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## 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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### ► To cite this version:

Didier Bert, Violaine Bousquet, Myette Guiomar, Francesco Bariani, Emmanuel Faure, et al.. 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). *Geoheritage*, 2022, 14 (3), pp.101. 10.1007/s12371-022-00739-z . insu-03767996

**HAL Id: insu-03767996**

**<https://insu.hal.science/insu-03767996>**

Submitted on 5 Sep 2022

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1       **The geotouristic project ‘the Geological Adventure’ to the rescue of an**  
2       **iconic world heritage geosite, the Ammonites Slab of Digne-les-Bains**  
3       **(National Geological Nature Reserve of Haute-Provence and Unesco Global**  
4       **Geopark, France)**

5  
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29

### 30 **Abstract**

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

50

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

53

## 54 **1. Introduction**

55

56 At the beginning of the Jurassic (Sinemurian), 197 million years ago, the sea covered a large  
57 part of France. This geological period represents a key moment in connection with the  
58 dislocation of Pangea, then the opening of the Tethys Ocean with the flooding of the northern  
59 European margin (Fig. 1). The Ammonites Slab of Digne-les-Bains (Southwestern Alps,  
60 France) corresponds to an ancient fossilized seabed from this period. This sea floor, formerly  
61 horizontal, was then lifted, moved and tilted during the alpine surrection. Today, the result of  
62 this long history is an exceptional geological site (Fig. 2), emblematic of the National  
63 Geological Nature Reserve of Haute-Provence (RNNGHP by its acronym in French), of the  
64 UNESCO Global Geopark of Haute-Provence (UGHP) and of the French Department of the  
65 Alpes de Haute-Provence (Bert & Pagès 2021). More than 1,550 ammonites are exhibited on  
66 an inclined surface of 320 m<sup>2</sup>. The site's location in the open air, along the roadside, allows  
67 easy access for the public. The Slab is consequently very visited by both the local population  
68 and tourists, but also by scientists and schools, including geology students (from 21,000 to  
69 30,000 visitors per year according to 2016–2019 data; for comparison, the local population of  
70 Digne-les-Bains amounted to 16,068 inhabitants in 2020). The quality and size of this  
71 outcrop, the numerous fossils exposed, as well as its scientific and heritage importance, make  
72 the Ammonites Slab a unique site in the world. Consequently, it obtained the maximum score  
73 of 3 stars (geological site of high heritage value at national/international rank) on the French  
74 national inventory of geological heritage managed by the National Museum of Natural  
75 History (PAC1989 site: <https://inpn.mnhn.fr/site/inpg/PAC1989>, accessed in September,  
76 2021; De Wever et al. 2014, 2015).

77

78 Despite its importance and fame, the Ammonites Slab had never been truly developed or  
79 landscaped, the bias being to leave it to a certain ‘naturalness’ (Fig. 3), regardless of a  
80 suburban context (Fig. 4). Exposed to weather conditions, the fossiliferous layer can only be  
81 deteriorated over time. Since 2014, the Departmental Council of the Alpes de Haute-Provence  
82 manages the RNNGHP, and therefore also the Ammonites Slab. Despite the works carried out  
83 on several occasions to delay its degradation, a diagnosis carried out in 2016 (Bert et al.  
84 2019b and this work) highlighted the imminent risk of partially collapsing of the Slab,  
85 involving the need for an emergency response accompanied by major works. The extent of the  
86 operations required implied a high cost while taking into account a number of technical and  
87 administrative constraints. In this context, the 2015–2016 call for projects of the European  
88 Interreg V-A France-Italy Alpes Latines COopération TRAnsfrontalière program  
89 (ALCOTRA; Guiomar et al 2018 and this work) was a major opportunity for developing and  
90 launching a project allowing at the same time: (1) to ensure the protection work of the  
91 Ammonites Slab, (2) to enhance this exceptional geosite living up to its international  
92 reputation, and (3) to go further by networking the geoheritage of the ALCOTRA cross-  
93 border geographical area with other natural and cultural heritages. All of this with the aim of  
94 sustainable local development to meet the objectives of the European program: axis 3  
95 ‘attractiveness of the territory’, specific objectives 3.1 (‘sustainable tourism by increasing the  
96 attractiveness of the territory and preserving the natural and cultural heritage’) and 3.2  
97 (‘improve the management of natural heritage’). It was this project that came into being under  
98 the name 'The Geological Adventure'.

