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The performance of field scientists undertaking observations of early life fossils while in simulated space suit

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ABSTRACT

We conducted simulated Apollo Extravehicular Activity's (EVA) at the 3.45 Ga Australian 'Pilbara Dawn of life' (Western Australia) trail with field and non-field scientists using the University of North Dakota's NDX-1 pressurizable space suit to overview the effectiveness of scientist astronauts employing their field observation skills while looking for stromatolite fossil evidence. Off-world scientist astronauts will be faced with space suit limitations in vision, human sense perception, mobility, dexterity, the space suit fit, time limitations, and the psychological fear of death from accidents, causing physical fatigue reducing field science performance. Finding evidence of visible biosignatures for past life such as stromatolite fossils, on Mars, is a very significant discovery. Our preliminary overview trials showed that when in simulated EVAs, 25% stromatolite fossil evidence is missed with more incorrect identifications compared to ground truth surveys but providing quality characterization descriptions becomes less affected by simulated EVA limitations as the science importance of the features increases. Field scientists focused more on capturing high value characterization detail from the rock features whereas non-field scientists focused more on finding many features. We identified technologies and training to improve off-world field science performance. The data collected is also useful for NASA's "EVA performance and crew health" research program requirements but further work will be required to confirm the conclusions.

1. Introduction

1.1. Off-world field science

A Mars mission crew, as described by NASA's "Design Reference Architecture 5.0" [1], is expected to include scientist astronauts such as geologists and astrobiologists with one objective being, as suggested by the Mars Exploration Program Analysis Group [2], "To determine whether life ever arose on Mars". Human exploration will include scientist astronauts surveying geological formations on the Martian surface looking for evidence of present and past life. The evidence could be in the form of biologically-derived organic molecules buried in the subsurface soil horizons, or within surface rock. The evidence could also be visible fossils or other biologically-meditated sedimentary

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structures (geological biosignatures) located on the visible surface of rock units, or slightly within the rock fabric accessed by breaking open the rock during the exploration.

When field scientists such as geologists and astrobiologists explore rock units on Earth they typically first survey the site, and then photograph and document the general features characterizing the geology by identifying rock types and fabrics, reading the layer sequences and then interpreting the environmental and geological history. They select specific samples, break them open, inspect with hand lenses and if of science interest label and store them for future analysis. Equipment such as hammers, core drills, cameras, and portable geochemical sensors like X-ray diffractometers (XRD), X-Ray florescence spectrometers (XRF), and Raman instruments can be used to obtain further information while in the field. Astrobiologists have a further complication in ensuring samples are not contaminated with external organic material. Furthermore, the field scientist′s 'field observation skills' use the senses of vision, including color interpretation, sound (different rocks may emit different sounds when struck with a geological hammer), touch when examining surface textures and even taste for confirmation of grain size of fine sediments, pH, and chemistry. Field scientists also require body dexterity to gain access to locations, hand–eye dexterity and coordination for sample collection and manipulation during inspection as well as physical techniques to operate the equipment.

The first off-world field science exploration experience, the Apollo manned lunar exploration program, showed that there are big differences in doing terrestrial field science and off-world field science on EVA. Schmitt [3] in a "Field Exploration Analysis Team White Paper" summarized this as

> "Terrestrial field geology is usually a slow, deliberate, iterative process. Field geology in a space suit is physically an even slower process, however, the very difficulty of that process in space and the inherent constraints of time, requires that the practitioner be able to deliberate and iterate at a much more rapid rate than normally expected on Earth."…and…"a lunar field geologist must always be aware that time is relentless, that consumables are limited, that fatigue can be fatal, and usually, returning to a location is unlikely."

The Apollo experience showed that future scientist astronauts doing off-world field science will have their performance challenged by a combination of: the psychological pressure of exploring unfamiliar terrain, working to strict time bound periods governed by space suit consumables and mission schedules, and knowledge of a fatal outcome if the space suit is damaged or consumables are depleted. In addition, operating in a space suit puts limitations on the senses including vision, color changes due to the helmet visor coatings, a lack of sense of sound, touch and smell as well as dexterity restrictions that slow mobility causing physical fatigue. Schmitt [3] argued these challenges demand scientist astronauts to have a greater than normal field experience background and faster scientific decision making ability to achieve results that match terrestrial field science exploration.

Since Apollo, improvements have been made to space suit dexterity, weight reduction, durability and better field equipment design as tested by the NASA Desert-RATS program [4] where space suit hardware integrated with rovers and habitats using, for example, 'suit port' technology, will make donning and removing a space suit easier. However the scientist astronaut′s ability to employ 'field observation skills' will still have limitations due to restricted senses. The questions we initially considered for assessing the effectiveness of scientist astronauts ability to employ his or her field observation skills were:

- "Which field observation skills are most used while in a space suit?"
- "Can we quantify what is seen and what is missed?"
- "Can we identify and characterize early life fossils?"
- "What level of effort is needed to survey rock units?"
- "Can a scientist astronaut′s field observation skills be augmented or improved through technology or training?"

These issues were investigated from a global perspective by Schmitt [3] and Lim [5]. Schmitt [3] noted that during the Apollo missions, from Apollo 13 onwards, astronaut geological training using simulated lunar analog landscapes, resulted in a significantly better science return. Similarly, Lim [5] emphasized the need for extensive scientific science classroom and field training for astronauts in the areas of field observation and data collection methodology. Lim [5] provided astronaut field science training as part of the 'Pavilion Lake Research Project' at Pavilion Lake, British Columbia, Canada, using single person submersibles to investigate lake floor microbialite formations. The training provided field science experience in which according to Lim [5] the scientist astronaut was:

- 100% reliant on technology for his or her safety;
- Operating in a lethal environment;
- Restricted mobility and human senses; and,
- Interfacing with the submersible technology and scientific instruments to achieve a science outcome.

In addition, Groemer [6] investigated an aspect of off-world field science, looking at reducing biological forward contamination by a space suited subject using the space suit simulator AoudaX. Groemer [6] tested a laser induced fluorescent emission technique to monitor micospherules simulating microbial life transported into Habs on space suits.

