The Geotouristic Project "the Geological Adventure" to the Rescue of an Iconic World Heritage Geosite, the Ammonites Slab of Digne-les-Bains (National Geological Nature Reserve of Haute-Provence and Unesco Global Geopark, France)

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Abstract

Protected under National Nature Reserve, managed by the Departmental Council of the Alpes de Haute-Provence, and labeled UNESCO Geopark, the Ammonites Slab of Digne-les-Bains (SE France) exhibits 1,550 ammonites over a large open-air surface. Despite the virtual absence of special enhancement for the visitors, this spectacular geosite of high scientific and heritage value has played an important role in the years 1990-2000 in the emergence of notions of geological heritage, geological nature reserve, geotourism, and Geopark. Due to its exposure to mountain weather conditions, the Slab suffers from significant conservation issues. Several studies have shown that its condition was much worse than expected. Without major restoration work, the Slab was in danger of collapse in the short term. Given the high cost of the needed rescue work, the geotourism project 'The Geological Adventure' was developed under European Interreg ALCOTRA funding. More broadly, this project aims to develop a sustainable experiential geotourism around the geoheritage of the Southwestern Alps cross-border (France-Italy), partly in situ and thanks to digital tools (22 geosites concerned). An important place is given to scientific pedagogy. Concerning the Ammonites Slab, the project consisted of: (1) stabilizing and ensuring the sustainability of the fossiliferous layer; (2) planning and developing the overall geosite (parking area, reception area, observation platform); (3) allowing accessibility for people with disabilities; (4) offering progressive and immersive educational mediation to make scientific culture accessible to as many people as possible.

Key-words: Ammonites Slab; Geoconservation; Geotourism; Geological Nature Reserve; UNESCO Geopark; European Funding.

1. Introduction

At the beginning of the Jurassic (Sinemurian), 197 million years ago, the sea covered a large part of France. This geological period represents a key moment in connection with the dislocation of Pangea, then the opening of the Tethys Ocean with the flooding of the northern European margin (Fig. 1). The Ammonites Slab of Digne-les-Bains (Southwestern Alps, France) corresponds to an ancient fossilized seabed from this period. This sea floor, formerly horizontal, was then lifted, moved and tilted during the alpine surrection. Today, the result of this long history is an exceptional geological site (Fig. 2), emblematic of the National Geological Nature Reserve of Haute-Provence (RNNGHP by its acronym in French), of the UNESCO Global Geopark of Haute-Provence (UGHP) and of the French Department of the Alpes de Haute-Provence (Bert & Pagès 2021). More than 1,550 ammonites are exhibited on an inclined surface of 320 m². The site's location in the open air, along the roadside, allows easy access for the public. The Slab is consequently very visited by both the local population and tourists, but also by scientists and schools, including geology students (from 21,000 to 30,000 visitors per year according to 2016–2019 data; for comparison, the local population of Digne-les-Bains amounted to 16,068 inhabitants in 2020). The quality and size of this outcrop, the numerous fossils exposed, as well as its scientific and heritage importance, make the Ammonites Slab a unique site in the world. Consequently, it obtained the maximum score of 3 stars (geological site of high heritage value at national/international rank) on the French national inventory of geological heritage managed by the National Museum of Natural History (PAC1989 site: https://inpn.mnhn.fr/site/inpg/PAC1989, accessed in September, 2021; De Wever et al. 2014, 2015).

Despite its importance and fame, the Ammonites Slab had never been truly developed or landscaped, the bias being to leave it to a certain 'naturalness' (Fig. 3), regardless of a suburban context (Fig. 4). Exposed to weather conditions, the fossiliferous layer can only be deteriorated over time. Since 2014, the Departmental Council of the Alpes de Haute-Provence manages the RNNGHP, and therefore also the Ammonites Slab. Despite the works carried out on several occasions to delay its degradation, a diagnosis carried out in 2016 (Bert et al. 2019b and this work) highlighted the imminent risk of partially collapsing of the Slab, involving the need for an emergency response accompanied by major works. The extent of the operations required implied a high cost while taking into account a number of technical and administrative constraints. In this context, the 2015–2016 call for projects of the European Interreg V-A France-Italy Alpes Latines COopération TRAnsfrontalière program (ALCOTRA; Guiomar et al 2018 and this work) was a major opportunity for developing and launching a project allowing at the same time: (1) to ensure the protection work of the Ammonites Slab, (2) to enhance this exceptional geosite living up to its international reputation, and (3) to go further by networking the geoheritage of the ALCOTRA cross-border geographical area with other natural and cultural heritages. All of this with the aim of sustainable local development to meet the objectives of the European program: axis 3 'attractiveness of the territory', specific objectives 3.1 ('sustainable tourism by increasing the attractiveness of the territory and preserving the natural and cultural heritage') and 3.2 ('improve the management of natural heritage'). It was this project that came into being under the name 'The Geological Adventure'.

As a possible textbook case about a major conservation threat, through the management and enhancement of an emblematic geosite, which could be of help or interest to be transposed to other geoheritage sites in need, the present work propose to detail (1) the history and context of the Ammonite Slab geosite, (2) the more global geotouristic project that provided the opportunity of a large amount of funding to rescue the site, (3) the rescue operation itself with technical elements for its safeguarding, (4) the new enhancement of the geosite, with structures and scenography elements and (5) some financial benchmarks.

2. The Ammonites Slab

2.1. Geographic location

The Ammonites Slab geosite (44° 07′ 10″ north; 6° 14′ 03″ east) is located about 1 km north of the town of Digne-les-Bains (Alpes de Haute-Provence, southeastern France - Fig. 4), along the D900a departmental road on the right edge of the Bléone valley. It is located immediately south of the Isnards farm and was willingly named “la dalle des Isnards” (the Isnards slab) by the local population.

2.2. Geological context

The Ammonites Slab is representative of the basis of the Digne-les-Bains thrust sheet (Fig. 5 - one of the outermost tectonic units of the southwestern Alps). This thrust sheet is mainly made of the thick Mesozoic rock sequence of the Subalpine Basin (the pelagic ‘dauphinois series’; Haug 1891). The decollement level lies in the Triassic evaporite layers (Goguel 1939), in such a way that the allochthonous thrust sheet has moved over the autochthonous Provençal ‘platform’ series. Near Digne-les-Bains, the western front of the sheet is a zone of strong tectonic deformation mainly linked to its sliding towards the south. The Ammonites Slab area is located between two dextral strike-slip faults: the Bès fault and the Saint Benoît fault

(Hippolyte et al. 2011; Fig. 5). These two faults have been active in sliding since the upper Miocene at least (10 Ma), with a slip rate estimated to 0.7 mm per year over the last three million years (Hippolyte et al. 2011, 2012). The Ammonites Slab is located in the relay zone between these two faults, in the southern part of the western zone of the thrust sheet, known as the 'La Robine Lobe' (Gidon and Pairis 1988). The eastward dip of the Ammonites Slab results from the sliding of the Digne-les-Bains sheet along these faults.

