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Synchronous in-field application of life-detection techniques in Icelandic Mars analogue sites

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1 Abstract

Field expeditions that simulate the operations of robotic planetary exploration missions at analogue sites on Earth can help establish best practices and are therefore a positive contribution to the planetary exploration community. There are many sites in Iceland that possess heritage as planetary exploration analogue locations and whose environmental extremes make them suitable for simulating scientific sampling and robotic operations.

We conducted a planetary exploration analogue mission at two recent lava fields in Iceland, Fimmvörðuháls (2010) and Eldfell (1973), using a specially developed field laboratory. We tested the utility of in-field site sampling down selection and tiered analysis operational capabilities with three life detection and characterization techniques: fluorescence microscopy (FM), adenine-triphosphate (ATP) bioluminescence assay, and quantitative polymerase chain reaction (qPCR) assay. The study made use of multiple cycles of sample collection at multiple distance scales and field laboratory analysis using the synchronous life-detection techniques to heuristically develop the continuing sampling and analysis strategy during the expedition.

Here we report the operational lessons learned and provide brief summaries of scientific data. The full scientific data report will follow separately. We found that rapid in-field analysis to determine subsequent sampling decisions is operationally feasible, and that the chosen life detection and characterization techniques are suitable for a terrestrial life-detection field mission.

In-field analysis enables the rapid obtainment of scientific data and thus facilitates the collection of the most scientifically relevant samples within a single field expedition, without the need for sample relocation to external laboratories. The operational lessons learned in this study could be applied to future terrestrial field expeditions employing other analytical techniques and to future robotic planetary exploration missions.

2 Introduction

Extreme environments on Earth are used as analogs to inform both the science and operations of future planetary exploration missions (Amils *et al.*, 2007, Amato *et al.*, 2010, Billi *et al.*, 2013). In particular, Icelandic lava fields have an especially good heritage as Mars analog sites (Farr, 2004, Warner and Farmer, 2010, Cockell *et al.*, 2011, Cousins and Crawford, 2011, Mangold *et al.*, 2011, Ehlmann *et al.*, 2012, Cousins *et al.*, 2013). Lava fields are relevant for astrobiological science due to the presence of extreme conditions, including desiccation, low nutrient availability, temperature extremes (e.g. due to high elevation or close proximity to fumaroles), relatively young ages, and their isolation from anthropogenic contamination (Allen *et al.*, 1981, Bagshaw *et al.*, 2011). From an operational perspective, many Icelandic lava fields are remote enough to require that field expeditions address several sampling operational constraints that are also experienced in robotic planetary exploration (Arena *et al.*, 2004, Preston and Dartnell, 2014).

Terrestrial field campaigns designed to conduct scientific studies of planetary analogs can also serve as operational analogs for robotic planetary missions. Field campaigns typically involve *in situ* sampling, followed by preservation of any collected samples and subsequent return to an institutional laboratory where the samples can then be analyzed, analogous to planetary sample return missions. However, some field expeditions may carry limited instrumentation for *in situ* analysis (Ehlmann *et al.*, 2012), and like robotic planetary missions, these instruments must be chosen ahead of time. Limited on-site consumables further constrain the amount that can be accomplished in the field by both terrestrial field expeditions and planetary exploration robots. Furthermore, sending samples to an institutional laboratory with a delay of potentially several months before full scientific analysis is possible.This may prevent results of prior sampling being available to influence sampling strategy throughout the expedition, and this applies to whether on Earth or elsewhere in the solar system. Although the results obtained might be available to assist in the planning stages of future field campaigns or missions, such follow-up expeditions might be weeks, months, years or decades in the future. The ability to maximize science return from limited in-field planetary exploration analyses is far more critical given that a sample return mission from Mars, or other astrobiologically relevant planetary bodies, is still decades away (McLennan, 2012), and raises significant planetary protection issues (Bridges and Guest, 2011).

The capacity for rapid sample analysis and interpretation can alleviate the problems posed by terrestrial or planetary expeditions. Firstly, it allows for the down-selection of sampling sites in the field. Rather than being dependent solely on previous mission data or remote sensing provided by partner programs, sampling choices can be made in the field based on near-real-time results. Secondly, it allows for 'tiered analysis', in which a single sample may be subject to a faster or lower-cost analysis (either non-destructively or by partitioning) to determine whether it is sufficiently interesting to warrant a second, more resource-intensive or more limited-capacity analysis. These features can be combined to maximize science return if a balance is struck between the cost of carrying additional resource-light 'pre-sampling' instruments and the increased science return from more resource-intensive instruments.

Choosing the exact locations and samples that a field team, rover, or lander will analyze is critically important given the operational constraints. The planetary mission team must select a location to sample using the vehicle's remote sensing instruments (*e.g.* the ChemCam instrument on the Mars Science Laboratory (Meslin *et al.*, 2013)) and assume that this site is representative of the area of interest. If a difference in sampling location of a few meters, centimeters, or even hundreds of microns could make a significant difference in the results, it may mean that science objectives are not met. This will be especially critical when life-detection is the primary goal, given the inherent variability in the distribution of living things as we know them on Earth. Successfully characterizing multiple parameters across the multiple scales of a field site will help to reduce the number of initial sampling rounds needed.

We conducted a planetary exploration analog expedition to two recent Icelandic lava fields, Fimmvörðuháls (2010) and Eldfell (1973), with a specially developed field laboratory. Our main goal was to prove the feasibility of real-time sampling and site down-selection in a life detection robotic exploration context through quick-turnaround 'pre-sample' analysis and extrapolation of the likely presence of biomarkers. To inform the development of current and future *in situ* planetary missions, this was broken down into three interrelated operational sub-goals:

1. Demonstrate the feasibility of performing multiple rapid cycles of sample selection, sample analysis and interpretation in-field under simulated robotic exploration constraints.

2. Demonstrate the synchronous application of multiple life detection techniques within these multiple cycles.

3. Demonstrate the potential of fluorescence microscopy (FM), adenosine triphosphate (ATP) bioluminescence, and quantitative polymerase chain reaction (qPCR) assays as quick-turnaround terrestrial life detection techniques.

Here, we report upon the operational and logistic lessons learned during the expedition, which could influence the design of future field studies. Scientific results of the expedition will be reported separately (manuscript in preparation). Follow-up expeditions are planned and will be reported upon in relation to this work.

3 Methodology

The expedition consisted of cycles of sampling, rapid preliminary analysis, and follow-up based on the results from the previous sampling and analysis cycle. The expedition personnel were split into two teams, allowing two of these repeated sampling and analysis cycles to be run in staggered parallel, thus increasing the expedition's throughput and ensuring that the field lab was neither idle nor acting as a bottleneck. After sampling cycles were completed all samples were more extensively analyzed over three additional days in the field lab to address the more detailed question of sample site homogeneity.