99

100 As a possible textbook case about a major conservation threat, through the management and  
101 enhancement of an emblematic geosite, which could be of help or interest to be transposed to  
102 other geoheritage sites in need, the present work propose to detail (1) the history and context

103 of the Ammonite Slab geosite, (2) the more global geotouristic project that provided the  
104 opportunity of a large amount of funding to rescue the site, (3) the rescue operation itself with  
105 technical elements for its safeguarding, (4) the new enhancement of the geosite, with  
106 structures and scenography elements and (5) some financial benchmarks.

107

## 108 **2. The Ammonites Slab**

109

### 110 **2.1. Geographic location**

111

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

117

### 118 **2.2. Geological context**

119

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

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

134

### 135 2.3. Lithology, palaeobiodiversity and biostratigraphy

136

137 The Ammonites Slab belongs to an alternation of limestone beds and thinner marly interbeds  
138 (Fig. 6). The facies suggest subpelagic deposits beneath the storm-wave action limit without  
139 any obvious role of currents (Corna et al. 1991; Dommergues and Guiomar 2011). Alongside  
140 with rare nautilus of the genus *Cenoceras* Hyatt, 1884 and a few belemnites, the Slab  
141 currently bears more than 1,550 ammonites, often large (up to 70 cm), which make the geosite  
142 famous. Suspensivorous epibenthic bivalve mollusks and echinoderms (pentacrins in isolated  
143 articles) are also very common despite often in debris. This benthic fauna is also clearly more  
144 diverse than the nectonic cephalopods, with the presence of at least four bivalve genera  
145 (*Plagiostoma* Sowerby, 1814, *Gryphaea* Lamarck, 1801, *Liostera* Douvillé, 1904 and  
146 *Oxytoma* Meek, 1864). In comparison, only three species of ammonites (Arietitidae Hyatt,  
147 1874 and Schlotheimiidae Spath, 1923) are present: (1) *Coroniceras multicoatum* (Sowerby,  
148 1824) very largely dominates (99.74% - Fig. 6), (2) *Angulaticeras (Sulciferites)* cf.  
149 *charmassei* (d'Orbigny, 1844) (0.19%), and (3) *Coroniceras (Arietites)* sp. (0.07%). This low  
150 biodiversity of ammonites, with populations often very largely dominated by a single species,  
151 was observed throughout the Sinemurian and lower Pliensbachian of the subalpine basin with  
152 paleobiogeographic affinities towards the NW of Europe (Burgundy, southern Jura, England;

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

156

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

167

#### 168 **2.4. Historical background**

169

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



178 Very recently, one of us (JSP) found some new information: actually, the Slab was unearthed  
179 in June, 1941 by Mr. Roux, a civil engineer, during work to widen the road of Barles. At that  
180 time, less than a quarter of the current surface was exposed. A first excavation work was  
181 made in July, 1979 as part of the project to create the National Nature Reserve in the vicinity  
182 of Digne-les-Bains (Martini 1979): the surface of the Slab was extended to 160 m<sup>2</sup> on which  
183 there were approximately 600 ammonites. The road has been deviated slightly to leave a little  
184 more space for visitors, and a basic layout was proposed (a lectern).

185 With the birth of the concept of natural heritage and nature reserves in French law (see De  
186 Wever et al. 2019), Guy Martini gave rise to the idea of classifying 18 geological sites,  
187 including the Ammonites Slab, in the Digne-les-Bains area under this strong legal protection  
188 status (Martini 1979; see Guiomar 2009). This project came to realization on October 31,  
189 1984 with the creation of the RNNGHP. However, the Ammonites Slab took a long time to  
190 become known outside the Digne-les-Bains region. The site was officially brought to the  
191 attention of the international community only in 1991, following the study by Corna et al.  
192 (1991) and the holding in Digne-les-Bains of the First International Symposium on the  
193 protection of geological heritage (Martini 1994; see also the 1991 International declaration on  
194 the rights of the memory of the Earth). The growing notoriety of the Slab, and its diffusion on  
195 Japanese television (The Miracle Planet, Chikyû Daikikô, NHK, 1987), led to the realization  
196 of the molding in 30 pieces of the fossiliferous stratum (the 160 m<sup>2</sup> then exposed) for the city  
197 of Kamaishi (Iwate Prefecture) in Japan, where it is still displayed at the Iron and Steel  
198 History Museum.

