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## **Training astronauts for scientific exploration on planetary surfaces: The ESA PANGAEA programme**

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33 skills in analogue geological environments is a key part of the training. Classroom and  
34 field lessons are tightly interwoven in the course structure with a time separation often  
35 of only hours between being introduced to a concept in the classroom and seeing it in the  
36 field. The course forms part of the basic and pre-assignment training for European  
37 astronauts and is open to trainees from all other agencies. PANGAEA has been running  
38 since 2016, with participants including ESA and NASA astronauts, and Roscosmos  
39 cosmonauts, as well as mission designers, operations personnel and engineers. The  
40 primary field sites selected for the course are Permo-Triassic sedimentary sequences in  
41 the Italian Dolomites, impact lithologies in the Ries Crater, Germany, a comprehensive  
42 suite of volcanic deposits in Lanzarote, Spain, and anorthosite outcrops in Lofoten,  
43 Norway. Each is used as a base to deliver the main learning sessions, respectively: 1)  
44 Earth geology, rock recognition and sedimentology on Earth and Mars, 2) Lunar geology  
45 and impact cratering, 3) volcanism on Earth, Moon, and Mars, and astrobiology 4)  
46 intrusive rocks and lunar primordial crustal evolution. The four sessions are designed to  
47 increase trainee autonomy in field geology by including guided or autonomously  
48 executed geological traverses and practicing of sampling techniques. Whilst PANGAEA's  
49 primary focus is astronaut training, where appropriate and complementary to this  
50 training, technologies being developed for future missions are used and tested by the  
51 trainees during geological traverses. This provides an opportunity to evaluate the  
52 performance of new equipment and software in analogue field environments, whilst also  
53 providing trainees with experience using technology that might support future missions.

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55 Keywords: training; planetary geology; human spaceflight; exploration; flexecution;  
56 lunar missions;

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## 64 **1. Introduction**

65 Geology and astrobiology research underpins many of the primary scientific goals of  
66 current robotic missions to the Moon, Mars and asteroids [1-5]. Although human  
67 spaceflight has been confined to low Earth orbit since the Apollo programme, recent  
68 plans to return humans to the surface of the Moon through the Artemis programme  
69 means that in the near future astronauts will be involved in the definition, planning and  
70 execution of missions with geological or astrobiological objectives [6]. Lunar exploration  
71 will pave the way for human missions to Mars, meaning the long-term future of science  
72 conducted during human spaceflight will continue to involve geology and astrobiology.

73 Compared to the last five decades of human exploration (the Apollo programme ended in  
74 1972), which were limited to spacecraft or artificial orbital habitats (Skylab, MIR, ISS),  
75 missions to the Moon and Mars will mark a shift in the activities astronauts will perform  
76 in space. Astronauts will once again be required to function as field scientists exploring  
77 unknown planetary surface environments. This will involve examining the surrounding  
78 environment to identify scientifically interesting locations using handheld  
79 instrumentation and camera systems to gather information, working reflexively with  
80 ground-based operations and science teams to select samples and modify traverse plans  
81 as new information is gathered (applying flexible execution or “flexecution” as in Hodges  
82 and Schmitt, 2011), and collecting samples with specifically designed tools. Utilising  
83 human explorers instead of robotic platforms to complete these exploration tasks brings  
84 many benefits, such as faster data gathering and rapid real time adaptability to new  
85 information, thereby facilitating more efficient and effective operations and increasing  
86 the chance of novel discoveries. However, for astronauts to be effective field scientists,  
87 significant preparation is required.

88 The need for geological field training for astronauts was recognised at the beginning of  
89 the Apollo missions [7, 8]. At that time, each crew participated to between 16 and 19 field  
90 trips, with 250-300 hours of classroom time and instruction in order to prepare for the  
91 geological tasks of each mission [9]. This training was seen as fundamental to the  
92 scientific success of the Apollo missions, and the crews recognised that “No substitute  
93 exists for working in the field to learn the principles of field observation and sampling”  
94 [10]. As the focus on space exploration changed during the space shuttle and ISS eras, this  
95 field science training was significantly reduced, although astronauts were, and still are,  
96 involved in science training related to specific payloads.

97 Today, some astronauts have scientific backgrounds, although only a very small number  
98 have field science experience. Harrison Schmitt, the only formally trained geologist to  
99 take part in the Apollo missions, has strongly suggested to include professionals with  
100 significant experience in field research and exploration in future astronaut classes [10].  
101 Despite this, today few astronauts have geology, biology or similar environmental science  
102 degrees, and fewer still have significant field geology expertise. As astronauts are chosen  
103 from a variety of backgrounds, both scientific and non-scientific, there is a good reason  
104 to broadly enhance astronaut skills with those akin to an experienced terrestrial field  
105 scientist and explorer.

106 During the Constellation programme development, when the Moon and Mars were  
107 officially declared as the main objective for future space exploration, several geologists  
108 and field scientists began discussing how to approach training a new generation of  
109 astronauts to be efficient “instruments of scientific discovery” - as advocated by Gene  
110 Shoemaker during the Apollo era [10-14]. These discussions not only better outlined  
111 some of the main lessons learned from the Apollo programme in the frame of field geology  
112 and operations, but also highlighted a clear need to apply new learning principles to  
113 future training. This includes the need to find a balance between the concepts of  
114 “Execution” and “Discovery”, which underpins space missions on unknown planetary  
115 surfaces [11]. Unfortunately, with the cancellation of Constellation, the preparation for  
116 such training activities slowed. Interest in them has now restarted with the Artemis  
117 programme, and their implementation is again on the priority list of space agencies [15-  
118 17].

119 In the last two decades, several astronauts have been involved in field geology  
120 expeditions together with scientists [18, 19], analogue testing programmes such as  
121 Desert Research and Technology Studies (D-RATS) or Biologic Analog Science Associated  
122 with Lava Terrains (BASALT) [20, 21], or other training programmes in analogue  
123 environments including geology/geobiology-related operations as Cooperative  
124 Adventure for Valuing and Exercising human behaviour and performance Skills (CAVES)  
125 (Sauro et al., 2021) and NASA Extreme Environment Mission Operations (NEEMO) [22,  
126 23]). However, most of these experiences were not specifically focused on field geology  
127 training and were not designed and structured around a progressive learning strategy.  
128 Currently, training in geology and astrobiology is provided to NASA and CSA astronauts  
129 through its Geoscience Training Program [24]. This is divided into three phases. Phase 1

130 consists of the initial training, which teaches the conceptual basics of geoscience,  
131 planetary geology, and astrobiology through classroom lessons over a one-week period.  
132 This is later followed by a second week of field training in geological mapping, and with  
133 guided hikes and visits. Phase 2 involves sending astronauts to be field assistants to  
134 scientific expeditions and participating in a variety of analogue activities [25, 26]. Phase  
135 3 is not yet implemented, but will provide mission specific training once astronauts are  
136 assigned. At other major space agencies, such as JAXA and Roscosmos, no formal  
137 geoscience training programme is implemented currently, although JAXA astronauts  
138 have participated in phase 1 of NASA's Geoscience Training Program.

139 Before 2016, astronaut field science training at ESA was limited. To address this, the  
140 European Astronaut Centre (EAC) designed the PANGAEA (Planetary ANalogue  
141 Geological and Astrobiological Exercise for Astronauts) field training course. PANGAEA  
142 takes place across 4 weeks, and is designed to provide the basic skills and knowledge for  
143 astronauts prior to mission specific training. The course incorporates both geology and  
144 astrobiology into its core training modules and is open to astronauts from space agencies  
145 world-wide. PANGAEA has a strong field-based approach using geological analogue sites  
146 in Europe. Its classroom lessons and field activities are taught by a small team of  
147 experienced world leading experts from Europe's community of planetary geologists and  
148 astrobiologists. At the time of writing, PANGAEA has trained astronauts from ESA, NASA,  
149 and Roscosmos.

150 This paper describes how PANGAEA has been developed, its strategy, and structure. In  
151 addition, it provides an overview of the European geological sites used for the training  
152 and how they have been selected to address specific analogies with the Moon and Mars.  
153 Finally, it discusses the outcomes and lessons learned during the four editions of the  
154 training implemented between 2016 and 2022.

155

## 156 **2. The legacy of the Apollo programme**

157 Almost fifty years have passed since Apollo came to an end, and yet it remains the only  
158 example of a space programme where an extensive geological training programme was  
159 developed and delivered to different astronaut classes that included both basic and  
160 mission-oriented training. Training programmes such as PANGAEA must build on this  
161 legacy, and address lessons learned at the time. They must also take into account the  
162 significant advances in technology made in the fifty years since Apollo, which has yielded

163 technologies that can support and enhance field geology. In addition, the substantial  
164 improvements in our current understanding of the geology and lithologies on the Moon  
165 and Mars must also be incorporated.

166 A highly detailed description of how the Apollo geological training evolved from 1964 to  
167 1976 is provided by Phinney [9], and the major lessons learned have been underlined by  
168 Lofgren, Horz and Eppler [13]. The approach used during the Apollo geology training  
169 started with basic training subdivided in three series, including both classroom lessons  
170 (mainly taught at Johnson Space Centre) and field trips (in USA, Mexico, and Iceland). In  
171 general, the training grew in complexity from “introductory field exercises” (Series I),  
172 next to “supervised field exercises” (Series II) and finally to “individual field exercises”  
173 (Series III). However, this early training displayed some crucial problems [9]. Most of the  
174 astronauts complained about a detachment between the classroom lessons and the field  
175 trips, commenting that they only found understanding and motivation for the theoretical  
176 part of the course later once they had spent time observing in the field. There were also  
177 problems in the consistency of the training, since field scientists were often not aware of  
178 specific subjects previously taught during theoretical lessons in the classroom , and vice  
179 versa, classroom lesson contents were not always fully complementary with field  
180 activities. This inhomogeneity and separation between classroom and field lessons  
181 brought additional problems such as inconsistent terminology and uneven levels of  
182 scientific complexity in material delivered by instructors.

183 To address some of these problems, after the first series of Apollo geological training, it  
184 was clear that all the instructor teams should be briefed and made aware of a common  
185 teaching strategy. Every activity then had to employ either a “knowledge-transfer” or  
186 “problem-oriented” approach. In the first case, instructors delivered knowledge related  
187 to a geological site or concept through demonstrations and explanations with minimal  
188 discussion with the trainees. In the second case, instructors provided scientific questions,  
189 data and advice, and allowed the trainees to formulate their own hypotheses and  
190 interpret the field observations. While both methods could be used, depending on the  
191 objectives and complexity of the field trips, most of the astronauts found the second  
192 approach to be more effective and engaging, allowing them to fix knowledge through  
193 active participation. Additionally, this process not only provided an effective method of  
194 retaining knowledge, but it also taught and refined essential field science exploration

195 skills, which should start from a scientific question and then use data and observations  
196 to provide preliminary answers that are refined with new observations and discoveries.  
197 The Apollo geological training was further improved with the arrival of the sixth  
198 astronaut class in 1967, several of whom had strong science background and provided  
199 key inputs to the training. These astronauts included Jack Schmitt, Karl Henize and Bob  
200 Parker [9]. During this round of geological training, the focus was shifted to ensuring the  
201 operational effectiveness of the astronauts as field scientists, as put by Jack Schmitt in  
202 Phinney (2015), they focused on: “getting the maximum amount of good information,  
203 good samples and good documentation as they could in a very short amount of time and  
204 to get them interested to learn the things that would be helpful in that whole process”. It  
205 also became clear that after a certain number of supervised and autonomous field trips,  
206 it was important to insert more mission operations into the training through having a  
207 simulated mission control and science backroom to support the discovery process during  
208 traverses. This also enabled the involvement of important support personnel, allowing  
209 the entire process of exploring an unknown terrain with remote support teams to be  
210 developed. Following the initial training for the sixth astronaut class, the training moved  
211 to a “mission-oriented” phase which was specifically designed for each Apollo crew and  
212 selected landing site. These lessons learned from the Apollo programme directly  
213 influenced the development of the ESA PANGAEA training programme.