3.1 Field Sites

Two lava fields were chosen for our expedition: Fimmvörðuháls (63º 38' 12.30" N, 19º 26' 49.20" W) and Eldfell (63º 25' 08.30" N, 20º 14' 38.70" W) (Figure 1). The Fimmvörðuháls lava field formed between 20 March and 12 April 2010, from a basaltic effusive eruption associated with the 2010 Eyjafjallajökull eruption located approximately 7.5 km away. The field site is located in a saddle between the larger Eyjafjallajökull and Myrdalsjökull volcanic structures (Figure 2) (Edwards *et al.*, 2012). The Eldfell volcano, associated with the Vestmannaeyjar volcanic system, began erupting on 23 January 1973 on the island of Heimaey. The Eldfell eruption had both effusive and explosive alkali basalt eruptions and lasted for five months, producing ~0.23 km^3 of volcanic material (Thorarinsson *et al.*, 1973, Higgins and Roberge, 2007). Both field sites have very similar basaltic tephra (unconsolidated volcanic material) sediment types with limited vegetation cover. The two sites are approximately 45.0 km apart.

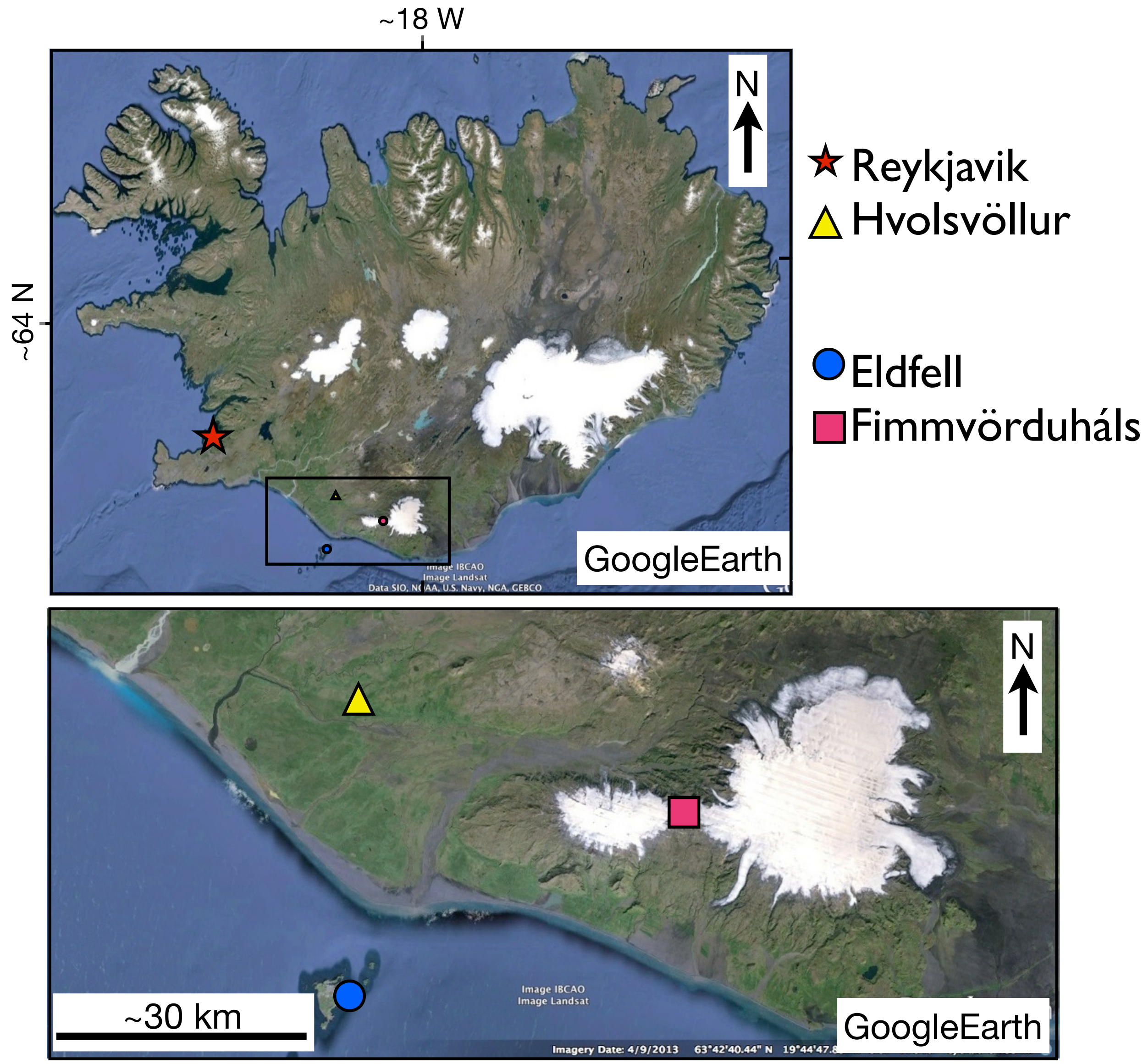

Figure 1 - A map of Iceland with the expedition's field sites marked.