2.3. Lithology, palaeobiodiversity and biostratigraphy

The Ammonites Slab belongs to an alternation of limestone beds and thinner marly interbeds (Fig. 6). The facies suggest subpelagic deposits beneath the storm-wave action limit without any obvious role of currents (Corna et al. 1991; Dommergues and Guiomar 2011). Alongside with rare nautiluses of the genus *Cenoceras* Hyatt, 1884 and a few belemnites, the Slab currently bears more than 1,550 ammonites, often large (up to 70 cm), which make the geosite famous. Suspensivorous epibenthic bivalve mollusks and echinoderms (pentacrins in isolated articles) are also very common despite often in debris. This benthic fauna is also clearly more diverse than the nectonic cephalopods, with the presence of at least four bivalve genera (*Plagiostoma* Sowerby, 1814, *Gryphaea* Lamarck, 1801, *Liostera* Douvillé, 1904 and *Oxytoma* Meek, 1864). In comparison, only three species of ammonites (Arietitidae Hyatt, 1874 and Schlotheimiidae Spath, 1923) are present: (1) *Coroniceras multicostatum* (Sowerby, 1824) very largely dominates (99.74% - Fig. 6), (2) *Angulaticeras* (*Sulciferites*) cf. *charmassei* (d'Orbigny, 1844) (0.19%), and (3) *Coroniceras* (*Arietites*) sp. (0.07%). This low biodiversity of ammonites, with populations often very largely dominated by a single species, was observed throughout the Sinemurian and lower Pliensbachian of the subalpine basin with paleobiogeographic affinities towards the NW of Europe (Burgundy, southern Jura, England;

see Corna 1985, 1987; Corna and Mouterde 1988; Page 1992, 2003). Despite the more southerly position of the Ammonites Slab, we can exclude any Tethys influence because of the total absence of the Phylloceratoidae Zittel, 1884 and Lytoceratoidea Neumayr, 1875.

The presence in very large numbers of a single species of ammonite allowed Dommergues and Guiomar (2011) to carry out a detailed paleontological study on the basis of a 3D scan of the Ammonites Slab. This analysis was the first carried out in situ including quantitative topics of intraspecific variability in a large Sinemurian ammonite species. *Coroniceras multicostatum* is a species whose stratigraphic distribution is always very limited, which makes it a reliable index for biostratigraphic purpose. Due to its exceptional exposure conditions, the Ammonites Slab of Digne-les-Bains constitutes to date the best observation point of the *Coroniceras multicostatum* Interval Horizon, at the extreme top of the *Coroniceras* (*Arietites*) *bucklandi* Zone/Subzone (lower Sinemurian, Lower Jurassic, with a numerical age around 197 million years according to Cohen et al. 2013).

2.4. Historical background

The precise date of the discovery of the Ammonites Slab was unknown until very recently (this work), but it was deemed to be around the middle of the 20th century. No record exists before this period despite the regular visits of many geologists and learned societies in the immediate vicinity (Hebert 1861; Garnier in Vélain and Dieulafait 1872; Haug 1891, 1909; Kilian and Zürcher 1895). Gérard Thomel (palaeontologist specialised in ammonites, formerly curator of the Natural History Museum of Nice, France; pers. comm.) relayed that the local Scientific and Literary Society was at the instigation of the installation of a fence and a sign prohibiting the direct access to the Slab in the 1960s, because of an act of vandalism.

Very recently, one of us (JSP) found some new information: actually, the Slab was unearthed in June, 1941 by Mr. Roux, a civil engineer, during work to widen the road of Barles. At that time, less than a quarter of the current surface was exposed. A first excavation work was made in July, 1979 as part of the project to create the National Nature Reserve in the vicinity of Digne-les-Bains (Martini 1979): the surface of the Slab was extended to 160 m² on which there were approximately 600 ammonites. The road has been deviated slightly to leave a little more space for visitors, and a basic layout was proposed (a lectern).

With the birth of the concept of natural heritage and nature reserves in French law (see De Wever et al. 2019), Guy Martini gave rise to the idea of classifying 18 geological sites, including the Ammonites Slab, in the Digne-les-Bains area under this strong legal protection status (Martini 1979; see Guiomar 2009). This project came to realization on October 31, 1984 with the creation of the RNNGHP. However, the Ammonites Slab took a long time to become known outside the Digne-les-Bains region. The site was officially brought to the attention of the international community only in 1991, following the study by Corna et al. (1991) and the holding in Digne-les-Bains of the First International Symposium on the protection of geological heritage (Martini 1994; see also the 1991 International declaration on the rights of the memory of the Earth). The growing notoriety of the Slab, and its diffusion on Japanese television (The Miracle Planet, Chikyû Daikikô, NHK, 1987), led to the realization of the molding in 30 pieces of the fossiliferous stratum (the 160 m² then exposed) for the city of Kamaïshi (Iwate Prefecture) in Japan, where it is still displayed at the Iron and Steel History Museum.

A second work for securing and clearing the Slab was carried out in July, 1994 with the participation of the University of Bucharest, and led to the doubling of the exposed surface (320 m²) and the number of visible ammonites (1,550). On this occasion, drilling showed the continuity of the Slab to the north with the presence of the same ammonite density over several thousand square meters; various on-site museum projects did not emerge mainly for financial reasons and the matter ended there. However, under exceptional financing, restoration and security work was carried out in 2009, 15 years after the previous operation. The objective of this stabilization work was to remedy the conservation problems of the Slab in the short term (ideally 2–5 years), still awaiting for a financial opportunity and a political commitment to achieve equipment for lasting protection and enhancement of the site. This latter is presented in this work.

2.5. Management of the Ammonites Slab by the National Geological Nature Reserve of Haute-Provence (RNNGHP)

The RNNGHP is governed by the Environmental Code from French law. Its classification is justified by the scientific interest of the natural heritage, with the objective of preserving the integrity of geological sites (including fossils and mineral substances). The RNNGHP now has 18 sites classified as National Nature Reserves (RNN by its acronym in French), including the Ammonites Slab, for a total of 270 ha (currently in the process of being extended - Bert et al. 2019a). These sites are surrounded by a protection perimeter of approximately 2,300 km² (Fig. 7), making it possible to ensure the conservation of the exceptional geological heritage in the territory of 59 municipalities of the Provençal Pre-Alps (52 in the Alpes de Haute-Provence and 7 in the Var departments). Throughout the protection perimeter, the removal, destruction or degradation of fossils, minerals and concretions is prohibited. Removals without tools of elements naturally released by erosion are tolerated only if they are carried out in limited quantities. On RNN classified sites, the regulation is more restrictive and prohibit, among other things, any sampling of mineral or fossil substances and any change in the character or aspect of the place. Sampling authorisations are issued for scientific purposes with specific conditions for the two levels of regulation. Concerning the Ammonites Slab, the strong legal protection of the RNN classification was complemented by land control: first (1987) by acquisition of the Slab by the township of Digne-les-Bains and then (2018) by its assignment, extended to a larger part of the geosite bought from its private owner, to the Departmental Council of the Alpes de Haute-Provence.

The Departmental Council of the Alpes de Haute-Provence drew up the third management plan of the RNNGHP (Bert et al. 2019a) through which it is responsible for ensuring (1) the protection of the geoheritage (environmental protection under police missions; physical conservation; management of ex situ collections), (2) the acquisition of knowledge (inventories and scientific research) and (3) the general functioning of the nature reserve. The studies carried out, the rescue work and the opening of the Ammonites Slab to the public, are in direct line with these missions. As the RNNGHP manager since 2014, the Departmental Council's first ambition was to requalify the major sites of the nature reserve whose facilities were aging. Thus, in order to provide the sites protective and enhancement equipment up to their international reputation, additional funding to the Department Council's investment funds and to the State endowment was sought.

3. The European project ‘The Geological Adventure’

The Geological Adventure project was carried out within the framework of the European cross-border cooperation program between France and Italy, Interreg V-A ALCOTRA 2014–2020. This project aimed to enhance the great landscapes as well as the remarkable mineral heritage, representative of the history of the Southern Alps, which is illustrated between the Department of the Alpes de Haute-Provence (France) and the Province of Cuneo

(Italy). The project took place over 3 years, from April, 2017 to December, 2020, and mobilized 7 cross-border partners (for France: the Departmental Council of the Alpes de Haute-Provence - project leader and manager of the RNNGHP -, the Provence-Alpes-Agglomeration community - manager of the UGHP -, and the municipality of Les Mées; for Italy: the Union of Fossanese municipalities, the municipalities of Cherasco and Frabosa Soprana, and the Federico Sacco Foundation). The Geological Adventure responds de facto to one of the objectives, designated as a priority, of the tourism plan of the Department of the Alpes de Haute-Provence for the period 2016–2020 (ambition renewed for the period 2022–2027): to develop experiential and sustainable geotourism. Thus, geoheritage, as a natural quality of territories, is considered as an asset for tourist diversification and a driver of local and economic development (François et al. 2006; Bétard et al. 2017). This is in this context that the financing of the rescue and layout of the Ammonites Slab geosite of Digne-les-Bains was made possible.