In mid-2011, NASA Spaceward Bound and Mars Society Australia undertook an expedition to 3.45 Ga "The Dawn of life Trail" which includes stromatolites and microbalites near Nullagine in the Pilbara region, Western Australia, to investigate early life on Earth [7,8]. Participants included field scientists and teachers specializing in geology, earth sciences, astrobiology and engineering. A space suit field trial at the site was conducted using the University of North Dakota′s NDX-1 pressurizable space suit with the aim to undertake a preliminary overview study, assessing the performance of scientist astronauts when searching and characterizing geological biosignatures while in simulated EVA. The participating field scientists and teachers were the 'scientist astronauts'. The objective was to gain an overview of the issues and quantify scientist astronaut field performance while in simulated EVA, and identify new technologies and training to augment off-world field science.

We define a simulated EVA as an EVA where scientist astronauts are traveling by rover to a series of locations to undertake surveys on foot. Each location EVA is time-bound to the mission schedule governed by the rover and space suit consumables. We considered the "Dawn of Life Trail" early life geological biosignatures as analogs of hypothetical visible Martian fossils at a location on the Martian surface, to be visited and surveyed by scientist astronauts as part of a Mars field science mission.

2. Material and methods

2.1. The 'Dawn of life trail' stromatolite fossils: an analog for potential visible fossils on Mars?

The oldest and least controversial biosignatures identified that are visible to the human eye are stromatolite and microbalites fossils found at the "Dawn of Life Trail" dated 3.45 Ga, the early Archean epoch period [9–11]. They could be analogs to potential visible fossils on Mars. The fossils occur in silicified limestone and minor banded and black chert outcrops and low ridges overlaying a 50 m thick band of, flow-banded, fine-grained and porphyritic, fragmental felsic volcanic rocks [12]. The silicified limestone, due to its age, is structurally deformed, fragile and fragmented to < 1 m long and wide size blocks. Many fossils are present but they can be faint or hard to discern in the outcrops. The most common stromatolites seen are convex stromatolites, followed by low relief convex stromatolites and cones (Fig. 1 [12]).

Stromatolites and microbalites are microbial organo-sedimentary deposits with planar to sub-planar laminated internal macro-fabrics of benthic origin [13]. They are not single entities but made of independent photosynthetic microbes growing on top of a lower sandwich of sand and dead microbial layers. They live in an aqueous environment as shown by their present day counterparts at Shark Bay Western Australia (Fig. 1 [14]). Independent fossilized microbes from the early Archean, or before, are difficult to verify and remain controversial biosignatures [15–18]. Given that stromatolites are simply 'heaped' microbes on lake or ocean shorelines, and Mars had a warm and wet period at the same time that the early Archean stromatolites were flourishing on Earth [19], it is not unreasonable to suggest that hypothetical first visible life on Mars would be similar [20,21]. Certainly stromatolites would be potentially observable by scientist astronauts on the surface of Mars, whereas microfossils would not be visible.

The Pilbara fossils are preserved in silicified calcium carbonate or limestone and are evidence of atmospheric CO_2 dissolved in bodies of water. According to Ehlmann [22], the Mars Reconnaissance Orbiter's CRISM has detected, magnesium-carbonates and kaolinite in the Nili Fossae region with evidence of mineral phases and assemblages indicative of a low-grade metamorphic or hydrothermal aqueous alteration, typical of neutral to alkaline conditions. Brown [23] suggests that Nili Fossae may have been, during the Noachian period, 3.7–4.1 Ga, a habitable location and the magnesium carbonates were deposited in an aqueous environment from a hypothermal vent. Brown [23] also argues

Fig. 1. Stromatolite fossil examples in silicified calcium carbonate rocks at the "Dawn of Life Trail", Pilbara Western Australia: The stromatolites are seen as (A) pyramid shaped striated wave patterns, a few with a spine from the base to a pinnacle, sometimes crenulated (C), or (B) 3 dimensional pyramid structures; and (D) magnesium carbonate sample from Basque Lake British Columbia possibly similar to the Nili Fossae magnesium carbonates on Mars. (E), living stromatolites (dark rocks) and macrobalites (yellow material) at Shark Bay Western Australia.

that the mineral assemblages in the Archean Warrawoona Group of Western Australia, which includes the "Dawn of life trail" in the Pilbara, have a low-grade metamorphic aqueous history and are a potential analog to the Nili Fossae carbonate-bearing rock units. An outcrop of magnesium-carbonate rocks at Nili Fossae may look very similar to the calcium carbonates in the Pilbara if both rock units have been subjected to low grade metamorphism as seen in Fig. 1D.

Thus, on the basis of similar age, somewhat similar material aspect and color (Fig. 1A–D) and similar low-grade metamorphic depositional history in an aqueous environment, we argue that the stromatolite fossil bearing 3.45 Ga silicified limestones in the Pilbara used for the space suit trials are a reasonable analog for hypothetical stromatolite fossil bearing magnesium-carbonates located at Nili Fossae on Mars. This statement does assume that the Nili Fossae rocks, which have not yet been closely examined, have a similar level of metamorphism and alteration as the Pilbara formations.

2.2. The North Dakota Experimental-1 (NDX-1) space suit

The North Dakota Experimental-1 (NDX-1) space suit system [24] is a pressurized planetary space suit concept demonstrator for analog Moon and Mars testing, made by the University of North Dakota in 2005 and funded by NASA's Experimental Project to Stimulate Competitive Research Program. The space suit is part of an iteration of planetary suit concepts designed to be analog test-beds trialing new materials and component assemblies. These are evaluated in field tests and results applied to future planetary suit development projects.

Prior to the Pilbara expedition, the NDX-1 field tests included: (1) manual core sample drilling into an esker, North Dakota in 2009 [25]; and, (2) manual drilling in permafrost subsurface, Antarctic in 2011 [26]. Additional qualification testing was performed in other sites. We used the space suit in the Pilbara as a 'concept demonstrator' located in an analog environment simulating off-world field science. Table 1 and Fig. 2 summarizes the technical description of the NDX-1

2.3. Space suit safety and operation Issues

The NDX-1 space suit is air-tight and thus poses critical safety issues, particularly in field applications. These include:

– Failure of air supply resulting in rapid build up of CO_2 resulting in asphyxiation;

Table 1
The NDX-1 Space suit technical description as used in the Pilbara Field Trials.