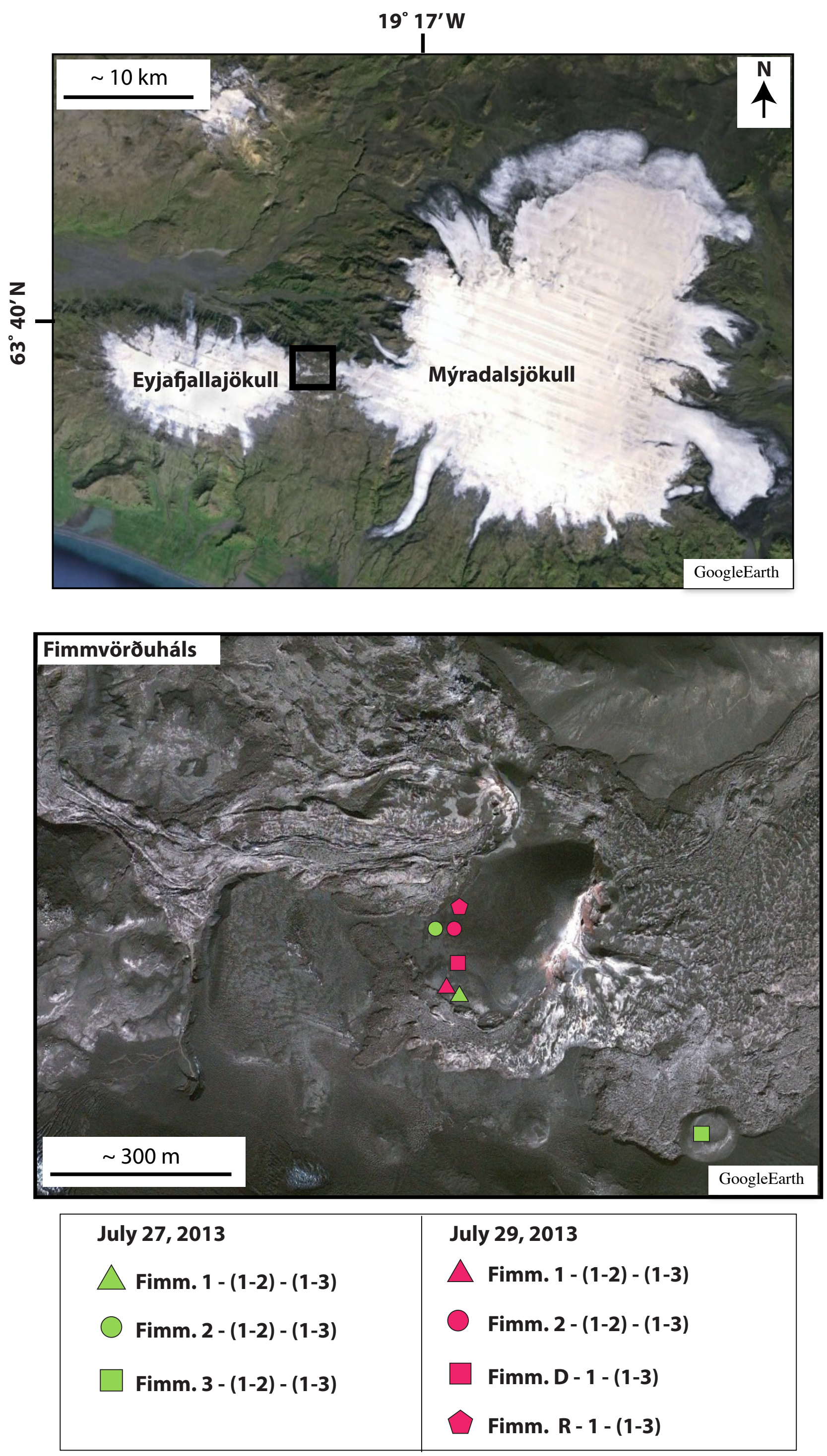

Figure 2 - Sampling locations within the Fimmvörðuháls field site.

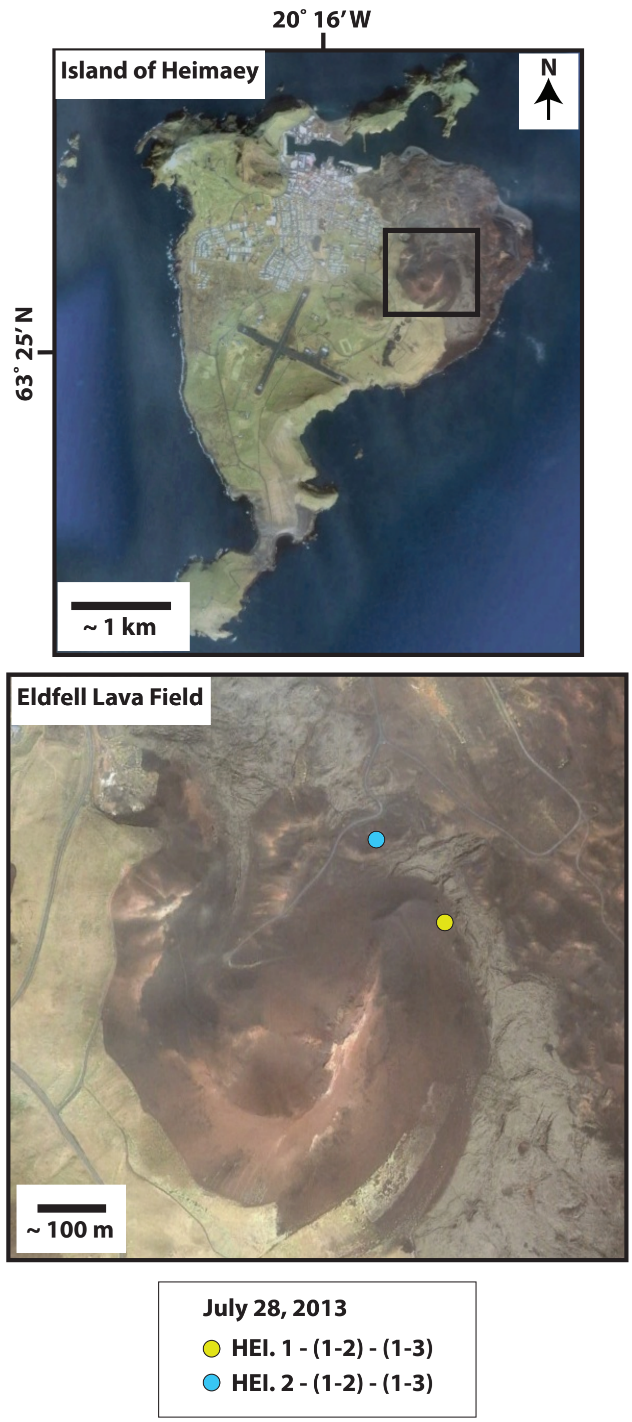

Figure 3 - Sampling locations within the Eldfell field site.

3.2 Sampling

A grid of sample locations spaced at 1 m, 10 m, and 100 m intervals (see Figure 4 and Figure 5) was established at each of the two main sites in an area where the basaltic tephra appeared to be visually homogeneous by color, morphology, and grain size. A triplicate sample set was taken at each grid point.

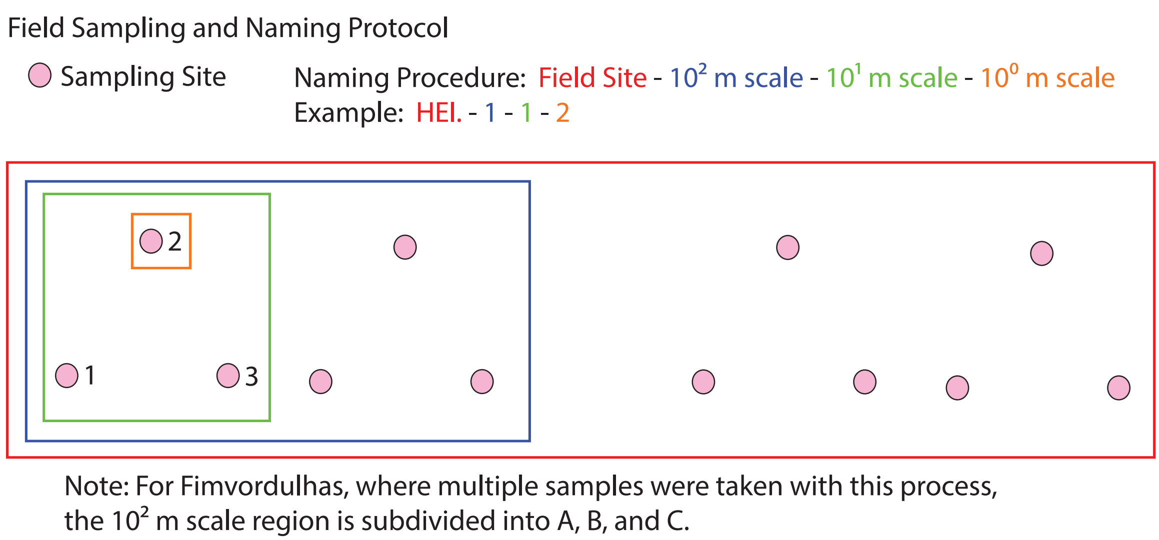

Figure 4 - Field sampling and naming protocol.

