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Speleology as an analogue to space exploration: the ESA CAVES training programme

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Abstract

Caves remain among the most challenging exploration frontiers on planet Earth. They are difficult to access, present a range of unique and unusual environmental characteristics, and can only be mapped through direct human exploration. These challenges and several environmental factors specific to caves mean that speleology shares several analogies with space missions. For humans, cave exploration imposes isolation, confinement, minimal privacy, technical challenges, limited equipment and supplies, a sense of disconnect from the surface and regular life, a lack of diurnal cycles, and the constant presence of risk. As many of the same challenges are imposed on humans during space exploration, in 2005 the European Space Agency (ESA) began examining the possibility of using natural cave systems as a platform for astronaut training. These efforts resulted in a new ESA training programme named CAVES (Cooperative Adventure for Valuing and Exercising human behaviour and performance Skills) being launched in 2011, involving astronauts from partner space agencies. The primary objective of this training is to enhance astronaut individual and team performance and behavioural competencies by exposing them to the challenges of a real mission into an unknown and dangerous environment. To achieve this, the course's training activities are based around a real scientific and technological programme focused on cave science. Many aspects of the location and course content have been designed by a team of behavioural experts, scientists, trainers, operations engineers and speleologists with the support of caving organizations and schools. CAVES training events leverage cave exploration to create situations that are analogues to spaceflight in terms of safety protocols, perception and management of risk, crew composition and role assignments, group living, isolation, and confinement. In addition, these

courses provide an opportunity for astronauts to experience spaceflight-like or relevant operations, science, equipment testing, and exploration, in preparation for future planetary endeavours. The scientific, exploration and equipment testing aspects of the course are real (not simulated). This ensures that these activities provide benefits to the speleological and scientific communities, whilst guaranteeing the realism of these activities for training purposes. During six editions of CAVES, from 2011 to 2019, 34 astronauts from 6 different space agencies (ESA, NASA, JAXA, ROSCOSMOS, CSA, and CNSA) have taken part in the training. The CAVES training programme has been recognized by all participant astronauts and, in particular, by those who have travelled to space, as one of the best space analogue training opportunities available on Earth. The learning outcomes are applicable to both current and future orbital missions, as well as surface and subsurface missions to other planetary bodies.

Key words: astronaut training, cave science, human spaceflight, space analogue, planetary exploration, human behaviour and performance, isolated confined environments, technological testing

1. Introduction

Training astronauts for long duration missions is highly important to space agencies, not only for current and future orbital activities (e.g., International Space Station – ISS), but also for future human and robotic planetary surface exploration (i.e. Moon and Mars). Preparing for expeditions to other planets requires the extreme environmental and situational characteristics of space to be replicated on Earth in analogue environments where stressors similar to those experienced in long duration spaceflight can be safely and repeatedly encountered [1]. Using terrestrial extreme and/or unusual environments as space analogues [2] can provide predictive insight into the multitude of factors that impact group performance, health, and well-being in challenging environments [3]. In order for training in analogue environments on Earth to be valuable for improving human performance and team processes on long duration space missions, they must combine realistic perceived risks, whilst enabling the execution of complex technical tasks, group work, and prolonged cohabitation in isolated and/or confined settings. Achieving this requires the identification of suitable terrestrial analogue environments and the design of high-fidelity training courses/mission scenarios. This should enable valuable and transferable experiences to be gained from working within an environment, as opposed to simply experiencing an environment's characteristics, as proposed by Suefeld [4]. Presently, only a small number of high fidelity space analogue training platforms are available and suitable for astronaut training. These programmes provide combinations of behavioural stress, technology use, safety protocols, scientific objectives, and operationally realistic mission concepts within alien environments, to replicate the conditions of long-term space exploration. The most established of these organised by NASA is NEEMO (NASA Extreme Environment Mission Operations), taking place in the underwater base "Aquarius" in Florida [5]. NEEMO incorporates technological, scientific as well as operational analogies, within an environment and habitat very relevant to orbital space missions, to provide astronaut crews with a highly valuable training experience. It also provides a convincing and realistic testbed for testing technologies and operations being developed for future space missions.

In 2005, ESA began to study cave environments as a potential platform for creating space analogue missions [6]. Early on, it was clear that speleological exploration and cave research had a lot in common with current and future space activities, including not only technical progression protocols and science operations, but also individual and team behavioural dynamics. Speleology, along with ocean exploration, is one of the last frontiers of exploration on Earth [7]. Extended cave expeditions require complex logistics, detailed planning, multidisciplinary expertise, detailed safety protocols and teamwork [8]. The challenges and dangers are real, resources are limited, and travel time through a cave system is comparable to human space missions (about eight hours of daily activity, multiple days from "launch" to reach base camp, week-long expeditions). Rescue operations in case of emergencies are also very complex and slow, requiring coordination amongst trained personnel with complementary roles using highly specialised equipment and communicating via audio channels.

These analogies between space and cave missions were leveraged to create an astronaut training concept called CAVES (Cooperative Adventure for Valuing and Exercising human behaviour and performance Skills), which was first implemented in 2011. Nine years and six editions after its first implementation, CAVES has become an established analogue training course for astronauts from many international space agencies. In this article, we describe the main analogies developed in this course, its philosophy and structure, as well as the general feedback from the astronauts who have participated, and its evolution over time.

2. Speleological expeditions vs spaceflight

2.1 Characteristics of the cave environment

More than 50,000 km of caves have been explored on Earth in the last forty years, with geologists estimating that over a million more are still waiting to be discovered and explored

[7]. Caves develop mainly in karstic areas, where infiltrating water dissolves soluble rocks such as limestone, dolostone, gypsum, to create extensive networks of voids underground [9]. However, caves can also be found in volcanic areas (lava tubes and evacuated magma chambers)[10], in extremely resistant lithologies such as quartzites [11], in salt deserts [12] and inside glaciers (ice caves due to melt [13]). Although caves can be found in a wide range of environments, they share some general characteristics, such as complete darkness. Caves can be complex labyrinths of horizontal, vertical, and inclined passages spread across different levels, requiring the use of climbing skills, rope techniques, bolting and safety lines to traverse [14, 15]. Despite the rapid advance of technology in the past decades, there are still no technological methods available to easily map the extent of deep cave systems from the surface. This means the best way of extending our knowledge of these subterranean worlds is still direct human exploration.

Cave landscapes are varied and often challenging to navigate. Sequences of passages such as tubular galleries, high canyons, deep shafts, giant chambers, lakes, waterfalls and extremely tight spots can all be found in a single cave system. Speleologists have to find their path through rock piles, or climb along walls and ledges to avoid obstacles and dangerous areas. The floor of the cave can be rocky, muddy and wet. Typically caves lack vegetation and animal life, aside from a few vertebrates (i.e., bats and swiftlets), small often specialized invertebrates, and microbial communities. Atmospheric conditions in caves can be characterized by stable temperatures, high relative air humidity, CO_2 levels frequently ten times higher than at the surface, and sometimes significant radon concentrations.

The complexity of the cave environment, combined with the darkness and lack of reference points requires caves to be carefully mapped and documented [16]. Specific equipment is of vital importance to all cave explorers, and artificial lights with long-lasting power supplies, ropes and progression tools for anchoring, obstacle negotiation and safety are all crucial to successfully navigating a cave [17]. Communication with the surface is often not possible given the often hundreds or thousands of meters of depth reached when exploring cave systems. Gas monitoring equipment is also important, with gasses like radon and CO_2 sometimes being at increased levels [18].

In general, caves are environments very different from the surface of our planet, and exploring them requires constant awareness, capacity for adaptation, training and teamwork. Humans can find cave environments uncomfortable, with (often) low temperatures and high humidity. The main forces that shape caves (solutional weathering and erosion by flowing water) can also create peculiar underground landscapes. All of this combines to give exploring natural caves a sense of exploring an extra-terrestrial landscape (see the Giant Crystal Cave of Naica as an example [19]).

