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Deception Island (Antarctica) as an analog environment for human space missions: A comparative analysis of Gabriel de Castilla base (Spain) and Decepción base (Argentine)

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ABSTRACT

Terrestrial analog environments play a critical role in preparing for future human missions to the Moon and Mars, as they facilitate the validation of technologies, operational protocols, and human performance under extreme conditions. Deception Island (Antarctica), an active volcanic system that hosts two seasonal research stations: 1) Spanish Antarctic Station Gabriel de Castilla (BAEGdC) and 2) Argentinian Antarctic Base Decepción (BAAD), has long been recognized for its geological similarities to Mars. However, its potential as a comprehensive analog for human exploration has not yet to be systematically evaluated.

This study presents a multidimensional assessment of Deception Island as a natural analog site, together with a comparative evaluation of BAEGdC and BAAD as analog stations. Ten parameters were analyzed, including geology and geomorphology, environmental conditions, infrastructure and habitability, life support and telemedicine, risk management, planetary protection and biosecurity, human factors, logistical sustainability, and the potential for scientific experimentation and technological validation. The methodology integrates a literature review, infrastructure and operational analysis, and perception surveys conducted during the 2022–2023 austral summer campaign.

The results indicate that, within the evaluation framework applied in this study, Deception Island achieves the maximum site-level score, highlighting its strong potential as a natural analog environment. Nevertheless, these scores should be interpreted within the scope and methodological limitations of the proposed framework. At the

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station level, BAEGdC met or exceeded the defined threshold across all evaluated parameters, whereas BAAD exhibited comparatively lower analog fidelity, mainly due to limitations related to human habitability, life support systems, and space-oriented technological validation. These findings suggest that Deception Island, particularly BAEGdC, represents a promising platform for analog missions aimed at supportingpreparation for future human exploration beyond Earth.

Abbreviations

AEMET	Spanish State Meteorological Agency
AHP	Analytic Hierarchy Process
BAAD	Argentine Antarctic Base Decepción
BAEGdC	Spanish Antarctic Base Gabriel de Castilla
BP	Behavior and Performance
CAB	Centro de Astrobiología
CO2	Carbon dioxide
COSPAR	Committee on Space Research
EVA	Extravehicular Activity
HF	Human Factors
HI-SEAS	Hawai'i Space Exploration Analog and Simulation
ICE	Isolated, Confined and Extreme
MDRS	Mars Desert Research Station
MELiSSA	Micro-Ecological Life Support System Alternative
SD	Sleep Disorders
SMS	Space Motion Sickness
UTC	Coordinated Universal Time

1. Introduction

1.1. Analog sites for the development of analog missions

Terrestrial analog sites have proven to be essential tools in preparing for future space missions, particularly those focused on the exploration of the Moon and Mars [1–3]. These environments allow for the replication of extreme Earth conditions that simulate the physical, psychological, operational, and environmental challenges of extraplanetary destinations, thus facilitating the testing of technologies, operational protocols, and human behavior in scenarios of high isolation and operational demand [4,5]. The significance of analog bases has grown alongside the development of long-duration crewed missions, as they provide a controlled and secure setting to assess human performance, life-support systems, habitat design, and decision-making strategies under conditions of both physical and psychological stress [2,6,7].

To be considered an effective extraterrestrial analog environment, a site must replicate conditions that are pertinent to the objectives of the simulation, including geological and/or climatological characteristics comparable to those of the planetary body under investigation, geographic isolation, or extreme climatic conditions [2]. It must also enable the performance of extravehicular activities (EVAs) and facilitate the simulation of operational routines [8]. Furthermore, some sites offer limited logistical support, are sufficiently accessible to enable systematic research, or are remote enough to create conditions of confinement and autonomy [9,10]. Polar [11,12], desert [13], volcanic [14], and underwater environments [15–18] have been the most commonly utilized, as they effectively integrate these key variables.

In addition to physical conditions, analog sites must facilitate the study of human factors, defined as the psychological, physiological, cognitive, social, and cultural variables that influence individual and group performance in extreme environments [6]. The integration of methodologies such as habitability debriefing and the use of advanced simulators (e.g., virtual reality, closed laboratories, or mobile habitats) enables a systematic evaluation of habitability and quality of life under analog conditions [19], which are crucial for the design of future space missions. Campaigns such as EuroMoonMars [2,8,20], Mars Desert Research Station (MDRS) [21], and the EDEN ISS project [22] have demonstrated that the inclusion of well-being strategies (e.g., artistic activities, circadian rhythm regulation, nutrition, and multisensory stimulation) significantly enhances resilience and group performance during extended simulations.

Consequently, the design of an analog site should be envisioned as a transdisciplinary platform, where engineering, biology, architecture, human factors, and design intersect [6]. This integration not only supports the evaluation of emerging space technologies, such as autonomous recycling systems [23], controlled-environment agriculture [24], or modular inflatable habitats [25]. Also, facilitates the transfer of knowledge to terrestrial applications, including disaster management, telemedicine, urban sustainability, and environmental education [6].

1.2. Analog bases

Analog bases are terrestrial infrastructures specifically designed to simulate, either wholly or partially, the operational, environmental, infrastructural, and social conditions anticipated in future space missions [26]. Their primary function is to serve as validation platforms for technologies, habitat architectures, life-support systems, sociocultural aspects, and crew training, all within controlled environments that replicate the constraints and challenges of space exploration [27,28]. These facilities provide a unique opportunity for experimentation under conditions of isolation, confinement, limited resources, and extreme environments, thus enabling the systematic assessment of human performance and the integrated systems necessary for missions to the Moon, Mars, or other celestial bodies [6,26].

Analog bases can be categorized according to various criteria, including their level of realism, specific objectives, and geographic location [29]. From a functional standpoint, at least five distinct types can be identified: planetary simulation bases (focused on geology, habitability, and EVA operations), human training bases (centered on psychosocial and operational factors), platforms for technological validation, facilities for habitability and health studies, and those designed to evaluate closed-loop life-support systems [4–6]. These bases may be situated in extreme natural environments, such as deserts, polar regions, or volcanic settings, or within closed laboratories that offer full environmental control (e.g., Hawai'i Space Exploration Analog and Simulation (HI-SEAS) or Lunares Research Station) [4,15,26,30,31].

The relevance of analog bases lies in their capacity to reduce the risks associated with real space missions through the iterative testing of procedures, tools, and human and technological systems under simulated conditions [32,33]. In particular, they enable the study of interactions between technical and human variables in scenarios of prolonged isolation, providing critical information for the design of habitats, operational routines, emergency protocols, and autonomous decision-making systems [34,35]. Furthermore, these infrastructures offer unique opportunities to assess the impact of the environment on the physical and psychological health of crews, which is essential to ensure the sustainability of long-duration missions [36,37].

Beyond their operational relevance, such facilities also play a strategic role in the formulation of space exploration policies and the strengthening of international cooperation. By integrating scientific research, technological development, and human-factor analysis within a unified experimental setting, analog platforms facilitate the establishment of shared standards, the consolidation of collaborative networks, and the transfer of knowledge to terrestrial applications, including disaster response, self-sufficient architectural design, and remote or telemedicine-based healthcare systems [29,38–40]. Initiatives such as the Micro-Ecological Life Support System Alternative (MELiSSA) program of the European Space Agency, the EuroMoonMars simulation campaigns, and the HI-SEAS missions in Hawaii exemplify how analog bases have become indispensable instruments for advancing safe, resilient, and evidence-driven space exploration strategies [26,31,41,42].

1.3. Antarctica as a site of interest among analog bases

Antarctica is one of the most extreme and remote environments on Earth and has consequently emerged as a prime setting for the development of analog space exploration missions [43–47]. The reasons are persistently low temperatures, extreme environmental aridity, elevated levels of ultraviolet radiation, prolonged periods of continuous daylight or darkness, and sustained isolation, together with the presence of permafrost soils and geothermal activity, which constitutes an ongoing environmental hazard. All these conditions closely resemble those expected on Mars and on the icy moons of the Solar System [48,49]. Collectively, these characteristics position Antarctica as a natural laboratory of exceptional scientific relevance for investigating human adaptation, assessing technological performance under extreme conditions, and evaluating the habitability of extraplanetary environments [4,50].

From an operational standpoint, Antarctica represents a highly controlled yet logistically complex environment, rendering it particularly suitable for testing mission protocols, emergency response procedures, and resource management strategies. Antarctic field campaigns demand rigorous planning, autonomous management of constrained resources, and sustained performance under isolation, core elements that closely parallel the operational requirements of crewed missions to Mars. Moreover, Antarctic research stations provide a valuable context for examining the effects of prolonged confinement and interpersonal dynamics within closed systems, yielding critical insights into human factors and crew performance in scenarios analogous to deep-space missions, as example, the Concordia Station [51,52].

Among Antarctic sites, Deception Island (Fig. 1) stands out as one of the recognized planetary analogs, proposed as a multifunctional analogue due to the convergence of extreme environments that serve as natural laboratories for investigating the origin and persistence of life, its active volcanic setting that enables in situ geological, geomicrobiological, and climatological studies, and the presence of Mars-relevant conditions such as low temperatures, elevated radiation, desiccation, environmental weathering processes, permafrost, glaciovolcanic activity, perchlorates, and evidence of microbial mats capable of developing under extreme conditions [4,53,54]. This active volcanic system is characterized by shallow hydrothermal activity, debris-covered glaciers [4,55,56], and the presence of perchlorate deposits [57], all of which have also been identified on Mars [58,59]. Deception Island has been investigated for its geomorphological analogies [4,53] and has served as a testing platform for scientific instrumentation, some of which was subsequently deployed in operational Mars missions [60,61]. Furthermore, the interaction between volcanic geology, the cryosphere, and microbial communities on Deception Island enables the simulation of processes directly relevant to astrobiology, biomarker detection, and the exploration of subsurface environments [4,62].

The Spanish Antarctic Base “Gabriel de Castilla” (BAEGdC) and the Argentinian Antarctic Base “Decepción” (BAAD), both located within this environmental setting, operate seasonally during the austral summer as temporary scientific stations. These facilities have been utilized for technological testing and for investigations into human habitability under extreme environmental conditions [4]. Despite the fact that Deception Island has been recognized as a multifunctional Martian analog [4,63], the specific attributes that enable and constrain the development of analog missions have not yet been comprehensively characterized. Moreover, systematic and comparative assessments of the infrastructure and operational capacities of BAEGdC and BAAD remain notably scarce.

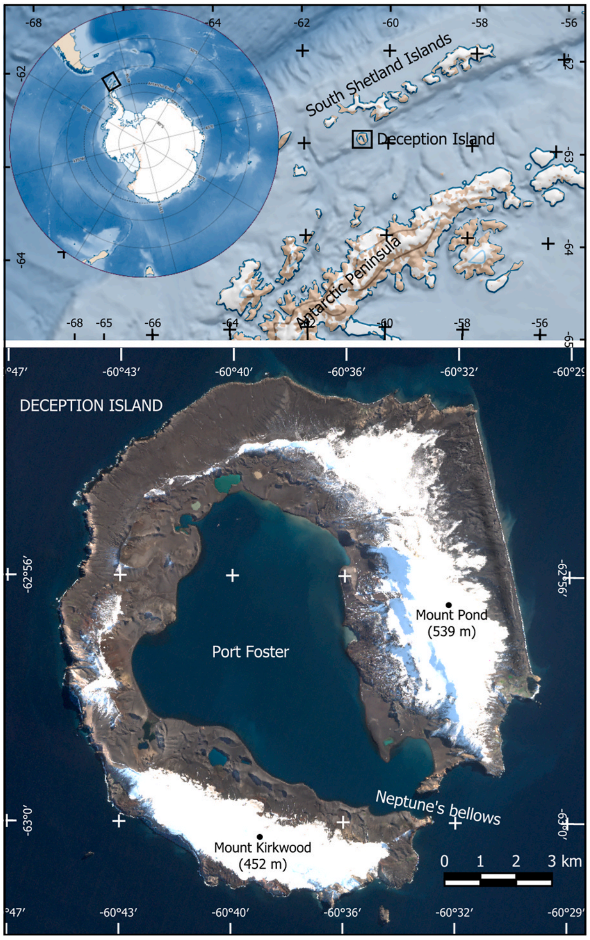

Fig. 1. Location map of Deception Island within the South Shetland Archipelago, in the western sector of the Antarctic Peninsula (Cartographic base: Quantarctica3, Norwegian Polar Institute. Satellite image: Sentinel-2/Copernicus/ESA).

Therefore, the present study aims to characterize Deception Island as a site for the development of planetary analog missions and to evaluate BAEGdC and BAAD as analog infrastructures for the simulation of long-duration space missions, based on an analysis of their geological, environmental, operational, and human conditions.

2. Methodology

This study employed a transdisciplinary methodological framework to evaluate Deception Island (Antarctica), the BAEGdC, and the BAAD as analog environments and operational stations for the simulation of crewed space missions. The core evaluative criteria initially proposed by Ref. [53] were integrated into the present analysis. To achieve a comprehensive characterization, ten key parameters were defined on the basis of established literature on planetary analogs [4–6]: (1) geology and geomorphology; (2) environmental and meteorological conditions; (3) interior habitability; (4) infrastructure and modular architecture; (5) life-support systems and telemedicine; (6) risk management and operational safety; (7) planetary protection and biosecurity; (8) human factors; (9) logistical sustainability; and (10) capacity for scientific experimentation and technological validation.

The assessment of these parameters was conducted through specific methodological phases, as detailed in the following section.

2.1. *Documentary characterization of the environment and its regulatory constraints*

A thorough analysis of the scientific literature and specialized operational documentation was carried out to characterize the physical, geological, topographic, regulatory, and logistical conditions of Deception Island, BAEGdC, and BAAD as planetary analog platforms. This process involved a comprehensive review of technical manuals provided by the Spanish Polar Committee, internal operational guidelines of BAEGdC, official campaign reports, peer-reviewed scientific publications, and the current legal framework under the Antarctic Treaty System. Additionally, up-to-date cartographic sources were incorporated, including geological and geomorphological maps, as well as available architectural plans of one of the bases. The integration of these inputs facilitated a systematic identification of the environmental physical characteristics, the use restrictions imposed by environmental protection regimes, and the essential operational criteria necessary for validating it as a multifunctional analog environment for the development of human activities.

2.2. *Acquisition and analysis of environmental data*

The meteorological data used to characterize the environmental conditions on Deception Island were sourced from the database of the Spanish State Meteorological Agency (AEMET), Government of Spain, and are freely available through its web portal (https://opendata.aemet.es/centrodedescargas/inicio). These data were collected from the multiparametric meteorological station located at the BAEGdC facilities, which is the only station on the island that operates continuously throughout the year. The dataset, recorded at 10-min intervals, includes variables such as air temperature (°C), relative humidity (%), and wind speed (m/s), among others [64].

Additionally, indoor temperature and Carbon dioxide (CO_2) concentration data were collected from BAEGdC. Measurements were taken using a Zehnder Wöhler CDL210 device, with a resolution of $1\ \text{ppm} \pm 50\ \text{ppm}$ for CO_2 and $0.1\ ^\circ\text{C} \pm 0.6\ ^\circ\text{C}$ for temperature. These data were recorded manually throughout the entire Antarctic campaign, from January 11th to March 9th 2023, at two distinct times of day (morning and afternoon) coinciding with breakfast and dinner schedules. In some instances, measurements were also taken at midday during the lunch period at the base. While the precise measurement times were not always consistent on a day-to-day basis, the dataset provides a representative overview of the temperature and CO_2 conditions to which scientists and base personnel were exposed during their stay.

The estimation of thermal perception was conducted using two different indices, applied according to the observed temperature range: the Wind Chill Index and the Steadman apparent temperature. In both cases, the previously described AEMET meteorological data were used. The wind chill was calculated for temperature values equal to or below 10 °C, applying the formula developed by Environment Canada and adopted by the U.S. National Weather Service [65].

$$Twc = 13.12 + 0.6215 \times Ta - 11.37 \times v^{0.16} + 0.3965 \times Ta \times v^{0.16} \tag{1}$$

where Twc represents the wind chill temperature in °C, Ta the air temperature in °C, and v the wind speed in m/s. In cases where wind speed was below 1.33 m/s (equivalent to 4.8 km/h), the effect of wind on thermal perception was considered negligible; therefore, $Twc \approx Ta$, following the recommendations of [65].

In contrast, the apparent temperature was calculated following [66, 67] as an indicator of perceived thermal stress under moderate climatic conditions. This parameter was estimated using the following empirical equation, based on the thermal balance of the human body:

$$Tap = Ta + 0.33 \times p' - 0.70 \times v - 4.00 \tag{2}$$

where: Tap is the apparent temperature in °C, Ta s the air temperature in °C, v is the wind speed in m/s, and p' is the water vapor pressure in hPa, which is estimated using the following equation:

$$p' = (RH / 100) \times 6.105 \times e^{(17.27 \times Ta / 237.7 + Ta)} \tag{3}$$

where RH is the relative humidity of the air expressed as a percentage. This index was calculated independently from the previous one, as it is not restricted to specific temperature or humidity conditions and allows the representation of thermal perception across a broader range of meteorological situations.

2.3. *Design and application of perception surveys*

As part of the human factors analysis, an anonymous survey instrument (Fig. 2) was developed and administered for researchers, technical staff, and military personnel involved in the Antarctic campaign during the austral summer of 2022–2023 on Deception Island. This included individuals from both Antarctic bases. The survey design was guided by the parameters established by Ref. [68] concerning operational aspects in the field of space neuroscience. In line with this framework, four categories of operational alterations were assessed. Respondents were asked to indicate whether they had experienced specific signs or symptoms associated with each category, encompassing a total of 18 signs and symptoms.

1) Space Motion Sickness (SMS): gastrointestinal disturbances, loss of appetite, persistent hunger, and/or sensations of fatigue.
2) Human Factors (HF): language difficulties, interpersonal conflicts, perceived sense of danger, and/or cultural shock.
3) Behavior and Performance (BP): lack of personal space, monotony, environmental noise, lighting issues, isolation, confinement, increased workload, and/or abrupt temperature changes.
4) Sleep Disorders (SD): alterations in the number of hours of sleep and/or changes in bedtime.

Additionally, for the analysis of contextual questions regarding the respondents' background and their activities in Antarctica, the survey items were organized into two main contextual categories, evaluating a total of 18 variables.

1) Respondent profile: age, gender, country of origin, family composition, and whether the respondent had previously been in Antarctica.
2) Preparation for deployment to Antarctica: completion of medical examinations, psychological evaluations, training courses, physical training, and/or preparatory meetings.
3) The characterization of work performed in Antarctica included the following variables: the number of research project members present in Antarctica (scientists), the number of personnel supporting the respondent's activities (military staff), the average number of hours spent on fieldwork per day, the average number of hours walked per day, the average number of hours spent traveling by inflatable boat per day, the average weight of materials carried per day (kg), the average number of hours per day spent transporting these materials, and the types of materials transported.

