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► To cite this version:

Francesco Sauro, Samuel J Payler, Matteo Massironi, Riccardo Pozzobon, Harald Hiesinger, et al.. Training astronauts for scientific exploration on planetary surfaces: The ESA PANGAEA programme. Acta Astronautica, 2023, 204, pp.222-238. 10.1016/j.actaastro.2022.12.034 . hal-04176495

HAL Id: hal-04176495

<https://hal.science/hal-04176495>

Submitted on 3 Aug 2023

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1 **Training astronauts for scientific exploration on planetary** 2 **surfaces: the ESA PANGAEA programme**

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19 20 21 **Abstract**

22 Future human missions to the Moon and Mars will require astronauts to perform science-
23 focused surface exploration in complex geological environments. However, the scientific
24 expertise required for these activities is uncommon in the astronaut corps. PANGAEA
25 (Planetary ANalogue Geological and Astrobiological Exercise for Astronauts) is a field
26 training course of the European Space Agency (ESA) that seeks to address the topics of
27 geological and astrobiological planetary exploration. The course intends to impart the
28 essential basic theoretical and practical knowledge of geology and astrobiology, in order
29 to prepare astronauts for advanced mission specific training. Significant focus given to
30 skills in areas relevant to future missions, such as scientific decision-making, working
31 with a remotely located science team, and efficient documentation. For this reason,
32 although portions of the course are taught in classrooms, developing independent field

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.

54

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 3rd and
621 4th 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 Concepción, 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.

983

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**

1008

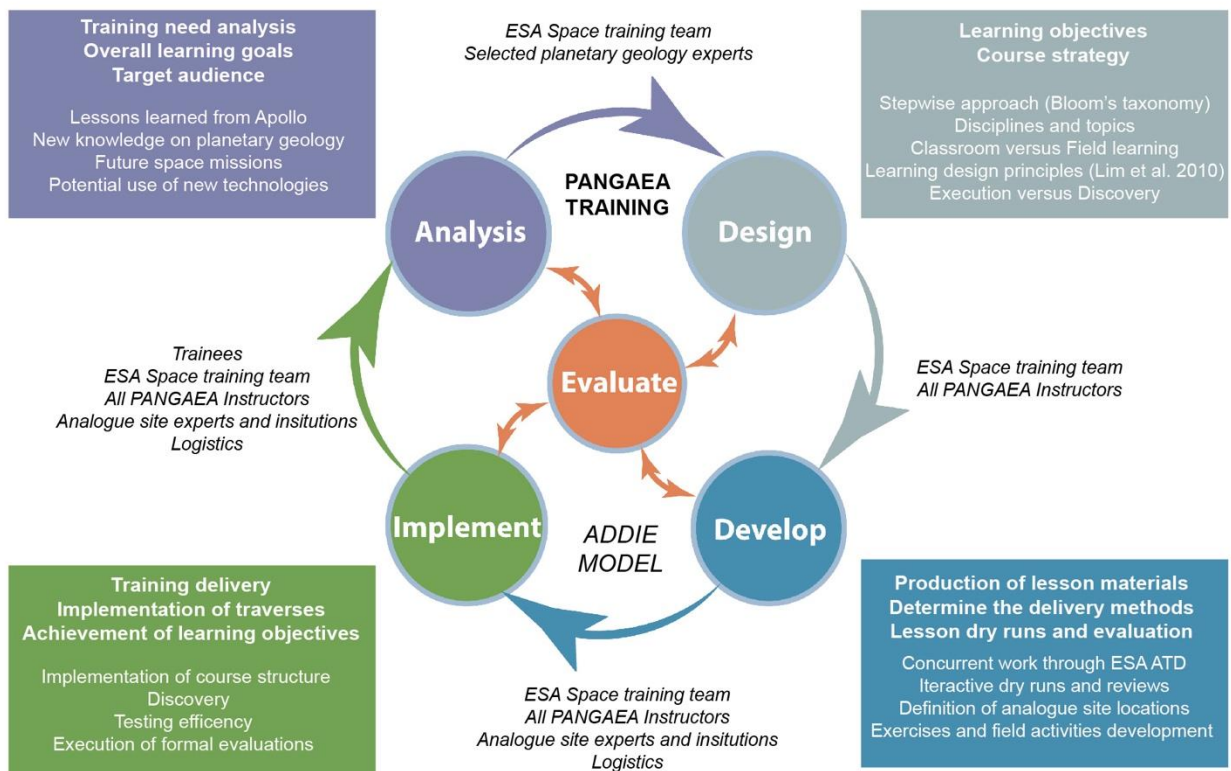
1009 PANGAEA would not be possible without the significant support offered by local
1010 authorities at each field location. We would like to thank Geoparc Bletterbach for its
1011 support in accessing Bletterbach Canyon, Ries Krater Museum for its the gracious hosting
1012 and use of facilities, and Geopark Ries for its support in accessing locations in Ries Crater.
1013 In Lanzarote, we would like to acknowledge the help and support provided by Cabildo
1014 Lanzarote, Timanfaya National Park and Casa de los Volcanes, which enabled us to access
1015 essential field sites.