199 A second work for securing and clearing the Slab was carried out in July, 1994 with the  
200 participation of the University of Bucharest, and led to the doubling of the exposed surface  
201 (320 m<sup>2</sup>) and the number of visible ammonites (1,550). On this occasion, drilling showed the  
202 continuity of the Slab to the north with the presence of the same ammonite density over

203 several thousand square meters; various on-site museum projects did not emerge mainly for  
204 financial reasons and the matter ended there. However, under exceptional financing,  
205 restoration and security work was carried out in 2009, 15 years after the previous operation.  
206 The objective of this stabilization work was to remedy the conservation problems of the Slab  
207 in the short term (ideally 2–5 years), still awaiting for a financial opportunity and a political  
208 commitment to achieve equipment for lasting protection and enhancement of the site. This  
209 latter is presented in this work.

210

## 211 **2.5. Management of the Ammonites Slab by the National Geological Nature Reserve of** 212 **Haute-Provence (RNNGHP)**

213

214 The RNNGHP is governed by the Environmental Code from French law. Its classification is  
215 justified by the scientific interest of the natural heritage, with the objective of preserving the  
216 integrity of geological sites (including fossils and mineral substances). The RNNGHP now  
217 has 18 sites classified as National Nature Reserves (RNN by its acronym in French), including  
218 the Ammonites Slab, for a total of 270 ha (currently in the process of being extended - Bert et  
219 al. 2019a). These sites are surrounded by a protection perimeter of approximately 2,300 km<sup>2</sup>  
220 (Fig. 7), making it possible to ensure the conservation of the exceptional geological heritage  
221 in the territory of 59 municipalities of the Provençal Pre-Alps (52 in the Alpes de Haute-  
222 Provence and 7 in the Var departments). Throughout the protection perimeter, the removal,  
223 destruction or degradation of fossils, minerals and concretions is prohibited. Removals  
224 without tools of elements naturally released by erosion are tolerated only if they are carried  
225 out in limited quantities. On RNN classified sites, the regulation is more restrictive and  
226 prohibit, among other things, any sampling of mineral or fossil substances and any change in  
227 the character or aspect of the place. Sampling authorisations are issued for scientific purposes

228 with specific conditions for the two levels of regulation. Concerning the Ammonites Slab, the  
229 strong legal protection of the RNN classification was complemented by land control: first  
230 (1987) by acquisition of the Slab by the township of Digne-les-Bains and then (2018) by its  
231 assignment, extended to a larger part of the geosite bought from its private owner, to the  
232 Departmental Council of the Alpes de Haute-Provence.

233

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

245

### 246 **3. The European project ‘The Geological Adventure’**

247

248 The Geological Adventure project was carried out within the framework of the European  
249 cross-border cooperation program between France and Italy, Interreg V-A ALCOTRA  
250 2014–2020. This project aimed to enhance the great landscapes as well as the remarkable  
251 mineral heritage, representative of the history of the Southern Alps, which is illustrated  
252 between the Department of the Alpes de Haute-Provence (France) and the Province of Cuneo

253 (Italy). The project took place over 3 years, from April, 2017 to December, 2020, and  
254 mobilized 7 cross-border partners (for France: the Departmental Council of the Alpes de  
255 Haute-Provence - project leader and manager of the RNNGHP -, the Provence-Alpes-  
256 Agglomeration community - manager of the UGHP -, and the municipality of Les Mées; for  
257 Italy: the Union of Fossanese municipalities, the municipalities of Cherasco and Frabosa  
258 Soprana, and the Federico Sacco Foundation). The Geological Adventure responds de facto to  
259 one of the objectives, designated as a priority, of the tourism plan of the Department of the  
260 Alpes de Haute-Provence for the period 2016–2020 (ambition renewed for the period  
261 2022–2027): to develop experiential and sustainable geotourism. Thus, geoheritage, as a  
262 natural quality of territories, is considered as an asset for tourist diversification and a driver of  
263 local and economic development (François et al. 2006; Bétard et al. 2017). This is in this  
264 context that the financing of the rescue and layout of the Ammonites Slab geosite of Digne-  
265 les-Bains was made possible.

266

### 267 **3.1. Terms and concepts**

268

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

274

275 **Geotourism.** Geology and geoheritage (considered here in a very broad sense, including  
276 palaeontology, geochronology, climatic evolution, etc., adapted from Ruban & Ermolaev  
277 2020), are usually considered as a large and complex subject often difficult to access for an

278 uninitiated audience. Historically, niche tourism in relation to geological heritage rather  
279 concerns geologists (including supervised university internships), enthusiasts, or is based on  
280 the personal appreciation of the mineral landscape from a form of aestheticism (i.e. [Gordon](#)  
281 [2018](#); [Ruban et al. 2021](#)).