214

### 215 **3. Developing a forward-looking geological and astrobiological training for astronauts**

#### 216 *3.1. PANGAEA course analysis and design*

217 The development of PANGAEA started in the last months of 2015 with requirements  
218 definition and training design involving the Space Training team of the European  
219 Astronaut Centre (EAC) and a group of European scientists, selected because of their  
220 specific expertise in both planetary geology and field research. In addition, a list of local  
221 experts and institutions (geoparks, natural reserves, geological museums etc.) from  
222 specific training sites were identified to evaluate relevant planetary analogue training  
223 sites.

224 The training was created through the application of the five steps of the ADDIE model  
225 (Branch, 2009) in order to obtain an effective learning experience (Fig. 1). The analysis  
226 of requirements (**Analysis** DDIE) was based on lessons learned from Apollo, new  
227 knowledge on planetary geology acquired in the last forty years and the planning of



228 future human and robotic missions to the Moon, Mars and other planetary bodies by ESA  
229 and its partner space agencies. The team carefully took into consideration the  
230 recommendations provided by Schmitt, Snoke, Helper, Hurtado, Hodges and Rice [10],  
231 Hodges and Schmitt [12], and Lim, Warman, Gernhardt, McKay, Fong, Marinova, Davila,  
232 Andersen, Brady and Cardman [11], but also lessons learned from other ongoing field  
233 trainings like CAVES [22]. The analysis also considered the potential use of new  
234 innovative technologies (like analytical tools) to support field geology activities.

235 The overall requirement was to create a training programme that would provide  
236 astronauts with a basic practical knowledge of planetary and field geology, as was the  
237 case in the initial Apollo training series before mission specific training. Additionally, it  
238 was decided to extend the course content not only to the Moon, but also to other future  
239 potential human destinations, like Mars and asteroids. Astrobiology was also  
240 incorporated into the course curriculum due to the synergies between geology and  
241 astrobiology. Table 1 summarize the set of training objectives defined during the  
242 PANGAEA course analysis and design phase.

243 To deliver these training objectives in an effective way that was suitable for astronauts  
244 being taught over a limited period, the course's educational approach was also structured  
245 around a core cognitive loop, which mirrors that typically used in planetary geology  
246 research (Schmitt et al., 20211; Fig. 2). In particular, the training repetitively applies three  
247 main phases. 1) Classroom based theoretical and practical lessons on Earth and planetary  
248 geology and astrobiology. 2) Field activities in analogue geological sites. 3) Discussion  
249 about features and samples observed in the field, and connections back to the big picture  
250 given in the classroom lessons. In order to make this efficient, one of the requirements  
251 was that all PANGAEA classroom theoretical and practical lessons would take place at the  
252 field locations using local facilities, making it possible to conduct field excursions to see  
253 features just described in classroom lessons, allowing this cognitive loop to be continually  
254 exercised.

255 Since limited time is available for astronauts to gather experience in field geology and  
256 astrobiology, it was clear that the training should focus on imparting decision-making  
257 methods, efficient documentation, and descriptive techniques, rather than focusing too  
258 much on theoretical knowledge. The team wanted to achieve this through constructing a  
259 course that delivered thorough, but concise and efficient theoretical lessons underpinned  
260 by real scientific mission examples, closely intertwined with focused practical field

261 activities in analogue terrestrial geological environments. The course design (A **Design**  
262 DIE) was developed through increasing steps of the revised Bloom taxonomy, from  
263 simple learning of basic concepts to full understanding of processes, practical application  
264 of methodologies, up to finally achieve the ability to analyze and autonomously find  
265 solutions to scientific questions [27].

266 Fieldwork would focus heavily on enhancing the astronaut's observational capacities,  
267 exercising the interaction between the astronauts and ground teams to practise  
268 operational skills such as scientifically relevant communication, documentation, and use  
269 of field terminology. From the beginning, the overall aim of PANGAEA was to give  
270 astronauts the ability to become efficient scientific explorers by being able to effectively  
271 coordinate with ground-based science teams and specialist scientist-astronauts, and to  
272 make high quality autonomous science decisions when required. Based on these  
273 philosophies, the PANGAEA course was designed around the following general strategies:

- 274 • The course should provide an essential knowledge base - theoretical and practical  
275 - for astronauts with no or limited previous experience in field geology or  
276 astrobiology.
- 277 • Both disciplines, geology and astrobiology, should be combined into one course to  
278 create learning synergies between the two subjects.
- 279 • Knowledge should be directly and quickly transferred from theoretical learning to  
280 real experience using analogue field sites.
- 281 • As planetary geology and astrobiology include discussing processes that are  
282 complex and sometimes poorly understood, the training should move from simple  
283 well understood principles to complex open questions.
- 284 • Where possible, terrestrial surface geological processes and orbital observations  
285 should be used as a starting point from which information on other planetary  
286 bodies is derived, mimicking the process of exploration.
- 287 • There should be a progressive transition throughout the training between the  
288 following learning methods:
  - 289 1. Supervised execution of geological tasks/exercises
  - 290 2. Guided discovery of geological terrains
  - 291 3. Self-directed discovery of unknown geological terrains
  - 292 4. Real science field work with defined scientific questions

293 These general strategies were influenced by both the Learning Design Principles  
294 proposed by Lim, Warman, Gernhardt, McKay, Fong, Marinova, Davila, Andersen, Brady  
295 and Cardman [11] and the benefits of field activities underlined by Hodges and Schmitt  
296 [12]. For this reason, theoretical lessons were strongly limited in favour of field work.

297 The audience requirement for PANGAEA was defined as between 2-6 trainees, allowing  
298 for a student/instructor ratio not lower than 1/2 during all practical field activities. If the  
299 number of trainees per instructor would exceed 2, for several exercises such as traverses  
300 and some practical lessons, trainees would be split into two groups to ensure discussions  
301 and demonstrations were effective. Although the training was specifically designed to  
302 target astronauts, it also had to be provide benefit to non-astronauts participating as  
303 trainees, including space engineers, Capsule Communicators (CAPCOM), extravehicular  
304 activity (EVA) and operation specialists, or other personnel that need to be trained in  
305 planetary field geology and astrobiology.

306 Once the training requirements were defined, the team began creating all the lessons,  
307 materials and training schedules (AD **Development** IE). Given the problems raised  
308 during the early phases of the Apollo geology training, it was decided to involve all the  
309 selected instructors early in the design and development stage of the course structure  
310 and content. This included extensive interactions between the instructors during  
311 preliminary development and following dry runs of each lesson. Overall, lesson content  
312 was linked to the global exploration strategies outlined by the world's space agencies to  
313 provide proper context where possible (ISECG reports, Schmidt and Neal, 2015).

314 All the classroom and practical lesson materials created during this phase were archived  
315 and tracked through the Astronaut Training Database of the European Astronaut Centre,  
316 an online end-to-end training development system that provides tools to manage  
317 instructor lesson assignment, instructor certification, lesson checklists, lesson  
318 summaries, printouts and experimenting with different training schedules. The ATD  
319 allowed the team to work on-site and off-site concurrently on a centralised database  
320 system.

321 After the first implementation of PANGAEA in 2016, the training outcomes were  
322 evaluated. Success was rated through examining the course's success in achieving  
323 training objectives through crew/instructors feedback. Lessons were improved after  
324 every edition and new materials were created to fill any gaps identified during  
325 subsequent training implementation. The culmination of this process of implementation

326 and evaluation (ADD **Implementation Evaluation**) led to the course configuration  
327 described in this article.

328

### 329 *3.2. Technologies and tools for enhancing learning and operations*

330 Site documentation and sample screening are fundamental activities in field geology  
331 research on Earth and become even more crucial during lunar exploration where  
332 feedback from science backrooms on ground is essential to support decision making.  
333 Training on these tasks and learning how to practically apply correct geological  
334 observation skills formed an important requirement for the development of the  
335 PANGAEA training. Because of this, the team decided to include a series of lessons  
336 covering how to correctly perform these activities. However, modern technologies can  
337 also greatly aid the process of site documentation and sample screening, especially  
338 compared to what was available during Apollo. In the last twenty years, the experience  
339 gathered from different analogue programmes like D-RATS, BASALT, CAVES, and NEEMO  
340 has provided useful data regarding which kind of technologies and methods could enable  
341 or enhance planetary field geology [21, 29, 30]. In order to incorporate these aspects into  
342 PANGAEA, several technological tools were provided to the astronauts to support  
343 efficient documentation and sample characterisation. In the first two editions of  
344 PANGAEA, these tools included a handheld portable Visual-Near-Infrared (V-NIR)  
345 reflectance spectrometer to analyse rock and mineral composition, and different types of  
346 cameras to provide geotagged images for site documentation. However, this information  
347 could only be stored locally on each device, providing limited possibilities for transferring  
348 geo-localised files to the instructors and a science backroom using available Long-Term  
349 Evolution (LTE) networks, which resulted in significant inefficiencies during field work  
350 and post mission analysis, but crucially created a training environment that likely did not  
351 align with a future planetary exploration scenarios.

352 To address these shortcomings, in 2017 the PANGAEA team started to develop a new  
353 system to record, structure, and deliver to ground the information collected in the field  
354 (images, data from analytical tools, audio notes) within a simple and practical user  
355 interface. The outcome of this development was the ESA Electronic FieldBook (EFB),  
356 which has become a crucial support element in the PANGAEA training. The EFB system  
357 and its functionalities are described in detail in Turchi, Payler, Sauro, Pozzobon,  
358 Massironi and Bessone [31]. Since 2018, the EFB has acted as the focal point for field data

359 collection and information sharing between trainees, instructors and the science  
360 backroom, and has significantly enhanced the overall efficiency of sampling activities.  
361 Specific incremental training on how to use the EFB and the devices linked to it is  
362 provided to the astronauts during the different PANGAEA sessions. The EFB and its  
363 associated tools (including machine learning algorithms and a planetary mineral  
364 database; Jahoda et al., 2020; Drozdovskiy et al., 2020) allow the astronauts to experience  
365 a set of representative mission scenarios during the most advanced phases of the  
366 PANGAEA training, where trainees must constantly exchange data and information with  
367 instructors and a science backroom. This tool provides the ability to maintain a high level  
368 of situational awareness between all the actors involved in the field traverses, whilst  
369 recording all the information needed to perform critical discussions about crew  
370 performance and scientific observation in following traverse reviews.

371

#### 372 **4. PANGAEA course content**

373 PANGAEA's course content was created following the ADDIE model as outlined in chapter  
374 2. It is important to mention that all activities (classroom lessons, practical exercises, field  
375 traverses, etc.) are carefully interlinked in the course structure, allowing a continuous  
376 flow from theoretical to practical learning.

377

##### 378 *4.1. Classroom lessons*

379 PANGAEA's classroom lessons specifically focus on the geology of the Earth, the Moon,  
380 Mars, and asteroids. They examine volcanic, intrusive, sedimentary, and impact settings,  
381 and distinguish between *in situ* lithologies, morphologies, weathering, and impact  
382 products. Practical exercises are employed during the classroom lessons, and include  
383 hand specimen description/recognition and describing/interpreting images collected by  
384 rovers and satellites. In addition, astrobiology lessons focus on signatures of life, the  
385 evolution of life and minerals, geobiology in volcanic environments, planetary protection,  
386 and practical exercises on sample contamination.

387

388 Classroom lessons are organised into six main blocks:

389

- 390 • *Earth and Planetary Geology*: this block includes overviews and introductions to  
391 general geology and planetary geology, with a focus on the Earth, Mars, and the  
392 Moon. It also covers introductions to meteorites, asteroids and comets.
- 393 • *Sedimentary Geology of Earth and Mars*: includes lessons on erosional and  
394 sedimentary processes, sedimentary rocks, and Mars surface geology.
- 395 • *Lunar Geology and Impact Cratering*: focuses on lunar geological evolution and  
396 impact cratering processes and products, volatiles, and *in situ* resources.
- 397 • *Volcanism of Earth and Planetary Bodies*: covers igneous rocks including volcanic  
398 processes on the Earth, Moon, and Mars.
- 399 • *Intrusive rocks, Crust Evolution and Lunar Highlands*: covers the evolution of the  
400 Earth and Moon's crust, including the magma ocean, mantle evolution, intrusive  
401 rocks, and a focus on the lunar highlands.
- 402 • *Astrobiology and Planetary Protection*: Includes lessons on signatures of life,  
403 planetary protection and contamination, life in volcanic environments, and the  
404 development of life and minerals.