For the analysis of the survey responses, analytical ranges were defined (Table 1), allowing respondents to be classified according to the different contextual variables.

2.4. *Comparative analysis and integration*

Once the information was compiled, the most relevant aspects of each factor were identified, and the corresponding rubrics (Table 2),

Interviewee code:

WORK PERCEPTION SURVEY IN ANTARCTICA

Age:

Gender:

Home country and city:

Whom you live in your home with:

Have you been to Antarctica before? If so, how many times?
☐No ☐Yes, how many times?______

Next, select and describe the prior preparation you did to come to Antarctica:

☐Medical exams Which ones? ______________________________
☐Psychological tests Which ones? ______________________________
☐Training courses Which ones? ______________________________
☐Sports training Which ones? ______________________________
☐Meetings Which ones? ______________________________

Describe some of the aspects of your work in Antarctica:

If you are a scientist, how many members of your project are in Antarctica? ________________
If you are in the military, how many members support the work you do? ________________
Average number of fieldwork hours in Antarctica ________________
Average number of hours a day you must walk ________________
Average number of hours per day that you must travel in Zodiac? ________________
Average weight of materials to be loaded per day (kg) ________________
Average number of hours per day that you must load such materials ________________
Type of materials to be loaded (Ex : scientific equipment, construction, samples...) ________________

Please select the issues you have faced during your work in Antarctica below:

☐1.Alteration in the number of sleep hours
☐2.Time you go to bed
☐3.Difficulties with language
☐4.Gastrointestinal problems
☐5.Lack of appetite
☐6.Constant hunger
☐7.Feeling tired
☐8.Lack of personal space
☐9.Monotony
☐10.Environmental noise
☐11.Lighting problems
☐12.Isolation
☐13.Confinement
☐14.Increased workload
☐15.Personal conflicts
☐16.Feeling of danger
☐17.Cultural shock
☐18.Sudden temperature changes

Of the above options, which are the 5 that most affect you?

This survey is part of the evaluation of parameters of analog space missions and astronaut training. All the data collected here has strictly scientific objectives and will be treated in accordance with the personal data protection policy.

Fig. 2. Anonymous perception survey for the evaluation of SMS, HF, BP and SD.

derived from the literature, were applied to evaluate both the island and the various bases. A qualitative scale, based on previously defined criteria, was employed, assigning each parameter a score ranging from 1 to 5. For the overall assessment of Deception Island as an analog site for the development of simulated space missions, the sum of the scores for parameters 1, 2, 7, and 10 was considered. The maximum possible score was 20 points, with a minimum threshold of 15 points (equivalent to 75% of the total) established for a site to be considered suitable as an analog environment. This threshold was adopted as an exploratory heuristic within the present framework rather than as a universally validated cutoff. The selection of a value above three quarters of the total score was intended to ensure that analog classification reflected the simultaneous convergence of multiple criteria, thereby avoiding the classification of environments displaying only partial or isolated analog characteristics.

For the evaluation of the bases as stations for the development of analog missions, the sum of parameters 2, 3, 4, 5, 6, 8, 9, and 10 was considered, resulting in a maximum possible score of 40 points. A minimum threshold of 30 points (75% of the total score), following the exploratory heuristic adopted in this study to ensure the convergence of multiple analog criteria, was established for a base to be classified as an analog station. Although parameters 2 and 10 were part of the evaluation of the island, they were also included in the assessment of the bases. Parameter 2 encompasses the evaluation of environmental factors available within the bases (where applicable), while parameter 10 addresses the institutional and national interest in advancing space technology-related studies, which is associated with each base.

3. Results

3.1. Geology and geomorphology of Deception Island

Deception Island can be subdivided into two principal stratigraphic units: a pre-caldera stage and a post-caldera stage, separated by a major caldera-collapse event [55]. Pre-caldera products comprise scoria and breccias generated by emissions from multiple effusive centers during the emergence of the volcanic edifice above sea level, together with a succession of subaerial lava flows [69]. These units are overlain by

Table 1
Analytical ranges of the contextual categories.

Contextual Category	Variable	Analytical Ranges
Respondent Identification	Age	20-29
		30-39
		40-49
		50-59
		60-69
	Gender	Female
		Male
	Country	Spain
		Argentina
		Canadá
		México
		Chile
		India
		Poland
	Number of Members in the Family Unit	0
		1
		2
		3
		≥4
	Number of Previous Visits to Antarctica	0
		1
		2
		3-7
		≥8
Preparation for Deployment to Antarctica	Medical Examinations Performed	Spanish medical protocol
		Argentinian medical protocol
		Medical protocol from another country
	Psychological Assessments Performed	Spanish medical protocol
		Argentinian medical protocol
		Medical protocol from another country
	Training Courses Completed	General pre-Antarctic course
		Specialized courses
	Physical Training	Completed physical training
		Did not complete physical training
	Meetings	Project presentations
		Sexual harassment
		Biodiversity protection
		Other
Characterization of Work Performed in Antarctica	Number of Project Members (Scientists)	1
		2
		3
		4
		≥5
	Number of Support Personnel Assisting the Activities (Military Personnel)	2
		5
		≥6
	Number of Hours of Fieldwork in Antarctica	2
		4
		6
		8
		≥9
	Average Number of Hours per Day Spent Walking in Antarctica	≤1
		2
		3
		4
		≥5
	Average Number of Hours per Day Spent Traveling by Zodiac	≤1
		2
		3
		4
		≥5
	Average Weight of Materials Carried per Day (kg)	1-5
		6-15
		16-30
		31-50
		≥50
	Average Number of Hours per Day Spent Carrying Materials	≤1
		2
		3
		4
		≥5
	Type of Materials to Be Carried	Construction materials
		Scientific equipment
		Personal protective equipment
		Other

pyroclastic flow deposits associated with the caldera-collapse phase. Overlying these deposits are pyroclastic rocks produced during explosive hydrovolcanic activity followed by subsequent subaerial eruptions, which collectively constitute the post-caldera sequence [70]. The latter forms the dominant surface cover and is widely distributed across the island (Fig. 3).

Owing to its volcanic origin, Deception Island displays a high degree of geomorphological and depositional diversity, including lava flows, tuff cones, ash cones, and recent pyroclastic deposits emplaced during the 1969–1970 eruptive episodes [72]. These materials, which are largely poorly consolidated, enhance mass-wasting processes such as rockfalls, slope instability, and the development of debris cones and debris flows, particularly in sectors associated with caldera-collapse pyroclastic deposits and pre-caldera lithological units.

More than half of the island's surface is covered by glaciers (Fig. 3), which represent a fundamental agent in landscape evolution. Glacial dynamics, in combination with periglacial processes, promote freeze–thaw cycles, gelifluction, permafrost development, and the formation of seasonal fluvial channels and meltwater lakes [53,54]. These settings favor the formation of small pyroclastic dunes and lag surfaces in horizontal to subhorizontal areas, particularly within the inner ring of the island. Concurrently, coastal erosion and sedimentary dynamics, together with aeolian processes, continue to actively reshape the surface. A clear relationship is observed between exposed lithologies and resultant geomorphology: sectors dominated by pyroclastic deposits and poorly consolidated materials exhibit elevated levels of instability and reworking, whereas lava- and scoria-dominated areas display comparatively greater stability, albeit with persistently rugged relief.

According to the evaluation rubric (Table 2), these geological and geomorphological characteristics warrant the assignment of the maximum score (5) for the geology and geomorphology parameter, as they fully satisfy the criteria of complex relief, landform diversity, and high analog value for the simulation of crewed space missions.

3.2. Environmental and meteorological conditions

During the austral summer months (December–March), when Antarctic field campaigns are typically conducted, meteorological conditions on Deception Island are representative of a maritime polar environment. This setting is characterized by positive mean air temperatures of approximately 2.9 °C, with extremes ranging from −1.2 °C to 5.8 °C, persistently high relative humidity, sustained wind regimes, and pronounced solar irradiance during the central hours of the day. The principal meteorological variables (e.g. air temperature, relative humidity, wind speed, maximum gusts, and solar radiation) exhibit well-defined monthly and diurnal variability (Fig. 4).

Mean monthly air temperatures range from 1.7 °C in March to 3.2 °C in January and display relatively low standard deviations, indicative of a

Table 2
Qualitative evaluation rubric for the analog parameters of the Island and the Base.

Analog Parameter	Criterion	Score
1. Geology and Geomorphology	Non-relevant geology; homogeneous and easily accessible terrain.	1
	Presence of interesting landforms or materials without complexity.	2
	Moderate geological risk (landslides, instability); mixed relief.	3
	Complex relief with diverse landforms (glaciers, pyroclastics, slopes).	4
	Relief and geology with high analog value (active volcanism, challenging EVA simulation).	5
2. Environmental and Meteorological Conditions	Temperate and predictable conditions.	1
	Mild thermal variability without operational limitations.	2
	Presence of wind, humidity, or moderate cold.	3
	Critical thermal perception; high daily variability; wind and humidity affect operations.	4
	Extreme environmental conditions; strong thermal perception contrasts requiring daily planning.	5
3. Infrastructure and Modular Architecture	Large, permanent, and adaptable buildings.	1
	Modular structure with potential for reconfiguration.	2
	Rigid modularity; moderate energy dependence.	3
	Enclosed spaces with no flexibility; high dependence on heating and artificial lighting.	4
	Confined architecture without internal modularity; realistic emulation of extraplanetary stations.	5
4. Interior Habitability	Comfortable infrastructure with adequate personal space and large recreational areas.	1
	Acceptable comfort; shared spaces; some privacy.	2
	Shared dormitories; limited leisure; mild environmental stress.	3
	Very limited spaces; no privacy or clearly defined recreational areas.	4
	Overcrowding, monotony, and sensory deprivation comparable to space missions.	5
5. Life Support and Telemedicine	Continuous on-site medical care with a fully equipped hospital.	1
	Medical care with clinical staff but without remote connectivity.	2
	Basic infirmary without advanced devices.	3
	Medical professional with limited resources and no telemedicine.	4
	Advanced telemedicine system; real-time videoconferencing; realistic extraplanetary training.	5
6. Risk Management and Operational Safety	No relevant geological or environmental risks.	1
	Minor risks with passive alert systems.	2
	Moderate volcanic risk; some evacuation protocols.	3
	Active protocols; evacuation routes; continuous monitoring; autonomous risk simulation.	4
	Real risk (volcanic, meteorological); in situ management with autonomy and limited communication.	5
7. Planetary Protection and Biosecurity	No access restrictions or environmental regulations.	1
	Limited biological control measures.	2
	Basic cleaning of equipment and footwear.	3
	Strict entry protocols; protected areas; vector control.	4
	Committee on Space Research (COSPAR)-like planetary protection regime: cleaning, restrictions, and impact monitoring.	5
8. Human Factors	Absence of stress or symptoms; optimal ergonomic and psychosocial conditions.	1
	Mild symptoms in some individuals.	2
	Moderate operational symptoms (fatigue, sleep disturbances, isolation).	3
	Clear impact on performance and well-being, documented through surveys.	4
	Conditions comparable to ICE (Isolated, Confined, Extreme environments); high value for space neuroscience.	5
9. Logistical Sustainability and Autonomy	Full access to resources; continuous resupply possible.	1
	Limited but flexible logistics.	2
	Requires daily planning and basic inventory control.	3
	Total isolation during campaign; active resource management.	4
	Full autonomy simulation: no resupply; survival with limited resources.	5
10. Scientific Experimentation and Technological Validation Potential	No experiments conducted and no institutional interest.	1
	Suitable location but without infrastructure or experimental background.	2
	Occasional experiments conducted.	3
	Active site for scientific testing without direct space validation.	4
	Validation of real space instruments; continuous campaigns; ideal testing conditions.	5

cold yet thermally stable atmosphere. Relative humidity consistently exceeds 80%, reaching monthly mean values of up to 86% in January, which reflects a persistently saturated atmospheric state with no evidence of significant drying episodes. Mean wind speeds vary between 6.3 m s^{-1} in February and 7.2 m s^{-1} in March, while daily maximum gusts may exceed 17 m s^{-1} (Fig. 4). Incoming solar radiation exhibits greater temporal variability, with average maximum values in January (198.8 W m^{-2}) and minimum values in March (81.1 W m^{-2}).

Wind, beyond its direct influence on thermal perception, constitutes an environmental factor with significant operational implications. The distribution of wind directions exhibits a bimodal pattern, dominated by northerly and south–southwesterly flows, indicating alternating airmass regimes likely associated with coastal dynamics and the passage of frontal systems (Fig. 5A). Hourly mean wind speeds display a progressive increase over the course of the day, with lower values during the early morning hours (approximately 6.5 m s^{-1}) and peak values exceeding 7.0 m s^{-1} during the late afternoon (Fig. 5B). This diurnal pattern promotes the occurrence of intense wind gusts during periods of maximum outdoor activity.

Hourly maximum gusts may reach or exceed 25 m s^{-1} during the most meteorologically active months, particularly January and February (Fig. 5C), while the frequency of daily events with gusts above 15 m s^{-1} remains consistently high throughout the austral summer. Overall, between 600 and 1000 events per month exceeding this threshold are recorded, together with approximately 100–200 monthly events characterized by gusts surpassing 20 m s^{-1} (Fig. 5D).

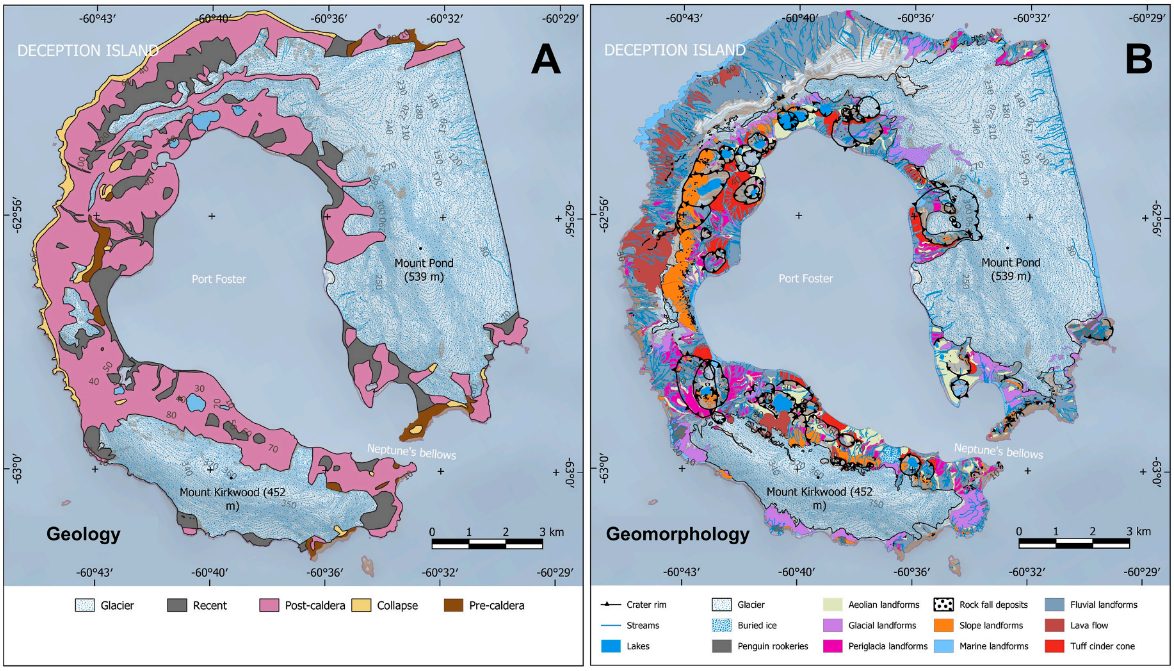

Fig. 3. Simplified A) geological and B) geomorphological maps of Deception Island (Modified from Refs. [43,71], respectively).

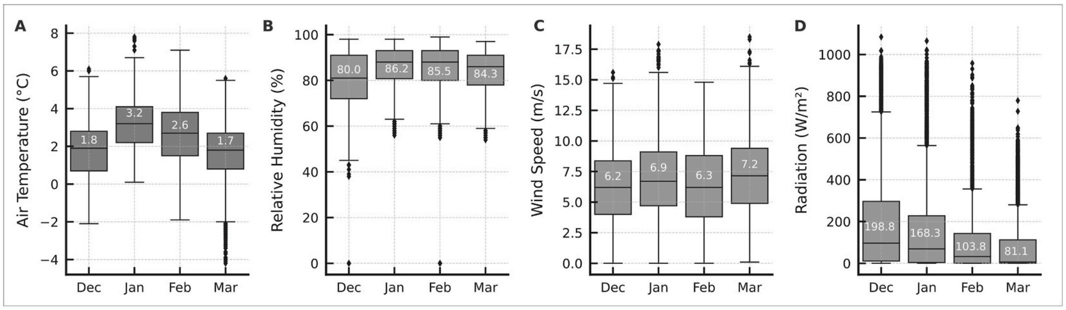

Fig. 4. Boxplots of the prevailing environmental conditions during the different months of the austral summer (recorded between December 2022 and March 2023): air temperature and relative humidity, wind speed, and incoming solar radiation.

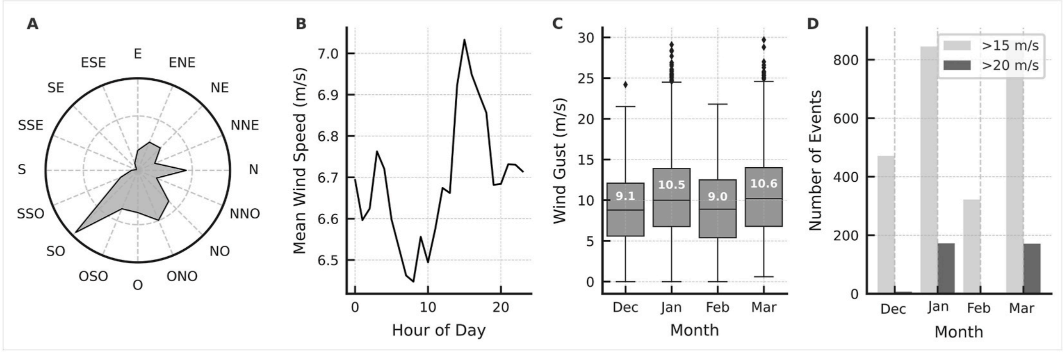

Fig. 5. A) Wind rose showing the frequency distribution of wind directions recorded during the austral summer on Deception Island; B) hourly mean wind speed distribution; C) boxplot of wind gusts; and D) number of monthly records with wind gusts exceeding 15 and 20 m/s (based on 10-min measurements).

Wind exerts a strong control on thermal perception, thereby amplifying the effects of both ambient air temperature and the prevailing diurnal thermal amplitude. Daily thermal amplitude (Fig. 6A) varies across days and months, with mean monthly values ranging from 1.7 °C in March to 3.2 °C in January, and with substantial day-to-day variability that may occasionally exceed 6 °C. Air temperature follows a well-defined diurnal cycle, with minimum values occurring between 03:00 and 06:00 UTC and maximum values between 14:00 and 17:00 UTC, coincident with periods of peak insolation (Fig. 6B).