General description	A high fidelity planetary pressurized test-bed space suit for analog Moon and Mars operations and hardware testing.
Mass	Suit mass = 23 kg, PLSS mass = maximum 9 kg ($_{max}$), total mass = 31 kg.
Construction	A two-piece suit consisting of a lower trouser assembly and upper composite hard torso assembly coupled at chest level via a dual-plane composite enclosure ring. The upper torso has a neck dam assembly and coupling ring for a removable helmet. The trousers and arm sections are constructed of fabric with adjustable straps for different body sizes.
Materials	All restraint layer joints and fabric are constructed of Milennia material, 60% Para-aramid fibers and 40% polybenzoxazole fibers. The pressure bladder is a fabric garment coated with latex.
Operating pressure	31 kPa (4.5 psi) above ambient air pressure (as per the Apollo Mission Space Suit).
Gas supply	Atmospheric air pressurized by two compressors located in the primary life support subsystem (PLSS).
Primary Life Support Subsystem (PLSS)	Two 12 V DC air compressors each with an independent umbilical tube to the suit or helmet driven via a trailing cable from an external power supply.
Communications	Scientist astronaut and external instructor have headsets linked with cable.

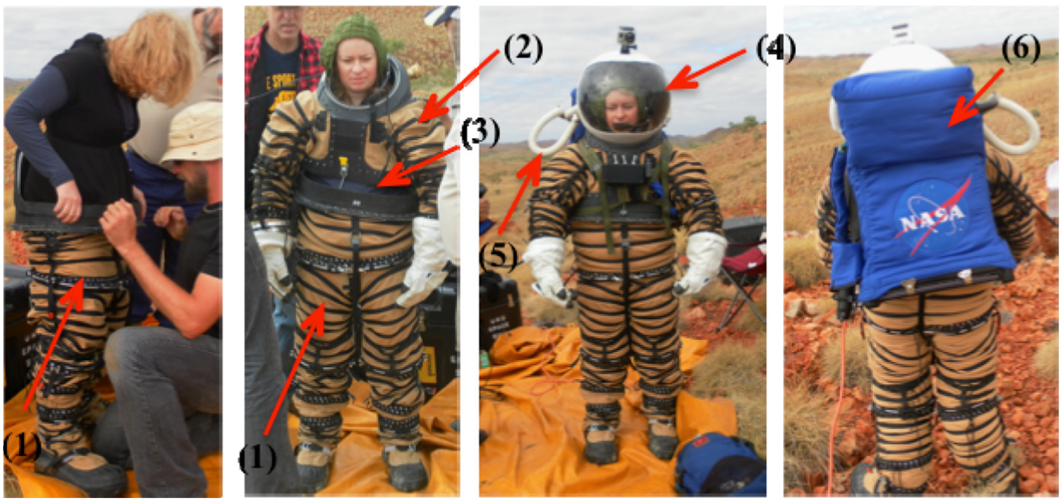

Fig. 2. The NDX-1 space suit: (1) lower torso, (2) upper torso, (3) dual plane composite enclosure coupling, (4) removable helmet clamped to neck dam assembly ring, (5) air lines, and (6) PLSS: two 12 V compressors and power cable.

– A lack of a cooling garment, (due to unavailability for this field test) potentially causing in hyperthermia; and,
– The confined suit and helmet space potentially inducing claustrophobia in untrained individuals.

A build up of CO_2 is possible if the primary life support subsystem (PLSS) dual air compressor power supply becomes disconnected from the external power source (see Table 1 and Fig. 2) or the compressors fail. The NDX-1 currently has a biomedical wireless sensor system that alerts to abnormal CO_2 and O_2 levels. A 20 m trailing cable was used to provide power from a nearby vehicle's 12 V DC battery. The air compressor must operate continuously to supply the user with air and keep the space suit pressurized. There was no bottled reservoir of air or spare battery power available in the PLSS in the event of a failed air compressor or power supply. The space suit user could go unconscious without warning and death from asphyxiation would be rapid given the confined helmet volume. We managed these safety issues by having three support people during deployment. The first support person, a 'cable operator', was responsible for shepherding the power cable, ensuring it did not hinder the scientist astronaut or become disconnected or tangled. A second support person, a 'safely officer' was located within meters of the scientist astronaut and was ready to decouple the helmet in the event of any safety issues such as asphyxiation hyperthermia and claustrophobia arising. The helmet could be removed in seconds by pulling and rotating a safety latch on the neck dam safety ring. A third support person, our 'scientist astronaut instructor', was linked to the suit communications. This person verified observations, passed on safety instructions and listened to the scientist astronaut comments and communicated any safety issues that arose to the rest of the support crew.

The Pilbara trials were conducted in July 2011, the Australian winter period, and the NDX-1 space suit was not equipped with a cooling garment, due to being unavailable at the time. The combination of thermal energy generated through heavy physical activity and the moderate Pilbara climate resulted in the user experiencing high temperatures and sweat condensation over time. We did not have a bio-medical data logger to monitor heart rates and temperature thus we managed metabolic stress by restricting the scientist astronaut field survey duration to a maximum of 15 min plus 5 min for suit familiarization. One subject terminated the experiment quicker than 15 min due to condensation inside the helmet restricting visibility.

Finally, the space suit, while adjustable, fitted best people of average height or slightly taller. Two of the subjects, a field geologist and a teacher were well below average height and did not fit the suit well, making mobility difficult. This affected their field performance compared to the others thus affecting our results. Scientist astronauts on EVA will have suits sized to fit the wearer. In general the safety issues and power supply practicalities resulted in the scientist astronaut being surrounded by people at all times and could only walk as far as the radius of the 20 m power cable thus restricting the size of the site accessible for close visual inspection.

2.4. The field trial methodology

We considered, for this preliminary overview study, a hypothetical Mars mission with the objective to undertake a general field survey of the Nili Fossae region. We perceived a plausible scenario where scientist astronauts are exploring the Nili Fossae region in a rover, visiting a series of locations that they survey on foot. Each location visit is scheduled as part of a time-bounded mission program that maximizes gathering of field data from all the locations within the rover and space suit endurances. Thus each location field survey is given a duration time estimate scheduled in the mission program. This scenario is similar to the exploration experiences of Apollo 14 to Apollo 17 lunar missions.