405

406 The purpose of these topical blocks is to offer the astronauts a general overview of the  
407 main planetary geology and astrobiology topics, with those topics linked to field trips.  
408 The topics chosen do not cover all aspects of Earth and planetary geology, but focus  
409 mainly on issues related to surface lithologies, processes, morphologies, weathering  
410 products, and field observations. The Earth and Planetary Geology block provides many  
411 of the base underlying principles and context for the other learning blocks. A simplified  
412 terminology and rock classification system was developed and used throughout all  
413 blocks.

414

#### 415 *4.2. Practical exercises: developing observational skills*

416 Several types of practical exercises take place in indoor classroom locations and are  
417 reinforced in field locations to directly apply the new skills to real natural environments  
418 (Fig. 3). Exercises are used across the theoretical blocks to allow trainees to apply their  
419 knowledge and reinforce their practical skills.

420

421 *4.2.1. Rock specimen recognition*

422 Trainees are taught how to distinguish and identify rock samples in hand specimen. This  
423 is done by direct observation, using geological hand lenses, and also with portable  
424 microscopes linked to the EFB system, the latter providing good analogue to  
425 technological tools that could be available to the astronauts on the Moon during future  
426 missions. The exercise starts with a practical lesson on how to distinguish layering and  
427 foliations, rock texture, rock components (clasts, crystals, fossils, etc.), and other physical  
428 characteristics that are simple to describe without using a specific rock classification  
429 terminology. These observations are then used to follow an interactive rock recognition  
430 flowchart that allows the trainees to derive preliminary classification at a rock family  
431 level. This approach enables the trainees to develop observational skills, without being  
432 influenced by their limited theoretical knowledge. Only a few major minerals are  
433 introduced to the trainees in this phase to keep the focus on feature recognition. In  
434 subsequent exercises, the astronauts have the opportunity to query the ESA  
435 Mineralogical Database on the EFB [33] to obtain additional information on the physical  
436 characteristics and significance of each mineral. Once the trainee's observational skills  
437 are improved, a more detailed theoretical and practical lesson is conducted introducing  
438 them to the most important igneous, sedimentary and meteoritic rocks in classroom.  
439 Metamorphic rocks are not covered in detail due to their lack of significance on the Moon  
440 and Mars, except those related to impacts and massif-type anorthositic intrusions on  
441 Earth. Following these two lessons on observation skills and rock types, the trainee's new  
442 skills and knowledge are then applied in the field. Trainees are taken to a riverbed with  
443 several different igneous and sedimentary lithologies present, where they must sort and  
444 classify them. These exercises are conducted during the first session of PANGAEA (see  
445 Section 5), and refreshers are given at each following session, with new samples specific  
446 to each training site. A more detailed overview and set of exercises on the 8 most  
447 important mineral families (olivine, pyroxenes, amphiboles, biotite, plagioclase, k-  
448 feldspar, muscovite, quartz) is provided only in the last session which is dedicated to  
449 intrusive rocks, since mineral recognition is a fundamental tool in these specific  
450 geological settings where rocks are macrocrystalline.

451

452 *4.2.2. Vocal description and drawing*

453 Trainees begin learning how to observe and describe geological landscapes and outcrops  
454 through interactively analysing images of the Earth, Moon, Mars, and asteroids/comets.  
455 An idealised methodology for completing a vocal description is provided in form of a  
456 flowchart to the trainees and demonstrated by the instructors. The trainees then practice  
457 describing outcrops/landscapes first on images and afterwards directly on real examples.  
458 The astronauts are firstly allowed to describe their observations in their own words, and  
459 then discuss them with an instructor, who coaches them on using the proper terminology  
460 to perform accurate and efficient descriptions. These exercises are often combined with  
461 the drawing exercises. The purpose of drawing is purely a learning exercise which is  
462 effective at teaching the trainees to focus their attention on details, and allow them to  
463 identify and describe large- and small-scale geological features and determine how they  
464 fit into the broader landscape context. The acquired skills and knowledge are then  
465 applied not only to terrestrial examples, but also to describe outcrops and landscapes in  
466 images from Apollo mission sites and Martian rovers.

467

468 *4.2.3. From satellite observations to the field: orbital images and geological maps*

469 These lessons introduce trainees to the geological interpretation of different terrains and  
470 features from satellite images. After a theoretical lesson covering the main aspects of  
471 orbital images interpretation (illumination conditions, tone/colours, contrast/shadows,  
472 spatial arrangements), the trainees exercise their interpretation skills on a set of images  
473 from Earth, Mars, and the Moon. The transition from a 2D representation of geological  
474 features to their real 3D shape in the subsurface is further discussed in a specific lesson  
475 followed by additional interpretative exercises. This set of lessons also incorporates an  
476 introduction to geological maps. Much like geological drawing, mapping is a basic  
477 geological skill important for developing an understanding of the stratigraphic  
478 relationships between geological units. However, the training objective is not to teach  
479 astronauts how to fully develop geological maps in the field, but rather how to read and  
480 understand their significance. Therefore, several exercises on orbital image  
481 interpretation and geological mapping are completed in classrooms, where trainees  
482 identify geological units/structures and apply the rules of superposition and intersection  
483 to understand them in 3D. The use of spectral images is also discussed in later sessions,



484 with focus given to using them to develop hypotheses regarding specific areas and then  
485 planning field traverse routes to investigate them.

486 Some “mission design” exercises provide an opportunity for trainees to put their  
487 knowledge of geological processes and orbital image interpretation into practice by  
488 having them discussing landing sites and designing geological traverses on the Moon and  
489 Mars together with scientists and engineers. They must learn to balance addressing  
490 science objectives with operational constraints. The discussion is performed together  
491 with instructors who are experts in specific regions of the Moon and Mars, and have  
492 authored the geological maps used to plan the traverse strategies of real missions. The  
493 same approach is later also used to plan the traverses performed in analogue sites. In  
494 general, satellite images and maps are used during the training to allow trainees to  
495 experience the process of traverse analysis and field verification. This process works as  
496 follows: 1) satellite images are used to get a general view of the area and formulate  
497 hypotheses on geological composition (spectral) and landscape features (DTMs); 2)  
498 panoramic views from ground can be used to observe and pre-evaluate potential  
499 outcrops of interest. 3) outcrops of interest are more closely assessed to identify areas of  
500 high scientific importance, relevant to the hypothesis generated at the start ;4) close-up  
501 views of rocks, including using a microscope, are used to confirm or refute hypotheses  
502 formulated through satellite observation. This sequence mimics the traverse analysis  
503 approach taken during the Apollo missions, or nowadays for rover missions on Mars [34].  
504

#### 505 *4.3. Field exercises and traverses: documentation, sampling, analysis*

506 Through learning from the lectures and practical classroom and field exercises, trainees  
507 are taught the fundamentals of geology and astrobiology. This allows them to begin the  
508 process of becoming independent field scientists able to communicate and work with a  
509 team of remotely located experts to solve scientific problems. This involves theoretical  
510 discussions and practical lessons that aim to draw attention to the importance of  
511 documentation and sampling strategy. The importance of proper documentation (sample  
512 description, geological field notes, geological sketches and maps) is underlined by  
513 establishing causality between landforms and rock types, ensuring quality  
514 interpretations are possible following a field activity. Trainees are taught a multiple  
515 working hypothesis methodology, where new observations and samples modify

516 sampling strategies and operational factors during an activity. From the basic principles  
517 of documentation and sampling, trainees are then introduced to the EFB system and  
518 associated tools (handheld analytical instruments, portable microscope, cameras) that  
519 they will use in the advanced field traverses.

520 These fieldwork practical skills are then fostered and exercised through a series of  
521 geological traverses. Trainees are taught documentation and sampling strategy through  
522 performing limited role-playing between ground and space, where remotely located  
523 science teams have to provide recommendations to the trainees in the field based on the  
524 information they receive. Through cycles of exploration during traverses and review, the  
525 trainees establish a strong link between the information and samples collected during the  
526 traverse and the ability of science teams to make quality interpretations and answer  
527 scientific questions. To this end, geological traverses involve four key steps, an overview  
528 of the regional geology in the classroom and field at each analogue location, guided  
529 traverses, self-directed traverses and traverses in support of real scientific research (Fig.  
530 3).

531

#### 532 *4.3.1. Principles of geological sampling*

533 A series of exercises provide practice with sampling tools and techniques to be used  
534 during the traverses. Demonstration-performance techniques are used to teach proper  
535 sampling methodologies and best practices to ensure high-quality samples are collected.  
536 Some focus is given to astrobiology sampling techniques, which require the  
537 implementation of specific protocols to ensure sample contamination is minimised.  
538 Trainees also practice with the EFB in order to familiarise themselves with how it fits into  
539 the various sampling procedures.

540

#### 541 *4.3.2. Understanding geological context: regional geology overview trips*

542 To prepare the trainees to execute scientific traverses, a specific overview of the local  
543 regional geology is provided. Satellite images are used to show the main geological  
544 characteristics of the site. Guided field tours of the areas around the traverse sites are  
545 provided by local experts together with the core instructors. This gives the astronauts a  
546 chance to observe hand specimens and geological structures and infer from them an  
547 area's geological history. This is later clarified through examining geological maps. It is  
548 important to note that the content is carefully coordinated to leave several questions

549 deliberately unanswered in order to stimulate trainees to observe and collect  
550 information during their time in the field to later derive their own hypotheses and  
551 interpretations to address scientific questions. These guided field trips are held in  
552 separate areas from the guided and self-directed traverses (see next sections), and  
553 display distinct, but comparable, geological characteristics. In this way, each trainee is  
554 forced to adopt a problem-solving mentality which creates a more involved and effective  
555 learning process [12].

556

#### 557 *4.3.3. Learning how to perform field research through mentoring: guided traverses*

558 Once introduced to the regional context, trainees begin performing geological traverses  
559 guided by instructors. These involve defining a series of scientific questions about the  
560 traverse region by examining satellite images of the area. Instructors then guide the  
561 trainees on a traverse through the region, helping them to select the correct outcrops,  
562 features, and samples to answer these scientific questions. During the guided traverses,  
563 the instructor team demonstrates to the crew how to follow a pre-planned route, locate  
564 sampling stations, collect samples, and achieve proper photographic documentation. The  
565 main focus is on the application of “flexecution” principles, where hypothesis-driven  
566 science objectives ensure a high chance of quality scientific return. Flexecution is a  
567 standard concept of operation for terrestrial field geologists, and serves as a model for  
568 how planetary field geology should be carried out [10, 12, 16]. It describes a method of  
569 operations where objectives, plans and timelines can change, based on what is discovered  
570 during a traverse.

571 Guided traverses also allow trainees to practice clear communication and geological  
572 description techniques. The trainees have to deliver descriptions and observations to a  
573 ground team over radio connection to prepare them for the self-directed traverses. This  
574 reinforces earlier training on vocal geological descriptions, and links it to communicating  
575 with a ground team. The team of instructors that follows are always available to provide  
576 corrections and suggestions to improve their execution of these activities. Trainees also  
577 practice using the EFB [31] or other documentation and analytical tools, and become  
578 accustomed to sharing their observations with ground teams through the system. Following  
579 the traverse, trainees discuss all the aspects of the traverse with the instructors and work  
580 together to link observations and samples to an evolving interpretation of the analogue  
581 environment.