Thermal perception, estimated using the Wind Chill index [65], departs markedly from measured air temperature during episodes of enhanced wind intensity, with mean reductions approaching 5 °C.

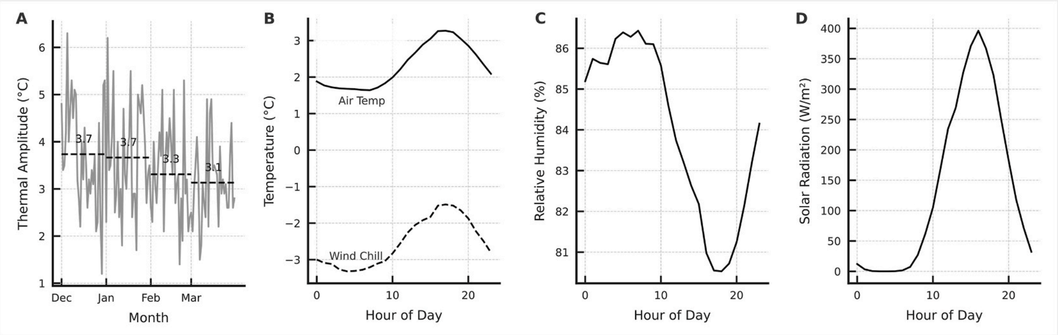

Fig. 6. A) Daily thermal amplitude; B) hourly evolution of mean air temperatures; C) relative humidity; and D) incoming solar radiation throughout the months during which the Antarctic campaign is conducted.

Relative humidity displays a pronounced hourly pattern, characterized by maximum values during the early morning hours (>86%) and a gradual decline toward values close to 81% by late afternoon (Fig. 6C). This behavior follows an inverse relationship with solar radiation, which attains its maximum between 13:00 and 15:00 UTC, reaching average hourly values of approximately 400 W m^{-2} in January (Fig. 6D). The concurrence of peak solar irradiance, intensified wind conditions, and the largest discrepancies between actual and perceived temperature defines a time window that is particularly demanding from both a thermal comfort and for operational perspective.

The interactions among these variables underscore the complex nature of the summer environment on Deception Island. Although solar radiation promotes a moderate increase in air temperature during daytime hours, this effect is largely offset by wind, which enhances convective heat loss and substantially reduces perceived temperature. Elevated relative humidity further intensifies the sensation of cold. Consequently, the most favorable conditions in terms of actual air temperature occur during the central hours of the day; however, these intervals are also those most exposed to strong wind gusts, resulting in the greatest discrepancies between measured and perceived temperature. While these environmental conditions are governed by predictable atmospheric cycles, they nonetheless allow for a certain degree of operational planning for the execution of outdoor scientific and logistical activities.

Regarding indoor conditions at BAEGdC, air temperature during the analyzed period (Fig. 7A) remained relatively stable, with a mean value of 20.7 °C (±1.1 °C) and a range between 15.7 °C and 22.6 °C. These values generally exceeded the comfort threshold defined for cold environments characterized by high relative humidity and the use of polar clothing (16–18 °C; [73]), although sporadic departures toward lower temperatures were occasionally recorded. In contrast, outdoor air temperature exhibited a mean of 2.9 °C (±1.5 °C), with values ranging from −1.2 °C to 5.8 °C, highlighting a pronounced thermal contrast between indoor and outdoor environments.

This contrast becomes even more evident when thermal perception is considered. Wind chill values, derived from air temperature and wind speed, yielded a mean of −1.4 °C, with minimum values reaching −8.3 °C. Similarly, Steadman's apparent temperature index produced mean values of −3.2 °C, with extremes as low as −10.1 °C, underscoring the potentially hostile nature of the outdoor environment, particularly

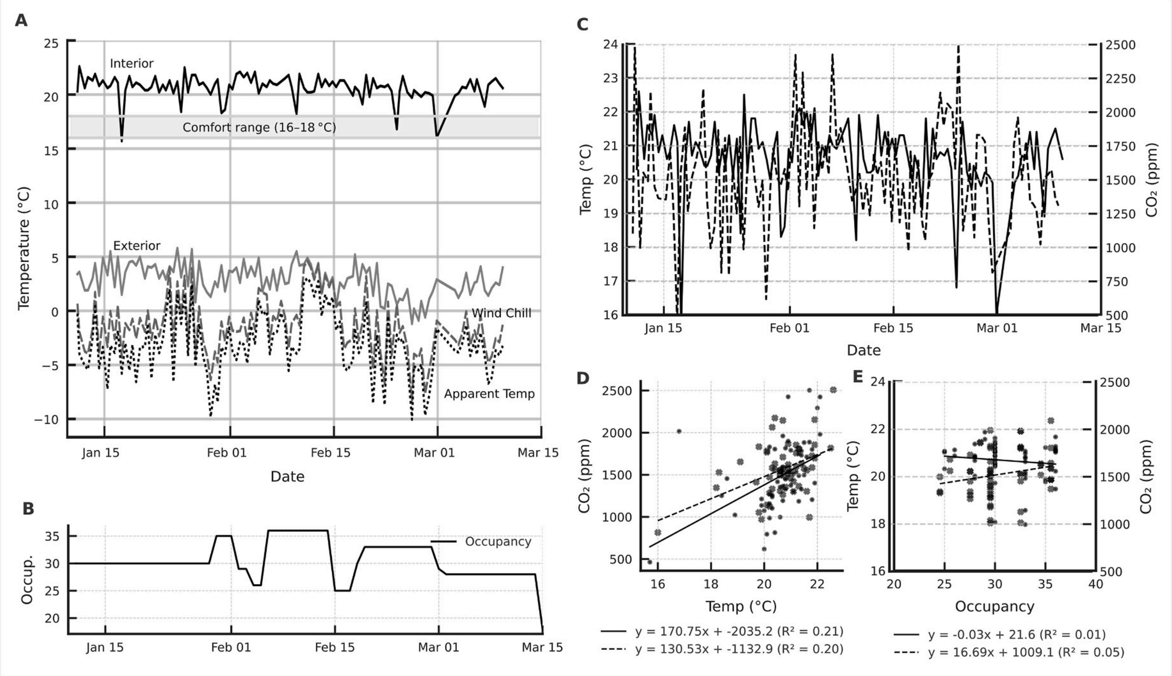

Fig. 7. Temporal evolution between 11 January and 15 March 2023 of: A) indoor air temperature at BAEGdC, outdoor air temperature, wind chill, and apparent temperature; B) base occupancy; and C) indoor temperature and ambient CO_2 concentration. Correlations between: D) CO_2 concentrations and indoor temperature measured in the morning and afternoon inside the base; and E) these parameters and base occupancy.

under windy conditions, and the strong thermal gradient relative to indoor conditions at the base.

With respect to indoor air quality (Fig. 7C), CO_2 concentrations ranged from 464 ppm to 2508 ppm, with a mean value of 1528 ppm and a standard deviation of ±377 ppm. Pronounced daily peaks were observed, occasionally approaching the maximum admissible concentrations for unventilated indoor environments (1000 ppm; [74]), although the majority of measurements remained below the 1750 ppm threshold.

Daily base occupancy ranged from 18 to 37 individuals throughout the campaign, with a mean of 31 and a median of 30, indicating a relatively stable population during the study period (Fig. 7B). Notably, these occupancy levels exceeded the nominal accommodation capacity of the base, officially set at 30 personnel. Statistical analyses revealed several correlations of interest among the evaluated parameters. Indoor air temperature exhibited a moderate positive correlation with CO_2 concentration ($r = 0.45$), suggesting a functional relationship between occupancy levels, ventilation efficiency, and the regulation of indoor thermal conditions (Fig. 7E).

In contrast, and despite low correlation coefficients, occupancy showed a weak positive correlation with CO_2 concentration ($r = 0.21$) and a weak negative correlation with indoor air temperature ($r = -0.19$), pointing to non-linear dynamics likely modulated by the operation of heating and ventilation systems. Indeed, abrupt decreases in both indoor temperature and CO_2 concentration were observed, which are plausibly associated with routine ventilation practices during morning hours, particularly through the opening of windows and doors (Fig. 7D).

Considering the combined influence of humidity, air temperature, wind, and thermal perception, Deception Island can be characterized as exhibiting extreme environmental conditions that necessitate daily planning of outdoor activities. Accordingly, based on the evaluation rubric, the maximum score (5) was assigned to the island for this parameter. In addition, given that BAEGdC displays pronounced thermal perception contrasts between indoor and outdoor environments, a score of 5 was likewise retained for the base under this criterion. In the case of the Decepción Antarctic Base (BAAD), the absence of indoor environmental measurements precluded an independent assessment; therefore, the score assigned to this parameter corresponds to the value obtained for Deception Island in the evaluation rubric.

3.3. *Infrastructure and modular architecture*

The facilities of BAEGdC have undergone a progressive evolution since the establishment of an initial tent-based camp in 1988, culminating in the ongoing construction of a new scientific module. This evolution was driven both by the early deployment of container-based units and by the subsequent development of purpose-built modular buildings elevated on columns, a design that facilitates air circulation beneath the structures and minimizes disturbance to the underlying permafrost [54,63]. This construction approach is well adapted to Antarctic environmental conditions and allows for dismantling with minimal environmental impact.

At present, the base comprises four primary buildings (Fig. 8A) constructed using this modular system, together with 15 auxiliary units based on repurposed shipping containers. The main buildings include: (i) the living module, which houses dormitories, sanitary facilities, a kitchen, a living–dining area, and the offices of the base commander and the communications center (Fig. 8B); (ii) the general storage module, containing the pantry, freezers, and storage for supplies; (iii) the workshop module, dedicated to maintenance activities involving base infrastructure, machinery, vehicles, and inflatable boats, as well as tool storage; and (iv) the new scientific module (under construction at the time of writing), which will also host the base infirmary. The auxiliary modules accommodate additional functions essential to daily life and base operations, including power generation, fuel and water storage, medical facilities, a gymnasium, emergency equipment, an incineration plant and waste management point, supplementary storage units (communications, scientific equipment, among others), and a navigation module.

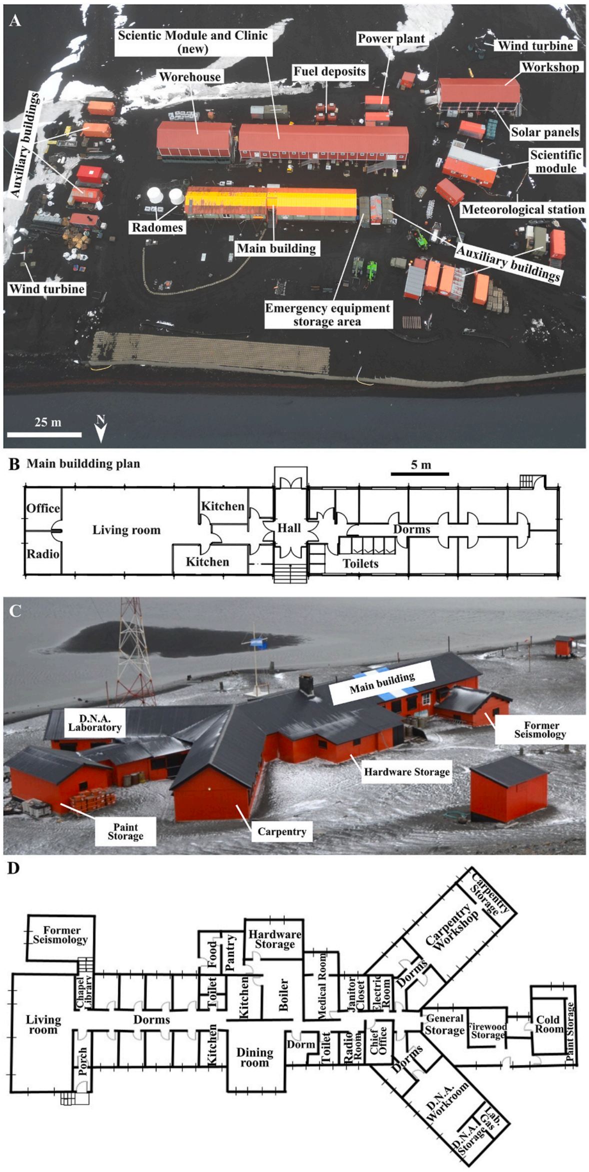

Fig. 8. A) Oblique picture of the Spanish Antarctic Station "Gabriel de Castilla" BAEGdC in Deception Island, showing the distribution of the buildings (Picture courtesy of M. Hernández); B) Plan of the main building of the BAEGdC station showing the inner distribution in the living area (left side) and dorms area (right side). C) Picture of the main building of the Argentinian Antarctic Base BAAD showing the distribution (Picture modify from Asociación Polar Pingüinera Antártica Argentina [75]). D) Plan of the main building of the BAAD station showing the inner distribution in the living area.

For safety considerations, the modules are spatially separated to limit fire propagation, forming a layout of four perpendicular corridors that enable rapid access to all buildings while maintaining short inter-building distances. This configuration facilitates safe movement of personnel between modules even under severe meteorological conditions, while ensuring adequate illumination during extended periods of darkness.

The base is designed to accommodate a total of 30 individuals, including permanent staff (12) and scientific personnel (18), distributed across seven four-person rooms and one two-person room. Nevertheless, on specific occasions occupancy has increased to as many as 43 individuals through the temporary installation of additional beds in the scientific module and selected auxiliary units adapted for this purpose. Such episodic overcrowding further reduces comfort and privacy levels, as living, sleeping, and sanitary facilities are constrained within the 321 m^2 footprint of the main living module.

Also located on the island is the BAAD (Fig. 8C), which has a total covered area of 1030 m^2, including 16 m^2 dedicated to scientific laboratories, a 337 m^2 logistics area, and accommodation capacity for 30 beds [75]. Established in 1948 as one of the earliest Antarctic bases operated by the Argentinian Navy, BAAD initially functioned as a permanently occupied facility. This operational status was subsequently modified following the volcanic eruptions of the 1960s, resulting in its current configuration as a seasonal base active during the austral summer.

The base comprises eight principal buildings constructed according to a traditional cabin-style architectural model, characterized by permanent structures with pitched gable roofs built using conventional, non-reversible construction techniques. The main building (Fig. 8D) integrates multiple functions, including dormitories, a kitchen, two dining rooms, a living room, a gymnasium, and the radio office, thereby centralizing a large proportion of daily activities. Additional auxiliary buildings include a fully equipped emergency shelter for temporary refuge, a maintenance workshop, a waste management unit, and the Volcanological Observatory, which constitutes a critical facility for monitoring the island's seismic and thermal activity.

The overall infrastructure provides approximately 1030 m^2 of built area, of which 337 m^2 are allocated to logistical functions, and includes accommodation capacity for 30 beds. Although several spaces incorporate large windows, these are internally covered with wooden panels in sleeping quarters to block incoming light during rest periods, an essential consideration in an environment where the Antarctic photoperiod can substantially disrupt circadian rhythms. Overall, the building layout follows a more spatially dispersed configuration than that of BAEGdC, with separated structures and independent access points. This arrangement reflects both the local topographic constraints and operational and safety requirements.

Regarding the evaluation of the *infrastructure and modular architecture* parameters, the BAAD exhibits modules with clearly defined functional roles and a moderate degree of energy dependence, as heating is required while large windows provide access to natural daylight. Consequently, and in accordance with the evaluation rubric, BAAD was assigned an intermediate score of 3. By contrast, the BAEGdC displays an architectural configuration that promotes confinement, characterized by a strong reliance on heating and artificial lighting and by limited internal modularity. These attributes generate infrastructural conditions that more closely resemble those expected in extraplanetary stations; therefore, in accordance with the rubric, a maximum score of 5 was assigned to BAEGdC for this parameter.

3.4. Interior habitability conditions

Human habitability is defined by the capacity of a space to satisfy human needs in relation to its surrounding environment, taking into account factors such as comfort, safety, and functionality. This concept evaluates how different territorial scales, from individual living units to entire regions, are configured to ensure adequate living conditions, integrating physical, social, and environmental dimensions that foster human well-being and sustainable interaction with the environment [76].

At the BAEGdC, buildings are arranged in a modular configuration, consisting of prefabricated shared units accommodating four occupants, together with a smaller module designed for two individuals. Sanitary facilities include three showers, four toilets, and four washbasins, all concentrated within a single shared area. Leisure spaces are largely integrated, combining the living room, dining area, and television space; only one independent recreational area was identified, corresponding to the gym, which is located outside the main living module. By contrast, at the BAAD, the living module comprises rooms designed for single or double occupancy, in addition to two independent, fully equipped bathrooms. The logistical sector of the main building houses electrical and mechanical workshops, as well as a carpentry area. Leisure spaces are clearly differentiated and include a living room with a bar, a main dining hall, a television area integrated into an auxiliary dining space, and a gym.

With respect to interior design, BAEGdC is predominantly characterized by cool color palettes, such as white and gray, whereas BAAD exhibits warmer tones associated with the extensive use of wooden structural elements. This design aspect, in combination with the chromatic characteristics of the surrounding landscape, tends to amplify perceptions of monotony and sensory deprivation at BAEGdC, while attenuating these effects at BAAD. Based on the *interior habitability* parameter, BAAD was assigned a score of 2, acknowledging that features such as single-occupancy or double rooms and independent full bathrooms provide a degree of privacy. In contrast, BAEGdC received a score of 5, reflecting the absence of privacy, the presence of overcrowding, and conditions of monotony and sensory deprivation comparable to those experienced during long-duration space missions.

Considering that the primary objective of the temporary inhabitants of Deception Island is the execution of scientific projects, a significant opportunity arises for advancing the study of habitability conditions at BAEGdC through the implementation of the new laboratory module. This facility is being constructed using a modular technological system designed to minimize environmental impacts on the island, incorporating features such as mechanical assembly, resistance to environmental loads, and high levels of thermal insulation, thereby enhancing researcher well-being while preventing heat transfer to the underlying permafrost [77]. The new module includes a dedicated meeting room, which is expected to enable the redefinition of the living module's combined living–dining area as a space primarily devoted to leisure and social interaction, thus limiting, or ideally eliminating, its use for work-related activities. This functional separation is particularly relevant for facilitating the study of key factors associated with human well-being in the context of future crewed space missions. In contrast, BAAD offers clearly defined spaces for laboratory activities; however, as was previously the case at BAEGdC, dedicated areas for meetings and scientific discussion remain limited. Consequently, work-related interactions frequently take place in spaces originally intended for leisure within the main building.

3.5. Life support systems and telemedicine

In the medical context of Antarctic operations, it is essential to acknowledge that all personnel must undergo comprehensive predeployment medical screening to identify pre-existing health conditions prior to arrival at the base. Emphasis is placed on maintaining up-to-date vaccination schedules and on the monitoring of chronic conditions, which may deteriorate in extreme environments characterized by isolation and restricted access to advanced medical care.