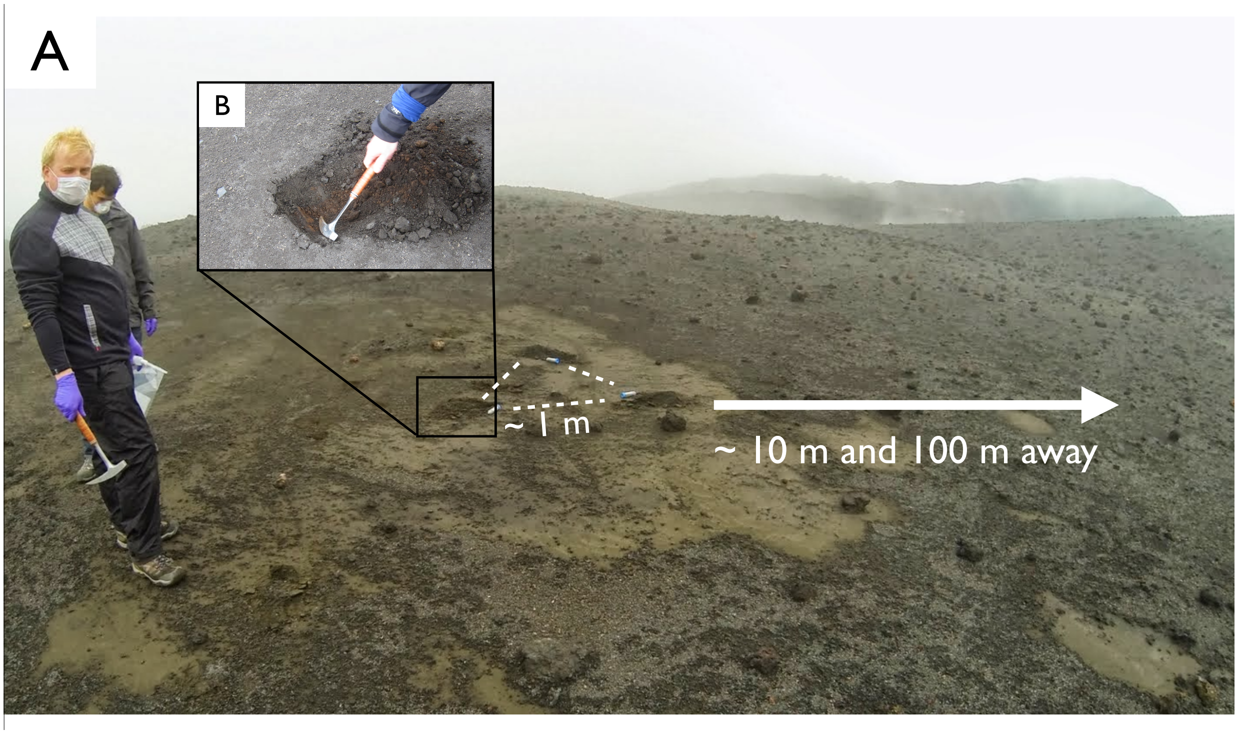

Figure 5 - (A) Samples being collected at Fimmvörðuháls by A. Stevens (front) and E. Schwieterman (back) using the sampling protocol shown in Figure . (B) A closer view of how the samples were collected.

Each sample was taken from approximately 5 cm below the surface by digging with a rock hammer that was wiped with isopropanol before each sample collection (Figure 5) and scooping the uncovered tephra with a sterile 50 mL falcon tube, which was sealed and returned to the field lab. During sample collection, team members wore facemasks and gloves and approached the pristine sampling site from a downwind direction to minimize anthropomorphic contamination. Gloves were rinsed with isopropanol between samples. Caution was taken to avoid stepping on or otherwise disturbing any potential sampling site.

Figure 6 – Example of a sample collected from the Eldfell lava field.

Fimmvörðuháls samples were collected along the base and in the surrounding area of the Magni cinder cone (Figure 2), which appeared to have had little foot traffic compared to the rest of the lava field. The basaltic tephra collected ranged from coarse ash to lapilli and reached up to 50 cm in thickness. On 24 July, four samples were collected from a small area of the cinder cone using the general method described above. Along with these, a 'positive control' sample was also collected from the ash around the roots of a small tuft of grass, on the assumption that this would be a likely habitat for microorganisms. All other samples were deliberately taken at locations away from any vegetation. A separate positive control was also collected from the grassy area around the field laboratory. First-round analysis of these initial samples was used to inform follow-up sample collection at Fimmvörðuháls (27 and 29 July), which were taken from the same general region (Figure 2).

The samples collected from the Eldfell lava field (28 July) were lapilli-sized or smaller and came from a large scoria cone associated with the main explosive eruption (Figure 6). As with the Fimmvörðuháls site, care was taken to collect samples from regions with little to no apparent anthropomorphic disturbance, but this was much more difficult given the status of Heimaey and Eldfell as a site for tourism. Further samples were taken from a site off the main eruption cone in an attempt to reduce the anthropomorphic contamination.

3.3 Field Laboratory

All analytical work was performed in a field laboratory located within a day's travel of the field sites at the Hvolsskóli school in Hvolsvöllur (Figure 1). While the classroom used had very little equipment itself, it provided the basis for a field laboratory with running water and access to power.

The majority of the scientific equipment used in the expedition was shipped directly to Hvolsvöllur in a single container. Some equipment (such as isopropyl alcohol) was purchased locally. A number of items required for the field lab were adapted from household items – for example, the autoclave used to sterlize equipment was a domestic pressure cooker. The equipment that was shipped to the field laboratory included a benchtop vortex mixer and centrifuge, sterilized pipettes and tips, a commercial water filtration system and ultrasonic cleaning system, Bio-Rad MiniOpticon™ real-time PCR system, the Partec CyScope®

fluorescence microscope and the Merck HY-LiTE® 2 portable luminometer used to quantify the ATP immunoassay. Consumables including sterile sample containers, gloves and masks, PCR and microcentrifuge tubes, filters, commercial qPCR assay kits, and the reagents for use with the ATP assay and FM were also shipped.

On arrival, the classroom was rearranged to form three analytical stations, one for each analytical technique, and each cleaned thoroughly with isopropanol. A second classroom was set up as a separate sample preparation room to reduce cross-contamination. A third classroom was assigned to be a darkroom for use with the FM.