1016 Our gratitude goes also to all the interns and ESA young graduate trainees that have been
1017 supporting the PANGAEA training activities. A special thanks to Prof. Stefano Debei from
1018 CISAS-University of Padova, in remembrance of his kind support for the first
1019 implementation of the training in 2016.

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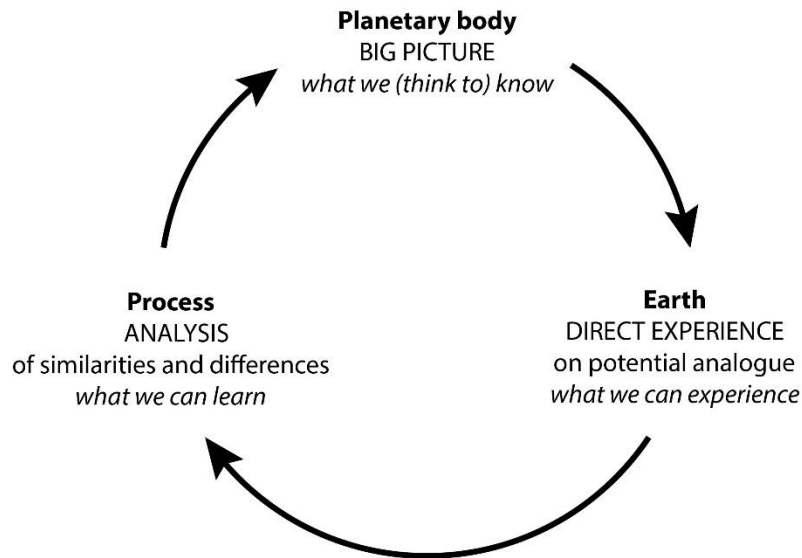
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Fig. 1. Application of the ADDIE model to the construction of the PANGAEA training. Actions and main actors are specified for each step of the model.