We considered at one hypothetical location the scientist astronauts find rock units embedded with numerous stromatolite-like features. Are these features true biological fossils, or simply an artifact resulting from metamorphism and water/mineral ingress? The scientist astronauts must explore and find these answers during their EVA, and choose whether to change the Nili Fossae field survey mission schedule, allowing for detailed investigation, or move on to the next location. Staying for detailed investigation could provide a major scientific discovery but at the price of canceling other location surveys planned for the mission. This presents a plausible and likely Mars mission scenario where scientist astronauts will be faced with gathering data to test hypotheses, and making choices in the field involving where to focus their limited resources to achieve best science outcomes, with little assistance from mission control due to time delays. The dilemma described here is typical in terrestrial field science surveys and we expect will be amplified on Mars exploration missions.

Thus our simulated EVA at the "Dawn of life trail" had the opportunity to overview and address five questions:

1. Can we quantify what is 'seen' and what is 'missed' while investigating the difference between a simulated EVA survey and typical terrestrial "ground truth" survey?
2. How well can we identify and characterize early life fossils in a space suit?
3. What is the performance difference between a field scientist and a non-field scientist?
4. What are the limitations on field observation skills while wearing a space suit? and
5. What technologies and training can augment off-world field science?

Ideally this type of overview investigation requires as many science-trained participants as possible to build the broadest and most comprehensive data set. However, our overview investigation only had 5 subjects available due to the travel and logistics costs, and the in-situ available time at the remote location in the Australian Outback. We defined our subjects as scientist astronauts when they were in simulated EVA. They were from one of two backgrounds:

1. The field scientist: Individuals with a science background combined with considerable (over 15 years) field experience; and

2. The non-field scientist: Individuals with a science background with undergraduate level field experience.

The subjects on our Pilbara trials included two field scientists, a geologist and environmental scientist with at least 15 years field experience, and three non-field scientists consisting of two science teachers and one physics undergraduate student, all with backgrounds in geology, biology, and some planetary science. One teacher had significant field experience in biology. All subjects had no previous training in space suit operation. We argue that all subjects be either fully trained, satisfying a competency based training standard (where subjects have demonstrated their ability to a certifier), or not trained at all. Thus we eliminating the performance variability between subjects caused by space suit training differences. All subjects were given a 1 h safety training prior to the trials.

Furthermore, when assessing performance, it is difficult to separate the effects of the variables: the psychological fear of exploring an unknown environment, fear of death in the event of an accident, space suit mobility restrictions, vision restrictions, and the strict time-bound nature of EVA and mission schedules. These variables integrate together making the overall EVA experience. We did not attempt to separate these variables, as this trial was a preliminary overview. Separation of the variables and measuring time and energy metrics for specific tasks was for future work. Each subject undertook a simulated EVA where we recorded: (1) the number of stromatolite features identified by the subject, and (2) the quality of characterizations of the features seen, by comparing the subject′s descriptions to the attributes listed in Table 3. After the simulated EVA was completed, each subject "ground truthed", out of suit the previous areas surveyed while in suit. The ground truth observations was compared to the observations done in the simulated EVA conditions. All observations were verified by an instructor that accompanying the astronaut scientists.

A "ground truth" [29] by field scientists is defined as all information that can be collected on location. In this case ground truth is the data from a suite of direct observations by the subject with no technology between the subject and the rock units. Ground truth surveys are by nature not time bounded, that is, time in the field is governed by the completion of the ground truth, whereas, for example, the Apollo EVA surveys were strictly time bounded, that is, the time in the field was governed by space suit endurance and mission schedules.

We chose an area on the "Dawn of Life Trail" that our scientist astronauts had not previously seen. It consisted of two narrow low silicified limestone ridge outcrops running parallel, 10 m apart, with a roughly level 6 m section, leading to a second 5–10° sloped 6 m section, followed by a third 25° sloped 6 m section (Fig. 3). All sections were rough, strewn with 150 mm sized rock rubble and vegetated with *Spinifex* grass. This provided a terrain that ranged from rough flat areas to rough steep sloped areas enabling the assessment our scientist astronaut abilities to act as off-world field scientists operating in challenging conditions. The challenges evident included the psychological pressure from the risk of slipping and falling on the slope to mobility and dexterity challenges on the rough surface and fatigue, all while attempting to find and characterize fossils in the space suit that limits or inhibits human senses. The level of geological field science investigation undertaken by the scientist astronauts from an overview perspective is listed in Table 2.

The scientist astronauts donned the space suit on the level area near a support vehicle and were given 15 min to find, identify and characterize as many fossils as possible within the three 6 m sections beginning from the vehicle start point (Fig. 3). During the course of their 15-min survey, they visited a choice of 12 possible locations along one ridge and part of the second ridge. When completed, they removed the space suit and then were directed to walk the same path to the same locations, previously visited while in suit, undertaking characterization ground truth with no time constraint. Overall, the time spent to establish their ground truth was about 30 min, which also ensured the trial proceeded in reasonable time.

Table 2
Field science investigation tasks undertaken at the "Dawn of Life Trail".

Field science investigation task	Investigated = X, Not Investigated = 0
Assessing the landscape geologically and geomorphologically for potential suitable sites to investigate in detail.	0
Identifying suitable rock outcrops for closer inspection.	0
Surveying the rock outcrops and morphology.	X
Identifying potential features of interest in the rocks.	X
Characterizing rock features.	X

Fig. 3. Field trial operations at the "Dawn of Life Trail" at: (Left) 'Cable operator' guiding the PLSS trailing cable near the flat section: (Center) A scientist astronaut bending down to investigate a rock outcrop with the astronaut trainer on the rough terrain ridge; (Right) A Scientist astronaut investigating a rock outcrop on the 25° slope section with on-looking children from Nullagine.

The simulated EVA survey was limited strictly to 15 min in order to: (1) simulate the time bound nature of an Apollo EVA field survey, and (2) manage metabolic stress as previously discuss. Furthermore, for a preliminary overview trial, 15 min was deemed enough time to experience traversing the rough and steep sloped terrain in suit, undertake observations, and characterize features in most locations. The subjects were free to select their own locations to investigate and in their own way, as per their normal field science work.

The astronaut instructor, a geologist with 20 years field experience particularly with the Pilbara stromatolites, verified both the simulated EVA and for the ground truth observations by the scientist astronauts, recorded the number of correct and incorrect stromatolites, their characterization descriptions, and their debriefing comments for when wearing and when not wearing the space suit.