With respect to the *life* support *and telemedicine* parameter, although, in the case of life support systems, Controlled Ecological Life-Support Systems (CELSS) are also considered, it is necessary to acknowledge the limitations present in Antarctica for cultivating plants intended for long-duration food production, as well as for water production, which is largely sourced directly from the environment. For this reason, the life support systems that are recognized as feasible in the evaluated bases were assessed. In this way, BAAD was found to possess an infirmary that lacks advanced medical equipment and is staffed by a nursing professional. The facility is suitable for managing minor injuries and low-complexity conditions, such as sprains, cuts, and mild pain, and is equipped with basic medical supplies, including a stretcher, stethoscope, blood pressure monitor, thermometers, bandages, gauze, analgesics, and materials for basic wound care. However, the infirmary does not have external medical support systems or technological capabilities for advanced diagnostic procedures or the management of complex medical emergencies. In addition, regarding to life-support preparedness under extreme conditions, no specialized protective clothing suitable for aquatic risk management was identified. Instead, padded overalls were employed, which fail to provide adequate waterproofing or thermal insulation for the extremities and head, thereby offering insufficient protection during water-based operations. Considering these limitations, BAAD was assigned a score of 3 for this parameter.

In contrast, the BAEGdC is equipped with a highly functional medical infrastructure specifically designed for extreme environments, enabling advanced primary care and remote health monitoring through integrated telemedicine systems. According to technical specifications published by the Spanish Polar Committee [78], the medical unit is staffed by a physician and includes an electrocardiograph, portable ultrasound scanner, digital dermatoscope, optical microscope, pulse oximeters, and compact clinical analyzers, thereby supporting first-response diagnostic and therapeutic capabilities. This equipment is integrated into a satellite-based videoconferencing system that provides direct connectivity with the Central Defense Hospital Gómez Ulla in Madrid (Spain), allowing remote medical supervision, resolution of clinical consultations, and real-time support during specialized procedures, including trauma management and the treatment of complex pathologies [79]. In addition, the medical team (comprising a physician and, when available, supported by the expedition's veterinarian) is trained to perform minor surgical interventions, hemodynamic stabilization, and to activate medical evacuation protocols when required.

Furthermore, regarding to aquatic risk management, the presence of specialized protective suits was documented (Fig. 9). These suits incorporate integrated thermal protection for the head and feet, built-in flotation devices, and emergency signaling equipment. Although such suits may reduce maneuverability, they provide essential life-support functionality for operations involving water transport.

Given the availability of advanced medical resources and a telemedicine system capable of delivering real-time clinical support in response to emergencies, exacerbation of pre-existing conditions, or health issues associated with prolonged exposure to extreme environments, BAEGdC was assigned the maximum score (5) for the *life* support *and telemedicine* parameter.

3.6. Risk management and operational safety

Deception Island, as an active volcanic system (e.g., Ref. [55]), is subject to a broad spectrum of hazards associated with potential processes triggered by heightened volcanic activity. These include seismic events, landslides, structural collapses and subsidence, tsunamis, gas emissions, lava flows, lahars, and pyroclastic fallout, among others. Consequently, ensuring the safety of personnel operating on the island constitutes a primary operational priority throughout each field campaign [80].

A specific base-opening protocol is implemented, encompassing a systematic visual inspection of the island for indicators of volcanic unrest through circumnavigation of both the island's exterior coastline and the interior of Port Foster. This procedure is complemented by the analysis of data acquired from the permanent seismic stations installed across the island [67]. Only after this information has been thoroughly assessed, and in the absence of evidence indicating elevated risk, only the authorities of the Spanish National Geographic Institute (IGN), who hold final decision-making authority, authorize personnel landing and the initiation of opening procedures at BAEGdC. Although a formally documented opening protocol was not identified for BAAD, observations from several austral summer campaigns indicate that BAEGdC frequently initiates operations prior to the Argentinian base. This pattern suggests that Argentinian authorities may rely on previously established operational assessments, implicitly assuming that such evaluations sufficiently ensure personnel safety.

For continuous surveillance of volcanic activity, an island-wide instrumental monitoring network has been deployed, replacing the system that for several decades was operated by researchers from the Andalusian Institute of Geophysics and the University of Cádiz [72, 80–83,]]. This network is currently managed by the Spanish National Geographic Institute (IGN), with recent contributions from Argentinian scientific institutions. The system comprises seismic sensors, Global

Fig. 9. Use of protective suits for water operations with integrated protection systems.

Positioning System (GPS) stations for surface deformation measurements, geochemical and thermal monitoring instruments, and time-lapse cameras (Fig. 10).

Each evening, during the coordination meeting held at BAEGdC, the team responsible for volcanic surveillance determines the current risk level using the so-called *volcanic risk traffic-light system*, which employs color-coded categories (green, yellow, orange, and red). This assessment is conducted in near real time based on the integrated analysis of data from the entire monitoring network and, together with meteorological forecasts provided by AEMET, directly constrains the range of scientific activities that may be undertaken on the following day, within the limits imposed by personnel capabilities and available resources. Depending on the assigned alert level, response measures range from the issuance of basic precautionary guidelines to the implementation of a full evacuation of the island [80].

In the event of a potential evacuation scenario, the Spanish Antarctic Base BAEGdC is equipped with specialized mountain equipment and emergency rations prepared for immediate deployment. The evacuation plan contemplates overland movement on foot toward designated evacuation points located along the outer coast of Deception Island, as vessels would not access the island's interior due to the navigational constraints of Neptune's Bellows (Fig. 10) and the risk of entrapment in the event of seafloor modifications associated with volcanic activity. The selection of evacuation points is contingent upon the location and nature of ongoing volcanic processes, as well as prevailing meteorological conditions and sea state. To facilitate evacuation, a set of pre-established routes connects the base with multiple locations along the outer coastline (Fig. 10), some of which traverse glaciated terrain.

A further critical component of operational safety, analogous to astronaut protocols, is the maintenance of continuous communication between the bases and any field teams operating beyond the immediate vicinity of the facilities. At BAEGdC, this is achieved through encrypted high-frequency (HF) radio communications, which support both the transmission of operational information and the periodic geolocation of teams via Global Positioning System (GPS) data. However, owing to the island's complex topography, radio coverage is spatially heterogeneous:

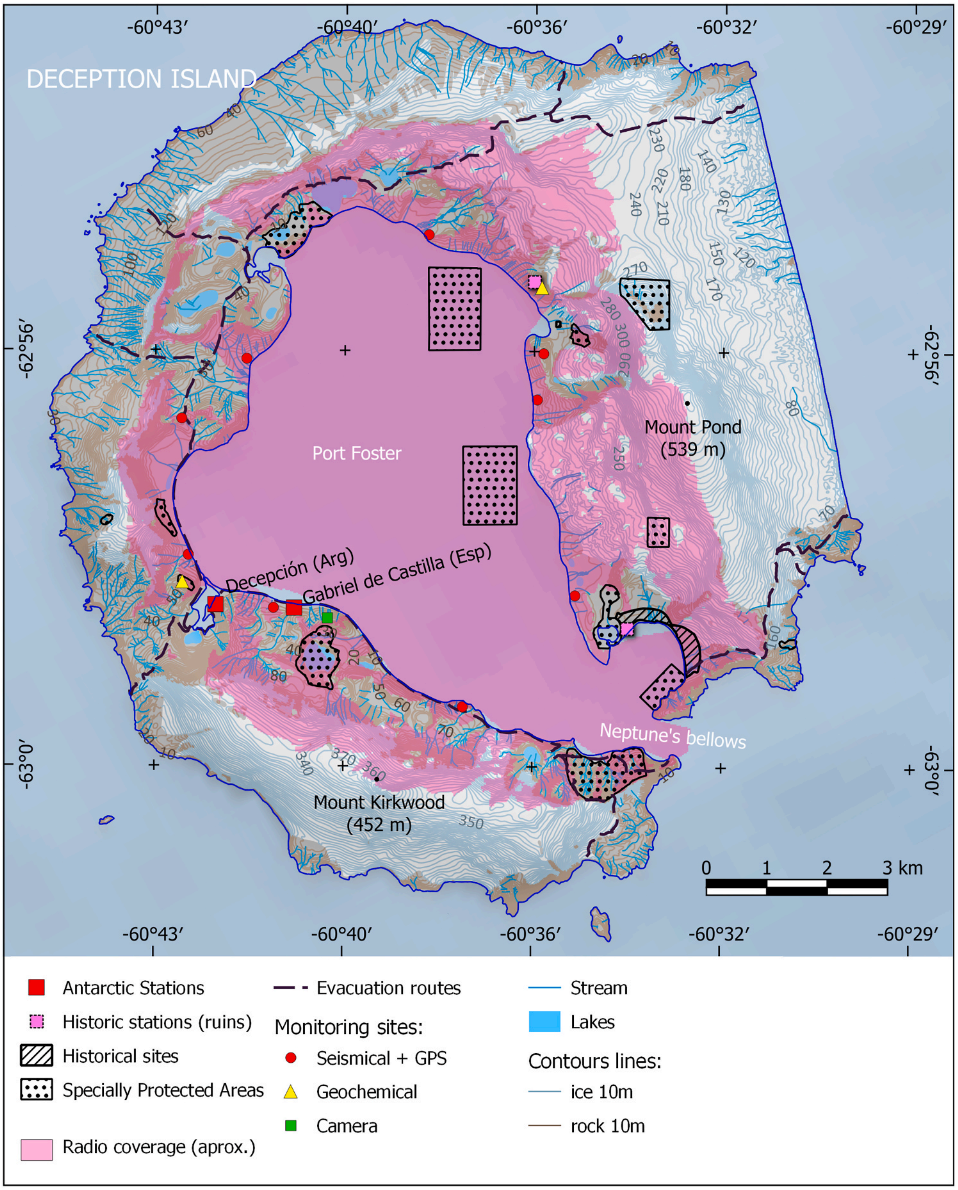

Fig. 10. Map of Deception Island showing the location of the Antarctic Stations, present and old, as well as the volcanic hazard monitoring sites for Spain and Argentina, evacuation routes in case of volcanic crisis, and the specially protected areas and historical sites. Approximate radio coverage in the island from the Spanish Station is also shown as a visual shed from its radio antenna.

while connectivity is generally reliable within the inner ring of the island, uninterrupted communication cannot be guaranteed along the outer coastline (Fig. 10). Consequently, when activities are conducted outside radio coverage zones, teams are additionally equipped with satellite telephones operating through the Iridium constellation.

At the BAAD communication systems include very high frequency (VHF) radios and satellite telephones, and comparable standards are applied with respect to base-opening procedures and volcanic activity monitoring. Similarly, evacuation routes are predefined at distances ranging from 7 to 10 km from centers of volcanic activity. These safety measures are implemented consistently across both bases, as, in 2000, within the framework of the Antarctic Treaty System, Argentina, Chile, Norway, Spain, and the United Kingdom reached agreements governing the management of activities on Deception Island [84].

Considering the well-defined risks associated with volcanic activity, prevailing meteorological constraints, the necessity for autonomous in situ operations under conditions of limited communication, the existence and implementation of evacuation protocols, and the continuous monitoring framework, both BAAD and BAEGdC were assigned the maximum score (5) for the *risk management and operational safety* parameter.

3.7. Planetary protection and biosecurity

In addition to operational safety protocols, a comprehensive set of measures is implemented to prevent the introduction of non-native species into the Antarctic ecosystem. This protocol, developed by the Spanish Polar Committee (CPE) in compliance with the Madrid Protocol to the Antarctic Treaty [85] and related agreements within the Antarctic Treaty framework [84], seeks to prevent the inadvertent arrival of exotic organisms via indirect pathways. Rather than relying exclusively on the explicit prohibition of introducing animal or plant species, the protocol places strong emphasis on the application of biosecurity measures, including the thorough cleaning and inspection of clothing, footwear, and equipment prior to deployment to Antarctica. These actions are intended to minimize the accidental transport of propagules (e.g., seeds, spores, microorganisms) attached to personal gear or materials, which could otherwise establish and proliferate under local environmental conditions, as has already been documented in certain regions of the continent [86]. Through these measures, biological exchange between external regions and Antarctica is effectively constrained, thereby contributing to the preservation of the ecological integrity of one of the most sensitive ecosystems on Earth.

In addition, human activities in Antarctica are regulated through specific territorial protection designations that govern the types and intensity of permitted activities. The two principal categories are Antarctic Specially Managed Areas (ASMAs) and Antarctic Specially Protected Areas (ASPAs). ASMAs are designated zones where scientific, logistical, and tourist activities may coexist, requiring coordinated management to minimize environmental impacts and avoid operational conflicts. Although formal authorization is not required to access an ASMA, strict compliance with the corresponding Management Plan is mandatory; this document establishes best practices and recommended operational procedures. In many cases, a post-visit report detailing the activities undertaken and their adherence to the Management Plan is required. Deception Island is entirely designated as ASMA No. 4, implying a shared management regime among countries with a scientific presence on the island, including Spain, Argentina, and others [84,87].

Antarctic Specially Protected Areas (ASPAs), by contrast, are clearly delimited zones established to safeguard exceptional values, including environmental (fragile or unique habitats), scientific (sites of long-term research interest), historical, aesthetic, or pristine attributes. Access to ASPAs is strictly regulated and may only be granted through an official permit issued under a Management Plan approved by the Committee for Environmental Protection (CEP) and the Antarctic Treaty Consultative Meeting (ATCM). These Management Plans specify the values under protection, permitted and prohibited activities, and detailed procedures for access, movement, and sampling. Following authorized activities, a comprehensive report must be submitted documenting compliance with the permit conditions. On Deception Island, two ASPAs (No. 140 and No. 145) have been designated, both aimed at conserving key scientific and ecological values (Fig. 10).

In addition, a third protection category applies: Historic Sites and Monuments (HSMs). These sites, also regulated under the Madrid Protocol, are designated to safeguard structures, remains, or objects of significant historical value associated with exploration, human presence, or scientific research in Antarctica. Although HSMs are not ecologically protected areas *per se* and do not require formal access permits, visitors are required to comply with established conservation rules, respect physical boundaries, and adhere to posted signage. Deception Island hosts several officially recognized HSMs (Fig. 10), including the remains of the British Base B, occupied between 1944 and 1969 and partially destroyed during the 1967 volcanic eruption; the Chilean Base Pedro Aguirre Cerda, likewise destroyed during the same event; and the remnants of a former Norwegian whaling station (1906–1931), where cetacean-derived products such as fats and oils were processed.

Overall, these protocols, management plans, and protection designations are intended to preserve the natural, scientific, and historical values of the Antarctic continent. They not only restrict or condition the types of activities that may be conducted, but also define where, how, and under what conditions such activities may take place. Compliance with these measures is mandatory under the legal framework of the Antarctic Treaty System and must be considered by all actors operating on the island, both during campaign planning and in the execution of scientific and logistical activities aimed at long-term sustainability.

In recent years, additional targeted protocols have been implemented to prevent the introduction of pathogenic agents into Antarctic ecosystems [88]. These include measures adopted to mitigate the risk of introducing SARS-CoV-2, the virus responsible for COVID-19, not only due to its potential impact on personnel stationed at Antarctic bases, but also the risk of transmission to local fauna, particularly marine mammals. Similarly, the emergence and spread of highly pathogenic avian influenza (HPAI) have prompted the development of specific protocols [89,90] designed to restrict contact with birds and other wildlife, minimize the risk of cross-species transmission, and avoid disturbances to animal behavior, thereby further tightening constraints on human–fauna interactions [91]. These measures are consistent with the precautionary approach and environmental protection principles that govern all activities conducted on the Antarctic continent.

Protective protocols include, among others, the mandatory cleaning of footwear upon disembarkation from vessels, ultraviolet (UV) sterilization of clothing prior to entry into specially protected areas, and continuous environmental monitoring. In light of these considerations, the procedures implemented on Deception Island may be regarded as functionally analogous to planetary protection protocols [92]. Accordingly, Deception Island was assigned the maximum score (5) for the *planetary protection and biosecurity* parameter.

3.8. Human factors and psychological perception

The conduct of activities, both within base scientific facilities and during outdoor field expeditions across the island, requires the implementation of a comprehensive set of safety measures. Beyond those previously described in relation to meteorological conditions and volcanic hazards, these measures encompass standard occupational risk prevention procedures associated with the handling of tools and instruments, as well as with the execution of field activities. They include the use of appropriate personal protective equipment for travel in mountainous terrain, glaciated areas, and maritime settings; protective eyewear to mitigate exposure to high albedo and wind; and the application of sunscreen as a barrier against elevated levels of solar radiation, among other provisions.

To this end, operators at the Spanish Antarctic Base BAEGdC provide personnel with standardized documentation outlining the fundamental safety measures to be followed during operations. Within the framework of Antarctic scientific campaigns, the CPE has developed a series of guidance sheets aimed at identifying hazards and defining preventive measures associated with a wide range of scientific and logistical outdoor activities. Although these documents do not substitute for formal institutional risk assessments, they provide essential guidance to ensure safety and minimize impacts during operations such as Zodiac navigation, glacier traversal, camp installation, movement in volcanic environments, and the use of terrestrial vehicles. They also address specific scientific tasks, including the sampling of soils, rocks, vegetation, continental water bodies, and the execution of drilling operations. Collectively, these guidelines contribute to the standardization of operational practices, enhance in situ decision-making, and enable activities to be adapted to the environmental and logistical context of each campaign.

In addition, the Spanish Polar Committee has issued specific guidance sheets for higher-risk activities or those requiring special authorization, such as scientific diving and the operation of remotely piloted aircraft systems (RPAS). These activities are strictly regulated and may only be conducted by duly accredited personnel with certified training and explicit authorization from both the Committee and the head of the corresponding facility. In all cases, compliance with operational and safety protocols is mandatory, including prior risk assessments, the use of specialized equipment, and detailed documentation of each intervention. These regulatory frameworks not only promote safe and sustainable research environments but also constitute a valuable reference for the development of extraplanetary operational protocols in analog exploration settings, where extreme conditions, operational autonomy, and environmental impact minimization are critical.

Nevertheless, despite the availability of guidelines and management systems, the adverse conditions inherent to Antarctic work are widely recognized as capable of generating stress levels comparable to those experienced during space missions. Results from a perception survey based on categories commonly evaluated in space neuroscience indicate that, at BAEGdC, the signs and symptoms most frequently reported by personnel included lack of personal space (54%), increased workload (43%), abrupt temperature changes (40%), bedtime schedule disruptions (37%), alterations in sleep duration (34%), sensations of fatigue (29%), interpersonal conflicts (23%), and monotony (20%). At the Argentinian Antarctic BAAD, the most frequently reported signs and symptoms were abrupt temperature changes (58%), increased workload (50%), alterations in sleep duration (33%), sensations of fatigue (25%), and bedtime schedule disruptions (25%) (Fig. 11C).