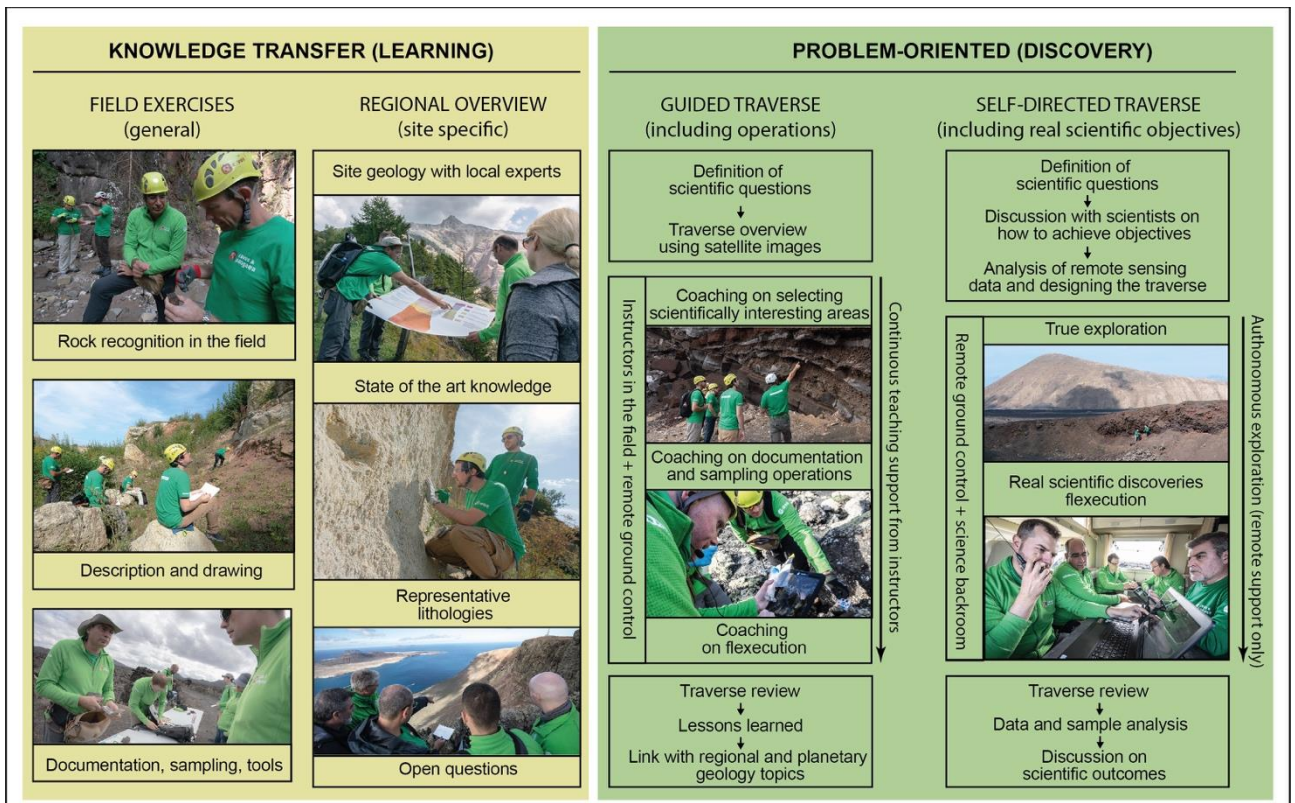
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1031 **Figure 2:** The “cognitive loop” used to design the PANGAEA training strategy, based on
 1032 that typically used in planetary geology research.

