].

3.5. Geosite 5. A textbook-example of an angular unconformity

At the base of Geosite 5, tilted strata of the white and the red *Scaglia* can be observed (*Scaglia Bianca* and *Scaglia Rossa*), rocks of marine origin dating back to Early to Late Cretaceous times [58]. They were deposited in a submarine sedimentary basin, and, in this outcrop, they are covered by a conglomerate (Figure 7) composed of gravel, pebbles and boulders, mixed with sand and cemented together. This is the *Pontegana Conglomerate*. Despite its rather chaotic appearance, more or less horizontal strata can be distinguished, marked by aligned boulders. As mentioned above, this is a continental rock of fluvial origin, dating back to the Tertiary, precisely to the Messinian [61,62]. Its absolute age is therefore a little more than 5 million years. Consequently, between the two rocks, about 100 million years are missing. The explanation for this gap in time is that the intervening rocks were carved by successive erosion, which produced an undulated roof at the top of the white and the red *Scaglia* after their strata were tilted by tectonic forces leading to the formation of the Alps. In front of the viewers is a textbook-example of an angular unconformity. This geosite enables to draw an interesting conclusion. The original layers of the white and the red *Scaglia* must have been more or less horizontal, as is natural for muds deposited on the seafloor. Afterwards, the formation of the Alps raised and tilted them, especially during the Nealpine phase, beginning 30 million years ago. On the contrary, the *Pontegana Conglomerate* flowed over the underlying formations like an avalanche [58].

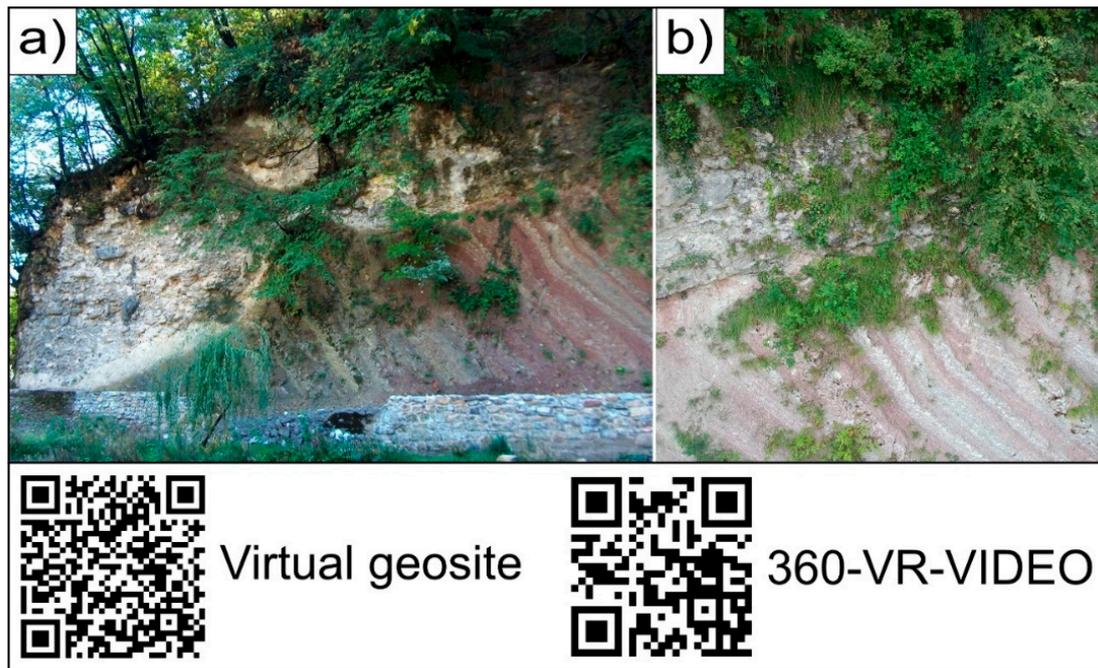


Figure 7. a) The angular unconformity between the two formations, separated by 100 million years of geological history. b) detail of the steeply dipping layers of the white and the red *Scaglia*, abruptly truncated by erosion and covered by the clastic sediments of the *Pontegana* conglomerate. The two QR codes enable viewers to access the Virtual Geosite and a 360° video.