3.1. Terms and concepts

The Geological Adventure project is based on several fundamental principles resulting from the reflections on tourism carried out since the end of the 20th century around geotourism, experiential tourism and sustainable tourism. Since there are several definitions around these principles (see Ruban 2015 and bibliography; Gonzalez-Tejada et al. 2017 and bibliography), it is necessary to clarify in which sense the concepts guided our project:

Geotourism. Geology and geoheritage (considered here in a very broad sense, including palaeontology, geochronology, climatic evolution, etc., adapted from Ruban & Ermolaev 2020), are usually considered as a large and complex subject often difficult to access for an uninitiated audience. Historically, niche tourism in relation to geological heritage rather concerns geologists (including supervised university internships), enthusiasts, or is based on the personal appreciation of the mineral landscape from a form of aestheticism (i.e. Gordon 2018; Ruban et al. 2021).

In the 1990s, the term geotourism emerged at a time when notions of sustainability and ecotourism were developing (see Gordon 2018) roughly at the same time as the concept of geoheritage (Gray 2013; de Wever et al 2019). Very early, the RNNGHP clearly stated as an actor in these concepts and initiated the European Geoparks Network with three other European territories and closely collaborated in the development of the Global Geoparks Network (Martini and Zouros 2008). Faced with the need to clarify the concept of geotourism (Gonzalez-Tejada et al. 2017), the 2011 Arouca Declaration (International Congress 'Geotourism in Action', 09–13th November, Portugal) defined geotourism as *"tourism that supports and improves the identity of a territory, taking into account its geology, its environment, its culture, its aesthetic values, its heritage and the well-being of its residents. Geological tourism is one of the various components of geotourism"*. Beyond the scientific component, this growing recognition of the cultural and aesthetic values of geoheritage, in relation to the development of geotourism, is reflected with the emergence and worldwide multiplication of UNESCO Global Geoparks since 2000 (the territory of the RNNGHP was one of the first to receive this label; see also Bétard et al. 2017). Their vocation is indeed to explore, develop and celebrate the links between geological heritage and all other aspects of heritage, whether natural, cultural or intangible, and to promote them. This fits with the notion of 'cultural landscapes', a concept adopted by UNESCO in 1992 in which the continuous interaction between natural processes and human activities is emphasized (Gordon 2018).

Experiential tourism. The notion of cultural landscapes of geotourism is also part of the principles of experiential tourism described as an emerging trend in the 21st century. Adventure tourism, ecotourism, and heritage or cultural tourism can be considered as experiential tourism (Smith 2006). Experiential tourism develops a participatory aspect that is nowadays highly sought after by tourists (Gordon 2018). In this, the exploration of the geological elements of the landscape through different educational, cultural, even artistic filters, engages in an interactive way the senses, the emotions, the imagination, while including the discovery and the learning of new knowledge or the commitment to the history of the place. In all cases, however, didactics must be based on advances in scientific knowledge in the way that the information offered is accurate, reliable and of high quality, even if adapted for an easier understanding.

Sustainable tourism. The objective of sustainable tourism development was defined by the Agenda 21 (1992) in the Sustainable Development plan for the 21th century. The aim is to reconcile long-term tourism, whatever its scale, form or type of destination, with the improvement of environmental and social conditions and the maintenance of development capacities (including economic). The principles of sustainable tourism were defined in the Charter for Sustainable Tourism of Lanzarote (UNWTO 1995), then updated in 2004 by the Committee for Sustainable Tourism Development of the Word Tourism Organization (UNWTO 2005, p. 11). While geotourism can offer tourists an enriching experience (and this is clearly also a major issue in sustainable tourism), it can also enable them to address sustainability issues (Bétard et al. 2017). This is also a very present theme in geology through the apprehension of the deep time. In all cases, it is up to the stakeholders (including geosite developers) to guide geotourists towards raising awareness and adopting responsible behavior.

3.2. The objectives of the Geological Adventure project

If the southern cross-border Alps (Alpes de Haute-Provence, France and Cuneo region, Italy) have many exceptional geological sites well known to insiders, the Geological Adventure offers to (re)discover some of them through an innovative and modern approach in line with the Arouca Declaration (2011). While other geotourism development projects in the Southern Alps are more oriented towards roaming alone (for example the Via GeoAlpina project, which also provides didactic cards e- see Cayla & Hobléa 2011) or around an ex situ museographic aspect (Cayla 2009), the Geological Adventure proposes to develop sustainable, experiential and joyful tourism through integrated site developments and digital technologies. The geological history of the Southern Alps is the common thread of this geotourism destination, physically or virtually connecting exceptional geosites with other heritages. To do this, the Geological Adventure offers various levels of interactivity: emotional, physical or intellectual, if possible in creating the conditions for a lived experience, the aim being to make the geological heritage accessible to as many people as possible.

3.3. The achievements of the Geological Adventure

The results of Franco-Italian deliveries within the framework of the Geological Adventure are rich in diverse achievements. The present work mainly details those carried out by the Departmental Council of the Alpes de Haute-Provence (France) as responsible and leader of the project. In order to meet the objectives, the actions focused on four axes:

The physical development of the geosites. Five spectacular geosites (3 in France and 2 in Italy) have benefited from specific developments with the dual objective of long-term conservation and heritage enhancement. These are (1) the Ammonites Slab of Digne-les-Bains (the main project here developed), (2) the Pénitents des Mées trail (Sensitive Natural Site of the Department), (3) the belvedere of the Vélodrome geosite at the Vieil Esclangon (RNNGHP, France), (4) the Cave of Bossea at Frabosa Soprana and (5) the Rio Crosio at Cherasco (Italy).

Scientific mediation. Twenty-two geosites have been selected to illustrate different steps in the geological history of the Southern Alps (the interactive map of the whole geosites is available at: https://aventuregeologique.com/decouvrir/, accessed in September, 2021). To make this story attractive, the mediation strategy was based on:

- the simplification of the scientific discourse in order to make accessible the concepts of geology, often complex, but by limiting the drifts which can be related to the simplification of the scientific concepts. This difficult work of science popularization required a lot of back and forth between didactic professionals and scientists;
- the design of educational tools offering an original and attractive aesthetic (timelines; geosite sheets; lecterns), and promoting knowledge and general understanding of the events by all audiences;
- the offer on certain developed sites, and in particular on the Ammonites Slab, of interactive didactic instruments (casts, 3D models and reconstructions);
- the creation of an educational package around the geological history of the Alps designed around sequences of playful handling and experimentation for schoolchildren;
- a story-telling in which Federico Sacco and Edouard-Alfred Martel, two illustrious promoters of geotourism at the start of the 20th century, icons of the project, invite the public to take a ‘journey through time and space’;

- the production of a four-minute animated fiction retracing the geological history of the Southern Alps; the elaboration of eight video sequences in augmented / virtual reality in the way to explain the genesis of current landscapes or to stage fossilised animals in their original environment (ammonites, ichthyosaurs, sirenians, rudists, etc.);
- the development in Fossano (Italy) of a modern museum space dedicated to the enhancement of F. Sacco's paleontological collection;
- the financing of an artist-made fresco representing the living palaeoenvironment of the urgonian deposits and displayed at the Municipal Museum of Orgon (Urgonian stratotype locality, France).