2.2 Speleological expeditions

Speleological expeditions aim to explore caves that are completely unknown, or extend our knowledge of those that are partially known through discovering and mapping new branches [20]. These expeditions must cope with complex technical, logistical and safety issues, as well as incorporating documentation, and scientific research activities. Inherent in exploring new environments is the difficulty in predicting the challenges ahead. Therefore pre-planning aimed at risk mitigation, such as correctly organising the required equipment, is fundamental to successful speleological expeditions [21]. Although national caving schools normally coordinate basic and advanced training for speleologists, most of the behavioural and operational skills needed to face real speleological explorations are gained through personal experience and exchanges with fellow cavers.

Although speleological expeditions require significant organization and planning, they lack the control and procedural thoroughness that characterizes space operations. In addition, speleological personnel are usually selected based on specific technical abilities, meaning training in multidisciplinary skills and team dynamics is often limited. Field specialists carrying out scientific activities during speleological expeditions, like geologists or biologists, sometimes do not have formal technical training, and rely simply on direct experience.

To be efficient in progression, maintain a high level of safety and manage the workload effectively, speleological expedition teams are typically composed of a minimum of 3 to a maximum of 6-8 speleologists. Expeditions are carried out over hours or days, depending on the size of the cave system and the level of prior knowledge available [22]. Typically, the further the exploration teams travel from the entrance, the more complex the logistics become. This can include the need to install fully equipped base camps for longer stays or rough bivouacs to allow the team to rest for one night or just a few hours.

During long speleological expeditions, activities are usually divided into four main phases: 1) campsite/bivouac phase (rest, organisation of samples and data, equipment preparation and maintenance review and planning of exploration progress); 2) transfer and transportation of equipment to the exploration area; 3) exploration, documentation and science in the new sector; 4) return and transportation of equipment to the campsite bivouac. If the exploration area becomes too distant from the campsite (more than 8-12 hours round trip), a new advanced campsite will be set up, and the activity phases restart from the new camp. These extended explorations can last for weeks, and may eventually require multiple campsites in order to extend the exploration to extremely remote areas. Examples of these extremely complex speleological expeditions are those organized by American cavers in Huautla System in Mexico (PESH project [23]) by Russian speleologists in the deepest caves in the world in the Caucasus region [22], or by Italians in complex Alpine karst systems [15]. With this approach, it has been possible to reach depths of over 2200 meters (Veryovkina Cave in Georgia) and cave lengths of hundreds of kilometres (e.g. Mammoth Cave mapped for 663 km, or Lechuguilla 242 km in the USA) [24, 25].

Although length/depth are important when evaluating the difficulty of a specific expedition, many other factors have to be considered, such as the cave environmental conditions (temperature and humidity), morphological complexity, the presence of extremely long narrow passages, deep shafts, and dangerous or flooded areas. These elements all require different approaches, the use of specific equipment, and combine to greatly influence the time needed to traverse or explore a cave.

2.3 Spaceflight analogies in speleological exploration relevant to the improvement of human performance

Future long term human spaceflight to distant planetary objects presents many complex challenges that are currently not well understood and difficult to address [26-29]. Isolation, communication limitations including significant delays, unusual physical and social environments, and reduced privacy and personal space have always affected the wellbeing of crews during long-term space missions [30]. The extension of these conditions to increasingly complex and dangerous long-duration missions will push human crews to their limits, and could potentially result in catastrophic failures related to human error (for an overview of incidents related to human error in space missions, see [29]).

In order to prevent such incidents from happening, it is important to expose astronauts to similar stressors and challenges on Earth to improve their team work, individual performance and behavioural skills. As mentioned in the introduction, cave expeditions are safety-critical activities with limited rescue options, in which participants rely on equipment and teammates to succeed [31]. Caves are highly complex environments that present major logistical, technological, physical, and psychological challenges for those who explore them. Effectively coping with these challenges is integral to the success and safety of caving expeditions [32]. These environments provide spaceflight-like stressors (Table 1) that influence human performance and therefore operations, and have been previously identified as having uses for space analogue training [33-37] and human research [38, 39]. In the dark environment of a cave, there is a lack of sunlight exposure, meaning adaptation to artificial light is required. Similarly, disruptive conditions occur on the ISS, with its sixteen day/night cycles occurring every 24 hours, and comparable issues will also be encountered during future interplanetary travel. From a physiological point of view, the absence of natural time parameters can cause alteration of the circadian rhythms [40] and the related physiological stress this causes can be avoided only through Earth-like work/rest schedules, as implemented on the ISS.

The isolation experienced by cavers also draws parallels to that experienced in space. As discussed, it can take days of progression to reach certain parts of a cave system. This, combined with the lack of communication with the surface, instils a deep sense of isolation in participants, who are constantly aware that further progression into the cave results in increased challenges and time for rescue should it be required. Depending on the emergency, rescue progression can also be substantially longer than regular progression, particularly if an injured person has to be transported on a stretcher.

The three-dimensionality of cave passages, combined with the lack of common reference points in the shadows and darkness, makes orientation very difficult. This shares some parallels to the orientation challenges experienced during orbital Extravehicular Activities (EVA). Also, typical daily exploration activities in cave systems last around 8-10 hours, which is similar to current ISS EVAs.

Some stressors are directly related to the nature of the cave environment. Like in space, it is difficult to create comfortable conditions at the campsite. Sleeping can be uncomfortable, there is a lack of privacy, hygiene is limited, often the air is cold and the humidity is high, meaning things do not dry, and clothing rapidly get dusty or muddy. All these stressors, if not managed, can, in the long term, easily induce personal irritation, social and decision-making conflicts within the team, or even physical health issues. Other stress elements during speleological exploration activities are related to human factors and logistics. Some of these stressors can be amplified by planning a speleological expedition in a specific way. For example, communication between the cave team and the surface can be limited, imposing a high level of autonomy in the decision-making process to the exploration team. This helps force the team to develop a clear definition of tasks, roles, leadership and responsibilities. Alternating between high and low workload levels makes the group consider the distribution of work within the team, both for efficiency and safety reasons. Equipment, food, and other supplies can be limited, meaning they must be carefully managed. To keep all these factors under control, a high level of situational awareness is required from all team members to ensure that individual mistakes do not propagate into serious issues that could compromise safety or mission objectives.

The ability to derive salutogenic effects from the stresses encountered in extreme and unusual environments is likely to be associated with, or even contingent upon, the employment of coping strategies that allow the stressor to be either successfully resolved or endured. MacNeil and Brcic [32] suggest that positive reappraisal could be part of a mechanism by which stressful encounters (or their associated memories) catalyze salutogenic effects. The CAVES training is therefore carefully designed to balance imposing stressors on particpants, with providing ample oppertunities for them to be managed and addressed as a team.

3. ESA CAVES training: history and location

The idea of using caves for training of astronauts was conceived at ESA in 2005, after an early test implementation of astronaut operational team training courses in the carbonate mountains of Supramonte in Sardinia, one of the most important cave areas of Italy. The exploration of a local cave system was introduced during a dry run in 2008, responding to the requirement of the course to increase the modulation of stress, the dependency on safety equipment, to have meaningful role assignments, and higher levels of decision making autonomy and team interaction during all operational activities. The goal was to create a framework within an existing technical and scientific activity in an extreme environment, which requires complex problem solving in unfamiliar situations, where a high level of autonomy is required, and the consequences of human error are perceived as real risk [6, 32]. During this early phase, the main structure and foundations of the CAVES course was formulated. Here, it became clear that the environmental challenges and the complex technical operations and safety rules required to progress in caves were promising for a new spaceflight analogue. However, it was also clear that the cave was just a "container", in which team processes, speleological exploration and scientific activities needed to be introduced and integrated into space-like mission operations. In order to address this, ESA training experts involved experienced speleologists and cave scientists to help create a speleological expedition that offered realistic scientific and exploration objectives. Having real science and exploration objectives was considered key to the expedition being experienced by trainees as a spaceflight analogue, since in space astronauts have to perform real exploration, documentation, and scientific experiments (Fig. 1). These objectives also ensured that high levels of motivation and engagement were created and maintained not only for the astronauts participating, but also for the scientists and speleologists involved. The caving progression techniques and tools were also adapted by the speleologists, in consultation with EVA specialists, to make them more EVA-like (Fig. 2), always ensuring and often improving the level of safety.

This speleological framework was then used to construct a space-mission analogue expedition based on structured team processes. An operationally relevant mission concept was created and typical spaceflight operational elements added, such as procedures, activity timelines, safety rules and emergency protocols, stowage notes and other space-like configurations.