582 The roles assigned for a guided traverses are as follows:

583

- 584 - The crew: composed of two to three astronauts (two different traverses are  
585 performed if the trainees are between 4 and 6 to allow each group to have  
586 dedicated instructors and ground teams).
- 587 - The instructor team: composed of a training coordinator and one or more topical  
588 instructors per team.
- 589 - The ground team: composed of a science communicator dedicated to talking to the  
590 crew, and one or more experts in geology/astrobiology and engineering support.

591

592 Once a series of these guided traverses are complete, trainees can begin self-guided  
593 traverses.

594

#### 595 *4.3.4. Developing autonomy: self-directed traverses:*

596 This activity represents the most advanced part of the field training, and aims to fully  
597 immerse the astronauts in the process of field geology exploration. The instructor teams  
598 present the crew with a set of scientific problems to address during a traverse across a  
599 scientifically interesting region they have not yet visited. They are introduced to the  
600 region only through examining remote sensing data (satellite images), which is  
601 sometimes viewed using a virtual reality (VR) system. Unlike the guided traverses, the  
602 crew is in charge of managing the traverse execution along a pre-planned route between  
603 stations, and must balance identifying, collecting, and documenting samples with the EFB,  
604 in order to address a scientific problem. Trainees must perform the activity over a limited  
605 time period, and they are only able to collect a certain number of samples. The instructor  
606 team follows at a distance, observes without interfering with the traverse, and documents  
607 the crew behavior and observations. The crew communicates by radio to the ground team  
608 using verbal descriptions of each sample and the general environment, and shares the  
609 documented information through the EFB. Ground teams provide recommendations to  
610 the field team based on the information they receive, and work with them to answer the  
611 scientific questions posed.

612 During the self-directed traverses, the trainees can apply the flexecution methods that  
613 have been taught during the guided traverses. The traverse is still bound by the limits of  
614 safety and operational constraints, but the crew has the freedom to make real-time

615 changes to planned tasks based on their field observations. For example, they can re-  
616 prioritise science objectives based on their discoveries. Since future crews, especially  
617 those visiting Mars, will require a high level of autonomy in their field activities, it is  
618 important that astronauts are able to make quality decisions without the support of  
619 geological experts or the ground teams.

620 To introduce an additional motivation to several self-guided traverses, during the 3<sup>rd</sup> and  
621 4<sup>th</sup> sessions of PANGAEA, some traverses are performed with real science-driven  
622 objectives developed together with local scientists to advance the knowledge of a specific  
623 site. In this case, the trainees are briefed on the state of the art regarding the research  
624 already done in this site, underlining the fact that their activity will contribute new data  
625 and samples that will be later analysed in the laboratory. In these traverses, the scientific  
626 questions provided as a base for the traverse execution include hypothesis that have not  
627 yet been tested. In this way, the self-guided traverses present a challenging experience  
628 for the crew with real expectations from the scientists. This allows the trainees to feel a  
629 sense of responsibility about their tasks, motivating their learning experience [11].

630

#### 631 *4.3.5. Traverse analysis and refinement*

632 Following both the guided and self-directed traverses, the crew and instructor teams  
633 examine together the samples and information collected by the crew through the EFB and  
634 associated tools. The significance of each specimen is analysed in relation to the scientific  
635 questions posed and the ground teams discuss their perceptions of the crew's  
636 observations and descriptions of the geology. Following this, a virtual or real walk-  
637 through of the entire activity is led by the instructor team to offer constructive feedback  
638 for both the crew and the ground team. They examine each stop and comment on the  
639 effective and ineffective aspects of the conversations, sampling methods and operational  
640 choices made by the team. This gives the trainees a broad overview of the traverse, and  
641 demonstrates how description techniques, communication, tools and sampling choices  
642 can impact the scientific outcome of a planetary exploration EVA.

643

### 644 **5. PANGAEA training sites**

645 As mentioned, all classroom lessons, practical exercises and traverses take place at the  
646 field locations using local facilities to allow for synergies between classroom lessons and  
647 fieldwork. The implementation of the PANGAEA course is therefore structured around

648 both its field locations, and the prerequisite learning requirements demanded by each  
649 lesson.

650 The selection of the appropriate field sites for PANGAEA in Europe was made after the  
651 definition of specific geological and logistical requirements. A candidate site had to  
652 include challenging geological problems, teaching facilities, permits, safety and suitable  
653 infrastructure, climate and amenities, all of which should be in relatively close proximity.  
654 The full list of requirements involved in this selection process can be found in the  
655 supporting materials. Following these criteria, a series of potential locations were  
656 evaluated, and finally four were chosen to host the PANGAEA course: 1) the Permian  
657 terrains of the Dolomites (Italy) for their pristine sedimentary sequences; 2) Ries crater  
658 in Germany for impact cratering processes and lithologies, 3) the island of Lanzarote in  
659 the Canary archipelago for volcanism; 4) the anorthosite massifs of Lofoten, Norway, for  
660 intrusive rocks similar to those found in the lunar highlands.

661

### 662 *5.1. Bletterbach, Italy*

663 Bletterbach Canyon (Fig. 4) is one of the most studied geological sites in Europe. The  
664 outcrops along the canyon walls display a geological sequence spanning from the  
665 Permian volcanic basement (270 Ma) to the lagoon dolostones of the Lower Triassic. This  
666 includes the Permo-Trassic mass extinction boundary and a variety of Permian  
667 terrigenous lithologies and sedimentary structures [35], with some lithological analogies  
668 to Martian sedimentary sequences in Gale Crater [36]. The lower and middle part of  
669 Bletterbach gorge is characterised by a volcanic porphyric group (Atesinian volcanic  
670 complex), generated by explosive volcanic events and pyroclastic flows. This is overlain  
671 by a sedimentary sequence with detrital lithologies like sandstones and shales from an  
672 alluvial plain environment with local evaporitic layers (gypsum and anhydrite),  
673 interpreted as ancient soils in semi-arid conditions (Val Gardena Sandstone fm., Massari  
674 et al. 1988). At the valley head, overlying the alluvial sedimentary sequences are deposits  
675 from coastal evaporitic to sub-tidal environments (Bellerophon fm., Massari et al. 1988),  
676 followed by peri-tidal deposits (Werfen fm.). This is covered by an erosive event  
677 (Richthofen conglomerate) and a final transgression represented by a carbonation  
678 platform facies (Contrin fm.), closing the Bletterbach stratigraphic series. Overall, the  
679 stratigraphic sequence is interpreted as evidence of a regional marine transgression,

680 where a continental environment evolved into a marine basin during the Permian-Early  
681 Triassic time span [38]. The entire sequence is crosscut by mid-Triassic volcanic dike  
682 intrusions. In the area it is also possible to observe quaternary periglacial and glacial  
683 morphologies and deposits, as well as tectonic, sedimentary and gravitational  
684 deformation structures.

685 The high diversity of lithologies, including volcanic effusive/intrusive, sedimentary,  
686 diagenetic and metamorphic rocks (the latter in glacial deposits) make this location very  
687 well suited to introduce and exercise rock recognition skills. The clear stratigraphic and  
688 depositional relationships between these layers provide an excellent place to understand  
689 the fundamentals of geological superposition, modification by subsequent burial and  
690 fluid circulation (diagenesis) and how paleo-environmental changes are reflected in the  
691 rock record. For this reason, the area is already used for geological training by several  
692 European universities. Moreover, several of the rock series like the sandstones  
693 intermixed with silt stones and clays of alluvial plain environments, and the evaporite  
694 rich layers and veins of the Val Gardena sandstone formation, are analogues for some  
695 Martian sedimentary environments, including those of Gale Crater explored by Curiosity  
696 [36]. The site is managed by the Bletterbach Geopark which supports the training by  
697 providing access to the outcrops and facilities.

698

## 699 *5.2. Ries Crater, Germany*

700 Nördlinger Ries (Fig. 5) is a large circular depression in western Bavaria, Germany,  
701 located north of the Danube in the district of Donau-Ries. This feature was originally  
702 interpreted as a volcanic caldera with typical pyroclastic fallout materials in the  
703 surrounding environment [39, 40]. However, in 1961 Eugene Shoemaker [41]  
704 demonstrated through morphological and mineralogical studies that this structure has  
705 been formed through a meteorite impact crater between 14.3 million–14.5 million years  
706 ago in the Miocene. Since then, the Ries crater has been considered as one of the best-  
707 preserved impact structures of medium-large size on Earth [42-44].

708 The original target rock consisted of a Mesozoic to Cenozoic sedimentary sequence  
709 including limestones, shales and sandstones [45] and an underlying crystalline basement  
710 made up of Variscan and pre-Variscan granites and gneisses of the Bohemian massif [46].  
711 After the impact, the crater was covered by late Miocene-Pliocene sedimentary deposits

712 of fresh water-limestones until the Upper Pliocene-Pleistocene, when the impact  
713 structure was exhumed thanks to the erosion and the southeast uplift and tilting of the  
714 entire sedimentary sequence due to the northward propagation of the Alpine belt. Today,  
715 the crater consists of a flat-floored 600-700m deep inner central basin filled with  
716 sediments, surrounded by an inner ring of uplifted basement and a structural outer rim  
717 covered by impact breccias and para-autochthonous mega blocks composed of the  
718 sedimentary sequences breached by the impact [44]. Within and partly outside the basin  
719 are fallout suevites, an impact breccia containing crystals, glass, partially melted material  
720 and rock fragments. The suevites underlie tertiary lake sediments within the inner rim,  
721 and consistently overlie impact breccias (Bunte Breccia) which, in turn, unconformably  
722 cover the pre-impact sedimentary sequence (Sturm et al. 2013).

723 This area is ideal for training, as it allows impact products and minerals to be observed  
724 in combination with all the morphological and structural elements constituting a regional  
725 impact basin, from the inner ring to the ejecta in the surrounding area outside of the  
726 crater. Trainees can observe how the pre-existing rocks have been modified by the  
727 impact, how lithostatic rebound brought deeper intrusive rocks to the surface in the  
728 central area, and how all these materials have been distributed in the surrounding  
729 environment during the impact process. Ries also provides a location to discuss and  
730 observe how impact events change the fracturing and porosity of rock, and thereby  
731 altering their suitability for life, providing training on the selection of astrobiology  
732 samples. Additionally, the site also has some historical significance, having been used for  
733 mission-specific training for the Apollo 14 crew in August 1970 [9]. The area is widely  
734 studied and easily accessible since several towns offer facilities and housing. The main  
735 city of Nördlingen, with its medieval buildings made of suevite impact rocks, is located  
736 about 6 km southwest of the centre of this depression.

737 The activities in this site are facilitated by the support of the Rieskrater Museum of  
738 Nördlingen, which provides classroom facilities and access to its sample collections,  
739 laboratories, and a library of geological cores obtained by different drilling campaigns  
740 inside the crater. The geological heritage of the whole area is also promoted by the  
741 Geopark Ries.

742



743 5.3. *Lanzarote, Spain*

744 Lanzarote is the north easternmost of the Canary Islands (Spain), and is located only 77  
745 miles (125 kilometres) from the African mainland in the Atlantic Ocean. It is the fourth  
746 largest island of the archipelago, with a surface area of 800,000 square kilometres and a  
747 population of 140,000 inhabitants (Fig. 6).

748 Lanzarote is a volcanic island with a long history of eruptions. It is often referred to as the  
749 'Island of the 1,000 volcanoes', although is actually the least mountainous of the Canary  
750 Islands. The highest point is the volcano Peñas Del Chache, near Haría, in the northern  
751 part of the island, which reaches 2,198 ft. (670 metres) above sea level.

752 The Canaries have warm and sunny weather all year round, with temperatures rarely  
753 under 16°C (61°F) in winter and 25°C (77°F) in summer. Rain is very rare, resulting in a  
754 dry climate with an average 16 days of rainfall annually, usually between December and  
755 February. Unlike the other Canary Islands, Lanzarote does not have any high mountains,  
756 which means there are very few clouds, lower evaporation, and moderate humidity  
757 levels. This climate makes vegetation cover limited. The interior of Lanzarote is covered  
758 with massifs and plains, dotted with small craters and cones and amorphous eruptive  
759 rock formations. This geology combined with the lack of vegetation makes the interior  
760 reminiscent of a lunar landscape and provides good exposure of the island's  
761 morphologies and lithologies.