Networking. With the aim of inviting the visitors to discover geoheritage, 18 circuits, for one day or over several days, have been created in the territory of the project around 7 themes (sporting, cultural, contemplative, biodiversity, etc.). Each of the circuits includes the discovery of at least one geological site and combines other cultural, natural or intangible heritages.

Digital tool. To attract the public attention (including the young public), and to embrace a certain modernity, the digital tool was positioned at the heart of the strategy of mediation, valuation and promotion of the Geological Adventure. A website (https://aventuregeologique.com/, accessed in September, 2021) and a Smartphone application (https://play.google.com/store/apps/details?id=com.easymountain.cd04, accessed in September, 2021) were thus deployed. The website allows the public to prepare their tourist trip upstream by providing complete information on the geosites. The Smartphone application invites people to live an in situ active experience through thematic circuits and interactive games using geolocation. These games, intended for young audiences, provide scientific concepts and raise awareness of the protection of natural heritage. Tactile tables left for free consultation allow the dissemination of all the digital content of the project; they have been installed in two museums and five tourist offices in the territory of the Alpes de Haute-Provence.

3.4. Discussion

The Geological Adventure has proved very demanding in terms of project management and in particular the mediation aspect. It was necessary to find the right tone: if the discourse remains too technical, we lose part of the lay audience, and conversely, if we simplify the scientific discourse too much, the risk is to deliver erroneous or irrelevant information because of lacking content (Martin et al. 2010). Injecting an emotional and imaginary component into didactics via story-telling is also tricky because it can spawn confuse between reality and fiction to a general lay audience. This requires sobriety and unequivocal explanations on the media facilities.

While the digital tool offers a wide range of possibilities, it also has drawbacks. The experience of the Geological Adventure shows the limits of digital deployment in rural and mountain areas where the telecommunication network does not yet cover the entire territory. The public is faced with uneven signal quality as well as difficulty in downloading the website or Smartphone application in the field. These conditions are obviously not favorable to the systematic downloading of cultural applications by Smartphone users, especially for heavy applications, as the products provided need to be light and quick to download. The Geological Adventure application presents numerous photos and videos, which weigh down its content and impose a long download time: some users may therefore become demobilized. In addition, in the digital field where technologies evolve very quickly, the tools developed can quickly become obsolete. It is relevant to question the durability of the various informative materials, of which the most classic (lecterns, in situ information panel, etc.) sometimes appear more robust over time and less demanding in terms of management, maintenance and updates.

Finally, as an experiential guarantee, we must not forget to put the human at the heart of the mediation and promotion processes. An all-digital/technological solution cannot replace the actors of the territories who are vectors of emotion and authenticity.

It should be noted that almost all the achievements within the framework of the Geological Adventure are free access and free of charge to the public, including the developed geosites. The only realizations with entrance fees are the Bossea Cave site, the F. Sacco Museum and the two museums where the digital tables are displayed. The project as a whole is thus ranked relatively high on the accessibility scale of Mikhailenko et al. (2021), with an overall average score of 15/20 for all the developed geosites (from 8/20 to 20/20 depending on the geosites, including 17/20 for the Ammonites Slab of Digne-les-Bains).

4. The Ammonites Slab rescue operation

4.1. The facts

The Ammonites Slab geosite is located in a bottom valley subject to mountain climatic conditions. Water infiltrations are present (Fig. 8g) and the limestone rock of the Slab shows many surface desquamation or delamination (Fig. 8a). Some ammonites are fractured due to the opening of joints (Fig. 8b). Ammonite repair, patching or sealing operations have already been carried out using various mortars for years (Fig. 8b). However, more recently, a block of rock (35 X 20 cm – Fig. 8c) illegally collected during May 2016 at the base of the Ammonites

Slab revealed the presence of a large void formed naturally at the interface of the limestone layer (the Slab) and the underlying marlstones. The presence of such other voids could be legitimately suspected. Their formation seemed recent, no cavity of this importance having been observed before (the bottom of the Slab, however, showed a slight swelling - Fig. 8d). Apart from this isolated act of vandalism, the unrestricted accessibility of the fossiliferous layer to the public has resulted in small damage, as well as wear of the fossils due to repeated contact with the hands of visitors (particularly present at children height - Fig. 8e–f); although it was forbidden, some unscrupulous visitors had even taken the risk of climbing the fossil wall!

These observations showed the alarming condition of the geosite. The alterations affect the ammonites, their calcareous matrix and, more worryingly, the substratum of the Slab itself. Diagnoses and precise studies were necessary in order to identify the conservation problem as a whole and to consider the appropriate treatments to remedy it.

4.2. The studies

4.2.1. The voids

A geophysical radar study was carried out by the Laboratoire d'Etudes et de Recherches sur les Matériaux (LERM, Arles, France - October, 2016), in order to detect and map heterogeneous zones, or voids, under the fossiliferous stratum.

Method. The principle of geophysical radar uses the reflectometry of electromagnetic waves at high rate pulses of short duration. Waves are differentially reflected at the interface of materials with different physical characteristics. The geophysical radar used is a LERM model with dual frequency antenna. The measurement was carried out according to the following parameters:

- double frequency of pulses at 400 MHz and 1 GHz;
- scan duration: 10 ns (1 GHz) and 35 ns (400 MHz), which corresponds to an investigation depth of respectively 0.5–1.50 m in the context of the Slab;
- realization of 35 measurement profiles spaced from 50 cm apart along the line of greatest slope (length of the profiles 5–24 m);
- vertical resolution: 512 samples per scan (i.e. 1–3 mm per sample); horizontal resolution: 50 scans per meter (i.e. 1 measurement every 2 cm).

The raw signal (Fig. 9) was processed so as to provide an anomaly mapping at two different depths (10–40 cm and 50–80 cm respectively).

Results. The first mapping at 10–40 cm depth (Fig. 10a) shows heterogeneities located mainly in the lower south part of the Slab, around 0.5–3 m from the bottom, for a cumulative surface area of approximately 6 m^2. The voids are probably not all in contact, but can extend over more than 1 m^2 continuously. These heterogeneities are distributed over two levels, respectively 10 and 20 cm deep, for an estimated thickness of 2–15 cm. Other heterogeneous areas are located in the upper part of the Slab, in the 2–3 m below the summit, for a varying thickness of 10–50 cm. Only the north lower part of the Slab seems homogeneous.

The second mapping at a 50–80 cm depth (Fig. 10b) shows heterogeneities partly correlated with the previous ones, but could be linked to inconsistent materials at an interface between two strata.

4.2.2. Deformation and fracturing

New 3D photogrammetric acquisitions led to the study of the geometry and fracturing of the Slab, as well as to produce a digital model, made by the Centre Européen de Recherche et d'Enseignement des Géosciences de l'Environnement (CEREGE, Aix-Marseille, France - 2017–2018).

Method. Eight hundred high definition constant distance photos were taken (material used: full frame digital camera of 36 Mpx). These images have a sufficient resolution (0.5 mm) to allow making digital models of the ammonites (Fig. 6; see for example https://sketchfab.com/models/b1299fc681314243a14a577775ca898a, accessed on September, 2021), and they constitute a database for monitoring the condition of the Slab and the ammonites over the long term from the previous data (Dommergues & Guiomar 2011). A second drone acquisition of 280 photos was carried out in order to remove acquisition artifacts (cast shadows, safety ropes, etc.). The 3D digital model was produced as a point cloud, which the surface was interpolated and textured (https://skfb.ly/6t9FS, accessed on September, 2021). The point cloud was then projected onto the average surface plane of the Slab to constitute a digital terrain model (DTM). The images used for the realization of the DTM were also used to make an ortho-rectified and calibrated photo of the entire Slab allowing precise digital studies (237 million pixels for a ground pixel resolution of 1.67 mm - Fig. 11).