After this development and preparation period, the first edition of the CAVES course took place in 2011, with a crew of five astronauts from ESA, NASA, ROSCOSMOS and JAXA. The following five editions also involved CSA astronauts, and during the 2016 course, a Chinese astronaut from CNSA participated. In total, 34 astronauts have been trained in six CAVES training courses over the past nine years (Table 2). While the general structure of the course has remained the same since the first edition, the scientific objectives and technology testing have evolved significantly over the years. Additionally, the application of space-like procedures and timelines within the expeditionary framework of CAVES has been improved and more rigorously implemented in accordance with feedback from the astronaut crews.

The first five editions of CAVES took place in the Valley of Lanaittu in the Supramonte limestone massif of Sardinia (municipalities of Oliena and Dorgali, Italy) [41]. The cave used for the course's main speleological expedition (see Section 4.2) was Sa Grutta, a huge underground system still being explored. The smaller Tiscali, Sos Jocos and Sa Oche caves were also used for the preliminary training phase of the course, between them offering increasing complex representative cave environments for the astronaut participants to learn skills and develop a high level of autonomy for the mission execution. All classroom lessons and preparatory activities were carried out in local mountain huts, re-arranged as training facilities (Budorrai, PICAVE).

In 2019, the course changed locations to the "classical karst" region between Italy and Slovenia [42]. Here, the course makes use of facilities provided by Škocjanske Caves Regional Park, with field activities happening in several caves along the underground course of the river Reka (also known as Timavo), both in Italy and Slovenia.

4. CAVES concept and training structure

Analogue team training for human spaceflight needs to be based on a well-defined concept of operations [43], and provide real challenges, stressors, and realistic science and exploration programmes. The CAVES training is structured as a full exploration mission divided in three main phases. These three phases are similar to those used in a typical human space mission, and all occur in a single event lasting sixteen days. The phases are: 1) a pre-mission training and preparation phase, 2) the "extended cave exploration" mission, 3) a post-mission phase, where the data and results are collected in reports and discussed with the science and the mission support teams, and debriefings are conducted with all involved support personnel.

4.1 Pre-mission: training phase

The pre-expedition phase (9 days) is fundamental to the success of the course, and enables the crew to conduct a safe and efficient mission in the cave system. Training activities include classroom lessons covering mission objectives and operations, safety, science and documentation, as well as an overview of the results obtained by previous CAVES crews in order to provide context on the current state of exploration. In this phase, the development of team processes is embedded into the training, which is constructed to promote team cohesion and cooperation, and is justified to the trainees by the technical and scientific requirements of the upcoming expedition, and reinforced by role modelling by the training team. The crew, with the support of scientists and mission support engineers, are trained in how to conduct science experiments and technological tests using exactly the same kits and procedures that will be used during the extended exploration in the cave. Documentation tasks, such as photography and mapping, are explained and demonstrated in the classroom, and later performed in a real cave to ensure that the complexities of working in a dark underground environment are encountered and understood during the preparatory phase. The pre-expedition phase has been designed, developed and implemented following the same structured approach (Instructional System Design) applied by ESA to all its spaceflight training curricula.

Aside from the training on specific activities, the pre-mission phase is also dedicated to familiarising trainees with the subterranean environment through visiting various caves with increasing complexity and difficulties. Astronauts are trained in rope progression techniques and safety rules. This technical training resembles skills and protocols that are required to move and operate during EVAs, with reduced field of view due to darkness, strong shadowing, three-dimensional progression paths, difficulties in the perception of obstacles and distances, and keep-out and no-touch zones. During the training, technical instructors evaluate the astronauts' performance in progression techniques to check if their acquired skills fully satisfy safety protocols.

During the pre-mission phase, responsibilities and roles are assigned to different crew members. The main roles are: Crew Commander, Campsite Manager, one or two Science Engineers with different operational tasks, Survey Engineer, and Photography Engineer.

Additional supporting roles are also required, depending on the mission phase and activities, such as flashlight support for photography, IT & communication management, video operation, and scouting. This role assignment is an important element of the behavioural training, but very different to that experienced in a space mission, as in CAVES roles are self-assigned by the crew, an activity that requires a high level of cooperation and understanding of individual preferences and ambitions, as well as an organised team decision, the consequences of which will resonate throughout the expedition. Specific needs on role exchanges and combinations of supporting roles are imposed either by specific pre-agreed rules, or by the construction of the activity timeline, which organises the crew's daily tasks. Although each role carries the overall responsibility for certain objectives, such as specific types of data collection, tasks can be delegated within the team.

The first opportunity for trainees to exercise their new crew roles comes when they are involved in the logistical preparation of the mission. The astronauts must choose food types and quantities, organize the resupply of equipment, and prepare their personal and team kits for transportation inside the cave. The latter activities require a high level of team coordination and decision-making, and provides an excellent opportunity for the crew to work on communication and leadership/followership in their new roles, whilst the instructors observe. Training throughout this phase is performed equally for all trainees until they have selected a prime role for the expedition. This means the last training conducted is role and equipment specific. Supporting roles and delegation within the team also requires on-the-job coaching by peers during the mission. This enhances the building of team processes, reinforced by behavioural exercises such as feedback and debriefings interspersed and embedded within the science, operations and technical training.

In this pre-mission training phase, the astronauts also familiarise with the support team that will accompany them throughout the real mission. This includes a Medical Doctor, three Speleological Instructors of which two are also Safety Supervisors and one the Course Technical Director, and the Behavioural Facilitator. The Course Technical Director has the role of supervising all technical and safety issues related to exploration and science. The Behavioural Facilitator supervises the execution of the mission and the team dynamics, interacting with the technical team and the remotely located mission support team and modulating the level of stress to ensure the achievement of mission goals and behavioural objectives as well as the team well-being.

4.2 Mission phase: the extended cave exploration

Once the pre-mission training is finalized, the crew is ready to enter the main cave system for the mission phase. This consists of an uninterrupted six-day long underground expedition divided in three main stages: 1) transfer from the cave entrance to the campsite, 2) daily exploration of the cave system from the main campsite to address exploration, documentation and scientific objectives, 3) transfer from the campsite back to the surface.

Phase 1 and 3 are the most delicate in terms of crew safety. In terms of emotional impact, these phases are analogous to the launch and entry phases of ISS missions and EVA activities. The transfer from the cave entrance to the campsite is also the most demanding in terms of technical requirements. In the Sardinian cave used for the first editions of the course, the path included a 700-meter long *via ferrata* over a fifty-meter deep canyon. In the Slovenian classical karst cave used in 2019, the astronauts had to descend a 200-meter deep vertical shaft with several technical passages (belays, deviations and traverses). As well as providing physical and technical challenges, these major obstacles help to provide a perception of remoteness and isolation from the outside world to the trainees. During the descent, the crew moves autonomously using the skills acquired during the training, but for safety reasons they are closely supervised at a one-to-one ratio by technical instructors.

Once the crew arrives at the main campsite, their mission begins. To kick this off, a formal leadership and campsite management handover between the support team and the crew is conducted. From that point on, for the rest of the expedition, it is the crew's responsibility to: 1) ensure completion of mission goals, which requires them to complete activities in a partially timelined list, including daily reporting back to a remotely located "ground" team through established communication lines, 2) maximise crew safety, efficiency and wellbeing, 3) establish and revise team processes and rules, conduct critical analysis of individual and team actions through debriefings, and establish team awareness for informed decision making.

Throughout the expedition, the support team keeps situational awareness to ensure safety, and is prepared to manage real emergencies. However, nominally they are required not to interfere with the crew, unless so instructed by the Behavioural Facilitator.

During the daily reporting, the crew commander must inform the mission support team about the status of the crew and the planned activities for each day. This is conducted at fixed times in the morning and evening, partially replicating a typical ISS Daily Planning Conference (DPC). Unlike on ISS, this DPC is the sole responsibility of the crew commander, monitored (directly or through review of the communication) by the Behavioural Facilitator. This helps highlighting and correcting potential weaknesses in team processes. It serves the purpose of requiring the commander to ensure clarity in their briefings to the crew, and to request, collect and thoroughly understand and then transmit reports on daily progress by team members to mission control. This process is also intended to enforce leadership within the team, which is somewhat limited by the short duration of the expedition and the unfamiliarity of the commander with the environment.