To contextualize these findings, variables related both to crew composition (Fig. 11A and D) and to working conditions in Antarctica (Fig. 11B) were examined. It is necessary to consider that N = 35 in the BAEGdC and in the BAAD, N = 12. At BAEGdC, the crew is predominantly male (80%), with a concentration in the 40–49 age range (40%), a high proportion of individuals living alone (40%), and a majority with no prior Antarctic experience (66%). The crew is mainly Spanish (85.7%), with participation from other nationalities. At BAAD, the crew is likewise predominantly male (75%), primarily within the 40–49 age

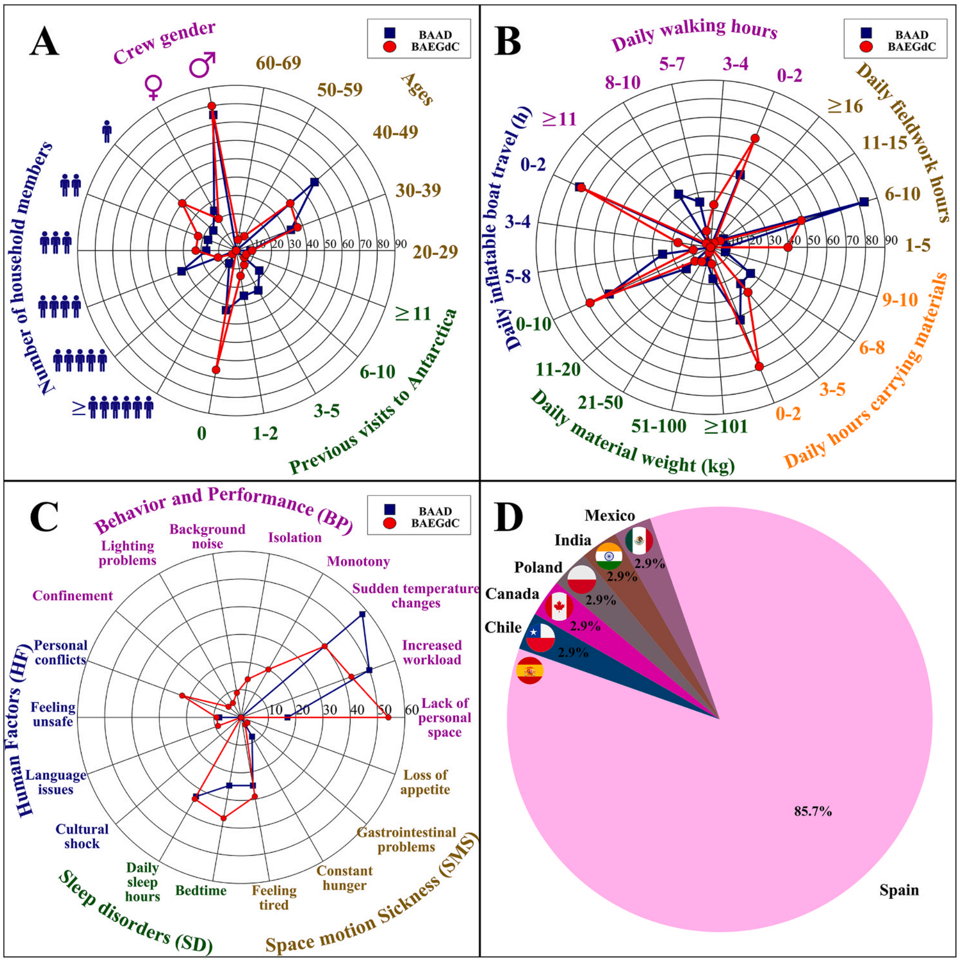

Fig. 11. A) Characterization of the crew at the stations; B) characterization of daily work activities in Antarctica; C) crew members' perception of work in Antarctica; and D) nationality of BAEGdC crew members.

range (58%), with a higher proportion of individuals sharing accommodation with four additional people (33%) and a smaller fraction of first-time Antarctic participants (33%); the crew is entirely Argentinian. In addition, personnel at both bases had undergone the medical examinations required by national polar authorities, participated in preparatory meetings and training courses, and conducted their activities accompanied by at least one member of their scientific team or military contingent; consequently, these factors did not constitute significant differentiating variables.

Regarding work activities, most participants at both bases reported engaging in 6–10 h of fieldwork per day (BAEGdC: 49%; BAAD: 83%). With respect to daily walking time, the most common category at BAEGdC was 0–2 h per day (63%), compared with 42% at BAAD, where this range was also predominant. At both bases, most personnel reported traveling 0–2 h per day by inflatable boat (BAEGdC: 74%; BAAD: 75%) and carrying loads of 0–10 kg (BAEGdC: 69%; BAAD: 58%) for an average duration of 0–2 h per day (BAEGdC: 69%; BAAD: 42%).

Considering that, at BAEGdC, more than 20% of the crew reported eight signs and symptoms across multiple categories, several of which correspond to human factors susceptible to behavioral modulation, the Spanish base was assigned the maximum score (5) for this parameter according to the evaluation rubric (Table 2). In contrast, at BAAD, five signs and symptoms were reported by more than 20% of the crew, corresponding to operational issues distributed across only three categories; accordingly, a score of 3 was assigned in compliance with the rubric.

3.9. Logistical sustainability and operational autonomy

Logistical sustainability and operational autonomy constitute critical factors in the characterization of analog environments, particularly in extreme settings such as Antarctica. In this context, marked differences were identified between the Spanish Antarctic Base BAEGdC and the Argentinian Antarctic Base BAAD, especially with respect to the sourcing, supply chains, and management of essential resources, including food and fuel. Both bases are equipped with adequate food storage systems supported by daily inventory control, enabling efficient consumption planning and waste minimization. Although this form of active resource management does not imply complete isolation, it does require sustained operational discipline to maintain activities throughout the campaign. At both bases, fresh food items, such as fruits and vegetables, were consistently identified as the first to be depleted, whereas non-perishable products, including canned goods, grains, and beverages, remained available toward the end of the campaign. Nevertheless, substantial differences emerged in intermediate resupply logistics.

BAAD benefits from robust logistical support provided by the Antarctic Logistics Hub in Ushuaia, which enables in-season resupply without reliance on external procurement or international transport. This structural advantage translates into enhanced storage capacity and provisioning flexibility, including the possibility of stockpiling supplies for subsequent campaigns. Moreover, the fact that the entire supply chain, from storage to distribution, is managed by the Argentinian State facilitates compliance with food safety standards, sanitary regulations, and phytosanitary control protocols applied at the continental level [93,94]. Consequently, BAAD's logistical sustainability is underpinned by a consolidated national infrastructure characterized by flexible yet effective planning, justifying the assignment of an intermediate score of 3 in the evaluation rubric, as it supports efficient operations while allowing partial resupply.

By contrast, BAEGdC operates under a considerably more constrained logistical framework, as it depends on provisioning from third countries, such as Argentina or Chile, which increases costs and imposes additional sanitary, administrative, and customs-related constraints. This context necessitates more rigorous planning from the outset of each campaign, with a strong emphasis on maximizing operational autonomy and minimizing reliance on intermediate resupply. Within this framework, the base has developed strategies centered on resource rationalization, meticulous inventory management, and close internal coordination with medical and veterinary personnel. Beyond ensuring food biosecurity, these professionals also contribute to organic waste management and to maintaining the safety of food preparation and storage processes [95]. Collectively, these conditions more closely mirror the challenges faced by extraplanetary installations in terms of isolation, limited resource availability, and preventive planning, thereby fulfilling the highest criterion of the evaluation rubric and justifying the assignment of the maximum score (5) for this parameter.

3.10. Potential for scientific experimentation and technological validation

Deception Island constitutes one of the most scientifically relevant analog environments for experimentation and technological validation in the context of space sciences, largely owing to the sustained research activities conducted from BAEGdC. The site has supported long-term research programs in astrobiology, planetary geology, habitability, extremophile microbiology, permafrost dynamics, and the simulation of space operations, thereby consolidating its role as a platform for continuous, real-world technological validation.

Among the most prominent initiatives are the experimental campaigns involving the Rover Environmental Monitoring Station (REMS), during which testing and calibration of the infrared ground temperature sensor were performed prior to its deployment on Mars aboard NASA's rover *Curiosity* [60,61]. These validation activities were conducted within the framework of the PERMAMODEL2 Project and demonstrate the suitability of Deception Island as an analog setting for reproducing extraplanetary meteorological and geochemical conditions. In addition, the island hosted validation tests of the Life Detector Chip (LDChip) technology, a core component of the Signs Of LIfe Detector (SOLID) instrument, an astrobiological system designed for the detection and identification of microorganisms and biochemical compounds in environmental samples [96–98].

Likewise, multiple scientific campaigns led by Spanish research teams have investigated the thermal behavior of permafrost and its relationship with subsurface heat fluxes, yielding critical data for advancing the understanding of the Martian subsurface [53,99], as well as conducting geomorphological analyses aimed at interpreting potential Martian glacial systems [63]. These investigations have been further complemented by geophysical surveys, detailed soil microanalyses, assessments of biological tolerance to extreme cold, and the development of habitability models, collectively underscoring Deception Island as a multifunctional testing ground for extraplanetary technologies, operational procedures, and methodological frameworks [4]. Additional research efforts have focused on the microbiology of extreme geothermal environments as terrestrial analogs for early Martian life [97].

By contrast, although the Argentinian Antarctic Base BAAD has a well-established record of research in geology, volcanology, biology, and environmental sciences, no ongoing projects were identified that are directly linked to technological experimentation or validation within the context of space exploration. Its scientific profile remains predominantly oriented toward conventional disciplinary research, and, to date, there is no clear institutional commitment to leveraging this site for the testing or validation of instruments and technologies intended for interplanetary applications.

Based on this body of evidence, the BAEGdC and Deception Island were assigned the maximum score (5) for the *potential for scientific experimentation and technological validation* parameter, as they satisfy the criteria of sustained research campaigns, direct validation of spaceflight instruments, and the availability of highly suitable testing conditions. In contrast, BAAD was assigned an intermediate score of 3, reflecting the presence of scientifically relevant activities without a direct connection to space-oriented validation efforts.

3.11. Evaluation of analogy with space missions

Based on the information compiled for each of the ten defined parameters and the application of the qualitative evaluation rubric presented in Table 2, the degree of analogy of Deception Island as a natural analog environment for the development of space missions was systematically assessed. For this purpose, parameters 1 (geology and geomorphology), 2 (environmental and meteorological conditions), 7 (planetary protection and biosecurity), and 10 (potential for scientific experimentation and technological validation) were considered. Deception Island achieved the maximum possible score of 20 out of 20, surpassing the minimum threshold of 15 points (75%), thereby confirming its suitability as a high-value natural analog for the execution of simulated extraplanetary activities. Particularly noteworthy are its active volcanic relief, pronounced climatic variability, the implementation of environmental protocols comparable to planetary protection standards, and a sustained record of scientific experimentation within astrobiological and space exploration contexts.

With respect to the Antarctic research stations, parameters 2, 3, 4, 5, 6, 8, 9, and 10 were evaluated. The Spanish Antarctic Base BAEGdC attained a total score of 40 out of 40, well above the minimum required threshold of 30 points. This base exhibits conditions that robustly replicate multiple aspects of an extraplanetary station, including extreme environmental exposure, confined and modular architectural design, restricted habitability, advanced telemedicine capabilities, active volcanic risk management, psychological stressors associated with isolation, autonomous logistical management, and the validation of flight-qualified space instrumentation, such as the REMS sensor aboard the *Curiosity* rover. Collectively, these characteristics position BAEGdC as a highly suitable platform for the design, testing, and refinement of extraplanetary operational protocols.

By contrast, BAAD obtained a total score of 27 out of 40, falling marginally below the established threshold. Although the base demonstrates several strengths (e.g. its location within the Deception Island analog environment, functional infrastructure, and extensive experience in geoscientific research), it presents limitations related to interior habitability, life-support systems, human factors, and the potential for space technology experimentation. The absence of modular architectural confinement, higher levels of interior comfort, and a more limited institutional orientation toward extraplanetary research constrain its qualification as a full analog station, despite its continued operational relevance within the region.

4. Discussion

4.1. Geology and geomorphology: A terrestrial environment with extraplanetary relevance

Deception Island constitutes an exceptional active volcanic system within the Antarctic realm, whose relevance extends beyond regional significance to position it as a high-value terrestrial analog for planetary studies, particularly with respect to Mars. Beyond its intrinsic geological complexity, the combination of an active caldera, lithological diversity, and extreme geomorphology creates an environment in which key processes relevant to the interpretation of volcanic, geomorphological, and potentially habitable planetary surfaces converge [4,55].

From a geological standpoint, the island's architecture as the remnant of a partially collapsed stratovolcano enables the analysis, within a single system, of the coexistence of volcanic products of differing origin and degrees of consolidation. The alternation of coherent lava flows, unconsolidated pyroclastic deposits, and hydrovolcanic materials not only reflect a complex eruptive history but also reproduces conditions comparable to those inferred for extensive Martian volcanic provinces. Regions such as Tharsis, Elysium Planitia, and Syrtis Major exhibit evidence of prolonged volcanism, superposed lava flows, caldera collapse, and processes associated with magma–volatile interactions that have a functional parallel on Deception Island [4,100].

In this context, the significance of Deception Island lies not in strict lithological correspondence, but rather in a process-based analogy. The coexistence of recent volcanism, active hydrothermal alteration, and continuous surface reworking enables an integrated assessment of the physical and geochemical evolution of volcanic materials under extreme conditions. This approach is particularly relevant for interpreting Martian units in which primary lithologies are obscured by secondary alteration, erosion, and sedimentary redistribution processes [101].

The island's geomorphology further reinforces its analog value by introducing an additional layer of operational complexity. The superposition of volcanic, glacial, and periglacial processes generates highly heterogeneous terrains dominated by unstable slopes, unconsolidated pyroclastic regoliths, and areas affected by surface and subsurface ice, both permanent and seasonal. Such conditions not only influence the preservation of geological structures but also impose direct constraints on mobility, sampling strategies, and the planning of field operations. These characteristics realistically reproduce the challenges faced by human and robotic missions on Mars, where traversal across poorly consolidated regolith and the presence of subsurface ice represents significant operational hazards [102–104].

From an operational perspective, Deception Island functions as a natural laboratory for the simulation of EVAs in geologically active settings. The requirement to plan safe routes, manage physical workload, optimize payload configurations, and operate under hostile environmental and geological conditions enables the evaluation not only of human performance but also of the functionality of tools, operational protocols, and communication systems in scenarios analogous to extraplanetary exploration [105,106]. In this sense, geomorphology transcends a purely descriptive role and becomes a central experimental variable in planetary exploration research.

Furthermore, the island's geological system has direct implications for astrobiology. The presence of active hydrothermal zones, shallow crater-associated lakes, and pronounced thermal and geochemical gradients generates microenvironments conducive to the development of extremophilic microbial communities. These settings facilitate the investigation of interactions among volcanic processes, mineral alteration, and biosignatures, providing critical reference frameworks for the interpretation of ancient Martian environments in which amorphous silica, phyllosilicates, and hydrated sulfates have been identified [11,107–109].

Taken together, the geological and geomorphological characteristics of Deception Island fully justify its classification with the maximum score within the proposed evaluation rubric. Rather than constituting an isolated site of geological interest, the island represents an integrated analog system in which volcanic, glacial, geochemical, astrobiological, and operational attributes converge. This convergence positions Deception Island as a privileged environment for the development and validation of scientific and technological strategies aimed at the exploration of Mars and other planetary bodies with complex volcanic histories.

4.2. Environmental and meteorological conditions: implications for extraplanetary operations and human habitability

The environmental and meteorological conditions documented during the austral summer on Deception Island (Figs. 4–6) define a highly demanding operational setting [37], in which the feasibility of outdoor scientific activities is controlled by the combined interaction of multiple atmospheric variables. Although mean ambient temperatures frequently remain above 0 °C during the campaign period (Fig. 4), the dataset demonstrates that elevated relative humidity, persistent wind regimes, and the systematic reduction of perceived temperature collectively generate a thermally hostile environment. This sustained divergence between measured air temperature and thermal perception, clearly illustrated by the comparison between air temperature and wind chill indices (Fig. 6B), closely reproduces the environmental stress conditions anticipated for future human missions to Mars, where atmospheric factors are expected to impose critical constraints on human performance and operational capability [110,111].

Among the variables analyzed, wind emerges as the primary operational constraint. Observational records indicate high mean wind speeds and a high frequency of gusts exceeding operational thresholds (Fig. 5B–D), with recurrent events surpassing 15 and 20 m/s. These conditions not only enhance convective heat loss but also directly affect daily logistical operations, particularly maritime activities within Port Foster. As evidenced by data from the 2022–2023 campaign, such conditions resulted in multiple days with restricted operations, in agreement with meteorological advisories issued by AEMET. This reliance on short, highly variable environmental windows is closely comparable to the planning constraints anticipated for EVAs on Mars, where dust storms, atmospheric pressure variability, and regional wind regimes are expected to similarly condition the execution of scientific tasks [112,113].

Daily thermal variability, although moderate in absolute magnitude (Fig. 6A), becomes operationally significant when examined in conjunction with the diurnal cycles of wind, relative humidity, and solar radiation (Fig. 6B–D). The data indicates that thermal maxima coincide with periods of peak solar radiation but also with increased wind speeds (Fig. 5B), thereby reducing the effectiveness of these intervals as favorable operational windows. This superposition of environmental drivers necessitates multivariable planning, in which decision-making cannot rely solely on air temperature but must integrate forecasts of wind intensity, radiative forcing, and thermal perception. Such complexity closely mirrors that anticipated in extraplanetary environments, where the optimization of time, energy expenditure, and crew safety will be critical to mission success [114,115].

From an instrumental standpoint, the meteorological datasets obtained (Figs. 4–6) have direct implications for the installation, operation, and long-term reliability of scientific equipment. Intense wind gusts promote mechanical vibrations and displacement of exposed platforms, while persistently high relative humidity (Fig. 4) increases the likelihood of condensation on sensors, optical components, and electrical connections. These environmental stressors necessitate the implementation of robust design strategies, reinforced anchoring systems, and frequent maintenance protocols that are directly transferable to the development of instrumentation and infrastructure intended for deployment on the Martian surface [116,117].

The marked contrast between outdoor conditions and those recorded inside the BAEGdC (Fig. 7A) enables a detailed evaluation of the performance of a confined habitat operating within an extreme environment, reinforcing its value as an extraplanetary analog. While the outdoor environment exhibited mean air temperatures close to 3 °C and negative thermal perception values, the interior of the base maintained a stable thermal regime of approximately 20–22 °C throughout the campaign. This stability, clearly reflected in the temperature time series (Fig. 7A), demonstrates the effectiveness of insulation and heating systems considered as critical components for energy efficiency and habitability in future planetary habitats. Nevertheless, the data also reveal a pronounced indoor–outdoor thermal gradient, which at certain times exceeds several tens of degrees and constitutes a potential source of physiological and cognitive stress for occupants [118,119].