Table 3 lists all the possible characterization descriptions for the fossil attributes seen in the rock units by the scientist astronauts. The data recorded enabled us to: (1) determine each subject′s observation performance by comparing the number of features seen in simulated EVA to the number of features seen in the ground truth; (2) measure a subject′s overall performance by ranking together (refer Section 3) the number of features seen and characterization data; (3) compare the field scientist overall performance to the non-field scientist overall performance; and (4) identify, from our observations of the subjects operating in simulated EVA and their comments, new technologies that could augment off-world field science performance.

3. Results

3.1. The exploration metric rating

The characterization descriptions of features listed in Table 3 was grouped and allocated to an exploration metric rating as shown in Table 4 where the exploration metric ratings range from 1, ‘Ambiguous evidence for proof of past life’ to 5, ‘Unequivocal evidence for proof of past life, with a new in-sight’. These rating values were derived from Forrest [27] who developed general exploration metrics to quantify the performance of underwater astronaut surveys in single person submersibles at Pavilion Lake, British Columbia, Canada, as part of the ‘Pavilion Lake Research Project’. The exploration metric rating is used, in this case, as a measure of a feature′s science value, based on the characteristics described by the subject that match those listed in Table 3. Table 4 also shows, in our view, the group of characteristics needed to decide whether the feature seen is a stromatolite fossil or not. We suggest the evidence proving past life would be the same for both

Table 3
The characterization attributes of stromatolite and microbial fossils as seen by the subjects as shown in Fig. 1.

No.	Fossil attribute	Characterization descriptions
1	Rock outcrops/ridge	Sedimentary and once been in an aqueous environment
2	Rock type	Calcium carbonate
3	Parallel laminations	Forming a layered triangle (Stromatolites) or flat (bio-mats)
4	Crenulated lamination	Elevated striations, triangular or flat
5	Spine in triangular pyramid	A central spine from the triangle mid base to the pinnacle.
6	Cones	2–5 cm high cones
7	Number	Many of 3, 4, or 5 together

Table 4
List of rating values for characterization descriptions for exploration metric rating (Forrest et al. 2010) and evidence for proof of past life.

Exploration metric or rating	Science descriptor	Definition	Characterization of evidence seen in the feature: refer Table 3 for characterization descriptions	Evidence for proof of past life: is the feature a stromatolite fossil?
1	Limited	Data provides limited scientific value.	Any one of characterization descriptions: 2–7	*Ambiguous evidence for proof of past life.* Not enough evidence for feature to be a fossil
2	Adequate	Data reaffirms existing hypothesis and facts.	Either set of characterization descriptions: (2, 3 & 7) or (2, 6 & 7), (6 & 7)	*Evidence supports proof of past life.* Feature could be a fossil
3	Significant	Date elucidates existing hypotheses in new areas or detail.	Either set of characterization descriptions: (2, 3, 4, 7), or (2, 4, 6 &7)	*Multiple observations supporting proof of past life.* Much evidence that feature could be a fossil.
4	Exceptional	Data resolves a major scientific question or highly significant hypothesis.	Either set of characterization descriptions: (2, 3, 4, 7 & 5), or (2, 3, 4, 7 & 6)	*Compelling evidence for proof of past life.* The feature is a fossil.
5	Discovery	Data introduces a novel idea or hypothesis.	All the above and with features not listed in Table 3.	Unequivocal evidence for proof of past life, with a new insight.

Earth and Mars although in practice, Table 3 fossil attribute no. 2, "calcium carbonate" may be different on Mars to Earth that could influence the interpretation of features showing attributes 3–7 in Table 3.

3.2. Ranking

Ranking the combination of the number of fossils seen, and the exploration metric rating assigned to each subject's descriptions provides the measure of performance. Appendix A lists the number of the features seen by the subjects in simulated EVA and ground truth, the sum of the exploration metric rating scores from in simulated EVA and ground truth, and the corresponding performance ranking for in simulated EVA and ground truth for each subject. The exploration metric rankings given to each feature seen by the subjects is not listed in this paper. Thus, the performance ranking for each subject is calculated as:

The performance ranking=

[The exploration metric rating × a level of importance factor (=5)]+

[The number of stromatolites identified × a level of importance factor (=1)].where

1. The exploration metric rating=a group of characterization descriptions listed in Tables 3 and 4 for a feature described by the scientist astronaut; and
2. The number of stromatolites identified=stromatolites or closely located sets of stromatolites identified by the scientist astronaut.
3. The level of importance factor=a factor which differentiates the importance between the exploration metric rating and the number of stromatolites identified.

We assigned a level of importance of 5 to the exploration metric rating, and a level of importance of 1 to the number of stromatolites. This reflected, in our opinion, that the quality of the characterizations seen was 5 times more important than the number of stromatolite examples found. That is, it is more important to find examples showing good evidence than to find repeated examples.

4. Discussion

4.1. Field trial objective questions

Analyzing the field trial results shown in Appendices A and B provided answers for the first four objective questions from Section 5. These are:

(1) Can we quantify what is 'seen' and what is 'missed' during an EVA field survey?
Table 5 taken from Appendix A data clearly shows that our 5 scientist astronaut ground truth surveys found approximately 25% more stromatolites compared to the simulated EVA surveys. It can be argued that this result is distorted by the fact that the scientist astronauts viewed the same locations twice, the first time while in simulated EVA conditions and the second time when conducting the ground truth. We suggest that what was seen for first time in simulated EVA conditions would be the minimum seen in the ground truth survey. Thus the 25% difference is a reasonable deduction from the trial.
The reasons for the difference become apparent in the comments and observations from the scientist astronauts listed in both Appendices A and B. The comments include: limitations to panoramic vision, short sight vision only, lateral and vertical vision restrictions, color changes due to visor tinting; poor suit fitting; limitations on mobility and dexterity, fatigue, time limitations, and fear of tripping when climbing over objects.
We noted that the shorter subjects found mobility harder because they were undersized for the space suit. However this did not appear to affect their ability to perform science, that is discern features in the rock fabric and characterize them. Space suit operation training may improve performance, given that all subjects had little training. This issue will need to be explored in future work.