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

301

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

313

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

326

### 327 **3.2. The objectives of the Geological Adventure project**

328

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

342

### 343 **3.3. The achievements of the Geological Adventure**

344

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

349

350 *The physical development of the geosites.* Five spectacular geosites (3 in France and 2 in  
351 Italy) have benefited from specific developments with the dual objective of long-term

352 conservation and heritage enhancement. These are (1) the Ammonites Slab of Digne-les-  
353 Bains (the main project here developed), (2) the Pénitents des Mées trail (Sensitive Natural  
354 Site of the Department), (3) the belvedere of the Vélodrome geosite at the Vieil Esclangon  
355 (RNNGHP, France), (4) the Cave of Bossea at Frabosa Soprana and (5) the Rio Crosio at  
356 Cherasco (Italy).

357

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

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



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

386

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

392

393 **Digital tool.** To attract the public attention (including the young public), and to embrace a  
394 certain modernity, the digital tool was positioned at the heart of the strategy of mediation,  
395 valuation and promotion of the Geological Adventure. A website  
396 (<https://aventuregeologique.com/>, accessed in September, 2021) and a Smartphone application  
397 (<https://play.google.com/store/apps/details?id=com.easymountain.cd04>, accessed in  
398 September, 2021) were thus deployed. The website allows the public to prepare their tourist  
399 trip upstream by providing complete information on the geosites. The Smartphone application  
400 invites people to live an in situ active experience through thematic circuits and interactive  
401 games using geolocation. These games, intended for young audiences, provide scientific

402 concepts and raise awareness of the protection of natural heritage. Tactile tables left for free  
403 consultation allow the dissemination of all the digital content of the project; they have been  
404 installed in two museums and five tourist offices in the territory of the Alpes de Haute-  
405 Provence.

406

### 407 **3.4. Discussion**

408

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

417 While the digital tool offers a wide range of possibilities, it also has drawbacks. The  
418 experience of the Geological Adventure shows the limits of digital deployment in rural and  
419 mountain areas where the telecommunication network does not yet cover the entire territory.

420 The public is faced with uneven signal quality as well as difficulty in downloading the  
421 website or Smartphone application in the field. These conditions are obviously not favorable  
422 to the systematic downloading of cultural applications by Smartphone users, especially for  
423 heavy applications, as the products provided need to be light and quick to download. The  
424 Geological Adventure application presents numerous photos and videos, which weigh down  
425 its content and impose a long download time: some users may therefore become demobilized.  
426 In addition, in the digital field where technologies evolve very quickly, the tools developed

427 can quickly become obsolete. It is relevant to question the durability of the various  
428 informative materials, of which the most classic (lecterns, in situ information panel, etc.)  
429 sometimes appear more robust over time and less demanding in terms of management,  
430 maintenance and updates.

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

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

441

## 442 **4. The Ammonites Slab rescue operation**

443

### 444 **4.1. The facts**

445

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

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

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

465

## 466 **4.2. The studies**

467

### 468 **4.2.1. The voids**

469

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

473

474 **Method.** The principle of geophysical radar uses the reflectometry of electromagnetic waves  
475 at high rate pulses of short duration. Waves are differentially reflected at the interface of  
476 materials with different physical characteristics. The geophysical radar used is a LERM model

477 with dual frequency antenna. The measurement was carried out according to the following  
478 parameters:

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

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

488

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

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

499

#### 500 **4.2.2. Deformation and fracturing**

501

502 New 3D photogrammetric acquisitions led to the study of the geometry and fracturing of the  
503 Slab, as well as to produce a digital model, made by the Centre Européen de Recherche et  
504 d'Enseignement des Géosciences de l'Environnement (CEREGE, Aix-Marseille, France -  
505 2017–2018).

506

507 **Method.** Eight hundred high definition constant distance photos were taken (material used:  
508 full frame digital camera of 36 Mpx). These images have a sufficient resolution (0.5 mm) to  
509 allow making digital models of the ammonites (Fig. 6; see for example  
510 <https://sketchfab.com/models/b1299fc681314243a14a577775ca898a>, accessed on September,  
511 2021), and they constitute a database for monitoring the condition of the Slab and the  
512 ammonites over the long term from the previous data (Dommergues & Guiomar 2011). A  
513 second drone acquisition of 280 photos was carried out in order to remove acquisition  
514 artifacts (cast shadows, safety ropes, etc.). The 3D digital model was produced as a point  
515 cloud, which the surface was interpolated and textured (<https://skfb.ly/6t9FS>, accessed on  
516 September, 2021). The point cloud was then projected onto the average surface plane of the  
517 Slab to constitute a digital terrain model (DTM). The images used for the realization of the  
518 DTM were also used to make an ortho-rectified and calibrated photo of the entire Slab  
519 allowing precise digital studies (237 million pixels for a ground pixel resolution of 1.67 mm -  
520 Fig. 11).