In addition, 22 geodetic markers were placed on the Slab and its periphery as part of the monitoring of possible deformations of the site over the long term.

Results. The DTM and orthophoto were used in 2D and 3D to map the fracturing of the Ammonites Slab in a 3D reference system. The model now allows a precise measurement of the Slab:

- Surface: 310 m²;
- Perimeter: 79.6 m;
- Width: 16.5–11.7 m (the latter at the top of the Slab);
- Height: 24.8 m;
- Tilt: 48 °;
- Orientation: 167°N (due to this slightly north orientation and its inclination, morning is the best for ammonites observation; in the afternoon the site is backlight).

It appears that the Slab has the general shape of a horizontal gutter due to flatness defects not exceeding 40 cm in amplitude (Fig. 12). This particular shape results essentially from the overhanging projection of the upper part of the fossiliferous layer (with respect to the presence of a horizontal fracture) and the bulging of its lower part, where the most voids were observed (see above chapter 4.2.1). This bulge is asymmetrical, present only in the south part of the Slab where it reaches 15 cm in amplitude (Fig. 8d); it is accompanied by a detachment of the limestone layer, already observed visually (chapter 4.1 – Fig. 8c), and open star fractures.

Analyzes and cartography of fracturing (Fig. 13). Analysis and mapping of the fractures typology allowed reconstructing their history from the deposition of sediments until the present time:

- Irregular diagenetic joints: without really being fractures, they are sinuous discontinuities more clayey than the rest of the Slab. These joints are often deep because they are easily eroded by the rainwater flow; they weaken the stratum while contributing to its bumpy appearance.
- Normal faults and tension joints (Fig. 14a): a dense series of horizontally oriented joints and faults chop the Slab. The faults almost always show a calcite filling and

have small normal slips (therefore perpendicular to the surface plan of the stratum), which can cut and offset ammonites. The tension joints have the same orientation and the presence of calcite suggests that they were formed at the same time than the normal faults in an underwater environment. These structures would therefore be linked to the deformations produced during the rifting phase of the Tethys Ocean, which created the western margin of the Digne-les-Bains thrust sheet basin during the Lower Jurassic.

- Strike-slip faults, calcite joints and associated stylolithic joints (Fig. 14b-d): the largest strike-slip fault cuts the Slab in half through the middle (dextral sliding movement, the upper part having moved to the north – Fig. 14c); calcite joints were formed in the extension relay zones (Fig. 14b). In contrast, stylolithic joints were formed at the end of the strike-slip fault in the compression areas. This strike-slip fault shows a total sliding of 10.2 cm (measured on the early diagenetic joints and the offset ammonites - Fig. 14d). The reactivation of these strike-slip cracks is probably linked to the beginning of the activity of the Bès and St Benoît faults, nearly 10 Ma ago, as part of the formation of the Alps.
- Joints without calcite: short compression joints without calcite filling are present at the end of the strike-slip faults; some appear to be in shear. They probably all resulted from compressive deformations during the tilting of the Ammonites Slab.
- Gravity and weathering fractures: they are mainly present in the south and upper parts of the Slab and are associated with the tilting/overhanging of this part. They were probably aggravated by mechanical unloading following the removal of the rock cover, above the fossiliferous layer, during the excavation works of 1979 and 1994.

4.2.3. Discussion and recommendations

Some of the fractures are filled with calcite (Fig. 14e) and are therefore stable and safe for the sustainability of the Ammonites Slab. On the other hand, other fractures are open and participate in its degradation. After 197 million years of history, the degradation of the Slab appears to be a very recent and rapid phenomenon partly of anthropogenic origin: it results from open air exposure following the withdrawal of the upper layers, which protected it until then. The too rapid mechanical unloading of the rocks associated with exposure to weather conditions favored the opening of fractures and infiltration. This degradation is favored by exposure to ENE and seasonal freezes and thaws alternating.

The numerous fillings carried out during the work operation in 2009, to slow down the degradation of the Slab, did not prevent the aggravation of the gravitational bulge and the opening of star fractures that recently appeared in its basal-south part. This deformation is associated, on the one hand, with anomalies detected by geophysical radar (cavities, heterogeneities - Fig. 10), and on the other hand with a dense network of open fractures in the weathered parts (Fig. 13), which allows the infiltration of rainwater.

The infiltrated water is blocked by the underlying marly layer and by the shotcrete sprayed in 2009 on the southern edge of the Salb (Fig. 11, left), even though equipped with barbicans for drainage, which was supposed to slow its erosion and lateral collapse. The chemical reactions caused by the presence of water in the pyrite-rich marls cause, among other things, the proliferation of small gypsum crystallizations. These crystallizations facilitate the detachment of the marlstone sheets and their swelling in the presence of humidity, which constrains the limestone layer of the fossiliferous stratum. At the same time, the pressurization of the infiltration water causes a reduction in the friction at the base of the limestone layer and causes the crawling of the southern half of the Slab (the most altered part), of which the local bulge is the most obvious manifestation.

As it stands, these observations suggest a risk of destabilization of the Ammonites Slab in the more or less short term, with the possibility of a sudden rupture of the south part of the limestone layer by a buckling mechanism, which would lead to the irreparable loss of part of the geosite.

It therefore appeared that to ensure the protection of the geosite, a rapid intervention was necessary. This operation was intended to limit the percolation of water, but also to ensure the maintaining (by anchoring) of the compartments destabilized by joints and fractures, in order to limit the effects of erosion by raveling and prevent them from falling. The elimination of the shotcrete from the lower/south part was also a necessity to allow a better flow of seepage water and to reduce the hydrostatic pressure.

Note that the problem of anthropogenic erosion, linked to free access to the fossiliferous layer, should also be resolved.

4.3. Sealing device

The installation of reinforcements by sealed metal inclusions (Fig. 15) is particularly complex in a heritage site with such a high density of ammonites to be protected, which considerably limits the methods and possibilities of surface installations. Drilling and coring tests without percussion with a fine implantation were performed to avoid any destabilization and to avoid the ammonites. They made it possible to carry out tensile tests on anchor bars sealed in the fossiliferous limestone using a hollow traction cylinder. The marls were sampled for laboratory analysis in order (1) to test the interactions with the chemical formulation of the envisaged sealing grout, (2) to test the swelling potential and (3) to analyze the corrosivity of the ground. These investigations enabled:

- to confirm the presence of heterogeneous materials/cavities to define the quantity of grout to be injected through the boreholes made for the installation of the anchors;
- to show that the soil corrosivity is low (Ph=7.7; chloride ion concentration =2.2 mg/kg; sulfate ion concentration =11.8 mg/kg; resistivity at 20°C=5.700 Ω/cm), which allows to optimize the composition of the sealing grouts and to define the protective treatment for the steel of the anchor bars;
- to define the boreholes diameter and the reinforcement bars diameter to avoid any risk of degradation of the fossiliferous layer;
- to define the density and number of anchor bars required (minimum mesh size) while avoiding ammonites;
- to test the lateral friction on the limestones during the conformity tensile tests according to the actual thickness of the beds;
- to calculate the necessary length for the sealing bars, knowing that the thickness of the area to be reinforced is limited to 0.6–0.75 m depth below the surface.

In order to control the movements of the Slab during the drilling and injection of the filling and sealing grouts (topographic monitoring), sensors of piston extensometer type were implemented for the duration of the intervention.

Choice of the filling/sealing grout. The main problem is the presence of pyrite in the marlstones underlying the Ammonites Slab, which induces the risk of sulphate reactions with the production of gypsum and sulfuric acid. In such a humid and porous environment, some cement compounds can go into solution and react with pyrite. Sulphates can also lead to the formation of thenardite crystals (anhydrous sodium sulphate - Na_2SO_4) or mirabilite (sodium sulphate decahydrate - Na_2SO_4, $10H_2O$) further increasing the risk of marls swelling and detachment of the Slab. This means that the sealing grout must have a limited content of sulphates, but also a reduced content of tricalcium aluminate (C_3A) to limit the formation of expansive secondary compounds (secondary ettringite).