The mission support (ground) team is composed of several positions. The CAVECOM is responsible for the communication with the crew during the expedition, while the Mission Director is responsible for the overall management of the surface team. Both are supported by a system engineer, who manages the technical side of the communications infrastructure and data transmission, and a backroom scientist, who examines the science and survey data collected by the crew, and provides feedback as required. A surface medical doctor is also available (in addition to a doctor in the cave who handles any emergencies on site), to advise on any minor medical issues as required. In addition, several personnel from the cave and logistics team are available around the clock to assist in logistical matters, and provide information to the Mission Director on various aspects, such as how surface weather conditions will affect the conditions in the cave.

To keep the mission support team up to date on the cave team's progress, the topographic maps and scientific data gathered during the day are transferred to them every evening. The ground team then checks the data and if necessary plans corrective actions for the following days (in 2019 data were transferred through the Electronic Field Book (EFB) system). Whilst exploring during the day, communication with the ground is limited to tests of wireless communication devices (TEDRA, XFerra [44]). Only a small subset of the data collected during a mission is recorded on paper for simplicity. Data loggers, topographic surveys and photos are mainly downloaded to electronic storage devices (laptops, EFB) for later transmission to the surface from the base camp.

A typical exploration day (Fig. 3) starts with a crew briefing by the commander, providing a confirmation of the activities planned in the timeline and informing the team about updates or modifications requested by ground during the morning DPC. At this point, the crew will have already have prepared all the progression, science and documentation equipment for the day: an activity timelined for the early morning. Following this early preparation, each member dons his/her individual technical gear. The progression from the campsite to the exploration area can take hours. In two editions of CAVES, it has been necessary to install an advanced bivouac camp where the crew could rest one night before advancing further to cut down travel times. However, in order to use the advanced bivouac, the crew is required to check some safety constraints, such as the ability to establish a successful communication by wireless cave radio

(XFerra, TEDRA) with the ground team. During their transfers between sites, the crew is asked to carry out scientific experiments or sampling in specific spots as indicated in their activity list and on the map, or by identifying potentially interesting new sampling sites.

When the crew reaches an unexplored area of the cave that has been not reported on the map of the previous crew, it is mandatory that they begin surveying and documenting the new area.

It is worth noting that the organization of activities during the exploration is subject to flexible execution, and has to be planned around unexpected terrain difficulties, the physical state of the crew, safety issues, and other obstacles or challenges the crew must deal with. It is the responsibility of the crew commander to balance achieving established daily goals with crew safety and wellbeing. The commander and team's lack of experience with caving means avoiding group pressure and risk-taking behaviours requires high levels of coordination and open communication amongst all members of the crew. Additionally, high levels of situational awareness from the Behavioural Facilitator and safety teams is required during critical passages and when the crew starts to become fatigued.

During exploration, the crew works under a structured operational method to ensure they perform science and document the cave system efficiently and accurately. Typically, the team is split into a scouting and science team, and a documentation and survey team, each with different roles and associated equipment. The science team goes ahead led by the commander and scouts the cave, selects science sites and performs experiments. The survey and photo team follows, and records and documents the dimensions of the cave system and takes photographs. A set of reflective markers are distributed between the two teams to leave indications of where scientific and survey information has been collected. These markers are removed at the end of the expedition by the support team to ensure the cave system remains pristine.

A typical daily exploration activity lasts around 8 hours. At all times, safety remains a priority over other activities, and the crew must return to the campsite in time for the evening DPC, for daily behavioural debriefings and to organize the data collected during the day, as well as for a daily routine of campsite science and equipment management. It is responsibility of the crew commander to ensure that these rules are respected for crew safety and comfort, regardless of the team's desire to continue exploration or other conflicting objectives.

After four days of exploration and activities, preparation for return to the surface begins, and the campsite manager again takes an important role in coordinating the logistics of equipment preparation for an organised resurfacing. The leadership is handed back to the support team on the exit day, and the crew transfers back from the campsite to the entrance (exit) of the cave. This is another critical phase, as the crew is often very tired. Finally, the mission ends with the exit of the entire crew and support staff from the cave. It is interesting to note that the overwhelming visual and olfactory sensations associated with the re-surfacing from darkness and lack of vegetation has been compared by experienced spacefarers as being similar to the exit from a spacecraft after its return to Earth.

4.3 Post-mission phase: reporting phase

Following the conclusion of the mission, each member of the crew reviews the data collected ready to provide the scientists and support engineers with an exhaustive report on each experiment and test. They must also review the survey and photography results, and detail the characteristics of the newly explored areas of the cave. These data are organized in a final document (and accessed through an EFB report since 2019) which forms the starting documentation for the mission of the following crews (e.g. the last point mapped by the crew will become the starting point for the crew of the next expedition). The commander and campsite manager are also responsible for preparing a handover report to the next crew, with their suggestions and lessons learned. This is very similar to the handover b/w ISS crews, but in written form, since the next crew will not be nominated for another few months. It is during this phase that peer feedback is also organised, and final behavioural debriefings are conducted, with the goal to ensure the transfer of learning from the expedition to future space activities.
In this phase, the crew also provides feedback to ESA about the course, with specific focus on the main analogies being identified, but also on how to improve the overall relevance of the course, based on their collective experience, to best help prepare astronauts for current and future spaceflight.

5. Human Behaviour and Performance approach in CAVES training

Behavioural and performance issues for isolated, confined teams in future planetary missions are not well understood, and can have significant negative impacts on mission success [45]. Training together as a team in analogue environments can help trainees understand, identify and mitigate these issues, allowing them to create their own toolbox of flexible coping strategies to be effectively used during future spaceflights [4, 46, 47].
During spaceflight, different cultural approaches to leadership, information-sharing, decision-making and teamwork are employed. These can change between different mission phases and with different vehicles, but must always respect the established codes of conduct, hierarchies, mission rules and procedures. Whilst not all speleological expeditions have such a structured approach to team processes [32], the CAVES programme builds upon the ISS HBP (Human

Behaviour and Performance) competency model team training objectives [48, 49] for improving behavioural skills (see tables in Supplementary Materials). Throughout the training, the main focus is given to maximising crew safety, team efficiency and individual wellbeing. This is obtained by providing mission goals to follow and behavioural facilitation, which are then continuously reinforced during technical training and instructor model behaviour through several processes: 1) establishment and revision of team processes and rules; 2) critical analysis of own and team actions through debriefings; 3) establishment of team awareness for informed decision making. The overall training structure imposes a dynamic and flexible, yet structured approach to the development of the team, strongly emphasising the team's growth through the analysis of its own activities, and transfer of the learning to space mission scenarios. This strategy is woven into the structure of the training and promoted by the Behavioural Facilitator, supported by the mission team, the Course Technical Director and speleological instructors during different phases of the training and relies on six key components: 1) establishment of behavioural-centered mission goals; 2) acceptance of individual and team roles and responsibilities by the crew; 2) seamless translation of behavioural competencies into technical behaviours and highlighting of the real consequences of those behaviours; 3) role modelling and technical reinforcement of those behaviours by instructors; 4) experience sharing by flown astronauts; 5) daily self-reflection and analysis of team behaviours; 6) transfer of the learning to future spaceflight.

During the pre-mission training phase, the development of team processes is embedded into practical and technical lessons, which are constructed to promote team cohesion and cooperation (Fig. 4A). Teamwork and roles definition is justified to the trainees by the technical and scientific requirements of the upcoming expedition, and reinforced by role modelling by the training team. By forcing this important communication and decision-making process in the pre-mission phase, the self-assignment of roles fulfils the important objective of forming a team. It is worth noting that all roles (Crew Commander, Campsite Manager, two Science Engineers with different operational tasks, Survey Engineer, and Photography Engineer) carry a component of leadership and of followership, each having to be exercised at various moments during the expedition. When the crew is autonomous during the main exploration mission, a continuous switching between leadership and followership behaviours for each member of the crew is required. This approach is similar to what happens on ISS where, even if a formal commander has been assigned, the practical leadership role can change depending on the activity [50, 51].