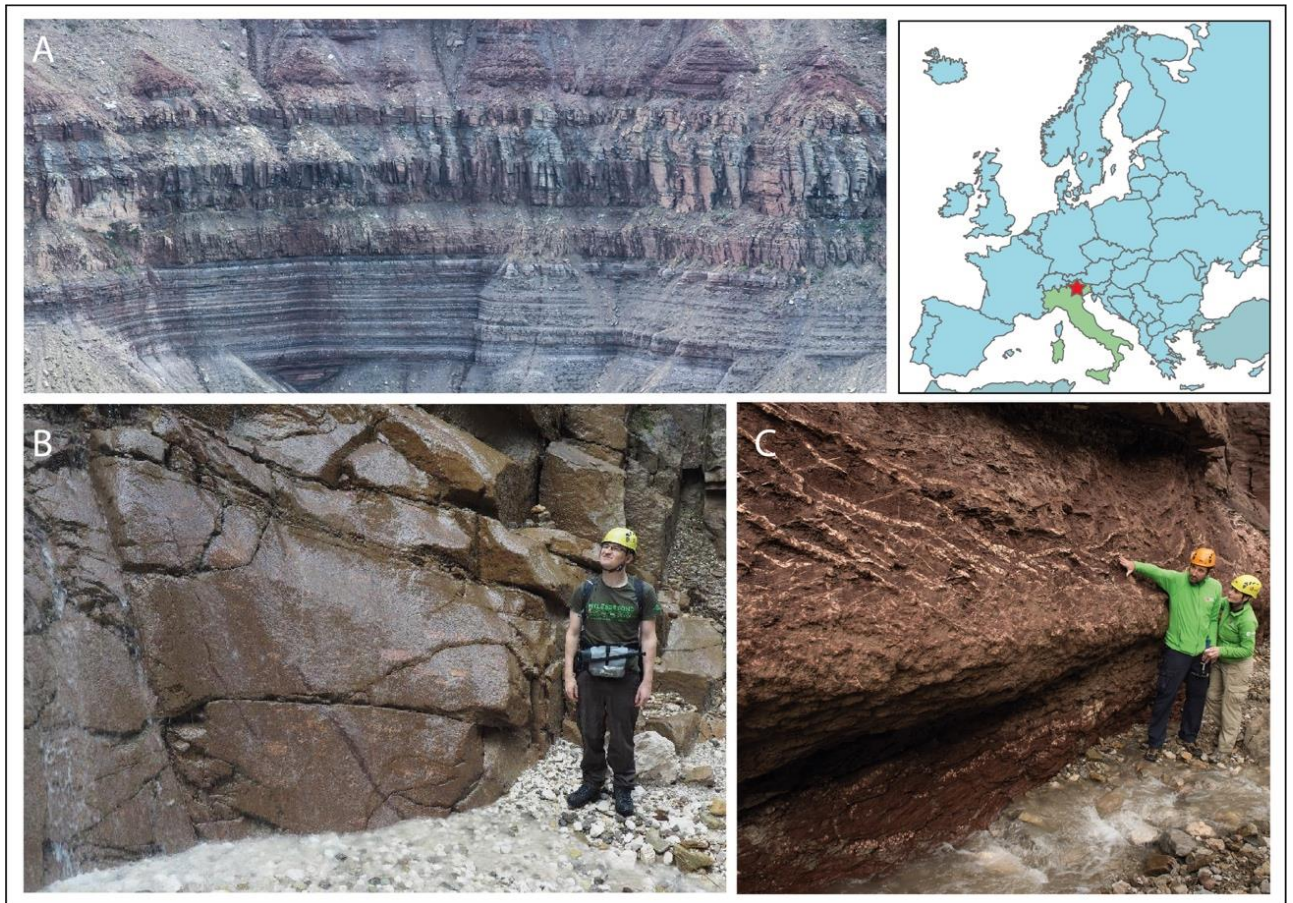
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1036 **Figure 3:** Different types of field exercises and activities performed during PANGAEA,
 1037 divided between “knowledge transfer” and “problem oriented” methodologies.



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.