762 The island of Lanzarote was formed through a sequence of several volcanic events  
763 starting approximately ~14.5 Ma (million years ago) that have continued up to recent  
764 times. Along with Fuerteventura, Lanzarote is located on a submarine ridge called Banco  
765 de la Concepcìon, which runs NE-SW parallel to the African coast.

766 The history of the island can be divided in four main events and sub-events according to  
767 the timing and type of volcanism [47, 48]. Phase 1 involved the emergence of two large  
768 shield volcanos from the ocean, Los Ajaces volcano formation (14.5-13.5 Ma) and Famàra  
769 volcano (10.2-3.8 Ma), which formed over alternating periods of activity and quiescence.  
770 Phase 2 is termed Peniferic (1.6-0.7 Ma), in which the Teguse volcanic group and Caldera  
771 Riscada formed. Rifting in Phase 3 then built the central part of the island between ~1.2  
772 and 0.8 Ma, covering much of the Phase 1 volcanos, with only some of the larger cones  
773 emerging from beneath. Finally, the most recent Phase 4 consisted of localised eruptions  
774 at several locations across the island such as the Corona volcano (~91-21 ka), and  
775 Timanfaya (1730-36) and Tinguaton (1824).

776 The island is very well suited to observing and studying volcanic rocks and processes.  
777 The geological heritage is managed and promoted by the Geopark of Lanzarote and  
778 Archipelago Chinijo, which is also supporting the PANGAEA training through a specific  
779 agreement between ESA and the local regional authority (Cabildo).  
780 The possibility to visit sites with different ages, from the pristine lava flows and  
781 monogenic cones of Timanfaya (in the National Park of Timanfaya), to the older massive  
782 shield volcanoes of Famara and Ajaches, allows the observation of volcanic morphologies,  
783 weathering processes and the study of superposing events, as can be observed on the  
784 Moon and Mars [49]. The interactions between volcanic activity and groundwaters makes  
785 Lanzarote an excellent analogue to Martian volcanism, with very well preserved  
786 monogenic cones, tuff rings, and hydrated thermal mineralization [50, 51]. The site is an  
787 ideal location to investigate how volcanic hydrothermal systems and their secondary  
788 minerals might host life or biosignatures of life, providing general insights into the link  
789 between volcanic processes and the search for life [52]. In addition, Lanzarote hosts some  
790 of the most impressive and well-studied lava tubes on Earth, like the Corona system [53,  
791 54], allowing for the astronauts to experience a traverse through these subsurface  
792 volcanic environments that have also been identified also on the Moon and Mars [55].  
793

#### 794 *5.4. Lofoten, Norway*

795 Lofoten, is an archipelago in northern Norway, north of the Arctic Circle (Fig. 7). The  
796 archipelago is composed of Meso- to Neoproterozoic gneisses, which were intruded by an  
797 extensive magmatic suite of anorthosite-mangerite-charnockite-granite about 1.8-1.7 Ga  
798 ago [56]. These old magmatic suites, including the Flakstadøy basic complex, are made  
799 up of anorthosites, gabbros, norites, troctolites and orthopyroxene bearing monzonite  
800 and granites (i.e. mangerites and charnockites), and originated in the deep crust of the  
801 Baltica continent before its merging into the Rodinia supercontinent at 1300-1000 Ma  
802 [57, 58]. The processes in which these features formed, though fractional crystallization  
803 of a deep magmatic chamber and diapiric uprising of anorthositic mushes followed by  
804 intrusions of mangerites and charnockites [59-61] are similar to the formation of the  
805 lunar primordial crust, where the Fe-anorthositic rocks, segregated from the early  
806 magmatic ocean, and were followed by younger intrusions of Mg- and Alkali- suites [62].

807 The Rodinia break up at 750 Ma with the formation of the Iapetus ocean followed by its  
808 closure during the Caledonian orogenesis (Pangaea supercontinent, 420 Ma), as well as  
809 the more recent opening of the north Atlantic Ocean (200 Ma), allowed the exhumation  
810 of the ancient Precambrian rocks in Lofoten archipelago. In this way, this basement  
811 crustal segment defines an emerged horst bounded to the east by thrust nappes of the  
812 Scandinavian Caledonides, in a similar setting to the Western Gneiss Region of South  
813 Norway [63].

814 Quaternary glaciations and the limited vegetation means that these rare rocks are well  
815 exposed and can be observed and studied across a broad area, providing some of the best  
816 outcrops of lunar highland analogue rocks in the world [59] and excellent opportunities  
817 for traverses exploring magma-genesis processes. The mountains around the village of  
818 Nusjord in particular allow the design of different traverses crossing the entire intrusive  
819 complex and observing contacts (either intrusive and tectonic) between several units.

820 In summary, this location enables more advanced training on the topic of magma  
821 differentiation and igneous mineralogy. In addition, the long period of geological history  
822 exposed in the area can be compared and linked to what was observed at the other  
823 training sites to provide a holistic view into Earth's geological evolution. Facilities are  
824 available in the surrounding villages, but the timeframe for fieldwork is limited to  
825 summertime due to the high latitude, snow cover, and lack of light in the winter.

826

## 827 **6. PANGAEA course structure**

828 Matching the PANGAEA course analysis and design (Section 3) with content (Section 4)  
829 to the selected field sites (Section 5) enabled the course structure to be created.  
830 Classroom lesson blocks, practical exercises, and traverses were assigned to field sites,  
831 and ordered in a way that enabled lessons with prerequisite learning requirements to be  
832 met. The course structure has evolved through time, reaching its current configuration  
833 only in the last edition, following crew/instructor feedback sessions and internal review  
834 after each edition since 2016. The overall and current PANGAEA course structure is  
835 shown in Figure 8.

836 The course structure gradually builds trainee skills and knowledge through the cognitive  
837 domains described in Kratwhohl (2002). Each session of the course begins in the  
838 remember and understand levels of the knowledge domain, with knowledge being  
839 transferred from the instructors to the trainees during more theory heavy lessons. This

840 quickly builds into exercises where trainees must apply that knowledge to narrow to  
841 specific problem identification and finding solutions through interactive discussions. This  
842 application of knowledge is advanced further through practice in more realistic field  
843 environments, where the same skills are applied to solving problems in more complex  
844 information-rich environments. Finally, the trainees reach a level of knowledge and  
845 experience allowing them to analyse specific scientific questions and evaluate traverse  
846 plans or information coming from satellite images in order to apply their skills in the  
847 geological exploration of new terrains.

848 A key feature of the PANGAEA course is the incremental introduction of autonomous field  
849 activities through the course structure. All sessions include regional geology trips and  
850 guided traverses. In addition, the last two sessions include self-guided traverses, some of  
851 which include real scientific objectives. This course structure enables trainees to learn  
852 the basics of geology in the highly didactic sedimentary sequences of Bletterbach Canyon.  
853 They can then confidently move on to the more complex environments created by the  
854 Ries impact crater. Lanzarote is dedicated to volcanism as it presents an excellent  
855 terrestrial analogue for the basaltic regions of the Moon and Mars, making it the best  
856 place to conduct the field traverse exercises thanks to its aridity and well-preserved  
857 outcrops. It is in Lanzarote that trainees start to exercise self-guided traverses and  
858 sampling protocols. Finally, Norway introduces the trainees to the very complex  
859 geological environment of intrusive rocks, allowing them to fully exercise their acquired  
860 skills.

861 It is important to note that this structure is distributed around the availability of field  
862 sites and other training activities throughout the year. Lanzarote, for example, is too hot  
863 in the summer for training, and Bletterbach Canyon is not accessible during winter when  
864 the river levels are too high, whilst Lofoten can be visited only during summertime due  
865 to the lack of light in the winter. Therefore, PANGAEA usually starts in September with  
866 the first two sessions (Bletterbach and Ries) one immediately following the other.  
867 Lanzarote is held in November, while Lofoten is scheduled in June/July of the following  
868 year. In this way, over 10 to 12 months the full PANGAEA training is completed, lasting a  
869 total of 23 days comprising approximately a total of 51 hours of classroom lessons, 25  
870 hours of practical exercises, 60 hours of field trips and traverses (Fig. 9).

871

## 872 **7. Results and discussion**

### 873 *7.1. Learning the principles of planetary and field geology*

874 Four editions of the training have been implemented since the beginning of PANGAEA in  
875 2016, with a fifth edition ongoing in 2022-2023, with a participation of 10 astronauts  
876 from ESA, NASA and Roscosmos and additional 5 non-astronaut trainees including space  
877 engineers, EVA and operation specialists (Supplementary Table 4). As happened during  
878 the Apollo geological training programme, astronauts approached the first training  
879 session with a limited understanding of how complex and experience-based field geology  
880 exploration is. They often assumed, due to their ISS experiences, that simply performing  
881 correct procedures would be sufficient to achieve science objectives in the field. As the  
882 training grew in complexity and the astronauts faced real geological environments, it  
883 becomes clear to them that their ability to observe and identify interesting rocks or  
884 outcrops, communicate, and apply flexecution are the most crucial aspects of this activity,  
885 where fixed procedures would drastically limit potential discoveries. In this way, the  
886 trainees typically experience a shift in perspective, and eventually find motivation in this  
887 less prescribed method of working, where they become the main protagonists of the  
888 possible discoveries and science advances. Therefore, this training not only appeared to  
889 provide basic knowledge and preliminary experience of field exploration, but also helped  
890 to foster the astronaut's appreciation for the process of true exploration.

891 Feedback on all lessons and activities have been collected throughout every edition of  
892 PANGAEA. The average evaluation by participants at PANGAEA, based on the standard  
893 student feedback forms used throughout the ESA space training, on a 1 to 5 scale, is 4.6  
894 for lesson content (clearly understood, beneficial), 4.7 for lesson material (enhanced  
895 understanding), 4.8 for instructors (promoted and maintained the desire to learn) and  
896 4.8 for facilities (greatly enhanced and aided the training). When only looking at feedback  
897 ratings gathered from field activities, the average evaluation reached in all editions  
898 between 4.9 to 5 (extremely beneficial, excellent for understanding, inspirational). This  
899 indicates that field activities are the highlight of the course where all the main topics and  
900 practical exercises learned in classroom are finally consolidated and acquired. The final  
901 feedback from all course editions always identified PANGAEA as a very relevant training  
902 in the framework of future lunar missions, particularly in later editions when the Artemis  
903 programme existed.

904 Astronauts at the end of each training edition were very positive about the course,  
905 especially regarding the close link between classroom and field, with supportive joint  
906 statements from the trainees such as, «the course is a really good blend of classroom  
907 lessons, exercises and fieldwork (...) so you get to see what it is that we've discussed in  
908 classroom and then you get a hands on experience, you get to see the real world  
909 examples» (astronaut trainees from feedback session 2021). Similarly the participation  
910 of a NASA astronaut from the Artemis group in 2021 and 2022 underlined the importance  
911 of learning in the field, with one of them saying (from feedback session 2021): «I found it  
912 very interesting the concept of learning in the field (...) so that we can have a discussion  
913 in the morning about how volcanoes form, and then actually walk around on different  
914 volcanic terrains in the afternoon; this is really useful for a training perspective because  
915 you get to see the geology that we are learning in the proper context». We also received  
916 the recommendation not to overwhelm the traverses with too many operational tasks,  
917 keeping the right balance between the experience of geological exploration and the  
918 operational simulation in the more advanced session 3-4 of PANGAEA.

919 The positive feedback received for PANGAEA can be attributed to the course building on  
920 the legacy of the Apollo experience, such as fostering the learning process through field  
921 activities, whilst bringing the modern advances made in planetary geology to its course  
922 content and incorporating relevant state of the art technologies. The realism of the  
923 analogue environments, covering all the most relevant lunar and Martian geological  
924 settings, and the addition of self-guided traverses with real scientific objectives provide  
925 valuable outcomes for enhancing trainees' performance in geological exploration,  
926 documentation, and sampling. The involvement of additional interlinked topics, such as  
927 astrobiology and In Situ Resource Utilization (ISRU), allows the astronauts to think  
928 towards the main challenges of future missions to the Moon and Mars. Overall, we believe  
929 the course provides a robust basic theoretical and practical knowledge of mission  
930 relevant field science to its trainees, and adequately prepares them for starting mission-  
931 specific training once details on mission scenarios, related scientific objectives, and  
932 landing sites become available.