In addition, during the pre-mission training phase, opportunities are created for the trainees to exchange experience with the support team, which is selected and evaluated on the basis of speleological certifications and specific experience in extreme scientific cave expeditions. This team is also evaluated and trained on the modelling of behavioural skills, and is continuously monitored and directed by the Behavioural Facilitator and course technical director during the course. As the trainees rely on this technical team for instruction on the technical aspects of speleology, throughout the training they build trust in them. This trust, combined with the link built throughout the course between behavioural tools and technical outcomes, facilitates the transfer of successful behaviours fulfilling the requirement to conduct a safe and efficient speleological activity, which creates a strong perceived analogy to a safe and efficient space expedition.

When the extended exploration mission starts, team positions and responsibilities are already defined and each individual will have to improve their proficiency and efficiency in a particular role during the mission. In the evening, at the end of daily activities, the crew debriefs the activities of the day, analysing all behavioural factors impacting the outcome [52], thereby continuously improving team processes (Fig. 4B). Corrective actions for the following day are discussed and new activities and the following day schedule are planned focusing not only on the technical and scientific tasks, but also on ensuring crew safety and wellbeing. If any task is too demanding for one member of the crew, the others are required to provide support and possibly reorganise task sharing if necessary. In parallel, as mentioned, the constant awareness of the team fatigue and cognitive load by the Behavioural Facilitator in coordination with the mission support team ensures a modulation of the level of stress throughout the expedition. Another important moment to develop behavioural skills is the preparation of the equipment and supplies for the expedition and for daily excursions (Fig. 4C). This requires individual attention to readiness and completeness of the daily kits (i.e. battery charge, science kits, etc.), but also involves optimising communication within the crew and with the mission support team. It also ensures an understanding of objectives and preparedness for the activities across all the teams, especially when plans are altered as unpredictable events occur. Any misunderstanding, inaccurate preparation or missing items could have a significant impact in the outcome of the activities, or even the safety of the mission.

Since the crew is inexperienced in cave environments and exploration the debriefing process and the planning of the following day is monitored by the Behavioural Facilitator. The Behavioural Facilitator seamlessly follows and observes the crew, supervising key decision making and briefing/debriefing activities on an unobtrusive basis [51]. Team dynamics is never forced on the crew, unless safety is in question. In this case, the Course Technical Director has the authority to intervene. Any behavioural considerations or technical methods that led to the intervention are analysed during the daily debriefing, or in a specific debriefing if required. In addition, the Behavioural Facilitator, in agreement with the Course Technical Director, can inject challenges or remove them to modulate stress by directing the technical and safety support team in the cave and the mission control on the surface. This includes the possibility of providing relevant mission operations, technical or scientific suggestions to the commander, or if possible and not urgent, via mission control during the nominal daily communications between the crew and surface team.

In the middle of the extended exploration mission (after two days of exploration), roles are exchanged among the crew (Fig. 4D). In this way, behavioural competencies (leadership/followership, workload management, communication, teamwork, etc.) required by each role can be experienced by different team members. This role exchange also allows the crew to experience and compare alternative leadership styles and followers behaviours.

Another important factor in improving behavioural skills and transfer to spaceflight is the experience exchange between astronauts with prior spaceflight experience and unflown crewmates [53]. In order to achieve this, the experienced astronauts are asked to help underline similarities and differences between the overall training and mission activities and their spaceflight experience. This process allows the focus to be kept on the transfer of the learning to space activities, and helps the support team identify key situations and behaviours to emphasise. This also ensures that analogies are based on similarities of experience, not necessarily of the environment or the activity, as suggested by Bishop [3].

At the end the course, during the reporting phase, a debriefing is fully dedicated to human behaviour lessons learned, peer feedback and discussions among the crew. These discussions are introduced by the Behavioural Facilitator, but with the specific goal to develop the habit within the crew to conduct such discussions proactively as an effective way to address issues and continuously improve team processes. The crew is also free to conduct peer feedback and team debriefings with or without the support of the Behavioural Facilitator. This ensures that full confidentiality is provided when needed, and trust in the overall course and support team is built.

6. CAVES scientific and technological programme

6.1 Scientific activities

As is the case for space missions, during the CAVES training course, astronauts are trained not only to explore the cave, but also to carry out a scientific programme. This programme is not the primary goal of the training, but remains highly functional to the purpose of improving team performance outlined in the previous chapter. Scientific tasks are integrated into the CAVES mission timeline, and space-like procedures have been developed to strengthen the similarity of the course to space missions. As discussed, during the pre-expedition training, crew members are trained by experts on methodologies and procedures inherent to every planned experiment, to ensure they are able to competently execute the scientific programme. It is important to note that these science objectives are real, and aim to enhance our understanding of cave environments, meaning the astronaut's successful completion of them has a direct impact on the research output of the science teams involved. Science training across all the experiments is provided to every trainee, even if during the extended exploration only a few team members will be in charge of the scientific activities.

The scientific tasks the astronauts carry out belong to three main domains (Table 3): 1) environmental parameters and air composition 2) hydrology, geochemistry and geological sampling 3) biological and microbiological observations and sampling.

The environmental research activities share several analogies with environmental monitoring on the ISS, and have both scientific and safety objectives [54-56]. These activities include monitoring of air temperature, relative humidity, air flow direction and speed, atmospheric pressure, air particulate matter, carbon dioxide (CO_2), and Radon concentration (Fig. 5). The Radon monitoring with Radim instruments [57] is performed continuously in several different locations, and provides an estimate of the radiation exposure experienced by the astronauts and support team in the cave. Limits on this exposure are defined by laws and space agency regulations (Fig. 5A), and the radon monitoring ensures the personnel involved stay under these limits during their permanence in the cave. CO_2 concentrations are also measured frequently. Typically, this is every fifty meters with handheld devices, or monitored continuously with loggers (CO2meters) in specific locations (Fig. 5B). If the CO_2 concentration rises over specific values, the astronauts are instructed to leave the area for safety reasons. These studies are not only useful for monitoring safety, but also to better understand the cave microclimate and the habitability of the subsurface environments on Earth [18, 58, 59] as an analogue for future exploration of Mars and the Moon [60].

Hydrology and geochemistry are investigated in the caves by sampling various water bodies and dip systems. Samples of these water bodies are analysed directly at the base camp with portable analytical kits (like titration or colorimeters kits) or transferred to the surface for later laboratory analyses. These analyses are important, not only to understand the quality of the water for human utilisation, but also to trace infiltration patterns, chemical contents and to identify water bodies of different origin within the cave.

The 2011, 2012, and 2013 editions of CAVES also included the sampling of minerals and sediments for further analysis in laboratories using XRF and XRD. This activity has analogies with geological sampling on planetary surfaces. However, since this task requires specific field geological training (for example, the ESA PANGAEA programme [61]) which not all of the astronauts participating had taken. These activities were limited in the following editions of the course.

The microbiological experiments conducted at CAVES have analogies with several activities performed on the ISS [62, 63] and with the astrobiology studies that will eventually be performed during future missions to Mars [64]. As a discipline, cave microbiology is relatively new [65]. Recent technological advances have allowed for increasingly sophisticated DNA analysis, enabling scientists to find several new microbial taxa in cave environments previously unknown to science. Several of the microorganisms discovered are adapted to nutrient-poor environments, and use biological cycles based not only on oxygen, but also on nitrogen or sulphur. Some can even live exclusively on rocks (chemolithoautotrophs), making them extremely interesting from a space exploration perspective. CAVES trainees typically sample microbial mats at several location in the cave system, following specific clean sampling protocols. The samples returned from the cave by trainees undergo a set of analyses, including metagenomics and transcriptomics, to determine the types of organisms present and their survival methods (metabolics) in the cave system. During CAVES 2019, the scope of microbiological sampling was extended [66]. It included two main experiments, one examining microbial mats that typically form on cave walls, pools, floors, and the other focusing on microbes attached to cave air particles. Microbial samples were identified and sampled opportunistically by the trainees as they explored the cave system, with the help of a library of images provided as examples. To collect samples of the mats without contaminating them, they used a set of sterile tools, such as scalpels.

CAVES trainees also contributed to surveying and characterizing cave invertebrate fauna since the project’s inception. They achieved this by collecting organisms from several habitats within the different cave systems. These organisms then had their DNA analysed and morphology characterized at specialist laboratories. These biological surveys help researchers better understand the ecology of the cave systems, and can be enhanced by linking to the other scientific data collected by the astronauts, such as hydrology, meteorology and geochemistry.