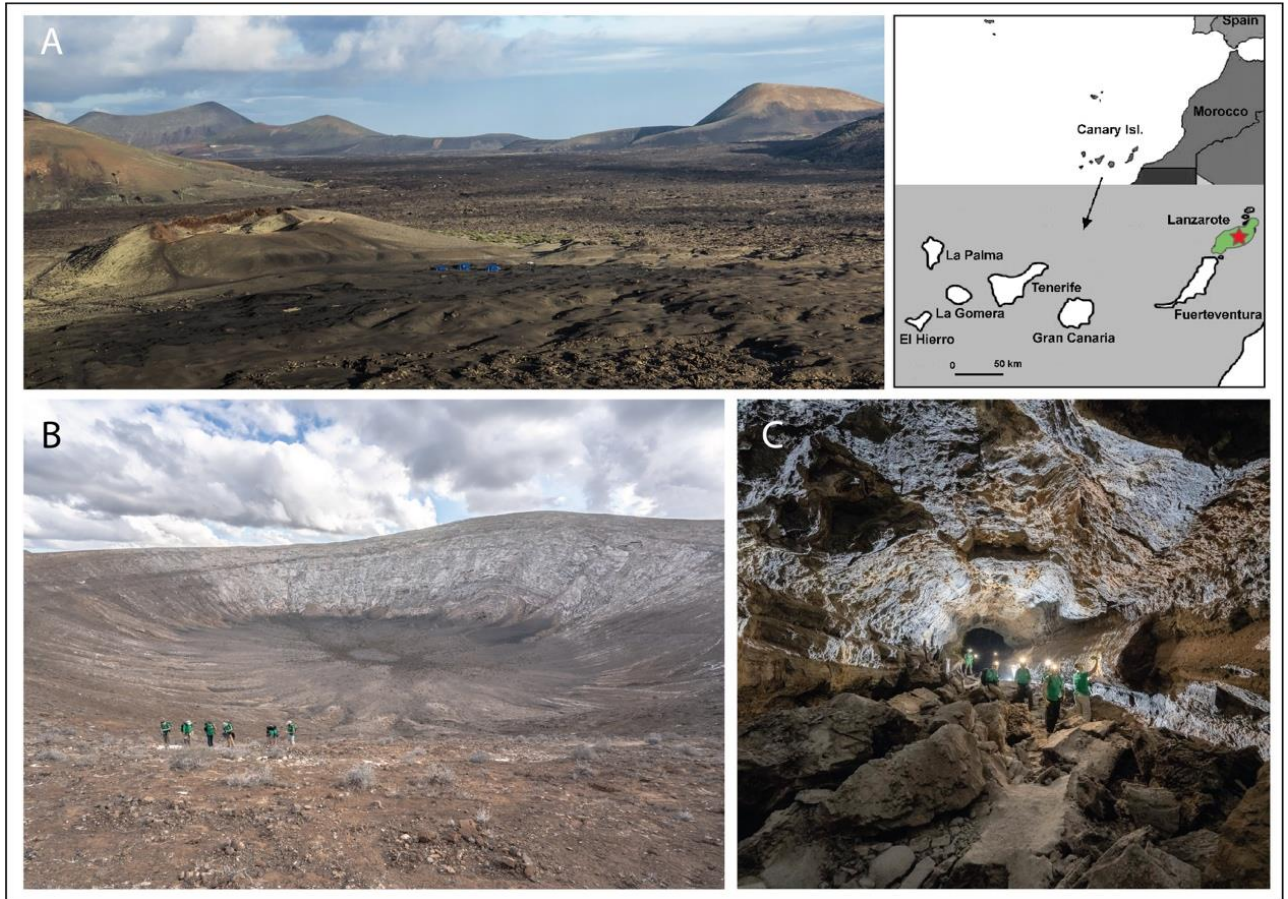
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1048 Figure 5. Overview of the Ries Impact Crater analogue site (Nördlingen, Germany): A)
1049 the trainees observing a crystalline mega-breccia block in the area of the crater inner