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935 *7.2. Lessons learned*

936 Over the various iterations of PANGAEA, many lessons were learned in how to effectively  
937 teach astronauts geology and astrobiology. Like any training course, standard best  
938 practices are used to build clear, consistent lessons that introduce new information in a  
939 structured and logical way. However, when teaching these subjects to astronauts, specific  
940 considerations and adaptations are required.

941 As mentioned in Section 3, tilting the course content towards practical, implementable  
942 knowledge over pure theory has been a key-asset, allowing to bring the trainees to the  
943 higher levels of learning of the revised Bloom's taxonomy of learning (Analysis and  
944 Evaluation). Astronauts tend to be practically minded, and long theoretical lessons do not  
945 provide them with the best opportunity to learn. Where theoretical lessons are required,  
946 providing examples of how knowledge might be applied in the future missions was found  
947 to be an extremely effective way of demonstrating the value of learning theories and  
948 concepts. Dissociating lessons from these goals for too long can lead trainees to question  
949 the point of the learning certain things and cause them to lose interest.

950 Field trip lessons should also be built around similar concepts. Typically, field trips used  
951 for academic teaching involve visiting locations to learn more about a particular  
952 environment in context. For training astronauts, these types of field trips are still  
953 important. However, in order for learning to be most effective and clearly relevant to the  
954 future work of trainees, bringing in some elements of planetary surface exploration and  
955 scientific research realism was found to be important for trainee motivation and  
956 knowledge retention. PANGAEA achieves this through having trainees perform  
957 increasingly autonomous traverses through geological landscapes with predefined  
958 science goals and remotely located science teams. This contextualises the knowledge  
959 trainees gained through the regular field trips in a planetary exploration setting and  
960 demonstrates the importance of the training. This also was found to promote the trainee's  
961 independence from the instructors, forcing them to apply their knowledge as a team and  
962 to make decisions. Adding to the traverses real scientific objectives defined with the local  
963 experts, aiming to address the still open scientific questions and with potential for further  
964 science advancements and publications, is also a very important motivational factor  
965 fostering the engagement and emotional satisfaction of the trainees.

966 When available, traverses should include technological capabilities relevant to planetary  
967 exploration. Although the exact set of capabilities for EVAs on the lunar or Martian

968 surface are yet to be designed and built, the core concepts of scientific data collection,  
969 documentation, and communication can still be effectively demonstrated by using  
970 Commercial off-the-shelf (COTS) hardware, prototypes and low TRL (technology  
971 readiness level) instruments to emulate the capabilities that should be available to  
972 astronauts conducting geological exploration on the Moon or Mars. This includes ways to  
973 collect images, notes, spectra, and other scientific data. Incorporating such systems into  
974 the training was found to be a highly effective way to allow astronauts to understand the  
975 types of information required for performing effective science during planetary surface  
976 exploration with remotely located science teams. Overall, it allowed them to appreciate  
977 the importance of quality data collection for enabling scientific interpretation.  
978 Finally, our assumptions about closely interweaving classroom and field trips were found  
979 to be important. Separating classroom theory from field observations by weeks or  
980 months resulted in less favourable learning outcomes, and trainees greatly preferred  
981 conducting classroom work in facilities close to the field sites so that classroom lessons  
982 and field trips could occur on the same day.

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## 984 **8. Conclusion and future directions**

985 PANGAEA has matured over the years, adding many new lessons and activities to enhance  
986 the course. While the main structure is now well-defined, some new lectures and  
987 exercises will be required when lunar missions are better outlined in terms of science  
988 objectives. As technology is developed for Artemis, new capabilities may have to be  
989 emulated and incorporated into the field traverses, and the exploration operations  
990 concepts updated or changed.

991 The course has proven itself to be effective at providing a basic theoretical and practical  
992 knowledge on planetary and field geology to astronauts. After PANGAEA, astronauts  
993 should have all the necessary practical and theoretical geological skills for future mission-  
994 specific training, which remain out of PANGAEA's scope and will be addressed when the  
995 Artemis missions are better defined. It also provides an opportunity for astronauts to  
996 work with some of the scientific community that will be driving scientific questions and  
997 objectives for the future lunar mission.

998 Echoing the experiences of Apollo, PANGAEA again highlights the importance of field  
999 geology training to get astronauts fully involved in the scientific research and activities  
1000 they will have to perform on the Moon and beyond. The outcome of the self-directed



1001 traverses, which often involved real scientific objectives, demonstrated how properly  
1002 trained astronauts are crucial for selecting the most scientifically interesting samples.  
1003 These skills will be required to fully exploit the potential of field geology on the lunar  
1004 surface, ensuring the true scientific potential of these dangerous and expensive missions  
1005 is realised.

1006

## 1007 **Acknowledgements**

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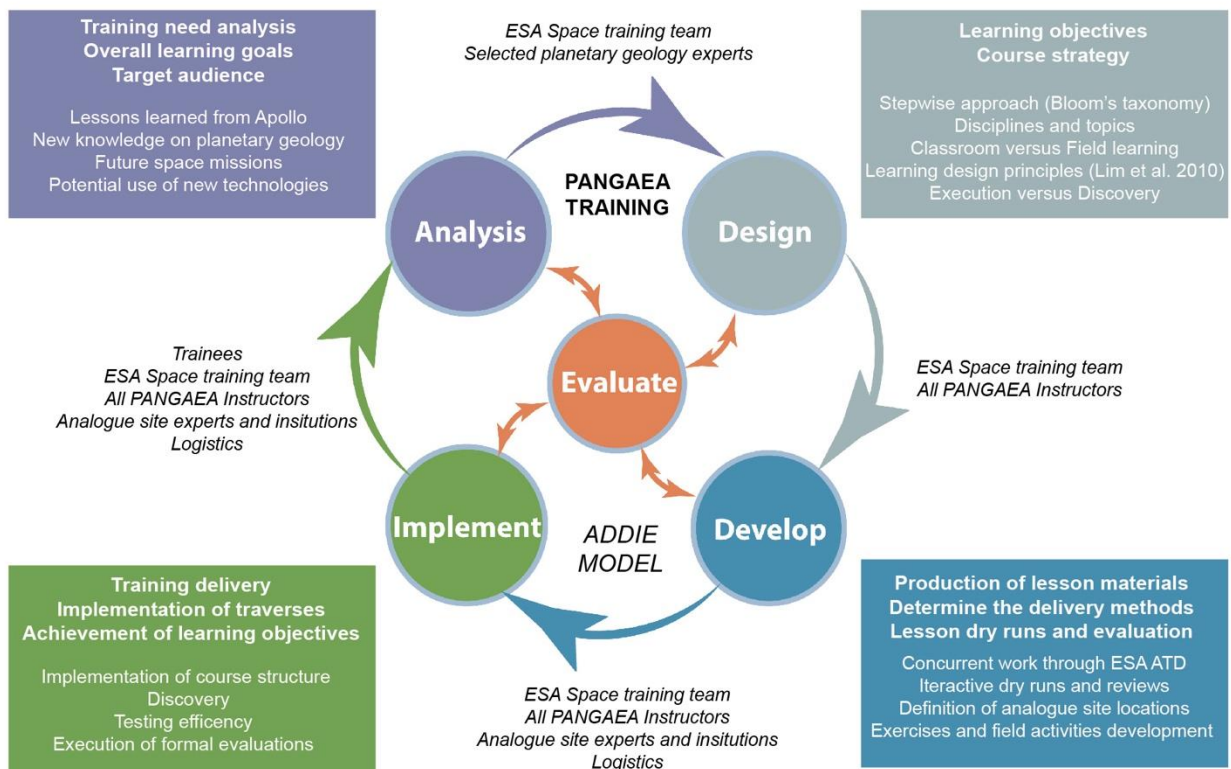
1009 PANGAEA would not be possible without the significant support offered by local  
1010 authorities at each field location. We would like to thank Geoparc Bletterbach for its  
1011 support in accessing Bletterbach Canyon, Ries Krater Museum for its the gracious hosting  
1012 and use of facilities, and Geopark Ries for its support in accessing locations in Ries Crater.  
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1019 implementation of the training in 2016.

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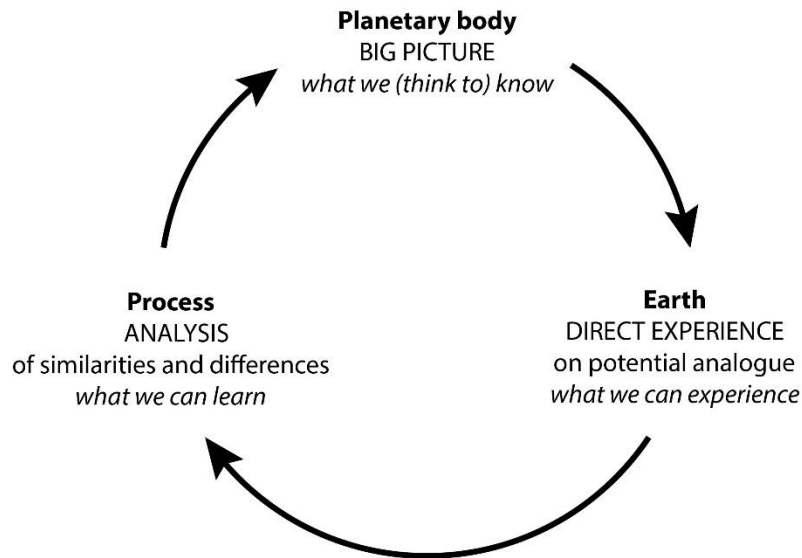
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Fig. 1. Application of the ADDIE model to the construction of the PANGAEA training. Actions and main actors are specified for each step of the model.



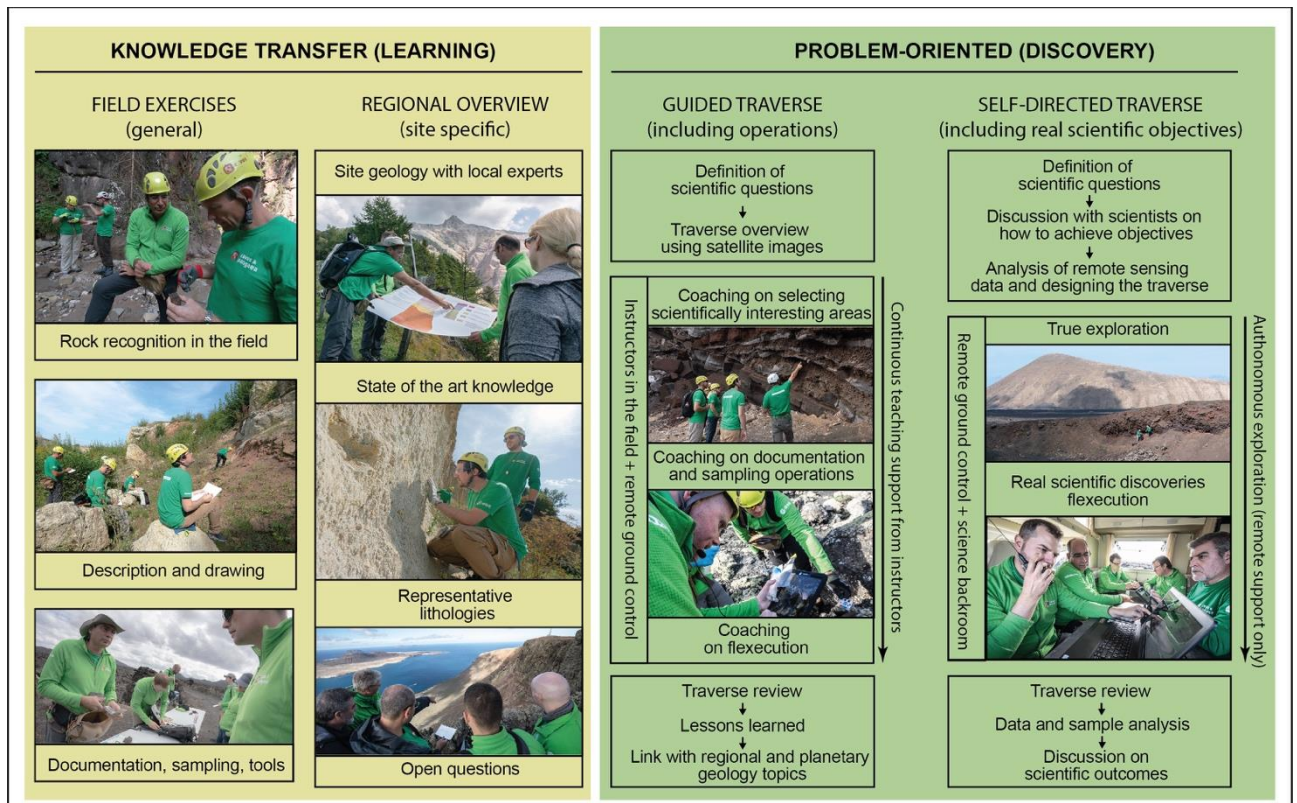
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1031 **Figure 2:** The “cognitive loop” used to design the PANGAEA training strategy, based on  
 1032 that typically used in planetary geology research.