Figure 7 - The three workstations as set up in our field laboratory. (l) DNA extraction, purification, and qPCR area, with general supply table in foreground. (c) ATP bioluminescence area, with FM staining area in the background. (r) 'Darkroom' established for fluorescence microscopy.

3.4 Analytical Methods

The analytical techniques used in the expedition were selected for their minimal laboratory overhead, low cost and consumables requirements, and established history in terrestrial life detection. Adenosine triphosphate (ATP) has long been considered a high-priority biomarker due to its indication of bioavailable energy and ease of detection via fluorescent dyes (Parnell *et al.*, 2007), and can be implemented with standard, commercially available solutions and a benchtop luminometer. Fluorescence microscopy (FM) offers the ability to directly quantify microorganisms under a microscope using a dye that binds to double-stranded DNA and fluoresces when illuminated under UV light. Counting cells via FM has been widely used in environmental samples (Kepner and Pratt, 1994), and can be implemented with standard, commercially available stains and buffer solutions and a microscope with appropriate illumination and filters. The quantitative polymerase chain reaction (qPCR) assay allows for simultaneous amplification and quantification of DNA that matches the set of primers used. By choosing an array of primers that correspond to different taxonomic groups, it is possible to assess both the quantity of DNA present in a given sample and the relative diversity (defined for our purposes as the relative ratios of the DNA recovery of different types of organism *e.g.* bacteria:fungi:archaea) of the organisms from which that DNA was extracted. The qPCR technique requires pre-synthesized primers, standard buffer solutions, and a thermocycler equipped with a well-plate fluorometer. We recognize that our chosen analytical suite is terrestrial extant-life-centric, and that other techniques could be more appropriate for extraterrestrial planetary expeditions.

The analytical workflow was designed to maximize overlap between techniques and stagger use of limited equipment. The same basic sample preparation techniques, including crushing using steel plates and a vice to visually homogenize particulate size, were used for all three life-detection techniques. Samples were then split into sub-sample groups for washing (used for the fluorescence staining) and cell extraction and lysis (used for both the ATP and qPCR analyses). The lysate was then subject to a final DNA extraction step for qPCR only. The cell wash for the fluorescence staining required an additional filtration step.

Expedition personnel on laboratory duty for a given day were divided into sample preparation, qPCR, ATP and FM teams, as shown in Figure 8. The FM and qPCR teams took sample input directly from the sample preparation team; the ATP team was split into preparation and analysis groups to account for their additional secondary sample preparation step. Analytical protocols are briefly described below, and will be reported in full detail in a future manuscript.

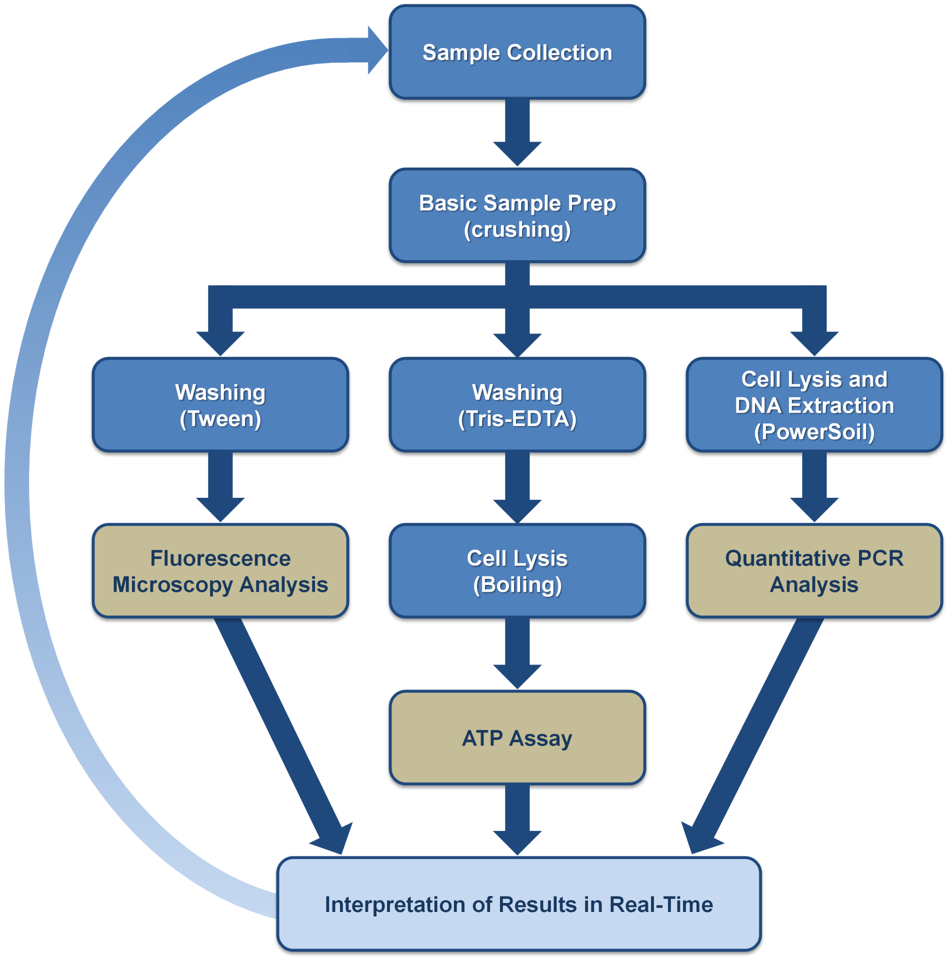

Figure 8 - Sample preparation and analysis throughput chart. Data are analyzed in real-time, informing the next round of sample collection and analysis.

3.4.1 ATP Bioluminescence

The ATP bioluminescence assay was implemented using the Roche ATP Bioluminescence Assay Kit HS II following the manufacturer's recommendations for a tube assay, with some modifications as discussed in Barnett *et al.* (2012).

3.4.2 Fluorescence Microscopy

The FM protocol follows that of (Kepner and Pratt, 1994) with some minor modifications and serves to remove any microorganisms from the sample matrix and allow them to be stained. Breifly, a 1 mL portion of crushed sample was combined with 0.75 mL of PBS/Tween buffer, vortexed, sonicated, then centrifuged for 5 minutes at 600 × g. The supernatant was removed into a separate sterile tube and the extraction process was repeated. The combined supernatant (extract) was loaded into a 2 mL syringe, pushed through a Whatman Nuclepore Track-Etch Membrane 0.2 µm filter, and flushed through twice with sterile water and twice with air. The sample filter was removed, stained with 100 µL of SYBR Gold Nucleic Acid Gel Stain (Invitrogen), covered with a cover slip, and incubated in the dark for at least 15 minutes before imaging with a Partec Cycscope (fluorescence and transmitted light microscope) equipped with a 455 nm (RB) “royal blue” emission light source and 500 nm (DM) “yellow/green” dichroic mirror long pass filter. The 100× (oil) objective was used in conjunction with the imager to record digital micrographs of sample fields. The cell counts were documented with manual counting from five randomly chosen locations in the field of view, and images were recorded for later verification and analysis.