4. Assessment of the five geosites

By applying the criteria briefly illustrated above, we can perform a qualitative assessment of the five geosites which we selected from a total of 23 geostops. Our selection was mainly based on the value of representativeness, as the five geosites are all particularly exemplary in terms of how well they represent important geological processes and phenomena. Geosite 1, which can also be observed as Virtual Geosite by clicking on the QR code embedded in Figure 3, is representative of deep-sea calcareous sedimentation leading to the formation of well-developed sedimentary layers. Also, the normal fault depicted in Figure 3b is exemplary in terms of the development of faults in rocks. Both the sedimentary layers of the *Moltrasio* limestone and the normal fault in Figure 3b are not rare occurrences, so rarity is not a value we can apply. The outcrop is very well preserved, being part of a Geopark, so integrity is a value which can be applied. The geosite is accessible and safe, being located along the Geopark's geotrail. Another value that can be recognized is by all means the educational one, as this geosite is part of a geotrail integrated by explanatory panels; moreover, geological tours with the help of expert geoguides are held at the Geopark on a regular basis.

Geosite 2, which can also be observed as Virtual Geosite by clicking on the QR code embedded in Figure 4, is highly representative of a sedimentary process dominated by gravity, in a pelagic environment. It is also a pretty rare occurrence, especially in terms of how the slump is clearly enclosed between regularly sedimented layers. The outcrop is well preserved, so that the integrity value can be assigned to this geosite. The geosite is accessible and safe, being located along the Geopark's geotrail. Here, the educational value can be applied as well, for the reasons explained for Geosite 1.

Geosite 3, which can also be observed as Virtual Geosite by clicking on the QR code embedded in Figure 5, is highly representative of a pelagic limestone, the *Maiolica*, especially interesting for the dark, bituminous layers that are found intercalated between its strata. However, it is not a rare occurrence, as generally, "anoxic" layers such as these (that is, connected with reduced oxygenation) are found in rocks all over the world and were formed in a very precise period of the Earth's history. The outcrop is perfectly preserved, so integrity is once again a value we can apply to this geosite. The

geosite is accessible and safe, being located along the Geopark's geotrail. Moreover, we can apply the scientific value, as the *Maiolica* in the Geopark was subject to scientific publications, such as [66,67]. Also here the educational value can be applied, for the reasons mentioned for Geosite 1.

Geosite 4, which can also be observed as Virtual Geosite by clicking on the QR code embedded in Figure 6, is highly representative of folding due to stresses resulting from mountain building processes. Moreover, by observing the outcrop in detail, viewers can notice the process of differential erosion of a sedimentary rock made of alternating beds of soft marl and harder marly limestone. The outcrop is well preserved, so the value of integrity can be applied as well. The geosite is accessible and safe, being located along the Geopark's geotrail. Also here the educational value plays a major role, for the reasons mentioned for Geosite 1.

Geosite 5, which can also be observed as Virtual Geosite by clicking on the QR code embedded in Figure 7, is representative of a process known as angular unconformity: in this case it can be observed, with exceptional clarity, the erosional surface that puts into contact tilted, sedimentary marine rocks of Cretaceous age with continental deposits of Messinian (Late Miocene) age. The outcrop is well preserved, so its integrity is ensured. The geosite is accessible and safe, being located along the Geopark's geotrail. The educational value, like in the previous geosites, can be applied for the reasons explained for Geosite 1.

5. Conclusions

The *Gole della Breggia* Geopark hosts a great deal of geosites, encompassing a time span of about 170 million years, from the Early Jurassic to the late Miocene. By walking along the geotrail, it is possible to observe a wide gamut of sedimentary and stratigraphic processes, as well as tectonic ones, the latter due to the formation of the Alpine chain. We selected five sites, which are representative of the above mentioned processes, and encompass the whole time span that characterizes the Geopark, starting with the oldest rock (the *Moltrasio* limestone) and ending with the youngest one, the *Pontegana* conglomerate. We have provided a description of the five geosites, highlighting their sedimentary, stratigraphic, tectonic and paleogeographic peculiarities. Then we have performed a qualitative assessment of the geosites, based on several values, among which are rarity, representativeness, integrity, accessibility, safety, scientific and educational significance. In terms of quality, the most outstanding of the geosites is the Lombardian *Maiolica*, which is marked by high representativeness, integrity, and was subject to scientific publications. Moreover, just like the other four geosites, it is characterized by very good accessibility and it has a high educational value, as the geotrail is integrated by explanatory panels, and geotouristic tours are organized in the Geopark on a regular basis, with the involvement of expert geoguides.

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