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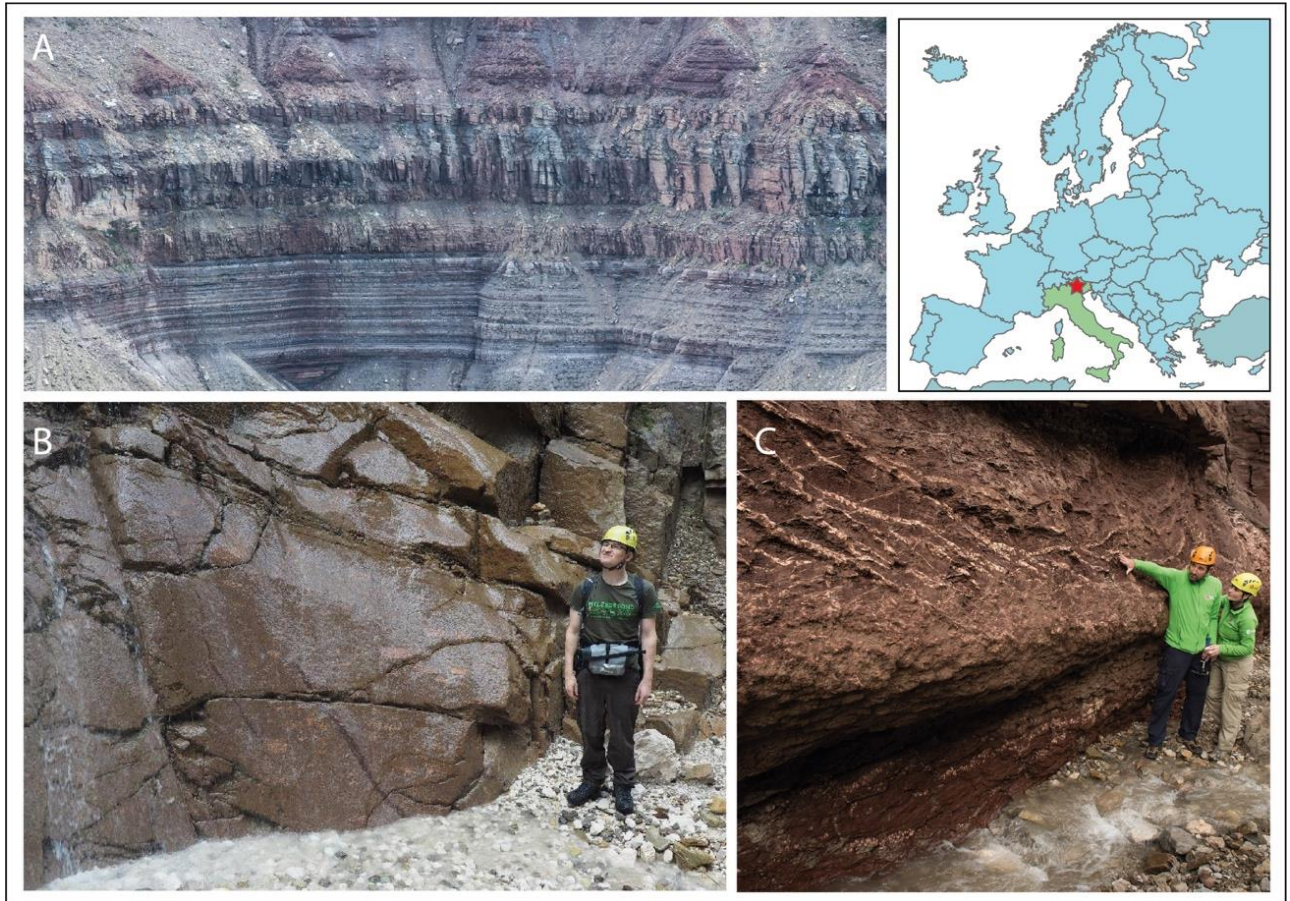
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1036 **Figure 3:** Different types of field exercises and activities performed during PANGAEA,  
 1037 divided between “knowledge transfer” and “problem oriented” methodologies.





1038

1039 Figure 4. Overview of the Bletterbach Canyon analogue site (South Tyrol, Italy): A) the  
1040 canyon is characterised by a well-exposed sedimentary sequence of sandstones, marls,  
1041 limestones, and dolostones with over 800 m of thickness; B) the sedimentary sequence  
1042 overlays a magmatic basement consisting of rhyolites representing the source of the  
1043 terrigenous sandstones; C) the lower part of the sequence is characterised by anhydrite  
1044 and gypsum veins indicating a sabkha-type environment, similar to those detected in  
1045 Gale Crater by the Curiosity rover.

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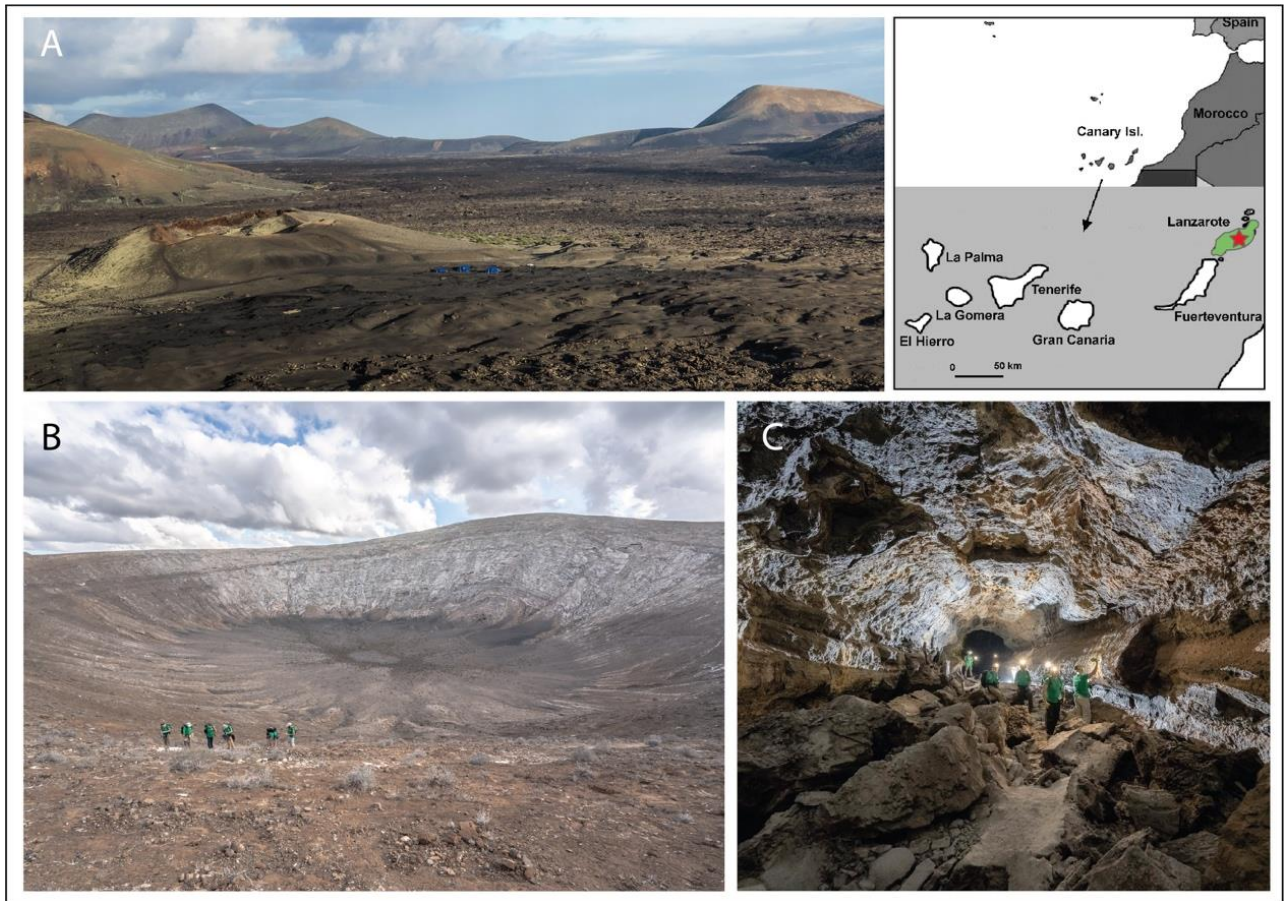




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1048 Figure 5. Overview of the Ries Impact Crater analogue site (Nördlingen, Germany): A)  
1049 the trainees observing a crystalline mega-breccia block in the area of the crater inner  
1050 ring; B) Suevite fall-out deposits covering the chaotic terrigenous Bunte Breccia  
1051 formation, representing the ejecta of the impact crater; C) classroom lessons are held in  
1052 the Ries Crater Museum, which offers a collection of rock cores from different depths  
1053 and locations inside the crater.