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

523

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

- 527 • Surface: 310 m<sup>2</sup>;
- 528 • Perimeter: 79.6 m;
- 529 • Width: 16.5–11.7 m (the latter at the top of the Slab);
- 530 • Height: 24.8 m;
- 531 • Tilt: 48 °;
- 532 • Orientation: 167°N (due to this slightly north orientation and its inclination, morning  
533 is the best for ammonites observation; in the afternoon the site is backlight).

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

542

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

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

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

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

575

#### 576 4.2.3. Discussion and recommendations



577

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

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

592 The infiltrated water is blocked by the underlying marly layer and by the shotcrete sprayed in  
593 2009 on the southern edge of the Slab (Fig. 11, left), even though equipped with barbicans for  
594 drainage, which was supposed to slow its erosion and lateral collapse. The chemical reactions  
595 caused by the presence of water in the pyrite-rich marls cause, among other things, the  
596 proliferation of small gypsum crystallizations. These crystallizations facilitate the detachment  
597 of the marlstone sheets and their swelling in the presence of humidity, which constrains the  
598 limestone layer of the fossiliferous stratum. At the same time, the pressurization of the  
599 infiltration water causes a reduction in the friction at the base of the limestone layer and  
600 causes the crawling of the southern half of the Slab (the most altered part), of which the local  
601 bulge is the most obvious manifestation.

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

606

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

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

615

### 616 **4.3. Sealing device**

617

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

- 627 • to confirm the presence of heterogeneous materials/cavities to define the quantity of  
628 grout to be injected through the boreholes made for the installation of the anchors;
- 629 • to show that the soil corrosivity is low (Ph=7.7; chloride ion concentration  
630 =2.2 mg/kg; sulfate ion concentration =11.8 mg/kg; resistivity at 20°C=5.700 Ω/cm),  
631 which allows to optimize the composition of the sealing grouts and to define the  
632 protective treatment for the steel of the anchor bars;
- 633 • to define the boreholes diameter and the reinforcement bars diameter to avoid any risk  
634 of degradation of the fossiliferous layer;
- 635 • to define the density and number of anchor bars required (minimum mesh size) while  
636 avoiding ammonites;
- 637 • to test the lateral friction on the limestones during the conformity tensile tests  
638 according to the actual thickness of the beds;
- 639 • to calculate the necessary length for the sealing bars, knowing that the thickness of the  
640 area to be reinforced is limited to 0.6–0.75 m depth below the surface.

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

644

645 ***Choice of the filling/sealing grout.*** The main problem is the presence of pyrite in the  
646 marlstones underlying the Ammonites Slab, which induces the risk of sulphate reactions with  
647 the production of gypsum and sulfuric acid. In such a humid and porous environment, some  
648 cement compounds can go into solution and react with pyrite. Sulphates can also lead to the  
649 formation of thenardite crystals (anhydrous sodium sulphate - Na<sub>2</sub>SO<sub>4</sub>) or mirabilite (sodium  
650 sulphate decahydrate - Na<sub>2</sub>SO<sub>4</sub>, 10H<sub>2</sub>O) further increasing the risk of marls swelling and  
651 detachment of the Slab. This means that the sealing grout must have a limited content of

652 sulphates, but also a reduced content of tricalcium aluminate ( $C_3A$ ) to limit the formation of  
 653 expansive secondary compounds (secondary ettringite).

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

660 According to the method of Zhang et al. (2014; 2018), laboratory tests of several potential  
 661 grouts were carried out using a 5 kg sample of crushed marls taken directly from the Slab site.  
 662 Under in situ conditions, the use of resistant sulphate cement should be preferred to avoid the  
 663 risk of swelling and cracking by delayed hydrate formation, which could jeopardize the  
 664 integrity of the Slab despite the seals. To fix the lime and avoid efflorescence, compound  
 665 cement with a low  $C_3A$  content based on pozzolan of CEM III type was chosen (Declair  
 666 2008). The chemical characteristics of this cement are summarized in Table 1.