Monitoring of indoor air quality further reveals environmental dynamics that are sensitive to occupancy levels and patterns of space utilization (Fig. 7B–E). CO_2 concentrations reached transient peaks exceeding 2000 ppm (Fig. 7C) during periods of high occupancy (Fig. 7B). The observed correlations between CO_2 levels, indoor temperature, and number of occupants (Fig. 7D and E) suggest a system governed by non-linear ventilation and thermal regulation processes. Although these excursions were generally short-lived, the recorded concentrations fall within ranges previously associated with measurable impacts on cognitive performance and perceived comfort [120–122]. This behavior further reinforces the relevance of BAEGdC as a testbed for environmental sensors, ventilation strategies, and habitat control protocols that will be essential in extraplanetary habitats employing closed-loop air recirculation systems, while simultaneously highlighting the need to assess comparable parameters at BAAD.

Taken together, the environmental and meteorological datasets presented (Figs. 4–7) demonstrate that Deception Island and BAEGdC integratively reproduce many of the challenges that future human missions will encounter on other rocky planetary bodies. These include pronounced climatic variability, sustained thermal stress, wind-driven operational constraints, the necessity for daily environment-based planning, and the management of habitability within confined spaces. Collectively, these lines of evidence support the assignment of the maximum score within the evaluation rubric and consolidate Deception Island and its scientific base as a high-value natural laboratory for research on extraplanetary exploration and habitability.

4.3. Infrastructure and architecture: spatial constraints and the simulation of extraplanetary habitats

The infrastructure of BAEGdC constitutes a particularly valuable analog for the study of extraplanetary habitability, not only because of its modular configuration but also due to the set of real operational constraints it imposes in terms of available space, occupancy density, and energy dependence. BAEGdC (Fig. 8A and B) combines an externally modular architectural layout with a highly compartmentalized internal organization, resulting in an environment in which logistical efficiency systematically takes precedence over residential comfort. This configuration realistically reproduces key functional conditions anticipated for future human bases on Mars or the Moon, where pressurized volume will represent a critical and finite resource and habitability must be managed under severe spatial and energetic constraints [123–125].

From an architectural standpoint, the distribution of BAEGdC into independent modules (Fig. 8A) responds to principles of safety, functionality, and risk mitigation. This distributed design, which limits the propagation of catastrophic failures such as fires, is fully consistent with modular architecture concepts proposed for extraplanetary habitats, where compartmentalization and the capacity to isolate subsystems are essential for operational resilience [124,125]. Similarly, the elevation of the modules on columns to minimize interaction with underlying permafrost [126] reflects design decisions aimed at reducing environmental impact and facilitating dismantling. These criteria that are directly transferable to planetary contexts in which surface intervention must be minimal, reversible, and tightly controlled.

A central component of the extraplanetary analogy offered by BAEGdC is the effective restriction of habitable volume. The main module concentrates essential daily-life functions, including rest, food preparation and consumption, work, and hygiene, within an area of approximately 321 m^2 (Fig. 8B), designed for a nominal occupancy of 30 individuals but which, during certain periods, has accommodated up to 43 occupants. This episodic over-occupancy amplifies limitations in privacy and comfort, reproducing high-density living conditions comparable to those anticipated for extraplanetary missions, where limited pressurized volume must be shared by the entire crew. Numerous studies conducted in Martian analogs and other confined environments have demonstrated that spatial density is among the most influential factors affecting crew psychological well-being, social dynamics, and performance [127,128].

The internal organization of BAEGdC (Fig. 8B) further reveals a pronounced degree of functional compartmentalization, characterized by narrow corridors, the absence of transitional spaces, and an almost complete reliance on artificial lighting. Although this configuration is efficient from a logistical perspective, it generates a sensorially constrained environment marked by low visual variability and limited opportunities for individual retreat. As documented in previous studies

[129,130], sensory monotony and reduced control over the immediate environment can contribute to psychological fatigue and heightened perceptions of confinement. Such effects must be explicitly addressed in the design of extraplanetary habitats through strategies such as biophilic elements, dynamic lighting systems, and the incorporation of micro-spaces for personal withdrawal.

Surprisingly, the lack of clearly defined personal spaces at BAEGdC constitutes one of its principal strengths as an analog environment. Shared dormitories with bunk-bed configurations (Fig. 8B) severely restrict privacy and opportunities for introspection, reproducing a critical condition identified in multiple space mission simulations: the difficulty of modulating social interaction in highly confined habitats. Research on human factors and habitability has consistently emphasized that even minimal private spaces can exert a disproportionately positive influence on mental health, sleep quality, and crew cohesion during long-duration missions [128,131,]].

From an energy systems perspective, BAEGdC's dependence on fossil-fuel generators for both electrical power and thermal regulation further reinforce its analog relevance. Although heating systems enable the maintenance of a stable indoor thermal regime, this stability is achieved at the cost of elevated energy consumption and complex supply logistics. This situation closely parallels the energy challenges anticipated for extraplanetary habitats, where self-sufficiency, redundancy, and resource optimization will be decisive determinants of mission sustainability [29,132]. In this respect, the base provides a realistic test scenario for evaluating strategies related to energy efficiency, resource management, and the resilience of life-support and environmental control systems.

The contrast with the BAAD further reinforces this interpretation and enables a more nuanced assessment of the type of analogy provided by each infrastructure. Although BAAD has a substantially larger built area (approximately 1030 m^2 under roof, including 337 m^2 of logistical areas, and accommodation for 30 individuals; Fig. 8C and D), its cabin-style architecture, characterized by permanent structures, larger interior volumes, and greater access to natural light, promotes higher levels of comfort and markedly reduces spatial confinement. This architectural approach, fully appropriate for scientific and logistical support in an extreme terrestrial environment, reflects a habitability paradigm oriented toward permanence and operational well-being rather than toward the reproduction of scenarios involving severe volumetric restriction.

From an extraplanetary standpoint, these same characteristics limit BAAD's capacity to simulate highly confined human habitats, where pressurized volume, privacy, and access to natural light will be strictly constrained by requirements related to radiation shielding, energy efficiency, and mass optimization. In this sense, BAAD is more representative of a planetary support node or outpost, with consolidated infrastructure and reduced psychological pressure associated with confinement, than of a primary habitat designed for deep-space missions. By contrast, BAEGdC, with its reduced interior volumes, elevated functional density, and near-total dependence on artificial lighting and environmental control systems, more faithfully reproduces the operational and habitational conditions expected during the initial phases of human exploration of Mars or the Moon.

Accordingly, the assignment of an intermediate score to BAAD, as opposed to the maximum score allocated to BAEGdC, should not be interpreted as an assessment of infrastructural quality, but rather as a reflection of the degree of analog realism relative to different profiles of extraplanetary missions. While BAAD enables the evaluation of logistics, structural robustness, and long-term facility operation in extreme environments, BAEGdC offers a more suitable framework for analyzing spatial constraints, dependence on life-support systems, and human dynamics under conditions of high confinement. Taken together, both bases should be regarded as complementary infrastructures, each contributing critical insights relevant to distinct phases and objectives of human extraplanetary exploration.

Consequently, the evidence presented in Fig. 8A–D (including modular configuration, limited habitable surface area, high occupancy density, and dependence on support systems), supports the conclusion that BAEGdC reproduces with exceptional fidelity the spatial, energetic, and operational constraints likely to characterize future human stations beyond Earth. These lines of evidence consolidate its role as a priority platform for the design, testing, and validation of extraplanetary habitability architectures and strategies.

4.4. Interior habitability: perception, comfort, and well-being in confined environments

The analysis of interior habitability on Deception Island enables the examination of a dimension that complements architectural design: the way spaces are perceived and experienced by occupants under conditions of isolation, confinement, and prolonged exposure to extreme environments. Within the context of human extraplanetary exploration, interior habitability extends beyond the provision of shelter or thermal regulation to encompass sensory, psychological, and social factors that directly influence human performance and long-term well-being [129,133,134].

At the Spanish Antarctic Base BAEGdC, the interior layout is characterized by high functional density and limited differentiation among living, working, and leisure spaces (Fig. 8B). Shared dormitories, the concentration of sanitary facilities within a single core, and the integration of the living room, dining area, and television space into a unified environment substantially reduce opportunities for privacy, environmental control, and modulation of social interaction. This configuration generates conditions of functional overcrowding, even when occupancy remains within nominal limits, and is further exacerbated during periods of over-occupancy, negatively affecting perceived comfort and the capacity for individual psychological recovery [135].

From a sensory standpoint, interior spaces at BAEGdC are dominated by cold and neutral color palettes, in contrast to the warmer chromatic schemes observed at the Argentinian Antarctic Base BAAD. When combined with an external landscape largely composed of white and gray tones, this chromatic homogeneity may reinforce visual monotony and sensory deprivation. These conditions are widely identified as risk factors for apathy, irritability, and diminished emotional well-being in confined environments [129,130,136,137]. In this respect, BAEGdC reproduces with notable fidelity one of the most critical challenges associated with space habitats: prolonged exposure to perceptually impoverished settings.

The near-total reliance on artificial lighting, mechanical ventilation, and heating systems inherent to the interior configuration imposes an additional and continuous sensory load. The absence of direct natural light restricts access to external temporal cues required for circadian rhythm synchronization, while persistent noise generated by life-support systems creates a constant acoustic background. Studies conducted aboard the International Space Station have identified such continuous sensory exposure as a contributing factor to chronic stress, cognitive fatigue, and sleep disturbances [138–140], further reinforcing the validity of BAEGdC as an analog environment for investigating these effects.

The functional rigidity of interior spaces constitutes another critical aspect of habitability. As evidenced by the internal configuration of the living module (Fig. 8B), BAEGdC lacks readily reconfigurable spaces that would permit adaptation to changing demands related to work, rest, or social interaction. This limited flexibility constrains occupants' ability to exert control over their immediate environment, a variable consistently identified as fundamental to mental health during long-duration missions [141,142]. In particular, the absence of micro-spaces dedicated to voluntary retreat or introspection hampers the management of interpersonal stress and emotional self-regulation.

By contrast, BAAD provides greater functional differentiation of interior spaces, including single-occupancy or two-person rooms, independent bathrooms, and clearly delimited leisure areas (Fig. 8D). These characteristics enhance perceived comfort, privacy, and environmental control, thereby mitigating stress associated with confinement. However, from an extraplanetary standpoint, these same features reduce the degree of similarity with highly constrained space habitats, where privacy will be limited and multifunctional spaces will predominate. Accordingly, the lower score assigned to BAAD for the *interior habitability* parameter should not be interpreted as a deficiency, but rather as reflecting a lower degree of analog intensity with respect to early human exploration scenarios.

A particularly relevant experimental opportunity arises from the incorporation of the new scientific module at BAEGdC. The availability of an independent meeting room will enable partial decoupling of work-related activities from the living module, thereby reserving common areas primarily for recreational and social functions. This modification constitutes a natural experiment for evaluating how relatively modest changes in functional zoning can positively influence perceived well-being, group cohesion, and performance, offering valuable insights for the design of extraplanetary habitats in which the separation between work and rest will be a critical design consideration.

Overall, the interior habitability data indicates that BAEGdC reproduces with high fidelity conditions of sensory deprivation, limited privacy, spatial rigidity, and technological dependence comparable to those expected during long-duration space missions. These characteristics justify the assignment of the maximum score in the interior habitability rubric and consolidate BAEGdC's value as a natural laboratory for the integrated study of perception, comfort, and human well-being in confined extraplanetary environments. In contrast, BAAD represents a setting better suited to the evaluation of operational comfort and logistical support, albeit one that is less restrictive from an analog perspective.

4.5. *Life support and telemedicine: operational capabilities and extraplanetary analogy*

Life-support systems and medical care constitute one of the most critical pillars of human extraplanetary exploration, as they directly condition operational autonomy, crew safety, and the ethical feasibility of missions conducted in environments where immediate evacuation is not possible [143,144]. In this context, the assessment of such systems at Antarctic bases enables the evaluation not only of equipment availability, but also of the actual capacity for integrated medical response under conditions of isolation, confinement, and exposure to extreme environmental hazards.

The results reveal marked differences between BAEGdC and BAAD for this parameter. At BAAD, the presence of a basic infirmary staffed by nursing personnel and equipped primarily for the treatment of minor injuries substantially limits response capability in the event of complex emergencies or acute pathologies. The absence of advanced diagnostic instrumentation, real-time external medical support, and formal telemedicine protocols significantly constrains its potential as a validation environment for extraplanetary life-support systems, thereby justifying the intermediate score assigned in the evaluation rubric. This configuration reflects a model of minimal on-site medical support, appropriate for seasonal terrestrial operations, but insufficient for simulating scenarios requiring prolonged medical autonomy.

By contrast, the data obtained at BAEGdC demonstrates a distributed medical care model based on the integration of portable clinical instrumentation, on-site medical personnel, and satellite connectivity for remote supervision. The medical unit is equipped with first-response diagnostic devices (including an electrocardiograph, portable ultrasound scanner, digital dermatoscope, pulse oximeters, and compact clinical analyzers) fully integrated into a telemedicine system that enables real-time communication with external specialists. This framework closely reproduces the principles of contemporary space medicine, in which diagnosis, clinical decision-making, and the execution of medical procedures are conducted in a semi-autonomous manner, supported by expert remote assistance [145,146].

From an extraplanetary perspective, the relevance of this system lies not only in its diagnostic capability, but also in its potential to test medical response protocols under conditions of limited resources and operational isolation. Although BAEGdC's satellite communications do not replicate the communication delays associated with those established with Mars, the operational logic (non-specialist personnel supported through telementoring, reliance on portable diagnostic devices, and local clinical decision-making), constitutes a direct functional analog of scenarios anticipated for interplanetary missions. Thus, the base enables the evaluation of critical variables such as cognitive workload on medical staff, reliability of portable equipment, and the effectiveness of response protocols under stress conditions.

An additional life-support component identified at BAEGdC is the use of specialized protective suits for aquatic operations, designed to provide thermal insulation, buoyancy, and visibility in emergency situations (Fig. 9). Although this equipment reduces maneuverability, its primary function is to ensure survival in high-risk environments. This design philosophy, prioritizing survival and redundancy over operational efficiency, is directly transferable to space suits and personal life-support systems, where protection against critical failures takes precedence over comfort or fine dexterity. Evaluating these trade-offs in real analog environments such as Deception Island provides valuable insights for the development of extraplanetary life-support technologies.

The implementation of telemedicine at BAEGdC further enables the exploration of a dimension that is often underestimated in space exploration: mental health and psychological well-being. Although the present results focus primarily on medical infrastructure and equipment, the existence of continuous communication channels with external healthcare professionals facilitates the early detection and monitoring of fatigue, anxiety, sleep disturbances, and cumulative stress. Factors widely documented in ICE environments [147]. Experience gained during the SARS-CoV-2 pandemic underscored the importance of remote psychological support systems in contexts of isolation, further reinforcing the relevance of integrating such approaches into long-duration extraplanetary missions [148].

By comparison, BAAD does not provide an appropriate framework for evaluating these dimensions, as the lack of telemedicine capabilities and advanced medical equipment precludes the implementation of continuous monitoring protocols, clinical telementoring, or remote psychological care. This limitation should be interpreted strictly as a difference in operational and analog profile: while BAAD is oriented toward basic on-site medical support, BAEGdC enables the exploration of scenarios involving progressive medical autonomy, which are more representative of human extraplanetary exploration rather than indicative of any functional deficiency of the base.

Taken together, the availability of advanced medical equipment, the integration of telemedicine systems, and the use of specialized life-support protective gear (Fig. 9) support the assignment of the maximum score to BAEGdC for the *life*-support *and telemedicine* parameter. These capabilities consolidate the base as a high-value natural laboratory for the development, evaluation, and validation of medical technologies, clinical protocols, and care models applicable to future human missions beyond Earth, where crew health will depend on autonomous, robust, and ethically responsible life-support systems.

4.6. *Risk management and operational safety: protocols, autonomy, and resilience*

Risk management in ICE environments constitutes a decisive operational axis for human extraplanetary exploration, not only because it reduces the likelihood of catastrophic events, but also because it defines a mission's capacity to sustain operational continuity under conditions of uncertainty and limited resources [149–151]. On Deception Island, risk is not hypothetical: the results establish a framework of tangible threats associated with an active volcanic system [55], rendering the island a particularly valuable setting for assessing how safety is operationalized through the integration of instrumental monitoring, formalized protocols, communication systems, and near–real-time decision-making [80].

A distinctive contribution of the Deception Island case lies in the fact that safety is underpinned by an integrated socio-technical system. A formal base-opening protocol for the BAEGdC is implemented, based on visual inspection (both external and internal circumnavigation of the island), and instrumental verification prior to personnel unshipping, with final authorization granted by the Instituto Geográfico Nacional (IGN). From an extraplanetary perspective, this mechanism is particularly relevant because it translates the *go/no-go* principle, fundamental to space operations [152], into a real-world context in which decisions are made with incomplete information, within constrained operational windows, and with direct consequences for crew safety. The existence of a pre-activity authorization procedure thus constitutes a functional analog to the safe-state criteria required prior to EVAs or other critical deployments in planetary missions.

Continuous monitoring, implemented through a distributed network of seismic sensors, GPS stations, geochemical and thermal monitoring systems, and time-lapse cameras (Fig. 10), further reinforces this analogy by enabling dynamic risk assessment. Beyond the technical instrumentation itself, the analog value resides in the operational translation of data: the volcanic risk "traffic-light" system applied daily during BAEGdC coordination meetings functions as a synthesis mechanism that converts complex technical metrics into actionable operational decisions (Fig. 10). In extraplanetary missions, where crews will be required to manage multiple, interacting layers of risk (e.g. environmental, medical, system-related, and communicational), such integrative tools will be essential for sustaining operations in the absence of immediate external support.

Another critical dimension of risk management concerns mobility and evacuation. In crisis scenarios, evacuation on Deception Island is primarily planned on foot toward exit points along the outer coastline, deliberately avoiding the interior of Port Foster due to the operational hazards associated with the Neptune's Bellows strait and potential changes in seafloor morphology (Fig. 10). The analog relevance here does not reside solely in volcanism, but rather in the fact that evacuation planning is conducted under real access constraints, environmental uncertainty, and the need to select routes dynamically based on the nature of the threat and prevailing conditions. The existence of predefined evacuation routes to multiple exit points, some of which traverse glaciated terrain (Fig. 10), enables realistic testing of principles such as redundancy, decision-making under pressure, and resource management during critical traverses [153].

In parallel, operational safety on the island is strongly conditioned by communication limitations, a central component of the extraplanetary analogy. BAEGdC relies on encrypted high-frequency (HF) radio systems for coordination and periodic GPS position reporting; however, coverage is spatially heterogeneous. While the inner ring of the island maintains reliable connectivity, segments of the outer coast lack direct communication links (Fig. 10). This discontinuity necessitates the implementation of redundancy procedures through satellite telephones operating via the Iridium constellation when activities take place beyond coverage zones. The coexistence of imperfect connectivity and redundant communication channels constitutes a direct functional parallel with extraplanetary operations, where communications may degrade due to geometry, topography, infrastructure failures, or mission contingencies. Critically, teams must operate under protocols that explicitly assume the possibility of link loss, thereby reinforcing local autonomy and decision-making capacity [154].