The multidisciplinary approach taken by the CAVES science programme provides a broad set of continues interlinking studies that have produced both quality training opportunities and scientific publications (see Section 7.1).

6.2 Technology testing and EFB applications

Alongside scientific experiments and research, the CAVES mission also acts as a playground for technological testing, focusing on new innovative equipment that can improve operations in cave environments, and has potential to be applied to space exploration. Much of the efforts have been dedicated to the evaluation of two wireless cave radio systems, called TEDRA (Through Earth Digital Radio Appliance) and Xferra [67, 68]. Both have provided compelling results, allowing the crew to communicate with the ground team through voice from an advanced bivouac, crossing up to more than 1 km of rock thickness. These tests are used to improve the instruments for the next training editions, but also in other cave systems. Similar wireless radios might also provide reliable communication systems for lunar lava tube missions in the future. Other technologies related to survey and documentation are also tested at CAVES, such as a new laser measurement tool (Cavesniper, Megaplot SJ [17]) for recording the cave system dimensions, and various novel equipment and clothing specially designed for caving (e.g. new concept of cave shoes with special soles for slippery surfaces, new CUPRON BEE1 fibres socks and undergarments).

During the 2019 edition of CAVES, the Electronic FieldBook (EFB) was used for the first time to integrate science and operations for the entire duration of the underground campaign/mission (Fig. 6). The EFB is an information system designed within ESA to support scientific documentation in extreme environments and automatic data exchange with extended mission teams supporting the expeditions [69]. During CAVES, the EFB allowed the crew to aggregate, save and share contextual information about their surrounding environment. This information includes the cave survey, geo-referenced environmental parameters and scientific data, experiments, and field notes.

As the EFB hardware and software can wirelessly interface with external instruments, it was used to support site assessments and experiment data collection through devices such as microscopes, sensor boxes for measuring environmental values and surveying instruments. The system is operated through portable devices (e.g. tablets) to allow users to store and synch exploration sessions directly in the field. Synchronization with the other users and the remotely located ground team was possible through wired and wireless relays. This included the test of tailored wireless mesh repeaters distributed within the cave from the entrance to the base camp, which provided internet connectivity and real-time communication. The connectivity and support for real time exploration and scientific information exchange provided by the EFB architecture and its wireless repeaters were shown to be very promising for the support of expeditions in extreme environments.

7. Results and discussion

7.1 A real exploration mission analogue

The CAVES course combination of real (not simulated) environments, activities and objectives makes the overall training highly credible. The realism of the environment and operations provide valuable outcomes for enhancing crew dynamics as well as individual and team performance. Experienced astronaut and cosmonaut participants have consistently highlighted the strong analogy between long-duration spaceflight and CAVES expeditions. Feedback from the astronauts at the end of each training edition has been very positive, with supportive joint statements from the crew such as “our group consensus is that this is one of the best, arguably the best, spaceflight analogue training we have received”. CAVES trainees have recommended their fellow astronauts and cosmonauts participate to the course prior to ISS assignment. Astronaut and cosmonaut participants and their agencies have requested to take the role of CAVES commander in preparation for their future assignments as ISS commanders. There have been cases of individuals acquiring confidence in their ability to perform EVAs based on feedback from their experienced fellow crewmates on the equivalent technical challenges and safety protocols they successfully exercised at CAVES. Fears have also been overcome by controlled, safe and incremental exposure during CAVES.

It is important to note that CAVES is a free exploration laboratory of behavioural competencies and human performance for participants. The CAVES course offers opportunities for confronting fears, analysing one’s response to stress and exercising one’s abilities to identify limits and overcome obstacles. It also offers a real expedition which provides opportunities to learn from mistakes in team processes. Through this, participants are able to experience a range of situations and devise solutions. The relevance of these lessons to spaceflight is reinforced naturally by crew members with spaceflight experience discussing similar circumstances they encountered during spaceflight.

Feedback on all lessons and activities has been collected throughout every edition of CAVES. The average evaluation by participants at CAVES, based on the standard student feedback forms used throughout the ESA space training, on a 1 to 5 scale, is 4.6 for lesson content (clearly understood, beneficial), 4.5 for lesson material (enhanced understanding), 4.7 for instructors (promoted and maintained the desire to learn) and 4.1 for facilities (greatly enhanced and aided the training). The final feedback from all course editions always identified CAVES as a unique and relevant analogue, and one of the best training experiences preparing participants for spaceflight, comparable in quality and relevance to NASA's NEEMO project.

The positive outcomes of CAVES have not only extended to the preparation of astronauts. During the first five editions of CAVES in Sardinia, trainees were able to explore a significant part of the Sa Grutta cave system, covering a section from 1.2 to 4.7 km into the cave. The scientific research conducted during these missions has significantly enhanced our knowledge of this natural underground geo-ecosystem (details below). At the newer location in the Slovenian karst region in 2019, the first astronaut team mapped from 0.6 km to 2.5 km into the cave. The scientific data collected here is currently being analysed by the various partner institutions.

The most important new findings to come out of CAVES have been the discovery of new species of cave dwelling organisms sampled by the astronauts in 2012 and in following years. Among the specimens discovered in Sardinia, the most noteworthy is a new species of crustacean, *Alpioniscus sideralis* [70], found in the cave waters. It was discovered living together with the well-known terrestrial crustacean *Alpioniscus fragilis*, and another aquatic crustacean *Alpioniscus* sp. (former *Utopioniscus* sp.). The latter organism is known from marine caves along the Gulf of Orosei coast, and was found here for the first time in the internal Supramonte, far from the influence of the sea. Other interesting species were collected both in Sardinian caves (like specimens of *Stenasellus* sp., another more archaic aquatic crustacean) and in the Classical Karst. These new findings will allow scientists to describe other new species in the future, and better understand the ecology of each cave system.

Microbiology has been another scientific activity carried out by the astronauts that has yielded useful information. Black wall coatings, sediments, moonmilk deposits, soils, and calcite rafts were sampled and analysed for microbial diversity with Ilumina MiSeq sequencing analysis. These different samples showed there is significant bacterial diversity in the cave. They also showed that human-related micro-organisms were very localized, despite occasional visits to these caves by speleologists [71]. This indicated that the impact of humans on the bacterial levels in this relatively isolated environment has been less significant than previously thought. As avoiding the contamination of extraterrestrial world's is of primary concern to space agencies, these microbiological studies aimed to giving some information on how efficiently and fast human-introduced micro-organisms thrive in oligotrophic cave environments [72].

In Sardinia, mean Radon levels in the cave during all the training courses were around 2,800

Bq m^{-3}, leading to a maximum dose rate received by the personnel involved of less than 1.5 mSv (well below legal limits). Lower values were measured in the main Slovenian Classical Karst cave system, at around 500 Bq m^{-3}, with few peaks over 1000. CO_2 monitoring has also provided interesting information, showing how the distribution of this gas in the cave systems is linked to the presence of air flows or water bodies [18].

These scientific results were achieved thanks to the astronauts' strict adherence to scientific protocols and procedures, showing how space operational protocols can be applied with success to exploration expeditions on Earth.

CAVES also holds promise for future studies related to physiology and neurology. However, few studies have been performed during the course because of time, logistics, potential conflict with the primary course objectives and safety restrictions [38, 39]. The integration of a small set of selected human science experiments at the campsite in future editions is being investigated in collaboration with ESA life science. However, research and science activities remain functional to the expedition analogies, meaning they cannot create a negative impact on the primary goal of the course, which remains astronaut behavioural training.

7.2 From ISS to planetary exploration

Despite obvious and important differences between space stations and caves, both are complex alien environments, offering analogous situations, science opportunities, team processes and varied levels of stress. Unlike what happens in other analogue environments, communication inside a cave is unreliable, forcing the astronauts to accomplish team goals autonomously, with reduced reliance on mission support teams. This offers an interesting testbed for future planetary exploration scenarios, which will include delayed communication or complete autonomy. This situation has been tested during CAVES 2019, through the use of the EFB. All data and activities performed in areas of the cave without connectivity were recorded and archived in the EFB, and transferred later to mission control when connectivity was restored. During this edition, communication during daily DPCs was organized through video-logs between the crew and mission support to simulate an expedition to a distant planetary body with significant communication delays. Since the challenges of communication in caves are real, they provide a useful test of human behaviour, performance, and crew decision-making processes during exploration.