For these reasons, the use of portland cements was excluded. In contrast, natural hydraulic lime has low sulphate content and is therefore more stable, but it has a long setting time, low resistance with a risk of going into solution in the presence of water. Air lime/portland cement mixtures would guarantee lower soluble alkali levels than cements alone, but with the danger of a high presence of more soluble portlandite. These solutions were therefore discarded for the treatment of the Ammonites Slab.

According to the method of Zhang et al. (2014; 2018), laboratory tests of several potential grouts were carried out using a 5 kg sample of crushed marls taken directly from the Slab site. Under in situ conditions, the use of resistant sulphate cement should be preferred to avoid the risk of swelling and cracking by delayed hydrate formation, which could jeopardize the integrity of the Slab despite the seals. To fix the lime and avoid efflorescence, compound cement with a low C_3A content based on pozzolan of CEM III type was chosen (Declair 2008). The chemical characteristics of this cement are summarized in Table 1.

Table 1. Chemical characteristics of the CEM III cement used for filling voids and sealing anchors on the slab. The main constituents are: clincker (28.5%, of which C_3A=2.85%), blast furnace slag (71.0%), secondary constituents (siliceous and limestone fly ash, 0.5%).

	Average value (%)
SO_3	2.8
Cl^-	0.14
Loss on ignition (950°C)	0.9
Insoluble	0.3
S^{2-}	0.44
Alkaline equivalents (Na_2O + 0.658 K_2O)	0.6
Alkaline actives	0.5

Results. The operation was carried out by the company NGE Fondations (Drap, France) between November, 2019 and February, 2020. A total of 262 anchors (Fig. 16-17) were installed perpendicular to the Slab with rods 0.016 m in diameter to a depth of 1 m. Drilling confirmed the average thickness of 0.3 m (0.4–0.13 m) of the Slab with thinner zones located especially at the foot (south part) and in the middle of the Slab. The drilling also confirmed the presence of heterogeneity in the marls, in the altered zones with a clayey tendency, and some of the voids observed during the radar studies. The latter were completely clogged by the filling grout. The low corrosivity of the soil, associated with the thinness of the fossiliferous stratum and the need to use small diameter for the tie bars reinforcements, led to the treatment of those rods by galvanization. In order to limit the impact of vibrations during drilling, as well as the visual impact, the drilling diameters have been limited to 0.032 m in diameter. The heads of the anchors were masked and surface protected by a tinted mortar up to 0.05 m depth.

Each inclusion provides a minimum resistance capacity of Tr=8.4 kN, thereby improving very significantly the cohesion of the Slab on its support with a resistant effect against possible forces due to swelling (freeze-thaw) and hydrostatic pressures.

During and after the work, the topographic monitoring of the Slab met the expectations and did not show any significant movement.

4.4. Water ingress

Whether by infiltration in marls or cracks, by chemical reactions caused by the action of freeze-thaw cycle, or by hydrostatic pressure, water plays a major role in the weathering of rocks and the behavior of the rocky massif. Water is one of the essential elements to be taken into account in studies intended for the conservation of geosites. Consequently, and in addition to the stabilization work on the Ammonites Slab, it was necessary to carry out work aimed at improving the management of seepage water.

Water infiltration takes place mainly at the fractures of the fossiliferous stratum, in particular in its upper part (Fig. 13). The work carried out in 2009 to limit this infiltration consisted of the construction of a concrete guttering to drain the upstream water of the Slab, and by filling (resins) the largest open cracks. The guttering, made for a lifespan of around 5 years, was, 7 years later, in very poor condition, leaving some of the water to seep into the marls.

On the south side of the Slab, the shotcrete intended to block the erosion of the marlstones and the fall of overhanging limestone layer elements actually partially blocked the flow of infiltrated water from the surface. The barbicans that were supposed to drain this water never allowed it to be evacuated. In rainy weather, water flowed from the base of the concrete in contact with the lower limestone layer. This installation certainly had a negative impact on water circulation in the southern part of the rock mass, with the consequence of increasing the pressure at the foot of the Slab.

Due to the geomorphology of the site, there is a potential infiltration zone of approximately 100 m² in the rocky massif located immediately above the Slab. It was therefore necessary to remove the 2009 improvements, then to strip and dig a drain behind the Slab over a line of 50 m for a 2 m width. This newly cleared area was thus sealed by a geomembrane covered with C30/37 fiber-reinforced concrete. This new guttering was extended downstream by a rainwater drainage ditch towards the dale.

The edge of the southern part of the Slab was also treated: part of the shotcrete was removed. The remaining concrete was treated to better integrate visually into the geosite. At the same time, the permeable cracks on the surface of the Ammonites Slab were sealed during the anchors and sealing grout installation.

4.5. Unsolved problems and perspectives

While the Ammonites Slab rescue work ensures the stability of the geosite over the long term, untreated conservation issues remain: in particular, the surface desquamation of the Slab, the shattering of the cracked limestone, the falling rocks, which result from the daily and seasonal temperature contrast and the action of the freeze-thaw cycle in winter.

The only effective protection solution would be to shield the site from meteorological agents with strict control of humidity and temperature. Such control would only be possible by complete insertion of the whole Slab inside a regulated building. Beyond its exorbitant cost, a building of the necessary size is currently not feasible for several reasons: (1) the Local Urbanism Plan in force in the municipality of Digne-les-Bains does not allow constructions over 10 m in the Ammonites Slab area, while the Slab itself already has an amplitude of 24 m; (2) the proximity of the road would imply its deviation, which is complicated by the occupation of land on the other side; (3) the geosite is located into several protection zones forbidding such constructions (national nature reserve and protection zone of the listed site of the neighboring antique plaster industry of Champourcin). The possibility of setting up an intermediate protection structure of courtyard type was also abandoned for the same reasons, by very strong technical constraints, by the fact that it would only have reduced direct rain and snow runoff (out of wind) without strict control of environmental conditions, and in fine by the very unfavorable benefit/cost balance.

A direct surface protection technique of the fossiliferous stratum was also considered by the installation of a protective synthetic layer, but this technique was very quickly abandoned. Indeed, current techniques allowing sufficient sealing also prevent residual moisture and soluble salts from escaping, which would actually have achieved the opposite effect.

Furthermore, the long-term resistance in mountain climatic conditions of this type of coating still needs to be strongly tested before being used on heritage sites. While waiting for new techniques or new materials, the only alternative in addition to the measures already in place (this work) remains the maintenance of the Slab ‘by hand’ (human interventions using safety ropes) as and when required to limit the ravages of time and bad weather. Beyond the necessity for monitoring the Slab itself to survey the evolution of its condition, for the moment, we are arriving at the limits of the in situ conservation of palaeontological sites.

Drilling and field surveys have shown that the extension of the fossiliferous stratum is proven beyond the currently exposed surface of the Slab with the same density of ammonites. On the 7,000 m² where the stratum has been recognized and mapped (Fig. 18), an extrapolation allows to estimate the presence of nearly 34,000 buried ammonites. Physically and legally protected, this exceptional site is left as a legacy for future generations: as long as the latest long-term conservation issues are not resolved, no new large-scale discovery of the ammonites bearing surface is possible.

5. Enhancement of the Ammonites Slab geosite

5.1. The previous state

The Ammonites Slab, exposed to the open air, is located near the road (Fig. 3, 19a). The road had been rerouted in the late 1970s to free up a safe, but strait, viewing area for the public. Another derelict part of the road served as a car park linked to the Slab by an old road bridge. These areas (the parking and the visiting area at the foot of the Slab) were never properly developed and the surroundings of the site actually looked more like a wasteland than a geosite of international stature.