With respect to BAAD, its operational practices are effectively aligned with the safety standards established for the island, including the use of VHF and satellite communications, defined evacuation distances, and shared principles derived from intergovernmental agreements governing activities on Deception Island [84]. The absence of a clearly identified, independent base-opening protocol, and the observation that in several campaigns BAEGdC has initiated operations earlier, may be interpreted as evidence of a cooperative safety model, in which instrumental assessment and decision-making conducted by a single entity (IGN/BAEGdC) contribute to the operational safety of all actors involved. From an extraplanetary perspective, this arrangement anticipates exploration scenarios in which multiple modules, crews, or agencies share critical monitoring and alerting infrastructure, creating operational interdependencies.

Taken together, the accumulated evidence, including: 1) instrumental monitoring network, 2) volcanic risk traffic-light system, 3) evacuation routes and exit points, and 4) communication coverage (Fig. 10), supports the assignment of the maximum score to both bases for the *risk management and operational safety* parameter. More broadly, it positions Deception Island as a high-value analog for investigating how operational resilience is implemented when risk is real, dynamic, and multivariate, and when decisions must be taken locally through the integration of technical information and predefined operational procedures.

4.7. Planetary protection and biosecurity: environmental ethics in analog contexts

One of the features that confers exceptional value on Deception Island as an extraplanetary analog is the presence of a strict and binding environmental regulatory framework that directly conditions the planning, execution, and post-assessment of human activities. As demonstrated in this study, the implementation of biosecurity protocols, the designation of Antarctic Specially Managed Areas (ASMA), Antarctic Specially Protected Areas (ASPA), and Historic Sites and Monuments (HSM), together with the mandatory reporting of all activities undertaken, establishes a system of environmental governance that operates in close analogy to the planetary protection principles defined for space exploration [92,155].

In the specific case of Deception Island, its designation in its entirety as ASMA No. 4 implies that all scientific and logistical activities must comply with a shared Management Plan, coordinated among the countries maintaining an active presence on the island (Fig. 10). This multinational governance model, based on common regulations, shared responsibilities, and coordinated oversight, anticipates future extraplanetary scenarios in which multiple space agencies may operate simultaneously in regions of high scientific interest, such as ancient Martian deltas or lunar polar environments. In such contexts, environmental protection will depend not only on technical decision-making, but also on international agreements, regulatory enforcement mechanisms, and compliance frameworks closely analogous to those currently applied in Antarctica.

The designation of ASPA No. 140 and No. 145 on Deception Island (Fig. 10) further strengthens this analogy by introducing additional constraints on access, transit, and sampling, including the requirement for specific permits and the submission of detailed post-activity reports. These areas safeguard exceptional scientific and ecological values, and their management necessitates rigorous planning of field campaigns, limitations on personnel numbers, and minimization of physical and biological disturbance. Such restrictions closely reproduce the operational conditions anticipated for astrobiological investigations on Mars, where particular outcrops, sedimentary deposits, or hydrated mineral assemblages will be classified as scientifically sensitive and therefore subject to stringent access and handling protocols [156].

Beyond territorial zoning, biosecurity on Deception Island is implemented through concrete operational measures, including the thorough cleaning of clothing, footwear, and equipment, sterilization procedures prior to entry into sensitive areas, and systematic control of potential biological vectors. These practices, designed to prevent the inadvertent introduction of propagules or exogenous microorganisms [86], constitute a clear parallel to forward-contamination prevention strategies in space exploration [157,158]. In both contexts, the overarching objective is the preservation of the integrity of unique environments and the prevention of irreversible human-induced alteration of systems of high scientific value.

The recent incorporation of specific protocols aimed at preventing the introduction of emerging pathogens, such as SARS-CoV-2 and highly pathogenic avian influenza, further reinforces this analogy. These measures include pre-deployment health screening, restrictions on contact with wildlife, and enhanced disinfection and monitoring procedures. Such actions respond not only to the protection of human health, but also to the need to avoid unintended biological interactions between humans and local fauna, a core principle of Antarctic biosecurity [88–90]. In an extraplanetary context, this approach translates directly into the necessity of preventing cross-contamination between terrestrial biological systems and potential extraterrestrial biosignatures, while simultaneously safeguarding crew health in biologically uncertain environments [159].

From this perspective, the systematic implementation of biosecurity protocols on Deception Island should not be interpreted merely as a local environmental requirement, but rather as a normative and operational laboratory for testing the ethical principles that will govern human exploration beyond Earth. The obligation to scientifically justify each intervention, document environmental impacts, and operate under the precautionary principle reflects a transition from extractive exploration toward a paradigm of responsible exploration, consistent with contemporary frameworks of planetary sustainability [132].

Within this framework, the assignment of the maximum score (5) to the *planetary protection and biosecurity* parameter for Deception Island is supported by the convergence of three clearly evidenced elements: (i) the existence of well-defined territorial protection designations (Fig. 10); (ii) the application of strict operational biosecurity and sanitary control protocols; and (iii) an international governance system that effectively limits and regulates human activity. Collectively, these elements position the island as a high-fidelity environment for the technical, scientific, and ethical preparation of future human missions in extraplanetary contexts.

4.8. Human factors: perception, adaptation, and performance

Human factors constitute one of the most sensitive and complex axes in the evaluation of extraplanetary analog environments, as they integrate psychological, physiological, and social dimensions that cannot be inferred solely from environmental or technical variables. In the case of Deception Island, the combination of geographic isolation, relative confinement, sustained operational workload, and exposure to extreme environmental conditions configures an ICE scenario that is highly representative of the challenges anticipated for future human space exploration missions [147].

Results derived from the perception survey administered during the 2022–2023 Antarctic campaign reveal clear differences between BAEGdC and BAAD in terms of the intensity, diversity, and distribution of perceived signs and symptoms among crew members (Fig. 11C). At BAEGdC, more than 20% of participants reported eight relevant factors across multiple categories, most notably lack of personal space (54%), increased workload (43%), abrupt temperature fluctuations (40%), alterations in bedtime schedules (37%), reduced or irregular sleep duration (34%), persistent fatigue (29%), interpersonal conflicts (23%), and monotony (20%). The coexistence of symptoms spanning multiple functional domains suggests a complex human response in which environmental, operational, and psychosocial stressors interact in a nonlinear manner.

By contrast, at BAAD the most frequently reported signs are concentrated within a narrower set of categories (Fig. 11C), with abrupt temperature changes (58%), increased workload (50%), disruption of sleep schedules (33%), fatigue (25%), and bedtime alterations (25%) predominate. This reduced breadth of the symptomatic spectrum supports the assignment of an intermediate score for this base in the evaluation rubric and suggests that, although both environments are demanding, BAEGdC more comprehensively reproduces the psychological and behavioral stressors expected during prolonged extraplanetary missions [160–162].

Analysis of crew-related factors (Fig. 11A) provides additional context for these findings. At BAEGdC, the high proportion of individuals with no prior Antarctic experience (66%), together with a predominantly male crew composition (80%) and an age distribution largely concentrated between 40 and 49 years (40%), may have influenced stress perception and adaptation processes. Furthermore, the fact that 40% of participants live alone outside the Antarctic context may exacerbate perceptions of confinement and lack of personal space, particularly in an environment where privacy is intrinsically limited. At BAAD, although a comparable age profile is observed (58% between 40 and 49 years), the lower proportion of first-time Antarctic participants (33%) and differences in social composition may act as moderating factors in environmental perception.

From the perspective of physical and operational workload, data associated with Antarctic field activities (Fig. 11B) indicate that both bases exhibit broadly comparable working schedules, predominantly ranging between 6 and 10 h per day. However, subtle differences emerge in the distribution of physical effort: at BAEGdC, a higher proportion of personnel reported shorter daily walking times (0–2 h; 63%), whereas this proportion is lower at BAAD (42%), potentially reflecting differences in site accessibility and logistical organization. Nevertheless, these differences alone do not adequately explain the greater diversity of symptoms reported at BAEGdC, reinforcing the conclusion that psychological and perceptual factors play a central role.

The coexistence of sleep disturbances, persistent fatigue, interpersonal tension, and monotony observed at BAEGdC (Fig. 11C) is consistent with findings from the space neuroscience literature on long-duration missions, in which loss of privacy, environmental repetitiveness, and limited capacity to modulate sensory input are identified as key drivers of chronic stress [68]. In this context, the perception of insufficient personal space, reported by more than half of the BAEGdC crew, emerges as a critical indicator of psychological risk, closely linked to cognitive performance, emotional regulation, and group cohesion.

These findings support the interpretation that BAEGdC not only exposes crews to extreme environmental conditions but also reproduces with high fidelity the human challenges associated with confinement, cognitive load, and social adaptation, core characteristics of extraplanetary missions. Consequently, the maximum score assigned to this base for the HF parameter is not driven by the isolated severity of individual symptoms, but rather by the convergence of multiple indicators distributed across distinct functional domains, making BAEGdC a particularly suitable environment for investigating mitigation strategies, psychological adaptation processes, and the optimization of human performance in space exploration. Additionally, the presence of a multinational crew at BAEGdC (Fig. 11D), in contrast to BAAD where personnel were exclusively Argentinian, introduces cultural and linguistic stressors that closely mirror the composition and operational dynamics of crews aboard the International Space Station [163,164].

Taken together, the data presented in Fig. 11(A–D) confirm that Deception Island, and particularly BAEGdC, constitutes a high-value natural laboratory for the integrated study of human factors in ICE environments. It enables not only the identification of psychological and behavioral risks, but also the empirical evaluation of how these factors are shaped by environmental configuration, operational workload, and prior experience, providing essential input for the design of selection criteria, training programs, and psychosocial support strategies for future human missions to the Moon, Mars, and beyond.

4.9. Logistical sustainability: Resource management in remote environments

Logistical sustainability and operational autonomy constitute one of the least visible yet most decisive pillars in the evaluation of analog environments for human extraplanetary exploration. Unlike other, more immediately perceptible parameters, logistics exert a cross-cutting influence on human performance, scientific continuity, and operational resilience. In this context, clear structural contrasts emerge between BAEGdC and BAAD, with direct implications for their respective values as extraplanetary analogs.

Both bases operate structured systems for food storage and daily inventory management, enabling controlled consumption planning and waste minimization. However, the key distinction lies in their capacity for intermediate resupply. BAAD benefits from continuous logistical support through the Antarctic Logistics Hub in Ushuaia, which allows resupply operations during the campaign and provides a higher degree of operational flexibility. While this capability is highly efficient from a terrestrial logistics perspective, it reduces the degree of effective isolation and, consequently, the fidelity of the environment as an extraplanetary analog, where rapid or recurrent resupply will not be feasible.

By contrast, BAEGdC operates under a markedly more restrictive logistical framework, as it depends on provisioning from third countries and on limited transportation windows. This condition necessitates exhaustive pre-campaign planning, in which consumption rates, technical failures, medical contingencies, and scientific needs must be anticipated well in advance. From an extraplanetary standpoint, this external dependence and the practical impossibility of immediate resupply more faithfully reproduce the operational scenarios anticipated for human missions to Mars or for lunar surface habitats, where autonomy is expected to be a structural requirement rather than a negotiable variable [165].

Food inventory management provides a clear illustration of this difference. At both bases, fresh food supplies are depleted during the early phases of the campaign, followed by a progressive transition toward diets dominated by non-perishable products. At BAEGdC, however, this transition is definitive, whereas at BAAD it can be partially mitigated through resupply. This distinction has implications extending beyond nutrition: reductions in dietary variety have been associated in the literature with decreased morale, heightened perceptions of monotony, and diminished psychological well-being [166,167]. In this sense, logistical management acts as an indirect modulator of several of the signs and symptoms reported in Fig. 11C, including fatigue, sleep disturbances, and perceptions of increased workload.

From a scientific and technical perspective, logistical autonomy is further reflected in the requirement for each research team to transport all consumables, spare parts, and specialized tools, while anticipating potential failures and maintenance constraints. This planning is not centralized exclusively at the base level, but rather distributed across individual scientific groups, fostering an operational culture of technical self-sufficiency. Such an approach is directly transferable to extraplanetary missions, where in situ repair, material reuse, and resource optimization will be essential competencies for both crew survival and scientific success [168].

In the energy domain, although consumption levels are not quantified in detail, a clear dependence on fossil fuels transported from the continent is evident for both electrical power generation and heating. This limitation highlights current boundaries in energy autonomy and underscores the need for more efficient and sustainable systems. From an analog perspective, the management of peak demand, prioritization of critical loads, and strategic planning of energy use constitute a realistic training ground for future extraplanetary bases, where energy will be among the scarcest and most strategically critical resources [169].

By comparison, BAAD (despite operating under conditions of seasonal isolation) exhibits a more robust and flexible logistical system, characterized by greater storage capacity and continuous institutional support. While this strength underpins its efficient and safe operation, it partially limits its suitability for testing scenarios of extreme autonomy. Accordingly, the assignment of an intermediate score (3) in the evaluation rubric reflects a lower degree of effective logistical restriction rather than any deficiency in management quality.

Overall, BAEGdC constitutes a high-fidelity environment for investigating logistical sustainability and operational autonomy under extreme conditions. The combination of genuine isolation, preventive planning, strict inventory control, and the absence of immediate resupply enables a remarkably realistic reproduction of the logistical challenges that future human extraplanetary missions will face. These insights are fundamental for advancing the design of logistical strategies, consumption models, and support systems capable of sustaining human presence beyond Earth in a safe, efficient, and sustainable manner.

4.10. Potential for scientific experimentation and technological validation

The potential of Deception Island as an environment for scientific experimentation and technological validation is grounded not only in the similarity of its physical conditions to extraplanetary scenarios, but also in the accumulated empirical evidence derived from real-world validation of space instrumentation. In this context, the role of BAEGdC has been decisive in consolidating the island as a high-fidelity test platform for technologies designed to operate on Mars.

One of the most significant milestones supporting this assessment is the calibration and in situ testing of the Rover Environmental Monitoring Station (REMS) instrument, whose sensors were evaluated on Deception Island during the 2007–2008 and 2008–2009 Antarctic campaigns (Fig. 12). Conducted within the framework of the PERMANTAR-3 project, these trials enabled the validation of instrument performance under extreme environmental conditions characterized by pronounced thermal variability, persistent wind regimes, and dark volcanic surfaces with complex radiative properties. The fact that REMS is currently operating successfully on Mars aboard NASA's Curiosity Rover [170] provides a direct demonstration of the predictive value and technical relevance of the Antarctic environment as an extraplanetary analog.

Complementarily, field trials of the Life Detector Chip (LDChip), the core component of the Signs Of LIfe Detector (SOLID) instrument, further reinforce the relevance of Deception Island as a validation setting for astrobiological technologies. These experiments focused on the detection of biosignatures and biomolecular compounds in extreme environments, particularly within geothermal and cryogenic contexts. The opportunity to assess instrument performance in a natural setting characterized by genuine geochemical gradients and extremophilic microbial communities provides a level of realism that is difficult to replicate in laboratory-based simulators, thereby strengthening the translational potential of these developments for future life-detection missions on Mars [97,98].

Beyond the validation of individual instruments, Deception Island has enabled the establishment of sustained experimental programs in disciplines central to planetary exploration. Long-term studies of permafrost dynamics and subsurface heat fluxes [53,99], together with geomorphological investigations aimed at interpreting glacial and ice-related landforms analogous to those observed on Mars [54], have generated essential reference frameworks for understanding Martian subsurface processes. Conducted over multiple field seasons, these investigations allow for the evaluation not only of natural processes, but also of the long-term robustness of sensors, sampling protocols, and data-acquisition strategies under persistently extreme conditions.

A defining feature of the island is its experimental multifunctionality. The coexistence of research in astrobiology, geosciences, extreme microbiology, and habitability renders BAEGdC an environment in which technologies, protocols, and scientific workflows can be evaluated concurrently. All together is an essential requirement for complex

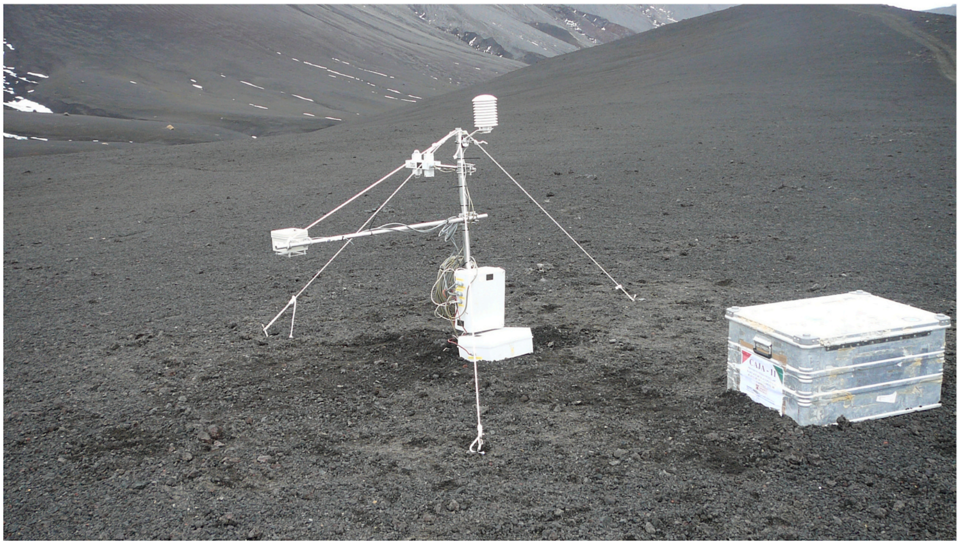

Fig. 12. Calibration tests of the REMS instrument conducted on Deception Island during the Antarctic Summer Campaigns of 2007–2008 and 2008–2009.

extraplanetary missions, where interdisciplinary integration is the norm rather than the exception. In this sense, Deception Island functions not merely as a test site, but as a comprehensive experimental ecosystem in which interactions among environmental conditions, technological systems, and human factors can be examined holistically.

By contrast, although the BAAD has a well-established record in traditional scientific research, particularly in geology, volcanology, and environmental sciences, no projects specifically oriented toward the validation of space instrumentation or technologies have been identified to date. This distinction does not imply lower scientific relevance for BAAD but rather reflects a divergence in experimental vocation between the two facilities. While BAAD is consolidated as a node for environmental and geoscientific research, BAEGdC has developed a distinct identity as a platform dedicated to the testing and validation of extraplanetary technologies.

Taken together, the evidence presented strongly supports the assignment of the maximum score (5) to Deception Island and BAEGdC for the *scientific experimentation potential and technological validation* parameter. Moreover, it positions this enclave among the few terrestrial environments where extraplanetary analogy has transcended the conceptual realm to materialize in technologies currently operating successfully on Mars, thereby reinforcing its strategic value for the design, testing, and optimization of future human and robotic space exploration missions.