667

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

	Average value (%)
SO <sub>3</sub>	2.8
Cl <sup>-</sup>	0.14
Loss on ignition (950°C)	0.9
Insoluble	0.3
S <sup>2-</sup>	0.44
Alkaline equivalents (Na <sub>2</sub> O + 0.658 K <sub>2</sub> O)	0.6
Alkaline actives	0.5

671

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

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

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

690

#### 691 **4.4. Water ingress**

692

693 Whether by infiltration in marls or cracks, by chemical reactions caused by the action of  
694 freeze-thaw cycle, or by hydrostatic pressure, water plays a major role in the weathering of  
695 rocks and the behavior of the rocky massif. Water is one of the essential elements to be taken  
696 into account in studies intended for the conservation of geosites. Consequently, and in

697 addition to the stabilization work on the Ammonites Slab, it was necessary to carry out work  
698 aimed at improving the management of seepage water.

699

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

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

712 Due to the geomorphology of the site, there is a potential infiltration zone of approximately  
713 100 m<sup>2</sup> in the rocky massif located immediately above the Slab. It was therefore necessary to  
714 remove the 2009 improvements, then to strip and dig a drain behind the Slab over a line of  
715 50 m for a 2 m width. This newly cleared area was thus sealed by a geomembrane covered  
716 with C30/37 fiber-reinforced concrete. This new guttering was extended downstream by a  
717 rainwater drainage ditch towards the dale.

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

722

723 **4.5. Unsolved problems and perspectives**

724

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

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

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

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

754

755 Drilling and field surveys have shown that the extension of the fossiliferous stratum is proven  
756 beyond the currently exposed surface of the Slab with the same density of ammonites. On the  
757 7,000 m<sup>2</sup> where the stratum has been recognized and mapped (Fig. 18), an extrapolation  
758 allows to estimate the presence of nearly 34,000 buried ammonites. Physically and legally  
759 protected, this exceptional site is left as a legacy for future generations: as long as the latest  
760 long-term conservation issues are not resolved, no new large-scale discovery of the  
761 ammonites bearing surface is possible.

762

## 763 **5. Enhancement of the Ammonites Slab geosite**

764

### 765 **5.1. The previous state**

766

767 The Ammonites Slab, exposed to the open air, is located near the road (Fig. 3, 19a). The road  
768 had been rerouted in the late 1970s to free up a safe, but strait, viewing area for the public.  
769 Another derelict part of the road served as a car park linked to the Slab by an old road bridge.  
770 These areas (the parking and the visiting area at the foot of the Slab) were never properly



771 developed and the surroundings of the site actually looked more like a wasteland than a  
772 geosite of international stature.

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

776

## 777 **5.2. The new visitor structures**

778

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

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

788 The old bridge (Fig. 19b: 2), the deck of which has been raised, is an infrastructure of quality  
789 and as such it materializes the new entrance door to the geosite, which opens directly onto a  
790 pedestrian reserved reception area (Fig. 19b: 3). Most of the mediation is now developed in  
791 this space. From the reception area, a 35 m long (1.60 m wide - 1.45 for the walkway)  
792 wooden/metal footbridge now provides access to a new observation platform, raised 2 m  
793 above the ground level, facing the Slab and the ammonites (Fig. 19b: 4-5). The slope of the  
794 footbridge at 4% meets accessibility standards for people with reduced mobility. The interest  
795 of the observation platform is threefold: (1) to offer visitors a new panoramic point of view on

796 the Slab partly decontextualized from the road and its nuisances (noise and safety). The foot  
797 of the Slab is no longer visible, and the point of view being closer to the wall due to its  
798 inclination lead to an increased immersion effect in the geosite (Fig. 20a); (2) the platform  
799 allows the neutralization of direct access to the fossil surface by the public, in order to avoid  
800 the anthropogenic degradation mentioned in chapter 4.1; (3) keeping the public at a safe  
801 distance also helps prevent the risks associated with rock falls, now minimized by the  
802 anchoring of the Slab.

803

### 804 **5.3. Didactic**

805

806 One of the aims of the geosite enhancement is to allow the public autonomy in their visit. On  
807 the one hand in terms of physical accessibility (materialization of paths; controlled slopes and  
808 drops; seating areas for prolonged station - Fig. 20b); sufficient space to accommodate  
809 groups; installation of a public transport stop awaiting to be integrated into the urban mobility  
810 plan of the city of Digne-les-Bains); on the other hand, by setting up educational furniture  
811 (which can also be used as a support for guided tours). The educational path was designed in  
812 8 stages, from the car park to the discovery of the Ammonites Slab itself, following a  
813 progressive and immersive approach (Cayla et al. 2010; Martin et al. 2010):

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

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

834

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

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

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

846 • *People with mental disabilities:* all the facilities provide security by keeping it away  
847 from the road and the car park. The signage is explicit and all the didactic themes are  
848 doubled by an insert Easy to Read and Understand (FALC, by its acronym in French)  
849 identified by the European Easy to Read pictogram.