The progression tools, safety and emergency procedures used in the CAVES training could be used partly to help develop concepts for moonwalks and surface traverse activities on low gravity planetary bodies, or even for lava tube exploration on the Moon or Mars. The astronauts participating to CAVES have suggested that the training could be possibly used as analogue not just for current space missions to ISS, but also for future flights toward the Moon (Artemis) or Mars.

7.3 Planetary speleology

In addition to the human behaviour and performance benefits that the CAVES training provides, caves on other planetary bodies (especially the Moon and Mars) could be among the main objectives for exploration and astrobiology research in the future [73, 74]. Recent studies have shown that the volume of these tubes on Mars and the Moon could be up to two or three orders of magnitude larger than terrestrial analogues, respectively [10]. Intact, open segments of lava tubes could provide stable shelters for human habitats shielded by cosmic radiation and micrometeorite impacts on the Moon [75]. These voids may have dimensions suitable for housing permanent Moon bases, providing potential access to several resources, including volatiles and possibly water ice trapped in cave sediments [60, 76]. In addition, skylights could provide direct access to the subsurface of Mars, which is considered one of the main targets for the search of past and present life [64, 73, 77].

Lava tubes are probably not the only type of cave on Mars. In recent years planetary geologists discovered that extensive areas of the Red Planet are characterized by soluble lithologies, such as sulphates [78]. The surface of modern Mars is arid and inhospitable, with no liquid water. However, in the past (mostly in the "Noachian" period, more than 3.7 billion years ago) the planet probably had extensive active fluvial systems, oceans and aquifers. In that time, soluble lithologies might have been eroded by deep solutional weathering, forming large cave systems similar to the terrestrial karstic systems explored by astronauts during the CAVES course. A recent joint white paper signed by several researchers from different space agencies [79] shows how, after robotic precursor missions, human exploration could provide the greatest benefits in the search for microbial life in these subsurface environments. The CAVES training course can provide useful insights on how future human missions should face these complex environments, including the development of technologies that allow safe access, progression and mapping, and communication systems to the surface.

8. Conclusions

The CAVES programme has trained astronauts from all major space agencies involved in human spaceflight, providing a powerful analogue platform for Human Behaviour and Performance training during real exploration in complex, unusual and dangerous natural environments.

Speleological exploration can provide stressors and situations with several analogies to human spaceflight, including to the ISS programme, and to future missions to the Moon and Mars. The training's success is directly related to the realism of the situations and experiences it creates, which was achieved through the involvement of a multidisciplinary team of experts in spaceflight operations, human behaviour, training and speleology. The result is a course with a continuum of exploration, science, operations and team processes, all occurring within an extreme, yet controlled, safe and logistically manageable environment. Astronauts get to experience personally why caves remain one of the last frontiers of human exploration on Earth. The CAVES course's use as a testbed for procedural approaches, communication, mapping and navigation technologies brings benefits to the development of these methodologies, but also helps to enhance the training's human spaceflight analogy. The course also provides an opportunity for training astronauts in science operations, where their performance directly impacts advancing human knowledge of these subsurface environments. Since caves are expected to exist on the Moon and Mars, the scope of this training in the future could be expanded to include the development of new EVA protocols and exploration technologies targeting these destinations.

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Figures

Fig. 1. Speleological environments and activities with analogies to space and related stressors: A) Shafts and traverses over canyon ledges requiring technical progression and safety protocols as an analogue to EVA (photo V. Crobu/ESA); B) Narrow and maze-like environments requiring orientation skills and control of movements in confined spaces (photo V. Crobu/ESA); C) The Base Camp, where the crew can perform science duties and communication with ground during DPCs, as an analogue to a space habitat (photo A. Romeo/ESA). D) Exploration and navigation with topographical surveys (photo V. Crobu/ESA). E) Team organization to perform shared technical or scientific tasks (photo S. Sechi/ESA); F) Science activities following space-like procedures (photo S. Sechi/ESA).

Fig. 2. Progression along a traverse with two safety tethers attached to a “*via ferrata*” handrail (left; photo Vittorio Crobu/ESA). This system shares several analogies with the tethers and protocols used during the Russian EVA techniques with the Russian Orlan spacesuit (right; photo credit NASA).

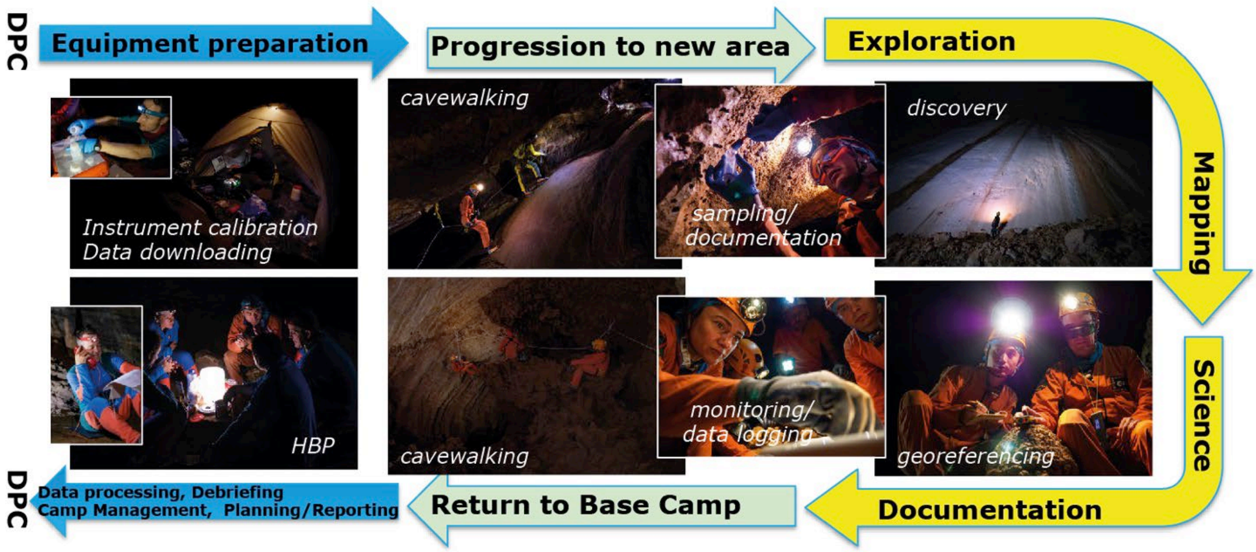

Fig. 3. Daily activity structure during the exploration mission. The daily plan can be considered as an analogue of an Extra Vehicular Activity lasting about 8 hours. The day starts with the morning DPC (Daily Planning Conference), equipment and scientific instrument preparation and technical equipment donning. When ready, the astronauts progress to the mission area, perform exploration, mapping and science, and then return to the Base Camp through the same route. The evening is dedicated to reporting (evening DPC), data transfer to the ground, and camp management. All photos are from ESA and the CAVES team photographers.

Fig. 4. Examples of activities where behavioural skills are exercised during CAVES: A) Activities during the pre-mission training where teamwork organisation is critical for success, like searching the right way through a labyrinth cave as a team (photo V. Crobu/ESA); B) Evening briefings among the crew during the extended cave mission to discuss the outcome and problems of the day, and plan corrective actions for the following one (photo S. Sechi/ESA); C) The crew during a food tasting session where they are required to prepare and agree on a list of food for the supply of the extended cave mission (photo E. Procopio/ESA); D) Command handover ceremony at the halfway point of the extended cave mission (photo A. Romeo/ESA).