(2) How well can we identify and characterize early life fossils in a space suit?
This issue is crucial in determining the effectiveness of off-world manned science exploration and we reviewed it with two approaches.
The first approach investigated the misidentification difference between the simulated EVA survey and the ground truth (Table 6). The geologist instructor accompanying the scientist astronauts verified the identifications and the characterizations for all surveys. Table 6 shows a total of nine incorrect identifications for the simulated EVA surveys where the instructor judged "no fossil" for features identified as "fossil" by the subject. The ground truth surveys had 3 features incorrectly identified. Thus, there were significantly more incorrect identifications made in simulated EVA compared to the subjects ground truth survey without a suit. Further trials exploring different geological formations, the effect of geological field experience and of space suit

Table 5
What is seen: in simulated EVA, and from ground truth survey.

	Total number of stromatolites found: while in simulated Apollo EVA	Total number of Stromatolites found: from the ground truth survey
Total	82	113
% difference	73	100

Table 6
Comparison of incorrect identifications.

Number of incorrect identification while in simulated Apollo EVA	Number of incorrect identified in the ground truth survey
9	3

training is needed to better understand this issue.

The second approach investigated how well the subject could characterize the features while in simulated EVA and the ground truth (Table 7). Table 7 shows the difference, expressed as a ratio, between the number of features identified for each exploration metric rating for simulated EVA and for ground truth and the ratio vs. the exploration metric rating trend is shown in Fig. 4. We see in Table 7 and Fig. 4 that the difference ratio is greatest for low exploration metric ratings and the least for high exploration ratings. That is the more significant the feature found, the less impact the simulated EVA experience had on the subjects capacity to characterize the feature.

We would have expected the reverse, but possibly when a fossil has important science characteristics, more attention is given by the subject to providing a good characterization regardless of space suit and EVA limitations. Again, this result needs reviewing on future trials on different geological formations.

(3) What is the performance difference between a field scientist and a non-field scientist?

This issue is about deciding whether an off-world exploration crew should consist of for example, in one extreme mostly engineers and pilots with field science training, or in the other extreme, mostly scientists with an extensive field science background. We approached this issue by looking at, for each exploration metric rating the average number of features seen, by the field scientists and by the non-field scientists in simulated EVA. This is listed in Table 8 and plotted in Fig. 5.

Table 8 shows clearly the field scientists found and characterized features with higher exploration ratings (metric 4) than the non-field scientists. Conversely Fig. 5 shows the non-field scientists finding more features than the field scientists. This fitted our observations of the subjects where we noted: the field scientist subjects generally focused more on capturing good characterizations of the features they found than finding the features, whereas the non-field scientist subjects generally focused more on finding features than capturing good characterizations.

We could conclude from these results that an off-world crew with non-field scientists will find good evidence but may find their lesser field experience skills harder to employ due to the EVA challenges, resulting in loss of information. Conversely an off-world crew with experienced field scientists would provide a better science return, particularly if the science discoveries are very important. In practice a Mars exploration mission crew skill profile will be mixed but having some experienced field scientists would capture high value science characterizations, test hypotheses and make key science decisions. Our preliminary trial shows they could be assisted by engineers trained in field science to search and find interesting features complimenting the field scientist skills. However, further field trials with more subjects that match hypothetical mission crew skill profiles will be required to support this conclusion and to determine the best crew skill profile.

(4) What are the limitations on field observation skills while wearing a space suit?

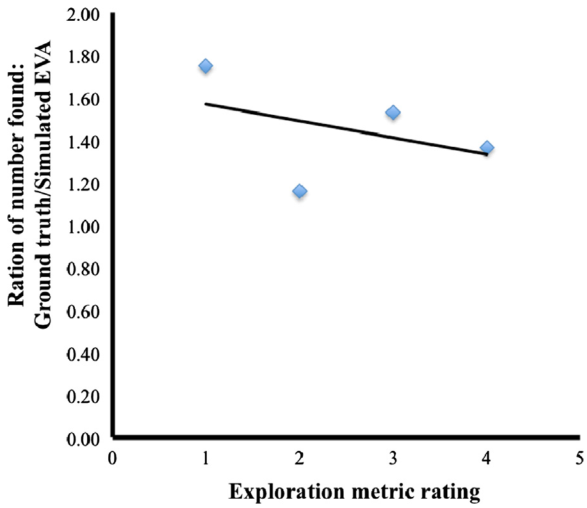

Fig. 4. Ratio of number found: ground truth/simulated EVA vs. the exploration metric rating. Data from Table 7.

Table 8
Number of features found per exploration metric for field scientists and non-field scientists.

Exploration metric	Field scientists average number found	Non-field scientists average number found
1	2.5	3.7
2	6.5	8.3
3	3.0	3.7
4	5.5	0.0
5	0.0	

Table 7
Table of exploration metric ratings and number of examples found, for in simulated EVA and for ground truth surveys.

Exploration metric rating	Science descriptor	The number found while in simulated Apollo EVA	The number found from the ground truth survey	Ratio of ground truth/simulated EVA
1	Limited	16	28	1.75
2	Adequate	38	44	1.16
3	Significant	17	26	1.53
4	Exceptional	11	15	1.36
5	Discovery	0	0	0.00

This issue is about identifying the limitations imposed on the scientist astronaut ability to undertake off-world field science leading to identifying technologies and training that can augment off-world field science performance.

Appendix B, starting on the left, lists: the attributes contributing to field observation skills, the use of these attributes while undertaking terrestrial field science, the limitations of the attributes by space suit operations during off-world observations; leading to, suggestions of new technology and training to augment space suit limitations. We noted the 'color identification' attribute listed in Appendix B could not be tested as the space suit did not have a tinted visor. Section 4.2 discusses the technology and training suggestions.

Our overview of the field work and comments is that our scientist astronauts needed to get close to the fossil features to enable best examination (Fig. 6) and also expended considerable energy moving between locations to survey the outcrops to search for more examples. Vision was the only useful human sense available, as touch, smell and taste were clearly limited or no option. Getting close to the rock units required considerable effort by the scientist astronaut to overcome the mobility, dexterity, and vision limitations imposed by the space suit and poor fitting of the space suit made field mobility very difficult for one field scientist and one non-field scientist as they were both below average in height.