3.4.3 Quantitative PCR

DNA extraction and purification was performed on a 1 mL portion of crushed sample using the PowerSoil® DNA Isolation Kit (MO BIO Laboratories, Inc.) following the manufacturer's protocol. Real-time qPCR was performed in duplicate for each sample on a 1:10 dilution of purified DNA extract using a BioRad MiniOpticon™ real-time PCR system. Primers were selected for breadth of taxonomic range, and included primers to identify bacterial, fungal and Archaeal DNA. The primers chosen also had similar extensions to increase the amount of samples that could be analysed at the same time. Soil gathered outside of the field laboratory in Hvolsvöllur was used as a positive control; the negative control was sterile deionized water.

4 Results and Discussion

4.1 Rapid Site-Selection Lessons

One of the main objectives of the expedition was to demonstrate the feasibility of performing multiple rapid cycles of sample selection, sample analysis and interpretation in a field setting. To accomplish this, we performed several cycles of sampling and analysis, allowing methods and protocols to be developed throughout the expedition.

4.1.1 Preliminary Sampling and Protocol Testing

After arriving at Hvolsvöllur and establishing the field lab, the first day of sampling was spent on a preliminary expedition to both potential sampling locations. The following day was spent analyzing these preliminary samples in the field laboratory. There were two goals: 1) to survey potential areas for sampling in terms of accessibility and anthropogenic disturbance and 2) to take preliminary samples with which to test our field protocols and ensure all participants were suitably trained on both field sampling protocols and the three analytical techniques.

After determining a common sample preparation protocol that could be used for all three techniques, preparation of all 22 samples took approximately two hours. However, samples were continually transferred into analysis as they were prepared, avoiding an initial two hour delay. All three analytical methods – FM, qPCR and ATP – were performed in parallel.

Fluorescence staining followed by microscopy proved to be the most rapid technique when used in a qualitative mode (i.e., gauging relative levels of microorganism abundance compared to the positive or negative controls). At this level of analysis, a day's sample set could be stained and measured in approximately one hour. The ATP bioluminescence assay took approximately two hours to produce a quantitative report regarding the activity of the microorganism abundance of the samples. The qPCR analysis required an entire day (~10 hours) to analyze the same number of samples as the other two techniques. Approximately five hours were required to perform the DNA extraction and purification; the remaining five hours were spent running the temperature cycling on a single qPCR instrument. On subsequent days, sample preparation for this analysis was given priority, and two team members were assigned to parallelize the extraction procedure in the morning.

4.1.2 First-Round Sampling and Analysis

Our rapid site selection protocol was put into place starting on Day 1, with one team departing to gather samples at the Fimmvörðuháls site while the other implemented and tested protocol changes resulting from our preliminary analyses the previous day. Day 1 samples were then analysed on Day 2 while the second team took samples from the Eldfell site. The results of samples collected on Day 1 were reviewed in the evening of Day 2 to inform decisions about the follow-up sampling trip to Fimmvörðuháls on Day 3.

The samples from Fimmvörðuháls taken on Day 1 and analyzed on Day 2 showed generally low cell counts and low levels of ATP. The qPCR assays were used with both 10x and 100x dilutions, and it was determined that a 10x dilution factor was the most effective; however, due to the complexity of qPCR data return, these results were not immediately available to guide first round analysis. The Eldfell samples, as expected given the older age and increased regional vegetation, showed a higher level of ATP than the results from Fimmvörðuháls, but still a lower level than the positive controls. Cell counts were also generally very low, but difficult to distinguish in magnitude from the Fimmvörðuháls samples. The results from the qPCR assays were mixed, indicating that the diversity of different cell types in our sampling area was not consistent.

A final change was made to our FM procedure after Day 1. Quantitative cell counts for all samples were proving to be infeasible in a single day's time frame under the constraints of our field laboratory and number of personnel. Fluorescent micrographs of the stained filters were taken for later detailed counts, and qualitative-level comparisons were used to guide future sampling decisions.

A final change was made to our qPCR procedure after Day 2. By reducing the number of replicate samples for qPCR analysis each day, the analysis could be completed in a shorter timeframe (about eight hours). The resulting data therefore could be made available in time for high-level judgments, and additional replicates could be run later from the same DNA extract.

These initial results from both sites showed that assessment of heterogeneity in the field sites was crucial. The purpose of our follow-up sampling was at this point defined as measuring internal site variance at each area for each of the three life detection techniques.

4.1.3 Subsequent Sampling and Analysis

Samples were prepared as in the first round of analysis, with minor changes in protocols to maximize throughput and minimize material use. Qualitative FM and ATP assays were performed in the morning while a reduced set of samples was selected for qPCR analysis. After the final round of on-site sampling, an additional day was included in the schedule to allow for follow-up analysis of particularly interesting samples and any additional work that early results indicated should be performed. The qPCR analysis was completed on this day, as was initial top-level analysis of site homogeneity.

4.2 Field Laboratory Lessons Learned

Our experience of establishing a field laboratory for real-time on-site life detection provides several valuable lessons, which could be applied more generally to similar expeditions to planetary analogue sites, or the future in-field testing of life detection instrumentation.

The minimum requirements for locating a field laboratory are power, water, protection from the elements, and control over entry and exit (to minimize contamination). This can be cost-effectively provided by any reasonable local structure and has been achieved in far more modest locations than our expedition (see Barnett *et al.* (2012)). Appliances for low-temperature preservation (refrigerator and freezer) and heat (stove top) are highly recommended. At least two separate areas (in our expedition, two classrooms) are strongly recommended to allow sample preparation to be physically separated from analytical measurements.

The requirement that all three techniques were run in parallel meant that some of the expedition participants were trained in their use before the expedition. Those without experience of the techniques were training during the expedition. The time spent developing protocols and training participants before the expedition was critical for meeting our scientific objectives, as without pre-training several days in the field would have been lost. It also meant that it was fairly simple for one person to supervise the setup of each technique in the field lab. In-field training proved to be very effective, even for those with backgrounds in different fields, and helped to streamline all the protocols.

All necessary equipment and reagents can be shipped in a single trunk (in our case, a KA64 Defender aluminium box, 1190 x 790 x 520 mm). Reagents can be shipped within the main container in a secondary insulating box with dry ice and will remain preserved for ~48 hours.

All consumables should be packed and shipped pre-sterilized whenever possible. The small autoclave (adapted from a consumer pressure cooker) was often a significant bottleneck.

Provisions should be made to take detailed data for later analysis. This was most notable with the fluorescence microscopy. The microscopes were excellent, but the low-cost camera attachments provided low image quality. A single higher-resolution camera and adapter would have been a worthwhile investment.