850 • *People with hearing disabilities:* moving away from the road allows better hearing  
851 comfort. The spaces are large enough to allow the animation of groups with a sign  
852 language interpreter.

853

## 854 **6. Funding**

855

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

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

867

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

- 870 • 134,771 € project management and technical and security control missions;
- 871 • 594,030 € rescue and reinforcement work;
- 872 • 683,247 € enhancing and landscaping work;
- 873 • 107,190 € didactic component;
- 874 • 140,435 € road shifting.

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

879

## 880 **7. Conclusions**

881

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

893 destabilization by a buckling mechanism would have resulted in the irreparable loss of part of  
894 the geosite.

895

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

917

918 In this context, the conservation works of the Ammonites Slab of Digne-les-Bains (up to  
919 1,659,673 €) consisted of (1) anchoring the Slab on its substratum; (2) filling the voids  
920 identified during the studies using an inert grout so as to avoid undesirable chemical  
921 reactions; (3) dealing with the problem of water infiltration; and (4) neutralizing direct public  
922 access to avoid anthropogenic damage. Enhancement work for the entire geosite was carried  
923 out in parallel. The new equipment consists of a parking area allowing the circulation of  
924 buses; a slight realignment of the road was necessary in order to comply with road safety  
925 rules. This new gateway to the geosite opens directly onto a pedestrian reception area, where  
926 mediation is developed. A raised platform offers visitors a new panoramic and immersive  
927 point of view in front of the ammonites, safe against any risk of rock fall or related to road  
928 circulation. A particular effort has been made to provide the public with progressive and  
929 immersive educational mediation using different media (lecterns, timeline, models, 3D  
930 reconstructions, digital tool). The entire geosite, whether through its facilities or adapted  
931 teaching methods, is accessible to people with motor, visual, mental or hearing disabilities.  
932 The easy access to the Ammonites Slab and its free admission to visitors rank the geosite very  
933 high on the accessibility scale of Mikhailenko et al. (2021) with a score of 17/20. This score  
934 could be revised and reach 20/20 when the geosite will be integrated into the city's urban  
935 traffic plan and served by public transport, a secure pedestrian path and a cycle lane.

936

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

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

951

## 952 **Acknowledgments**

953

954 First of all, the authors are pleased to thank very much the Editor and the both anonymous  
955 reviewers for the time they spent on the manuscript, their careful read and their very  
956 constructive comments. The rescue work for stabilization of the Ammonites Slab and the  
957 landscaping of the geosite were carried out respectively by the companies NGE Fondations  
958 and Eiffage routes Méditerranée-Alpes-Vaucluse. The company Terzatec Ingénierie et  
959 Expertise helped with the interpretation of the drilling data and the chemical laboratory  
960 investigations. The company Biotope Communication participated to the didactic aspect. The  
961 Office National des Forêts allowed the use of the land under their responsibility. Finally, the  
962 road shifting was conducted by the Maison Technique of the Department of the Alpes de  
963 Haute-Provence.

964

## 965 **Declarations**

966



967 **Funding:** This work was supported by the Departmental Council of the Alpes de Haute-  
968 Provence, France.

969 **Competing interests:** The authors declare no competing interests.

970 **Availability of data and material:** Not applicable.

971 **Code availability:** Not applicable.

972

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### 1156 **Figure captions**

1157

1158 **Fig. 1:** Palaeogeographic map at the Sinemurian age (-200 MY – from [Scotese, 2014](#)), with  
1159 position of the geosite of the Ammonites Slab (red star).

1160

1161 **Fig. 2:** The numerous ammonites present on the Slab.



1162

1163 **Fig. 3:** Stat of the geosite in 2016, before the work. Note the unique lectern and the absence of  
1164 particular enhancing.

1165

1166 **Fig. 4:** Location map of the Ammonites Slab geosite near the city of Digne-les-Bains (Alpes  
1167 de Haute-Provence department, SE France).

1168

1169 **Fig. 5:** Geological and structural context of the Ammonites Slab. The geosite is located along  
1170 the Bès and Saint Benoît faults, in the front of the Digne-les-Bains thrust sheet.

1171

1172 **Fig. 6:** Section of the Ammonites Slab series and a *Coroniceras* shell reconstruction  
1173 (modified from [Dommergues & Guiomar, 2011](#)). The digital model of the ammonite is part of  
1174 the new 3D photogrammetric acquisitions made by the CEREGE at a 0.5 mm resolution.