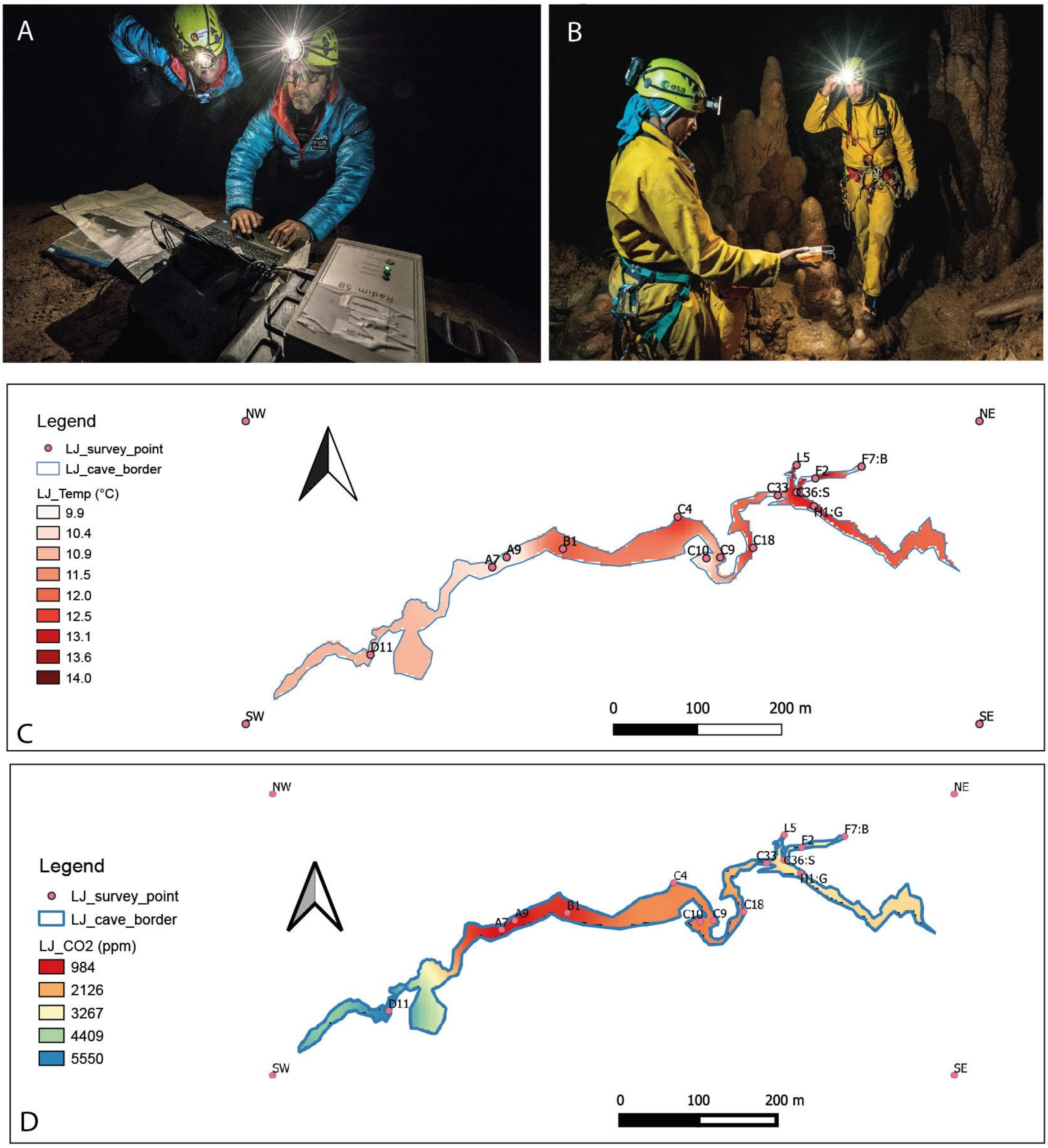

Fig. 5 Monitoring of the cave environment: A) Joe Acaba and Jeanette Epps (NASA) downloading data from a Radim 5B data logger (photo A. Romeo/ESA); B) Jeanette Epps (NASA) and Nikolay Chub (Roscosmos) measuring CO_2 levels during caves exploration (photo A. Romeo/ESA); C) Cave map with interpolated temperature measures (in ° Celsius) collected during the mission; D) Cave map with interpolated measurements of CO_2 collected during the mission.

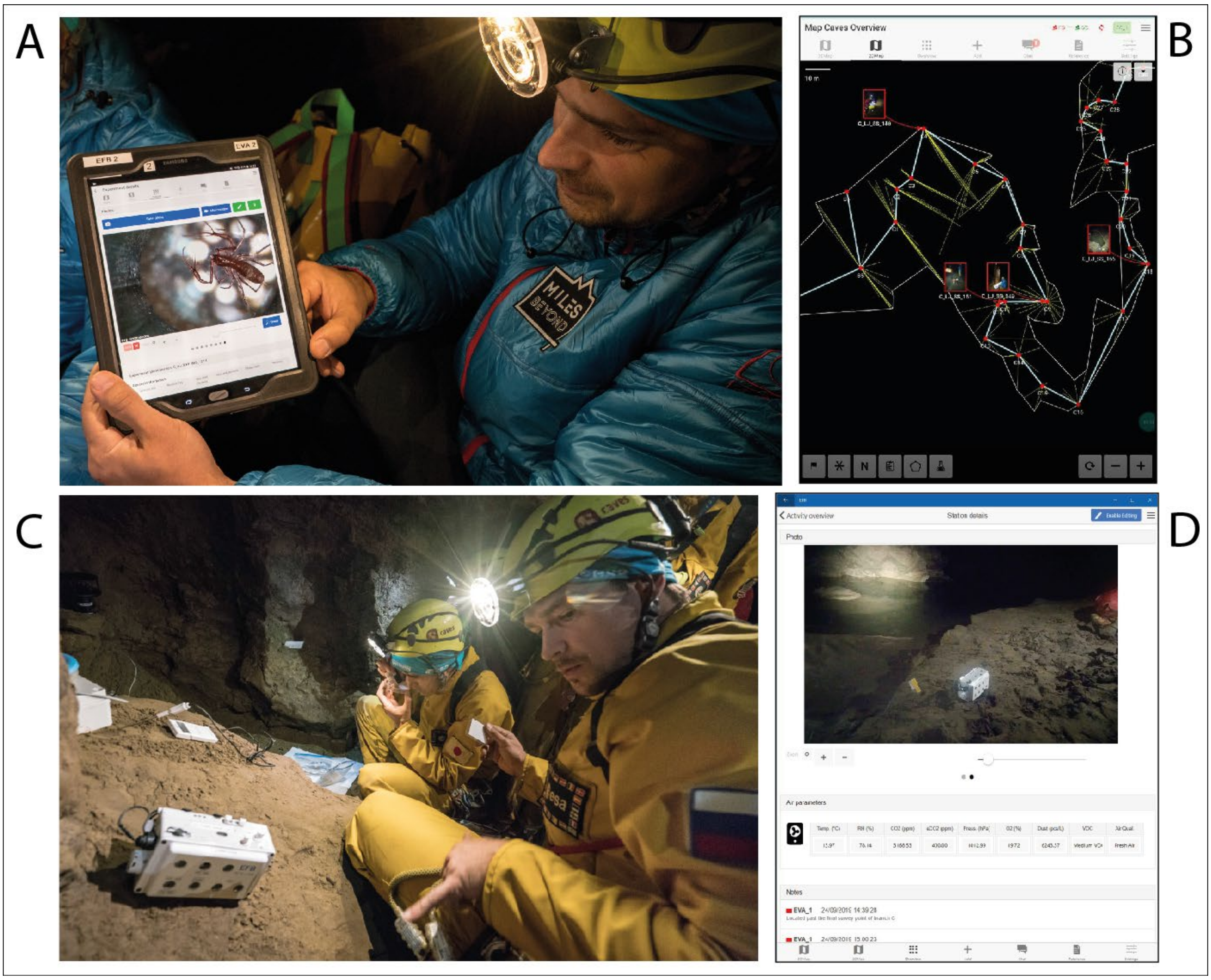

Fig. 6. A) The Electronic Field Book (EFB) tablet during experiment execution and microscope image collection, B) the experiment localisation in the interactive cave viewer, C) the EFB Sensors Box for environmental monitoring and its connection to D) the site documentation interface. The EFB and the Cavesniper mapping tool were used to perform geo-localized science throughout the cave during CAVES 2019. All data was gathered and transferred to the surface teams using a wireless system available at the base camp, at the end of every day. Photos A. Romeo/ESA.