We have demonstrated the feasibility of performing complex life-detection analysis in a field-based laboratory in a single day, which enabled heuristic development of techniques, methods and protocols and offered significant flexibility over the expeditionary standard of bringing samples back to an institutional laboratory. While some highly sensitive techniques and instruments could not be used in this context and would therefore require sample transport, advances in miniaturization technology means that more analytical techniques are becoming viable to use in a field context.

4.2.1 Lessons Learned: Techniques

Our initial FM protocol for cell quantification was impractical. The filters used for cell isolation and staining were challenging to use and to transfer between the filtering apparatus and the microscope slides. A potential alternative for future work is to stain and view the cells in solution. Manual cell counting by eye also proved too slow for meaningful sample throughput. The use of this technique in a similar field lab could be substantially improved with the use of a higher-quality microscope camera and automated image-processing software. Alternately, given that qualitative comparisons were of adequate value for rapid-turnaround analysis, a low-cost fluorometer could be used to rank sample fluorescence levels post-staining without the need for a microscope.

The ATP bioluminescence assay proved generally robust and reliable under the conditions of our field laboratory. The protocols were easy to follow and required simple laboratory equipment (*i.e.* vortex, hot plate) beyond the ATP luminometer. The assay provided useful data in a relatively short amount of time, and therefore enabled the processing of a significant number of samples each day. ATP bioluminescence is definitely suitable for future use in rapid examination of biomass distribution during field expeditions to extreme environments.

The qPCR assay was largely successful as a field technique. DNA was successfully extracted from all samples. Amplification protocols for all three primer sets (bacteria, fungi and archaea) were successful as confirmed by Cq values of 17.5-27.5 in the positive controls (soil gathered outside of the field laboratory in Hvolsvöllur). The clearest need for improvement is the throughput, due to the serial-batch nature of the technique. Each batch of samples required at least 4 hrs to run on the qPCR instrument, enabling a maximum of 48 individual samples (including replicates and different primers) to be run in a single day. Given the results of our site homogeneity analysis, it may be possible to reduce the number of samples taken in a given area to achieve the same level of confidence, though using more primers would require more sample wells. Alternately, the throughput could be increased by the addition of a second qPCR instrument or the substitution of one with a larger capacity.

5 Preliminary results

Here we present some initial results in order to illustrate more clearly how the different techniques were used in decision making and scientific investigation. A full statistical analysis of our results is currently in preparation.

The data collected suggest that sites that appeared to be homogeneous showed biological diversity at all spatial scales at but at different levels – *i.e.* there was diversity at a general microbial level (quantified by ATP), at a cell number level (quantified by FM), and at domain specific levels (quantified by qPCR).

5.1 Fluorescence Microscopy

Example micrographs are shown in Figure 9. There is a clear difference between (a) the positive control, (b) the negative control and (c) a sample taken from the Fimmvörðuháls field site. Micrographs showed very low cell counts across all field samples, but with variation at all spatial scales. However, the FM technique was generally only used as a qualitative estimate of the microbial levels in the samples, with the positive and negative controls providing the end member cases of well- or poorly-populated material. These qualitative estimates allowed us to judge whether a sample was worthy of further analysis.

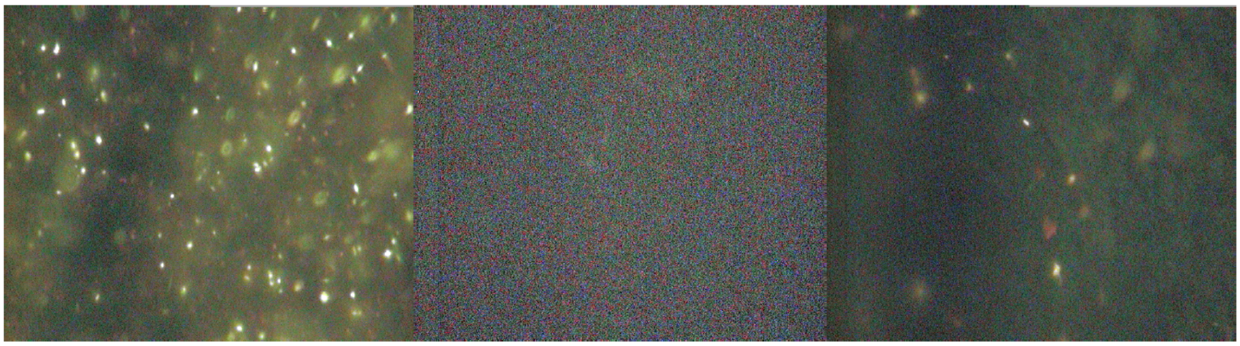

Figure 9 - Fluorescence microscopy micrographs. Left: Positive control from vegetated soil. Center: Negative control from sterile extraction. Right: An extraction from a sample collected at the Fimmvörðuháls location. Micrographs were taken using a 100× oil immersion objective.

5.2 ATP assay

Figure 10 gives a summary of the ATP levels across both field sites and for the positive control samples. There is a distinction between the very low levels of the Fimmvörðuháls field site and the slightly higher levels present in the samples from Heimaey, but both are low compared to the positive controls. There is also variation in the levels at different spatial scales within both field sites. Note that the RLU measurement produced by the assay is purely comparative and must be calibrated using a standard curve to provide details of ATP abundance in samples.