1175

1176 **Fig. 7:** Map of the National Geological Nature Reserve of Haute-Provence (RNNGHP by its  
1177 French acronym). The 18 green dots are the sites classified under National Nature Reserve  
1178 (RNN) with strong regulation, and the green area is the protection perimeter where the  
1179 removal, destruction or degradation of fossils, minerals and concretions is prohibited.

1180

1181 **Fig. 8:** The damages on the Ammonites Slab; **(a)** surface desquamation and delamination due  
1182 to climatic conditions; **(b)** open fractures repaired with mortar (visible just beneath the  
1183 ammonite); **(c)** the void recently identified behind the Slab due to an illegally collected block  
1184 in May 2016 (35 X 20 cm); **(d)** the slight swelling at the bottom of the Slab, where the most  
1185 voids were observed. The bulge reaches 15 cm in amplitude (picture reconstructed using 3D  
1186 photogrammetry); **(e)** unrestricted accessibility of the fossiliferous layer to the public can

1187 result in small damages; **(f)** a worn ammonite due to repeated contact with the hands of  
1188 visitors; **(g)** water infiltrations.

1189

1190 **Fig. 9:** Extract from the raw RADAR signal and its interpretation: voids/heterogeneities are  
1191 detected between 10–40 cm below the surface of the Slab (red dot-lines).

1192

1193 **Fig. 10:** Mapping of the heterogeneities at **(a)** 10-40 cm, **(b)** 50-80 cm behind the surface of  
1194 the Slab.

1195

1196 **Fig. 11:** Ortho-rectified and calibrated photography projected in the plan of the Slab.

1197

1198 **Fig. 12:** Digital model of the Ammonites Slab with colorization of the relief and artificial  
1199 shading. The shades from yellow to red are in front of the average plane of the Slab.

1200

1201 **Fig. 13:** Fracturing map of the Ammonites Slab showing the different generations of  
1202 fractures. The diagenetic joints are in green; normal faults and tension joints are in orange;  
1203 joints without calcite are in blue; open fractures (gravity and weathering fractures) are in red.  
1204 The yellow areas are concrete parts.

1205

1206 **Fig. 14:** **(a)** Small normal fault with vertical throw, which shifts an ammonite; **(b)** calcite  
1207 joints in the extension relay zone of the main strike-slip fault; **(c)** the main strike-slip fault  
1208 cutting the Slab in half through the middle (dextral sliding movement; total sliding of 10.2  
1209 cm); **(d)** detail of an ammonite cut by the main strike-slip fault (sliding of 2.8 cm at that  
1210 point); **(e)** closed joint filled with calcite.

1211

1212 **Fig. 15:** Principle of the anchoring with sealed metal inclusions. The voids to fill in with grout  
1213 are represented in orange.

1214

1215 **Fig. 16:** Location of the 246 anchoring bars (yellow dots) avoiding the ammonites.

1216

1217 **Fig. 17:** The drilling and anchoring operation showing the anchor metal bars.

1218

1219 **Fig. 18:** In red is the currently exposed part of the Ammonites Slab; in white is the potential  
1220 total unearthed mapped surface of the Slab (7,000 m<sup>2</sup>); an extrapolation allows to estimate the  
1221 presence of nearly 34,000 buried ammonites.

1222

1223 **Fig. 19:** Surroundings aspect of the Ammonite Slab geosite **(a)** before the  
1224 enhancement/conservative works and **(b)** just after these works: (1) is the car-park area in the  
1225 shape of roundabout to allow full accessibility to buses; the bridge that materializes the new  
1226 entrance door to the geosite; (3) the pedestrian reserved reception area where most of the  
1227 mediation is developed; (4) the wooden footbridge access (the 4% slope meets accessibility  
1228 standards for people with reduced mobility); and (5) the new observation platform, raised 2 m  
1229 above ground level, facing the Slab and the ammonites.

1230

1231 **Fig. 20:** the new didactic equipments of the geosite: **(a)** the observation platform offering a  
1232 new point of view to the Slab with the lectern-cast representing a tactile visit aid for the  
1233 visually impaired; **(b)** detail of the wooden footbridge in front of the strata; **(c)** lecterns that  
1234 explain stratigraphy concepts and the formation of the Slab; **(d)** ammonite reconstruction with  
1235 soft-body parts; **(e)** overview on the pedestrian reserved reception area; **(f)** explanations of the  
1236 fossilization process that occurred on the geosite with 3D life-size models.