1050 ring; B) Suevite fall-out deposits covering the chaotic terrigenous 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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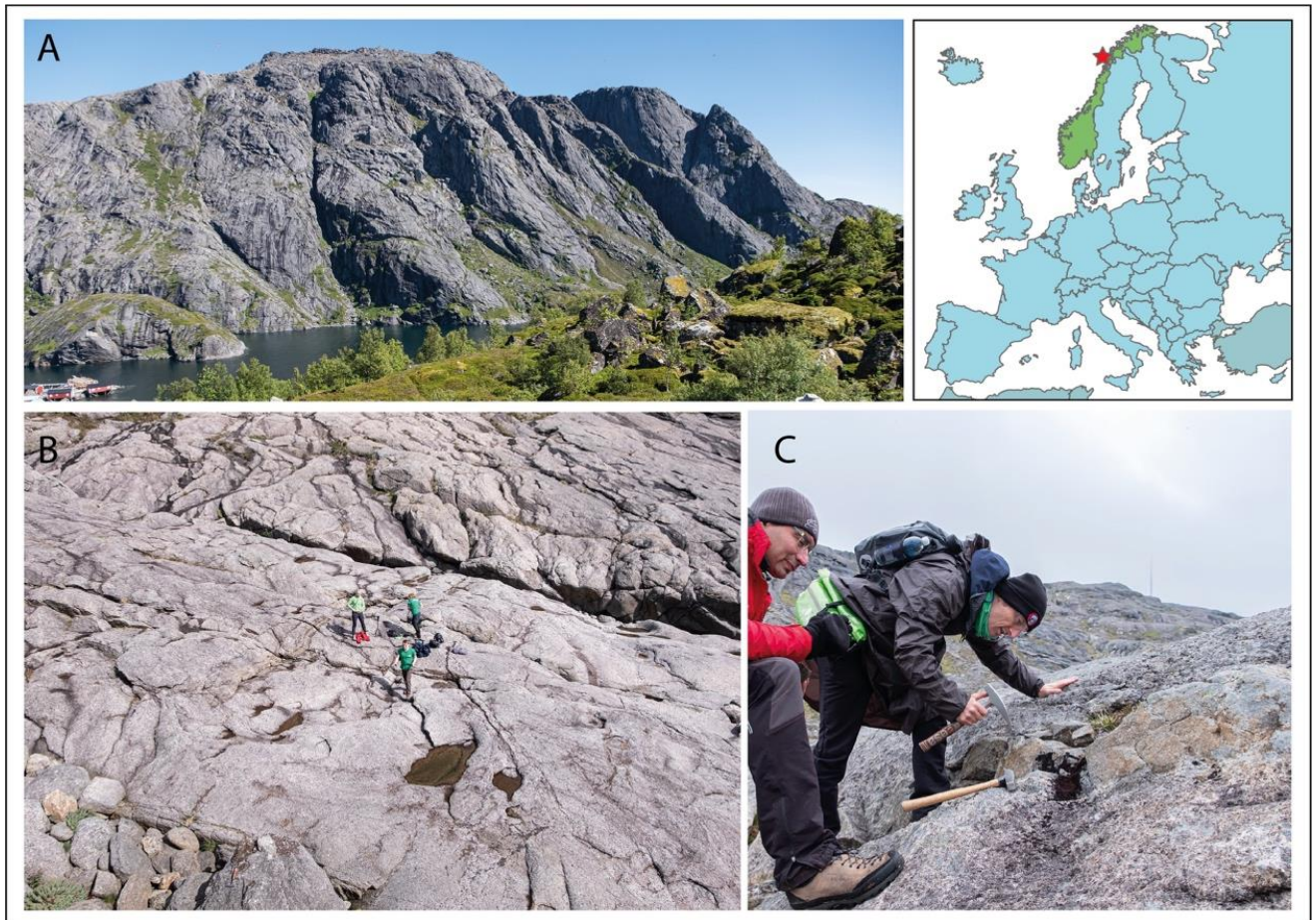