4.11. Analog value of Deception Island

The integrated assessment presented in this study enables the systematic evaluation of Deception Island as a natural analog environment for space missions, moving beyond approaches based on isolated similarities or exclusively environmental criteria. The consistent application of the qualitative evaluation rubric (Table 2), supported by empirical data, perception surveys, and operational evidence, suggests that the analog value of the site emerges from the functional convergence of multiple dimensions rather than from any single dominant attribute.

At the territorial scale, Deception Island simultaneously satisfies geological, environmental, regulatory, and scientific criteria that position it above the threshold defined for high-value natural analogs. Within the evaluation framework proposed here, the attainment of the highest territorial score (20/20) indicates that the environment not only reproduces physically demanding conditions but also imposes real constraints on scientific operations that are comparable to those encountered during extraplanetary missions. Nevertheless, these scores should be interpreted within the methodological scope and limitations of the present framework (see Section 4.10). This aspect is particularly significant, as it introduces logistical, regulatory, and access-related limitations that condition planning, execution, and decision-making.

At the infrastructure scale, comparison between BAEGdC and BAAD demonstrates that extraplanetary analogy is not determined solely by the surrounding physical environment, but rather by the operational model adopted by each facility. While both bases are embedded within the same insular context, BAEGdC attained the highest score within the proposed framework (40/40), reflecting the consistent integration of confined architectural design, restrictive habitability conditions, life-support systems, active risk management, logistical autonomy, and technological validation. In contrast, BAAD, despite its scientific productivity and operational relevance, falls below the defined threshold, underscoring that analog value derives not merely from location or environmental conditions, but from the strategic and operational use of the environment.

One of the most significant contributions of this integrated assessment is the explicit incorporation of human factors as a structural criterion of analogy. Results from the perception survey (Fig. 11) indicate that psychological and operational impacts at BAEGdC are distributed across multiple categories, reinforcing its similarity to ICE environments. Unlike other analog settings where such effects are simulated or attenuated, on Deception Island they emerge as a direct consequence of the interaction among confinement, operational workload, and isolation, thereby providing a realistic framework for the study of human adaptation during long-duration missions.

Likewise, the historical validation of real space instrumentation on Deception Island (Fig. 12) constitutes a key differentiating element within the overall analysis. The successful transfer of results obtained in this environment to active planetary missions suggests that the analogy extends beyond the conceptual domain and has generated verifiable technological outcomes, thereby strengthening the relevance of the site within the international network of terrestrial analogs.

Taken together, this integrated assessment suggests that Deception Island and BAEGdC represent a high-potential extraplanetary analog, not because of the exceptional performance of any single parameter, but owing to the simultaneous articulation of extreme environmental conditions, regulatory constraints, human challenges, operational autonomy, and scientific and technological validation. This convergence positions the site as a particularly suitable platform for the development of complex analog missions aimed at jointly addressing the technical, human, and operational challenges associated with future human exploration of deep space.

Beyond its value as a case study, the methodological approach applied in this work provides a potentially replicable framework for the comparative assessment of other analog environments. It contributestoward more integrated, operational, and transferable criteria for the preparation of future extraplanetary missions and for forthcoming space-related projects to be developed on Deception Island, considering the defined parameters, the scores obtained for each of them, the specific site characteristics, and the corresponding justifications (Table 3 and Fig. 13).

Thus, Deception Island fulfills the criteria required to be formally recognized as a planetary field analog, with the Spanish Antarctic Base "Gabriel de Castilla" (BAEGdC) classified as an analog base and its operational framework regarded as an analog mission. In this context, a logical subsequent step is the inclusion of this field analog within established terrestrial analog databases, such as the USGS Terrestrial Analogs Data Portal (TADP) [171], the Planetary Terrestrial Analogs Library (PTAL) [172], and the International Space Analog Rockstore (ISAR) [173]. To support this process, a concise analog fact sheet is provided (Table 4), compiled in accordance with selected parameters proposed by Ref. [176] and further operationalized by Ref. [54]. This standardized summary enables the clear identification and comparison of the different analogy dimensions addressed in this study and provides a structured basis for the continued refinement, expansion, and development of future analog assessment and evaluation projects.

4.12. *Limitations and future perspectives*

The methodological framework proposed in this study represents an initial approach to the structured evaluation of terrestrial analog environments for human space exploration. As such, several limitations must be acknowledged to properly contextualize the results and guide future developments.

One of the main methodological considerations concerns the equal weighting assigned to all parameters within the evaluation rubric. This decision was made intentionally to ensure methodological simplicity, transparency, and reproducibility, particularly given the exploratory nature of the study and the absence of a widely accepted standardized framework for assessing planetary analog environments. Furthermore, the evaluation was designed not only to assess infrastructure, but also to characterize the island itself as an analog site, requiring an integrative perspective across environmental, operational, architectural, and human factors. At this stage, the objective was not to establish a definitive hierarchical ranking, but rather to provide a comparative and structured framework capable of capturing multiple dimensions of analog fidelity. Nevertheless, it is recognized that the relative importance of each parameter may vary depending on the mission profile, such as short-duration surface operations versus long-term habitation scenarios. Future work could therefore benefit from the incorporation of weighted evaluation schemes, including methods such as the Analytic Hierarchy Process (AHP) [177,178] or structured expert elicitation [179,180].

Another relevant limitation relates to the potential for evaluator bias in the assignment of scores. Although the assessment was based on direct field observations, operational data, and predefined criteria established prior to the field campaigns, it reflects the interpretation of the research team. While some of the authors have participated in BAEGdC campaigns, they also have experience in Argentine Antarctic bases, which contributes to a broader operational perspective. However, the absence of a formal inter-rater reliability analysis limits the ability to quantify consistency in the evaluation process. Future studies should consider the inclusion of independent evaluators and the application of statistical measures of agreement, such as Cohen's kappa [181,182], to enhance the robustness and objectivity of the methodology.

In addition, the proposed rubric has not been calibrated against other well-established terrestrial analog sites, such as HI-SEAS, MDRS, or

Table 3
Comparative assessment of the degree of extraplanetary analogy of Deception Island and Its Antarctic bases.

No.	Analogy Parameter	Deception Island	BAEGdC	BAAD	Concise Justification
1	Geology and geomorphology	5	N/A	N/A	Active volcanism, collapsed caldera, glaciers, pyroclastic deposits, and EVA-challenging relief (Fig. 3).
2	Environmental and meteorological conditions	5	5	5	Extreme variability in wind, temperature, and humidity; mandatory daily planning (in situ meteorological data).
3	Infrastructure and modular architecture	N/A	5	3	Rigid, confined modular architecture at the BAEGdC versus more comfortable cabin-type architecture at the BAAD (Fig. 8).
4	Interior habitability	N/A	5	2	Crowding, monotony, and lack of privacy at the BAEGdC versus greater comfort and differentiated spaces at the BAAD (Section 4).
5	Life support and telemedicine	N/A	5	3	Advanced telemedicine with remote diagnostics at the BAEGdC versus basic infirmary services without remote support at the BAAD (Fig. 9).
6	Risk management and operational safety	N/A	5	5	Real volcanic risk, evacuation routes, instrumental monitoring, and operational autonomy at both bases (Fig. 10).
7	Planetary protection and biosecurity	5	5	3	Strict protocols, ASPA/ASMA areas, and active biological control; higher level of systematization at the BAEGdC (Fig. 10).
8	Human factors and psychological perception	N/A	5	3	ICE-related impacts documented across multiple categories at the BAEGdC versus more limited impacts at the BAAD (Fig. 11).

(*continued on next page*)

Table 3 (*continued*)

No.	Analogy Parameter	Deception Island	BAEGdC	BAAD	Concise Justification
9	Logistical sustainability and autonomy	N/A	5	3	High autonomy and strict planning at the BAEGdC versus flexible resupply from Ushuaia at the BAAD.
10	Potential for scientific experimentation and technological validation	5	5	3	Validation of real space instrumentation (REMS, SOLID) exclusively at the BAEGdC (Fig. 12).
Total score		**20/20**	**40/40**	**27/40**	**Analogy threshold ≥75%:** Deception Island and the BAEGdC exceed the threshold; the BAAD remains below it.

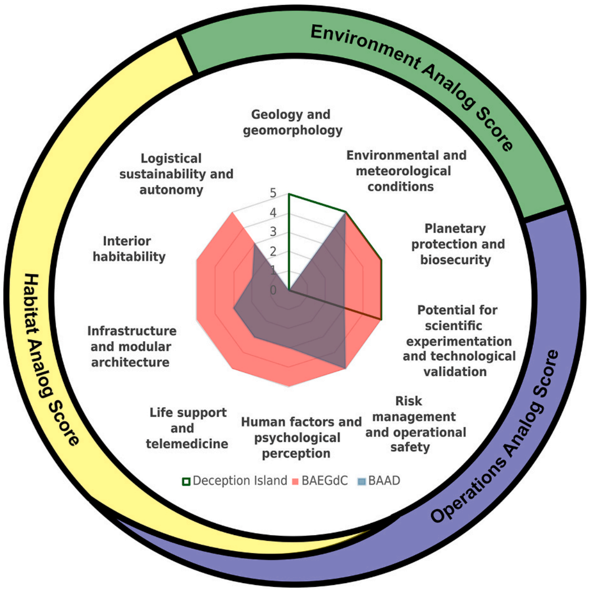

Fig. 13. Degrees of extraplanetary analogy for crewed missions of Deception Island and the Antarctic bases located on the island.

Concordia. While such comparisons would significantly strengthen the generalizability and external validity of the framework, conducting a rigorous cross-site evaluation would require a level of data access, methodological standardization, and field involvement that exceeds the scope of the present study. The current work focuses on a controlled comparison between two bases located within the same environmental context, allowing for a more consistent evaluation of operational and infrastructural variables. Nonetheless, future research should aim to validate and refine the rubric through its application to a broader range of analog environments.

The attainment of maximum scores in some cases highlights a potential ceiling effect in the evaluation scale. A maximum score does not imply the absence of limitations or opportunities for improvement, but rather indicates that the evaluated environment meets the criteria defined for the highest category within each parameter. However, this outcome suggests that the rubric may lack sufficient resolution at higher performance levels. Future iterations of the framework could therefore

Table 4
Analog site summary (Modified from Ref. [54]).

Analog Site		Deception Island, Antarctica.
Most important questions		How do glaciovolcanic, permafrost and geothermal processes interact to generate potentially habitable environments and operational conditions analogous to those expected on Mars? How can Antarctic stations be used to validate technologies and protocols for human planetary exploration?
Logistic and environmental constraints		Access by ship and helicopter (seasonal) Logistic support provided by Antarctic stations on the island (BAEGdC and BAAD) Strict environmental regulation under the Antarctic Treaty System Active volcanic hazard and permanent risk-management protocols Extreme and highly variable meteorological conditions Seasonal accessibility mainly from November to March
Summary table	Centre coordinates	62°55′36″ S; 60°34′15″ W
	Elevation	Max: 539 m (Mount Pond); Min: 0 m (sea level)
	Areal extent	~46 km^2
	Geological setting	Active volcanic caldera with post- and pre-caldera deposits, hydrovolcanism, pyroclastic sequences, lava flows
	Geomorphology	Glacial, periglacial and volcanic landforms; unstable slopes; debris-covered glaciers
	Climate	Polar maritime; high humidity (>80%), persistent strong winds, low thermal amplitude, extreme wind chill
	Environmental stressors and characteristics	Wind, thermal contrast, isolation, limited daylight variability, volcanic risk. Temperatures: Max ~13 °C; Mean ~1–2 °C; Min ~−22 °C; humidity ~90–95%; persistent strong winds; frequent storms; seasonal snow and ice coverage
	Biological context	Absence of vascular vegetation; presence of microbial mats, extremophiles and endolithic communities associated with cold and geothermal environments
	Prime science questions	- Glacial, periglacial and glaciovolcanic geomorphology - -Permafrost–volcanic interaction processes - -Climate variability and boundary-layer dynamics - -Astrobiological potential of geothermal and cold environments - -Endolithic and extremophile microbial habitats - -Validation of planetary exploration instrumentation
	Human factors relevance	Documented ICE environment effects, including workload, sleep disruption, operational stress and confinement-related impacts
	Infrastructure relevance	Presence of two Antarctic stations enabling long-term human occupation, confinement studies and operational simulations
	Technology validation	Historical validation of space instrumentation and operational protocols (e.g. meteorological and astrobiological sensors)
	Planetary protection analogy	Strict access control, biosecurity measures and environmental monitoring comparable to COSPAR planetary protection principles

(*continued on next page*)

Table 4 (*continued*)

Analog Site		Deception Island, Antarctica.
	Distance from airstrip	~140 km by ship from/to Teniente R. Marsh airfield (King George Island, South Shetland Archipelago)
	Representative Martian analog	Lower NW flank of Hecates Tholus volcano (Mars), characterized by volcanic–ice interaction and periglacial processes
	Previous studies at analog site	Geological and geomorphological cartography; glaciovolcanic and permafrost evolution; geochemical and mineralogical analyses; astrobiological and geomicrobiological studies; human-factor assessments; planetary instrumentation testing
	References	Leal et al., 2025 [4], de Pablo et al., 2012 [174], de Pablo et al., 2013 [175]

incorporate greater granularity or additional sub-criteria to better discriminate among high-performing analog sites. In line with this, the interpretation of the results has been adjusted throughout the manuscript to avoid absolute statements and to emphasize the exploratory and relative nature of the evaluation.

An additional methodological consideration concerns the threshold used to classify a site as a suitable analog. In this study, a threshold of 75% of the maximum possible score was adopted as a practical criterion to identify environments that meet a substantial proportion of the defined conditions. This threshold was intentionally adopted as an exploratory heuristic within the proposed framework rather than as a universally validated cutoff. The selected value was intended to serve as a conservative benchmark, ensuring that analog classification reflected the simultaneous convergence of multiple criteria rather than the presence of isolated or partial analog characteristics. In practical terms, a lower threshold could increase the likelihood of classifying environments that reproduce only limited aspects of extraplanetary conditions, thereby reducing the discriminative capacity of the framework. However, it is important to note that this threshold is heuristic in nature and is not derived from sensitivity analyses or established precedents in the literature. Variations in this threshold (e.g., 60% or 80%) could influence the classification of certain cases, particularly those close to the decision boundary, such as the BAAD. Consequently, this choice represents a limitation of the current approach. Future work should explore the impact of different threshold values through sensitivity analyses or data-driven methods, in order to strengthen the robustness and generalizability of the classification framework.

Regarding the survey component, the instrument was designed as a rapid exploratory tool suitable for deployment in a demanding operational environment, where time availability and logistical constraints limit the use of more extensive methodologies. However, the use of binary (yes/no) responses restricts the ability to capture the intensity or gradation of individual perceptions when compared to Likert-type scales. In addition, the analysis was conducted from a descriptive perspective, without incorporating multivariate approaches to control for potential confounding variables such as prior Antarctic experience, age, gender, or nationality. The relatively small sample size and the heterogeneity of the crews further limit the application of more complex statistical analyses. Moreover, the survey was applied at a single point during the campaign, without baseline or longitudinal measurements, which restricts the ability to assess temporal changes or cumulative effects of the environment on human factors. Future studies should therefore consider the implementation of more detailed instruments, larger and more homogeneous samples, and longitudinal designs to better characterize human performance and perception in analog environments.

Finally, the environmental monitoring of interior conditions was based on manual temperature measurements, which limits the temporal resolution of the data and does not allow for the identification of transient variations or complete daily cycles. Although this approach was conditioned by the operational constraints of the campaign, the use of automated continuous monitoring systems would provide a more comprehensive characterization of the indoor environment. Future work should aim to integrate such systems to improve data quality and enable more detailed analyses of environmental dynamics.

Despite these limitations, this work represents a comprehensive and integrative first step toward the development of a structured methodology for evaluating terrestrial analog environments. The broad scope adopted in this study, encompassing environmental, operational, architectural, and human dimensions intentionally prioritizes a holistic perspective over highly specialized analyses. As a result, the identified limitations also highlight clear opportunities for future research. These include refining the weighting and resolution of the evaluation framework, testing and calibrating heuristic thresholds, expanding comparative analyses across different analog platforms, incorporating advanced statistical and experimental designs, and adapting the methodology to specific mission objectives. In this sense, the present study lays the groundwork for future developments, opening new avenues for improving the assessment and utilization of terrestrial analogs in support of human space exploration. For example, among recently identified analog sites that have not yet been evaluated for the development of analog missions. In the case of Colombia, its first formally classified Martian analog, Nevado del Ruiz Volcano [183], represents a promising location where this type of analysis could be developed and implemented for future analog mission design. Or even other Antarctic bases that have recently been evaluated as sites for similar missions [184].

5. Conclusions

The integrated assessment of Deception Island suggests its suitability as a high-value natural analog environment for human space exploration within the framework applied in this study. The convergence of restrictive environmental conditions, operational isolation, active risk management, and stringent environmental protection frameworks provides a realistic representation of severalchallenges associated with extraplanetary missions.

The BAEGdC emergesas a particularly robust analog platform through the simultaneous integration of confined habitability, logistical autonomy constraints, pronounced human-factor impacts, life-support systems, and a demonstrated record of space-instrumentation validation. In contrast, the BAAD, although operating within the same physical setting and equipped with functional scientific and logistical infrastructure, exhibits a comparatively lower degree of integration of technological, habitational, and operational elements oriented toward the simulation of extraplanetary scenarios.

Taken together, these findings suggest that Deception Island, particularly the BAEGdC, represents a highly promising natural laboratory for the development, testing, and validation of scientific, technological, and operational strategies supporting future human exploration of deep space. Nevertheless, these interpretations should be considered within the methodological scope and limitations of the evaluation framework applied in this study.

Availability of data and materials

All the data generated or analyzed during this study are included in this published article.

Permit

This publication is part of the following projects: “Antarctica as a model for the development of astrobiology in Nevado del Ruíz and the return of its advances to Antarctic science,” endorsed within the framework of Colombia's Calls for Antarctic Research by the Colombian

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Within the framework of these projects, field campaigns were conducted on Deception Island during the austral summers of 2021–2022 and 2022–2023. Sampling activities and interviews were carried out under the following permits and authorizations: an environmental feasibility clearance issued by the Colombian Antarctic Program; authorization for access to and activities within Antarctic Specially Protected Areas (ASPAs) No. 140 and 145, granted by the Colombian Antarctic Program; certificates for the transport of biological samples from Antarctica issued by the Colombian Antarctic Program; approval from the Ethics Committee under Act No. 12-2020 of the Faculty of Sciences of the National University of Colombia, established under Resolution No. 023 of 2020 of the Faculty of Sciences; and Collection Authorization No. 005 of 2023 for Los Nevados and Gorgona National Natural Parks, issued within the framework of the General Permit for the Collection of Wild Specimens of Biological Diversity for Non-Commercial Scientific Research, granted to the National University of Colombia through Resolution No. 255 of 2014 by the National Environmental Licensing Authority (ANLA).

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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