Clearly, fatigue induced by the effort of moving became the dominant limitation reducing the performance of the scientist astronauts. A good strategy was to move as little as possible, concentrating on doing detailed characterization at a few locations instead of visiting many locations doing poor characterization of the examples expending considerable energy.

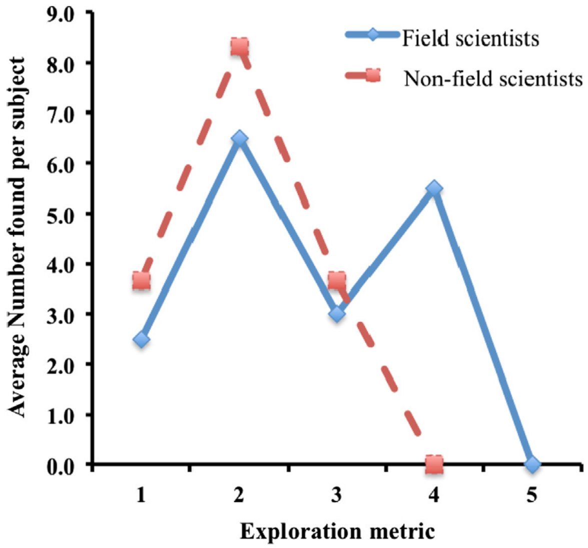

Fig. 5. The average number of features found per subject vs. the exploration metric, for field scientists and non-field scientists. Data from Table 8.

4.2. *Technologies and training to augment off-world field science*

We derived in Appendix B, from the scientist astronaut comments, proposed technologies and training to augment the performance of the scientist astronauts undertaking off-world field science. Common themes for identifying new technologies and training became apparent from Appendix B table. These were:

- Minimize the energy expenditure by the astronaut through maximizing the space suit hand and knee dexterity, fitting adjustment and vision;
- Provide field science observation tools aimed to minimize the expenditure of energy by the scientist astronaut;
- Provide training in analog locations aimed to improve management of time, motion, energy usage, and risk awareness; and
- Provide training in general field science competencies to improve efficiency of field science decision-making.

Tables 9 and 10 summarize our suggestions for technologies and training, stemming from the general strategy described above and in Appendix B.

4.3. *Applicability to the 'NASA Human Research Program'*

The Pilbara space suit trials are an example of a testing approach that can reduce risks and close gaps identified in the NASA Human Research Program (NASA Human research road mapWeb) [28] "Integrated Research Plan" HRP-47065 Rev C. For example, section, 2.3.1.4 "Risk of Compromised EVA Performance and Crew Health due to inadequate EVA Suit Systems (Short title EVA)" specifically

Fig. 6. A scientist astronaut attempting to get close to a rock unit to identify a 3.45 Ga stromatolite fossil.

Table 9
Technologies to augment off-world field science.

Space suit/augmentation	Technology in order of priority (Aim: Maximize field science outcomes for minimum energy expenditure by the astronaut)
Space suit improvements	Improving space suit dexterity for kneeling and hand operation. Improve adjustment for fitting space suits to different size and shape people. Improve vision vertically down and up and laterally.
Augmentation technology	Verbal directed scheduler and audio timer. Camera on extendable pole with display to see features close up. Camera and display with controls suited for glove handling. Verbal directed lable that lables on voice comand fixed on sample containers. Sample containers suited for glove handling. Sample handling devices. 'Safe' rock hammer design reducing damage to suit visors from chips. Safe Health monitoring of crew with audio feedback including a Radiation detector in the PLSS. Meteorological station linked to positioning device in PLSS for long term environment monitoring. Space suit friendly hand portable instruments: radiation detector, Raman, XRF and XRD and core sample drills and temperature probes.

Table 10
Training to augment off-world field science.

Training in order of priority
General Field Science activities conducted in analog locations. Field Science activities conducted in simulated EVA with pressurizable space suit in analog locations focusing on improving activity efficiency and safety. General time and physical exertion management. Field science work efficiency and safety assessment and planning. Assessing impact of fatigue on health. Data collection and logging.

states that crew performance during EVA and their health in the long term can be compromised by improperly designed EVA suit systems. The integrated research plan emphasizes the importance of understanding of the relationships between suit parameters, subject characteristics, health and performance critical to mitigating the risks when using EVA systems, and recommends a test program to collect objective data to make informed decisions across the spectrum of anticipated exploration operational concepts. The Pilbara space suit trials and future field testing of the NDX-1 provide a data set and testing approach (in particular the conclusions listed in Tables 9 and 10), useful to the NASA "Integrated Research Plan" for EVA.

5. Conclusion

We conclude that the stromatolite and microbialites fossils at the "Dawn of Life Trail" in the Pilbara Western Australia are a reasonable analog for space suit trials of hypothetical stromatolite fossils at Nili Fossae on Mars on the basis of: (1) both outcrops have been in a aqueous environment and subject moderate temperatures during formation; (2) the silicified calcium carbonates in the Pilbara would be similar in texture and color to the magnesium carbonates detected by CRISM at Nili Fossae; and (3) the Pilbara outcrops are dated to 3.45 Ga, similar to the 3.7–4.1 Ga outcrops at Nili Fossae. We assume that both examples have similar level of metamorphism and alteration.

We undertook a preliminary overview trial with five subjects consisting of two experienced field scientists and three non-field scientists acting as scientist astronauts in simulated EVA undertaking a science survey of the Pilbara stromatolite fossils using the University of North Dakota's NDX-1 pressurizable space suit. We ranked their performances as scientist astronauts in finding and characterizing the rock fossil features to determine evidence of past life at a hypothetical Martian location at Nili Fossae. We found from this preliminary overview trial the following trends:

- Scientist astronauts found 25% less examples and make more incorrect identifications while in simulated EVA compared to their ground truth survey;
- The quality of characterization descriptions became less affected by the EVA experience as the science importance of the fossil finds increased;
- Field scientists focused more on capturing high value characterization detail from the rock features whereas non-field scientists focused more on finding many features; and
- Fatigue induced by space suit and terrain challenges is the dominant limitation to a scientist astronaut's field science performance.

All scientist astronauts needed to get close to the evidence shown in the rock features to provide best characterization descriptions and mobility to access and

Table A1
The sum of exploration metric ratings, the number of examples found, and, the ranking while in simulated EVA and for ground truth surveys.