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1056 Figure 6. Overview of the Lanzarote analogue site (Canary Islands, Spain): A) Lanzarote
1057 is a volcanic island with several different volcanic edifices, lava flows, and pyroclastic
1058 deposits, with ages spanning from 7 million-years-old 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.

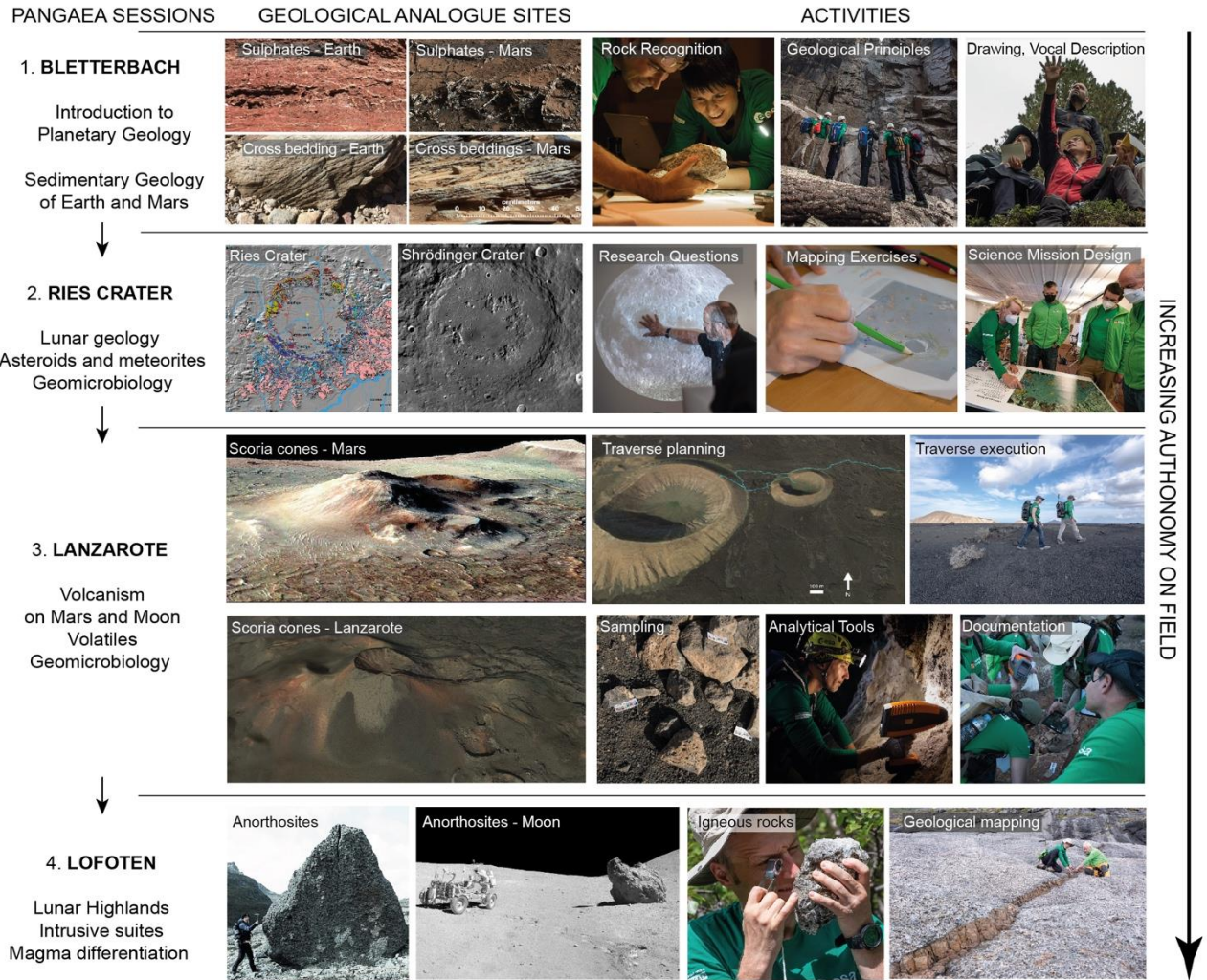
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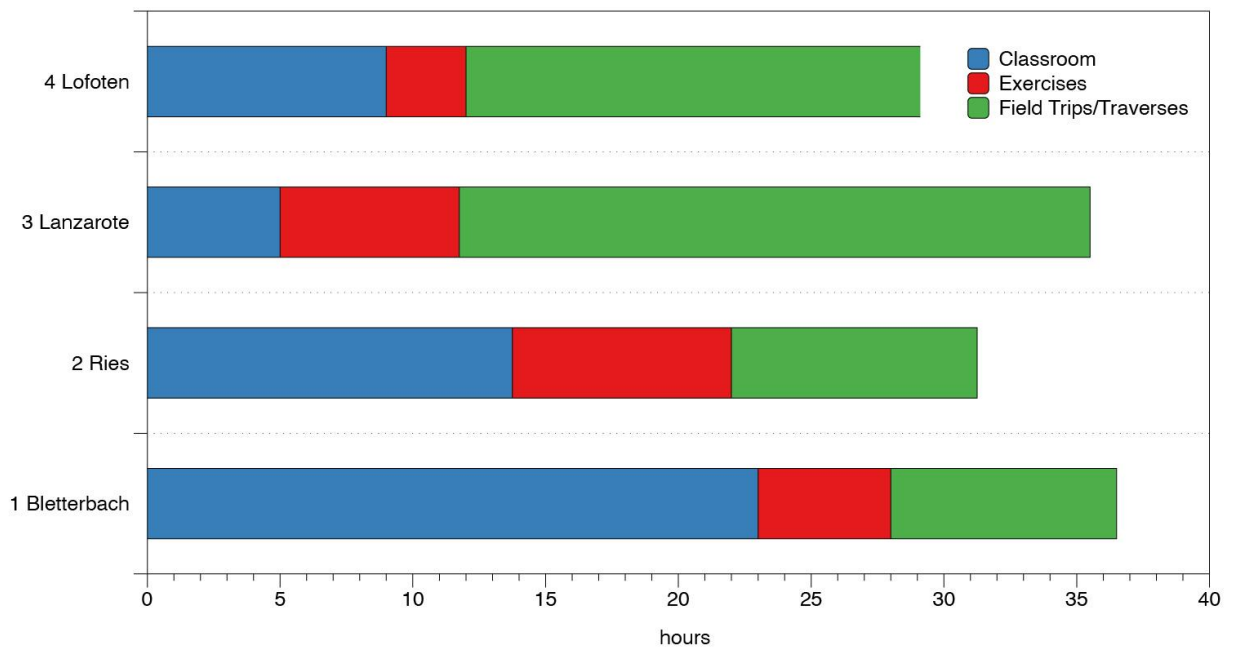
1066 Figure 7. Overview of the Nusfjord massif analogue site (Lofoten, Norway): A) the
1067 anorthositic massif behind the village of Nusfjord represents one of the best analogue
1068 sites in the world for studying the lunar highlands; B-C) glacial erosion has left the
1069 intrusive rocks highly exposed, 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"> • Recognise, describe and generally classify rocks and minerals common on Earth, the Moon, Mars and asteroids • Identify the major constructional (tectonic and volcanism) and destructional (erosion and weathering), exogenous and endogenous forces on Earth • Recognise and classify selected Earth features including constructional and erosional landforms
Astrobiology	<ul style="list-style-type: none"> • Recognise and describe potentially habitable geological environments • Note, document, and describe features that could be of interest for geo-microbiology • Work using methods that reduce contamination of samples
Planetary Science	<ul style="list-style-type: none"> • Recognise and describe the general geological characteristics and history of the Moon, Mars and asteroids • Compare field observations of geological features on Earth with Mars, the Moon, and asteroids • Derive how planetary parameters (gravity, internal structure, environmental conditions, etc.) contribute to producing different types of landforms
Field and science operations skills	<ul style="list-style-type: none"> • Use satellite images and maps, plan geological traverses, understand scientific questions • Identify interesting sampling sites from planned traverses on maps and satellite images • Identify relevant geological features while following a pre-planned route in the field • Efficiently describe the geological context and detailed features at large and small-scales along a traverse • Perform rapid, on the spot decision-making regarding prioritisation and sample collection • Collect rock and soil samples according to their geological description, while preventing contamination of the samples • Properly document sample collection sites • Adapt traverse strategies based on new information (apply flexexecution)

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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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