The mediation was limited to a single lectern with some information and an artistic reconstruction of the seabed with some organisms from the time of the ammonites present on the Slab.

5.2. The new visitor structures

As part of the Geological Adventure project, and in parallel with the work to ensure the sustainability of the Ammonites Slab, the entire geosite was enhanced for the public between November, 2019 and May, 2020. The work was carried out by the company Eiffage routes Mediterranée-Alpes-Vaucluse.

The old vacant wasteland has been transformed into a parking area (Fig. 19b: 1). It was designed in the shape of a roundabout to allow full accessibility to buses. In order to comply with road safety rules in terms of visibility, it was necessary to shift the road slightly from on the equivalent of a half-roadway in front of the car park entrance (work made by the Departmental Technical House in September, 2019).

The old bridge (Fig. 19b: 2), the deck of which has been raised, is an infrastructure of quality and as such it materializes the new entrance door to the geosite, which opens directly onto a pedestrian reserved reception area (Fig. 19b: 3). Most of the mediation is now developed in this space. From the reception area, a 35 m long (1.60 m wide - 1.45 for the walkway) wooden/metal footbridge now provides access to a new observation platform, raised 2 m above the ground level, facing the Slab and the ammonites (Fig. 19b: 4-5). The slope of the footbridge at 4% meets accessibility standards for people with reduced mobility. The interest of the observation platform is threefold: (1) to offer visitors a new panoramic point of view on the Slab partly decontextualized from the road and its nuisances (noise and safety). The foot of the Slab is no longer visible, and the point of view being closer to the wall due to its inclination lead to an increased immersion effect in the geosite (Fig. 20a); (2) the platform allows the neutralization of direct access to the fossil surface by the public, in order to avoid the anthropogenic degradation mentioned in chapter 4.1; (3) keeping the public at a safe distance also helps prevent the risks associated with rock falls, now minimized by the anchoring of the Slab.

5.3. Didactic

One of the aims of the geosite enhancement is to allow the public autonomy in their visit. On the one hand in terms of physical accessibility (materialization of paths; controlled slopes and drops; seating areas for prolonged station - Fig. 20b); sufficient space to accommodate groups; installation of a public transport stop awaiting to be integrated into the urban mobility plan of the city of Digne-les-Bains); on the other hand, by setting up educational furniture (which can also be used as a support for guided tours). The educational path was designed in 8 stages, from the car park to the discovery of the Ammonites Slab itself, following a progressive and immersive approach (Cayla et al. 2010; Martin et al. 2010):

- ***Welcome the visitor:*** the geosite is presented in the context of the 7 other geological or natural sites to be visited in the Bès Valley, and of which the Ammonites Slab is in some ways the gateway.
- ***Arouse curiosity:*** visitors are invited to disconnect from their daily reality in order to immerse themselves in the deep time using the geological timeline developed for the Geological Adventure project (on the background on Fig. 20c).

- ***Amaze:*** encounter with the animals that lived on the site 197 million years ago in Sinemurian times. Explanations on ammonites with accessible speech are based on the latest scientific findings (Fig. 20d).
- ***Explore:*** what makes the Ammonites Slab a remarkable site? History of the discovery of the Slab with a perspective of its heritage and scientific interest.
- ***Learn:*** the explanation of the different stages of the ammonite fossilization process on the Slab is given using life-size models (Fig. 20e-f).
- ***Experiment:*** explanation of the formation of strata and then of the folds and erosion that shaped the Slab as we see it today.
- ***Understand:*** the methods in paleontology, investigation of the past, are mentioned.
- ***Contemplate, and nothing else:*** the last station on the observation platform invites to contemplation. A cast of a portion of the Slab allows the public to better take ownership of the site and also represents a tactile visit aid for the visually impaired (Fig. 20a).

The new geosite enhancement as a whole takes into account accessibility to people with disabilities according to their specific needs:

- ***People with motor disabilities:*** the geosite is accessible to visitors in wheelchairs. Reserved parking spaces are positioned near the entrance. Seating is arranged regularly. The didactic materials are designed to be suitable for both standing and in wheelchairs people (or children).
- ***Visitors with visual disabilities:*** a contrasting tactile guide strip leads from the parking spaces to the entrance to the site. All graphic material is produced in large sans serif characters (>4.5 mm) with contrasting colors. All the themes are backed up by tactile

information allowing the understanding of the different concepts: the time scale, the animal ammonite, fossilization, geological strata, the molding of a portion of the Slab.

- ***People with mental disabilities:*** all the facilities provide security by keeping it away from the road and the car park. The signage is explicit and all the didactic themes are doubled by an insert Easy to Read and Understand (FALC, by its acronym in French) identified by the European Easy to Read pictogram.
- ***People with hearing disabilities:*** moving away from the road allows better hearing comfort. The spaces are large enough to allow the animation of groups with a sign language interpreter.

6. Funding

The Geological Adventure project was funded within the framework of the European program ALCOTRA, Interreg V-A 2014-2020 (Alpes Latines COopération TRAnsfrontalière in French). This program has covered the Alpine territory between France and Italy since 1990, where it has co-financed nearly 600 projects for around 550 million euros in European grants. Its general objective is to improve the life quality of populations, the sustainable development of territories and cross-border economic and social systems through cooperation affecting the economy, the environment and services to citizens.

The overall project budget supported by the 7 partners of the Geological Adventure amounts to 2,331,546 €. Support from Europe, via the European Regional Development Fund (ERDF), represents 85% of this amount (here the ALCOTRA program). This very high level of public intervention is an unexpected lever in order to implement ambitious projects.

Regarding the financing of the operation to rescue and enhance the Ammonites Slab, the total cost of this sole operation amounted to 1,659,673 €, distributed as follows (all taxes included):

- 134,771 € project management and technical and security control missions;
- 594,030 € rescue and reinforcement work;
- 683,247 € enhancing and landscaping work;
- 107,190 € didactic component;
- 140,435 € road shifting.

Fifty-nine percent were self-financed by the Departmental Council of the Alpes de Haute-Provence (contracting authority - 979,673 €), 31% by the European Union (ALCOTRA Interreg V-A 2014–2020 - 510,000€) and 10% by the Sud-Provence-Alpes-Côte d'Azur Regional Council (170,000 €).

7. Conclusions

Protected since 1984 under the National Geological Nature Reserve of Haute-Provence (RNNGHP), and labeled Geopark since 2000 (UNESCO Global Geopark of Haute-Provence), the Ammonites Slab geosite of Digne-les-Bains (Alpes de Haute-Provence, southeastern France) is the result of 197 million years in Earth history. Exposure to the open air of more than 1,550 large ammonites on this ancient seabed makes it exceptional and spectacular despite the virtual absence of infrastructure for visitors until recently. The Slab has only been exposed to light step by step since the last third of the 20th century, but it has since suffered from the effects of too rapid mechanical unloading of rocks, contrasting mountain climatic conditions, and direct contact with the public. A series of studies (unpublished) have shown that the state of conservation of the fossiliferous layer was much more degraded than expected. Without the completion of major works in the relatively short term, the risk of destabilization by a buckling mechanism would have resulted in the irreparable loss of part of the geosite.