Subject	**(1) Simulated Apollo EVA: sum of all exploration metric ratings**	**(2) Simulated Apollo EVA: total number of stromatolites or stromatolite sets found**	**(3) Ground truth: sum of all exploration metric ratings**	**(4) Ground truth: total number of stomatolites or stromatolite sets found**	**Rank 1: Simulated Apollo EVA: Evidence for Life: $=((1)\times 5)+((2)\times 1)$**	**Rank 2: Ground truth: Evidence for Life: $=((3)\times 5)+((4)\times 1)$**	**Summary of comments**
(1) Geologist	20	18	26	23	**118**	**153**	– Suffered fatigue and was out of breath here – Timing announcements was needed, not tracking time
(2) Geologist	16	17	17	24	**97**	**109**	– Fear of falling, especially on steep ground – Could not see more long distance away and restricted field of view made harder to see outcrop – Felt rushed due to time constraints limiting acquiring detail – The space suit did not fit well creating unsure footing – Timing announcements was needed, not tracking time
(3) Teacher	16	8	17	17	**88**	**102**	– When not in suit, saw more – It was too hard to crouch to do ID properly – Hard to view downward – At limit of physical endurance (after 14 min) – Condensation building up restricting view – Walked past lots of stromatolites when unsure of footing – Timing announcements was needed, not tracking time
(4) Teacher	11	13	12	19	**68**	**79**	– Hard to kneel – Get a 2D view in suit, very limited. See 3D with no suit – Terminated early at 9 min due to condensation – Timing announcements was needed, not tracking time
(5) Under grad student	16	26	16	30	**106**	**110**	– Width of view more limited in space suit – Perspiration main limiter – Microphone washing inside of visor, keeping visibility up. – Timing announcements was needed, not tracking time
Total		**82**		**113**			

Note (1): The exploration metric values: Ambiguous evidence for proof of past life = 1; evidence supports proof of past life = 2; multiple observations supporting proof of past life = 3; compelling evidence for proof of past life = 4; unequivocal evidence for proof of past life, with a new insight = 5.
(2) Level of importance to the mission for the exploration metric rating = 5, Level of importance to the mission for 'number of fossils identified' = 1.

search for more examples on the outcrops. This required considerable energy and risk due to space suit limitations in vision, mobility and dexterity, the space suit fit, the psychological fear of death from falling, and the resultant physical fatigue. A Mars exploration mission with a mixed crew of field scientists and engineers (with field science training) could optimize science return by matching field scientists with engineers on surface exploration surveys.

We propose new technologies and training to augment these issues. These are:

- Minimize the energy expenditure by the astronaut through maximizing the space suit hand and knee dexterity, fitting adjustment and vision;
- Provide field science observation technologies (refer to Table 9) aimed to minimize the expenditure of energy by the scientist astronaut;
- Provide training in analog locations aimed to improve management of time, motion, energy usage, and risk awareness; and
- Provide training in general field science competencies to improve efficiency of field science decision-making.

Finally, the Pilbara space suit trials have provided a data set that would satisfy the NASA "Integrated Research Plan" for EVA but further trials involving many more subjects is needed to develop a broader database. In addition confirmation of these conclusions requires more detailed investigation of: exploring different geological formations, more subjects with a range of geological field experience, effect of space suit training, longer EVA duration, alternative space suit designs and fits, surface explorations teams with different skill and profiles, and the measuring of time and energy expended metrics for specific tasks, to better understand the

Table B1
Subject comments and observations.

Attributes contributing performance of 'Field observation skills'	Operations and issues while undertaking normal terrestrial field observations (not wearing a space suit)	Limitation when wearing a space suit during off-world Field Observations	Affect of space suit limitations on performance of 'Field observation skills'	Technology or training to augment space suit limitations
Long sight vision	Panoramic long distance observation to understand landscape geo-morphology	Minor limitation. Suit helmet may cause a 2D view	Difficulty seeing long distance detail	Improve helmet vision design
Short sight vision	Close up including magnified with hand lens observation to understand rock morphology.	Helmet design limits close sample observation. Cannot use a hand magnifying lens.	Lack of use of hand lens restricts observations of rock crystal structures and material inclusions.	Zoom lens camera on an extendable pole with display screen
Lateral and vertical Vision	Assists with safe movement on and around terrain.	Limited lateral and vertical up and down vision	Difficulty in stepping over obstacles	Improve helmet vision design
Color identification	Identification of minerals	Colors are expected to be different. Not tested	Possible mis-identification of minerals	Training specific for this issue
Fogging of visor	Not applicable	Obstructs observations and mobility safety	Very big impact on safe mobility	Helmet defogger and water cooling garment
Touch	Identification of surface textures confirming rock chemical patters or crenulation	Severely restricted	Loss of one way to identify materials and pattern crenulation size	3D camera
Smell	Identification of gas seepage or liquid chemistry	Not available	Loss of method to identify material chemistry	Gas an liquid analyzer chip with audio feedback
Taste	Identification of minerals or liquid chemistry	Not available	Loss of method to identify material chemistry	Gas an liquid analyzer chip with audio feedback
The fitting of the suit to the scientist astronaut	Not applicable	Poor suit fitting clearly limits mobility, increases risk of accident fatigue	Diverts attention from field science	Improve adjustable mechanisms
Mobility	Need to move to get different perspectives of the morphology	Restricted and need to expend more energy for movement.	Diverts energy from field science	Technology to minimize movement when doing field science
Dexterity	Need to kneel to get close and to pick up tools and samples	Difficult to kneel made more work to achieve observations.	Difficulty seeing up close detail	Improve knee dexterity
Fear of falling or damaging the suit	Is an issue when climbing on surfaces to reach features	Fear of falling on rough terrain and steep terrain.	Diverts energy and attention from field science and limits access	Improve knee dexterity, vision, suit mass and balance
Observation time duration	Generally unrestricted and can return to the site	Restricted due to limited Space suit consumables	Can impede focus on the field science	Voice time reminder
Fatigue	Some energy is focused on mobility and can be managed	Energy is focused on mobility limiting decision making	Diverts attention from field science	Improve dexterity and minimize movement

effect of off-world EVA experience on scientist astronaut performance.

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Appendices A and B

See Tables A1 and B1.

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