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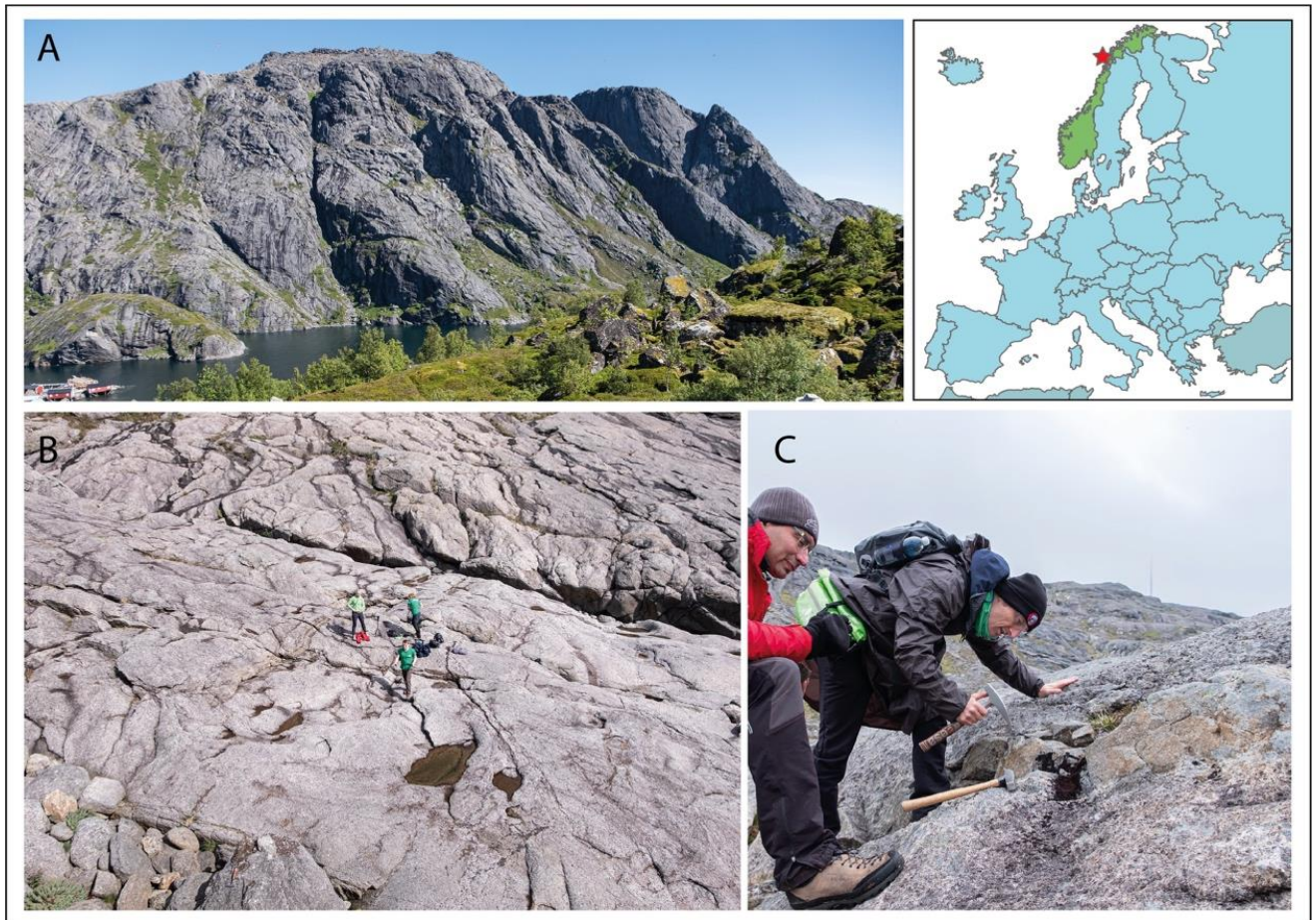
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1056 Figure 6. Overview of the Lanzarote analogue site (Canary Islands, Spain): A) Lanzarote  
1057 is a volcanic island with several different volcanic edifices, lava flows, and pyroclastic  
1058 deposits, with ages spanning from 7 million-years-old to a few centuries: B) the  
1059 phreatomagmatic edifice of Caldera Blanca, considered one of the best analogue to tuff  
1060 rings observed in the low plains of Utopia Basin on Mars (Brož and Huber, 2013); a  
1061 traverse inside the lava tube of La Corona, with 9.5 kms of length and a diameter reaching  
1062 over 35 m in some sections.

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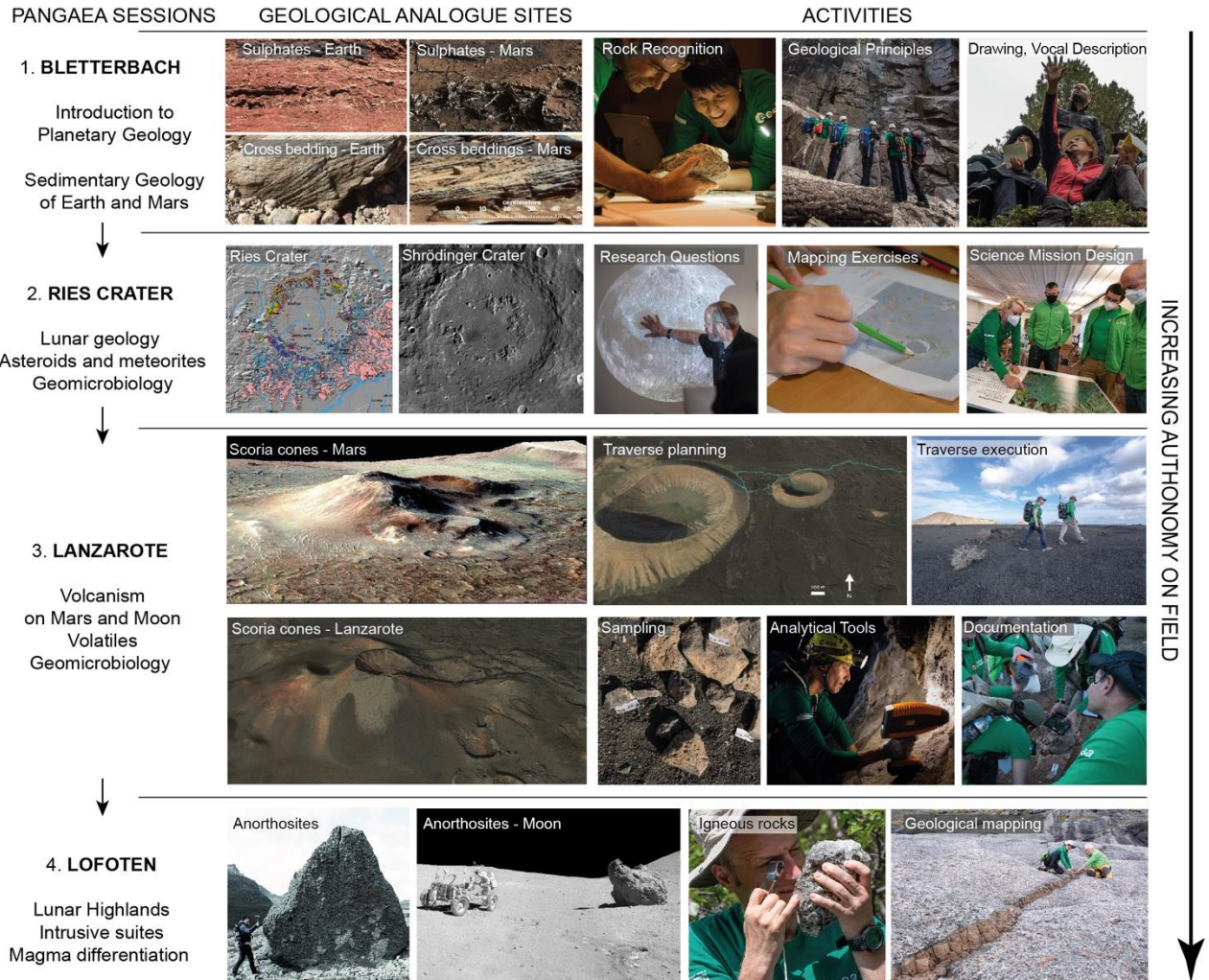
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1066 Figure 7. Overview of the Nusfjord massif analogue site (Lofoten, Norway): A) the  
1067 anorthositic massif behind the village of Nusfjord represents one of the best analogue  
1068 sites in the world for studying the lunar highlands; B-C) glacial erosion has left the  
1069 intrusive rocks highly exposed, allowing the observation of different magmatic  
1070 processes, like intrusions, dikes, magma mingling, and magma differentiation.

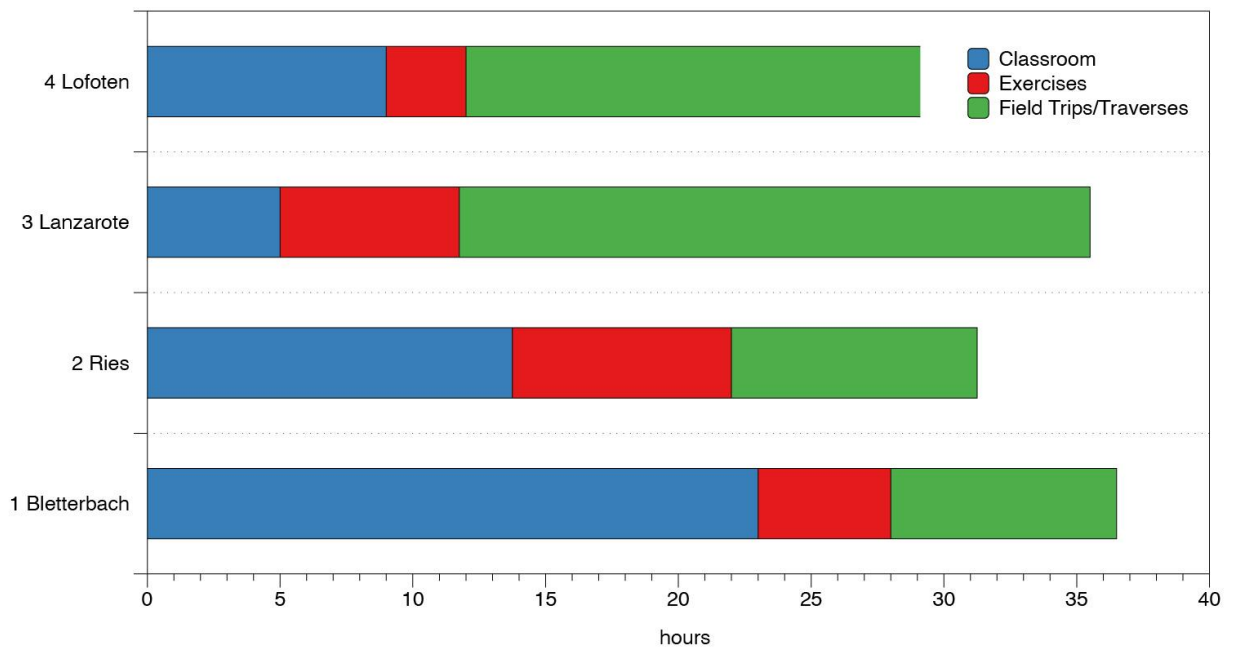


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Figure 8. The analogue sites, topics and activities integrated in the final course structure, divided in the four sessions.



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1077 Figure 9. Hour distribution of classroom lessons, exercises (both in field and classroom)  
1078 and field trips/traverses across the 4 PANGAEA sessions. The course progresses  
1079 towards field activities become predominant in session 3 and 4, when most of the  
1080 theoretical knowledge is already acquired by the trainees in session 1 and 2. After  
1081 session 4, the trainees are ready to be involved in mission-specific training and/or other  
1082 field trips to help maintain their skills.

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Topic	Training objectives – “the trainee should learn how to”
Geology	<ul style="list-style-type: none"> <li>• Recognise, describe and generally classify rocks and minerals common on Earth, the Moon, Mars and asteroids</li> <li>• Identify the major constructional (tectonic and volcanism) and destructional (erosion and weathering), exogenous and endogenous forces on Earth</li> <li>• Recognise and classify selected Earth features including constructional and erosional landforms</li> </ul>
Astrobiology	<ul style="list-style-type: none"> <li>• Recognise and describe potentially habitable geological environments</li> <li>• Note, document, and describe features that could be of interest for geo-microbiology</li> <li>• Work using methods that reduce contamination of samples</li> </ul>
Planetary Science	<ul style="list-style-type: none"> <li>• Recognise and describe the general geological characteristics and history of the Moon, Mars and asteroids</li> <li>• Compare field observations of geological features on Earth with Mars, the Moon, and asteroids</li> <li>• Derive how planetary parameters (gravity, internal structure, environmental conditions, etc.) contribute to producing different types of landforms</li> </ul>
Field and science operations skills	<ul style="list-style-type: none"> <li>• Use satellite images and maps, plan geological traverses, understand scientific questions</li> <li>• Identify interesting sampling sites from planned traverses on maps and satellite images</li> <li>• Identify relevant geological features while following a pre-planned route in the field</li> <li>• Efficiently describe the geological context and detailed features at large and small-scales along a traverse</li> <li>• Perform rapid, on the spot decision-making regarding prioritisation and sample collection</li> <li>• Collect rock and soil samples according to their geological description, while preventing contamination of the samples</li> <li>• Properly document sample collection sites</li> <li>• Adapt traverse strategies based on new information (apply flexexecution)</li> </ul>

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1098 Table 1. PANGAEA training objectives that should be achieved by the trainees after  
 1099 receiving all the lessons and performing all exercises and field activities.

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