As a committed manager, the Departmental Council of the Alpes de Haute-Provence has put in place the necessary means to ensure the proper functioning of the RNNGHP, with the desire to recharacterize the geosites to ensure both their physical conservation and public access. Despite the significant financial effort made by the Departmental Council for the rescue of the Ammonites Slab, the difficulty lay in mobilizing the significant additional funding required on the sole aspect of conservation. In this context, the 2015–2016 call for projects of the European Interreg V-A France-Italy ALCOTRA program was a major opportunity. It allowed developing the rescue, sustainability and enhancement project that lives up to the international reputation of the Ammonites Slab, within a broader geotourism project: the Geological Adventure. In order to respect the ambition and the axes of the European program, this project also concerned the development of other major geosites through the territory in a process of experiential and sustainable tourism, their networking by itinerant circuits and the setting up of a quality scientific mediation (including using of digital tools). Mediation was developed from a strategy of allowing making scientific culture accessible to as many people as possible. The overall project budget supported by the 7 Franco-Italian partners of the Geological Adventure amounted to 2,331,546 €. Support from Europe, via the European Regional Development Fund (ERDF, here the ALCOTRA program), represented 85% of this amount. Such a high level of public intervention is an unexpected lever in order to implement ambitious projects and it is a serious source of funding to be considered by project leaders for the protection and enhancement of European geoheritage.

In this context, the conservation works of the Ammonites Slab of Digne-les-Bains (up to 1,659,673 €) consisted of (1) anchoring the Slab on its substratum; (2) filling the voids identified during the studies using an inert grout so as to avoid undesirable chemical reactions; (3) dealing with the problem of water infiltration; and (4) neutralizing direct public access to avoid anthropogenic damage. Enhancement work for the entire geosite was carried out in parallel. The new equipment consists of a parking area allowing the circulation of buses; a slight realignment of the road was necessary in order to comply with road safety rules. This new gateway to the geosite opens directly onto a pedestrian reception area, where mediation is developed. A raised platform offers visitors a new panoramic and immersive point of view in front of the ammonites, safe against any risk of rock fall or related to road circulation. A particular effort has been made to provide the public with progressive and immersive educational mediation using different media (lecterns, timeline, models, 3D reconstructions, digital tool). The entire geosite, whether through its facilities or adapted teaching methods, is accessible to people with motor, visual, mental or hearing disabilities. The easy access to the Ammonites Slab and its free admission to visitors rank the geosite very high on the accessibility scale of Mikhailenko et al. (2021) with a score of 17/20. This score could be revised and reach 20/20 when the geosite will be integrated into the city's urban traffic plan and served by public transport, a secure pedestrian path and a cycle lane.

The RNNGHP is a privileged place to study Geology and Palaeontology for students and scientists from all over the world, and this example highlights the contribution of protected natural areas to the improvement of knowledge and scientific research. Beyond the scientific interest, the project approach of the Geological Adventure is based on the fact that the enhancement of the geological heritage, its protection and conservation, are also factors of sustainable local economic development (Betard et al. 2017). It is also undeniable that the

Ammonites Slab of Digne-les-Bains was a very strong source of inspiration enabling the emergence of concepts of geoheritage, geotourism and Geoparks (Martini 1994). To go further, the Ammonites Slab of Digne-les-Bains was very recently proposed as a candidate to be one of the first 100 IUGS (International Union of Geological Sciences) geological heritage sites. As part of the management of the RNNGHP, the pursuit of actions carried out by the Departmental Council of the Alpes de Haute-Provence for the conservation of geoheritage, the equipment of geosites for the public and the establishment of mediation tools aim to make the Alpes de Haute-Provence, and the UGHP, a leading geotourism destination.

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Figure captions

Fig. 1: Palaeogeographic map at the Sinemurian age (-200 MY – from Scotese, 2014), with position of the geosite of the Ammonites Slab (red star).

Fig. 2: The numerous ammonites present on the Slab.

Fig. 3: Stat of the geosite in 2016, before the work. Note the unique lectern and the absence of particular enhancing.

Fig. 4: Location map of the Ammonites Slab geosite near the city of Digne-les-Bains (Alpes de Haute-Provence department, SE France).

Fig. 5: Geological and structural context of the Ammonites Slab. The geosite is located along the Bès and Saint Benoît faults, in the front of the Digne-les-Bains thrust sheet.

Fig. 6: Section of the Ammonites Slab series and a *Coroniceras* shell reconstruction (modified from Dommergues & Guiomar, 2011). The digital model of the ammonite is part of the new 3D photogrammetric acquisitions made by the CEREGE at a 0.5 mm resolution.

Fig. 7: Map of the National Geological Nature Reserve of Haute-Provence (RNNGHP by its French acronym). The 18 green dots are the sites classified under National Nature Reserve (RNN) with strong regulation, and the green area is the protection perimeter were the removal, destruction or degradation of fossils, minerals and concretions is prohibited.

Fig. 8: The damages on the Ammonites Slab; **(a)** surface desquamation and delamination due to climatic conditions; **(b)** open fractures repaired with mortar (visible just beneath the ammonite); **(c)** the void recently identified behind the Slab due to an illegally collected block in May 2016 (35 X 20 cm); **(d)** the slight swelling at the bottom of the Slab, where the most voids were observed. The bulge reaches 15 cm in amplitude (picture reconstructed using 3D photogrammetry); **(e)** unrestricted accessibility of the fossiliferous layer to the public can

result in small damages; **(f)** a worn ammonite due to repeated contact with the hands of visitors; **(g)** water infiltrations.

Fig. 9: Extract from the raw RADAR signal and its interpretation: voids/heterogeneities are detected between 10–40 cm below the surface of the Slab (red dot-lines).

Fig. 10: Mapping of the heterogeneities at **(a)** 10-40 cm, **(b)** 50-80 cm behind the surface of the Slab.

Fig. 11: Ortho-rectified and calibrated photography projected in the plan of the Slab.

Fig. 12: Digital model of the Ammonites Slab with colorization of the relief and artificial shading. The shades from yellow to red are in front of the average plane of the Slab.

Fig. 13: Fracturing map of the Ammonites Slab showing the different generations of fractures. The diagenetic joints are in green; normal faults and tension joints are in orange; joints without calcite are in blue; open fractures (gravity and weathering fractures) are in red. The yellow areas are concrete parts.

Fig. 14: **(a)** Small normal fault with vertical throw, which shifts an ammonite; **(b)** calcite joints in the extension relay zone of the main strike-slip fault; **(c)** the main strike-slip fault cutting the Slab in half through the middle (dextral sliding movement; total sliding of 10.2 cm); **(d)** detail of an ammonite cut by the main strike-slip fault (sliding of 2.8 cm at that point); **(e)** closed joint filled with calcite.

Fig. 15: Principle of the anchoring with sealed metal inclusions. The voids to fill in with grout are represented in orange.

Fig. 16: Location of the 246 anchoring bars (yellow dots) avoiding the ammonites.

Fig. 17: The drilling and anchoring operation showing the anchor metal bars.

Fig. 18: In red is the currently exposed part of the Ammonites Slab; in white is the potential total unearthed mapped surface of the Slab (7,000 m^2); an extrapolation allows to estimate the presence of nearly 34,000 buried ammonites.

Fig. 19: Surroundings aspect of the Ammonite Slab geosite **(a)** before the enhancement/conservative works and **(b)** just after these works: (1) is the car-park area in the shape of roundabout to allow full accessibility to buses; the bridge that materializes the new entrance door to the geosite; (3) the pedestrian reserved reception area where most of the mediation is developed; (4) the wooden footbridge access (the 4% slope meets accessibility standards for people with reduced mobility); and (5) the new observation platform, raised 2 m above ground level, facing the Slab and the ammonites.

Fig. 20: the new didactic equipments of the geosite: **(a)** the observation platform offering a new point of view to the Slab with the lectern-cast representing a tactile visit aid for the visually impaired; **(b)** detail of the wooden footbridge in front of the strata; **(c)** lecterns that explain stratigraphy concepts and the formation of the Slab; **(d)** ammonite reconstruction with soft-body parts; **(e)** overview on the pedestrian reserved reception area; **(f)** explanations of the fossilization process that occurred on the geosite with 3D life-size models.