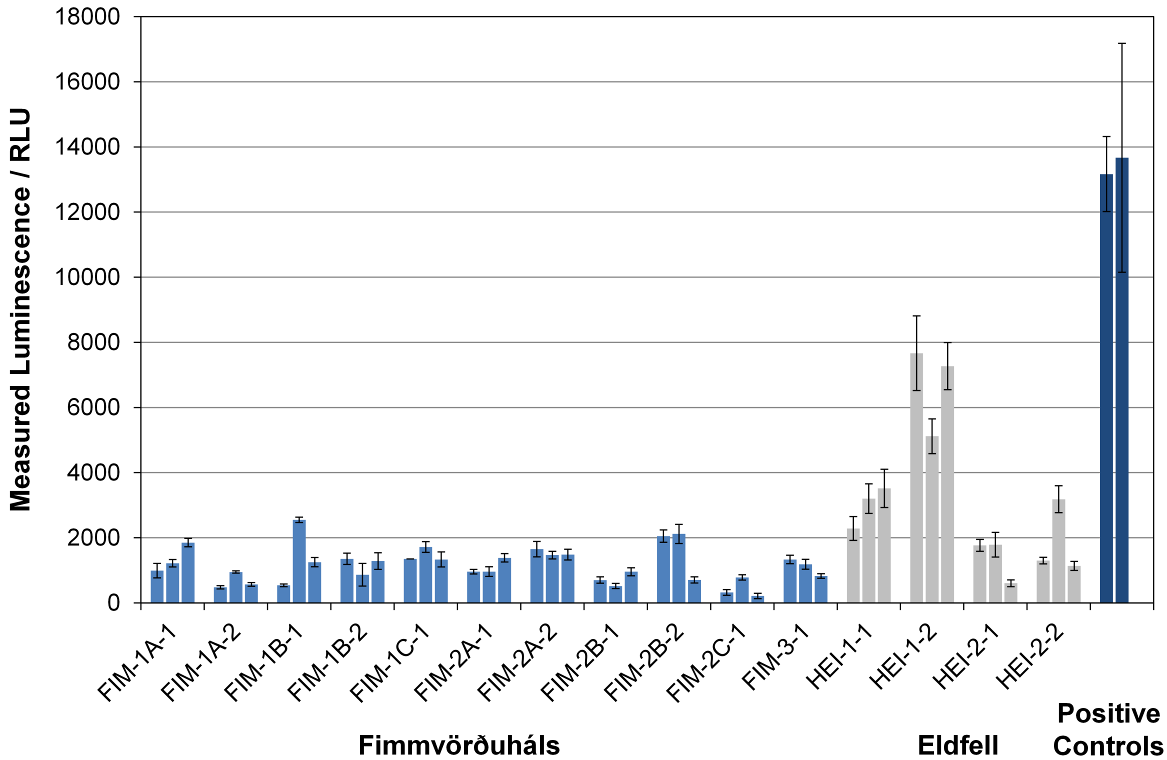

Figure 10 – ATP assay luminescence levels for the Fimmvörðuháls and Heimay field sites and the positive controls.

5.3 Quantitative PCR

Analysis of the qPCR data is more difficult as the instrument does not directly output DNA abundance. The DNA content was calculated from the output data using the following equation, a variation of the Livak method (Livak and Schmittgen, 2001):

$$E = 2^{Cq(r)-Cq(t)}$$

where E is the amount of DNA in a sample, Cq(r) is the quantification cycle value of the reference (equal to 40 in this case), and Cq(t) is the quantification cycle value of the target. Quantification cycle (Cq) is the number of replication cycles needed to reach a set threshold fluorescence value. This method assumes that the target genes are amplified with efficiencies near 100%.

The results for the three separate domain-specific primers are shown in Figure 11. They suggest that while the results of the FM and ATP analyses show broadly consistent microbial levels at each field site, this consistency obscures high domain-level diversity in the sample locations. For example, one sample location contained far more fungal DNA than any other, and archaeal DNA was far more abundant in samples from Heimaey than Fimmvörðuháls.

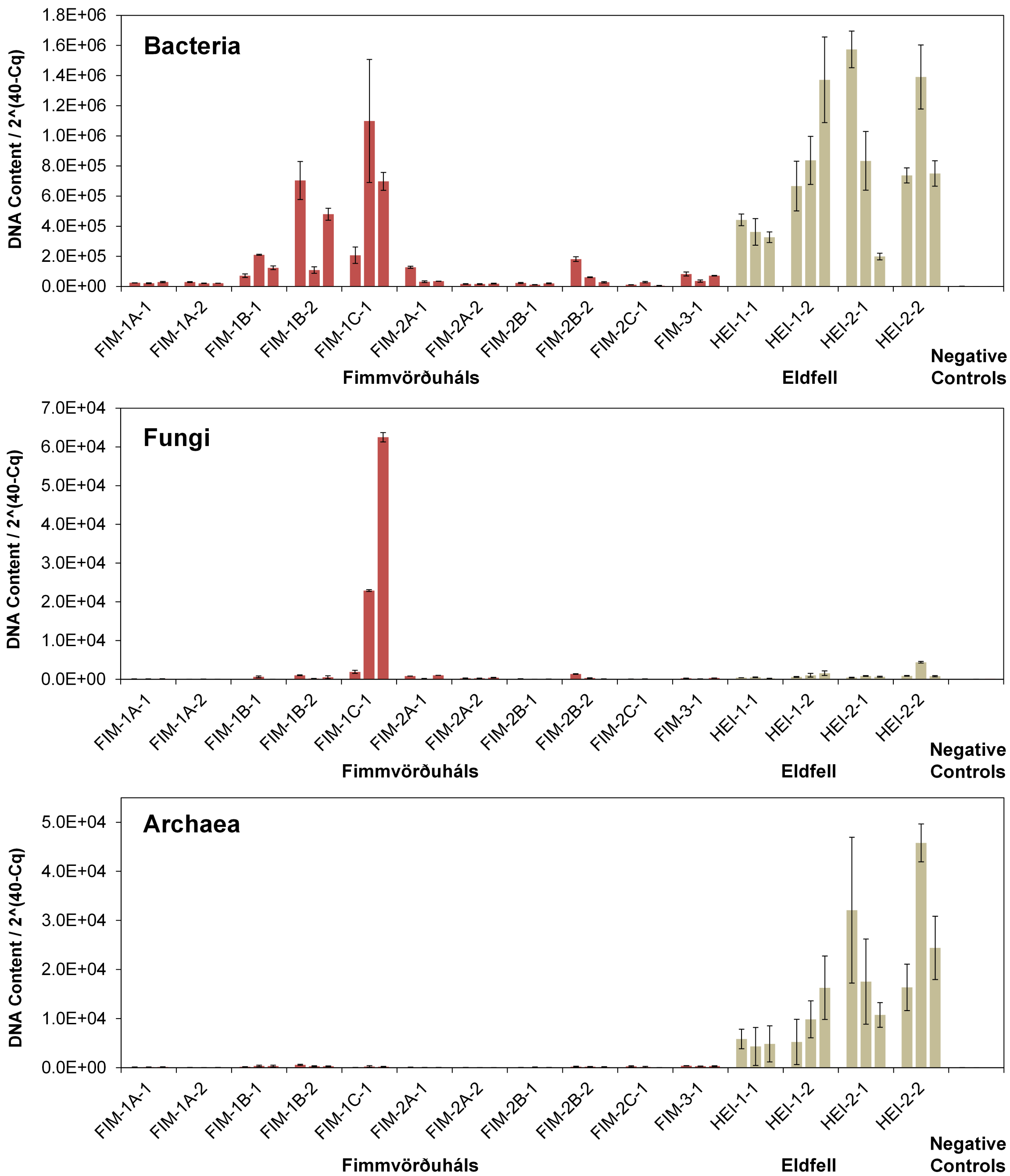

Figure 11 – DNA content for all sample sites.

6 Conclusions

Our experience shows that rapid in-field analysis to determine subsequent sampling decisions is operationally feasible for planetary analogue expeditions. A single-day turnaround for biomarker analysis was achievable on a relatively low budget with the use of basic local facilities. Similarly, no additional difficulties were encountered in running analyses synchronously (*i.e.,* in parallel) and by using sample subdivision, results were acquired from three separate analytical techniques each day. With carefully chosen equipment and protocols, ATP bioluminescence and nucleic acid staining assays can be used to provide same-day input into sample down-selection for quantitative PCR, conserving the most expensive equipment and reagents without increasing the one-day analysis turnaround. The techniques chosen for this study were designed to characterize extant, metabolising life, whereas we recognize life detection missions to extraterrestrial locations cannot make the same assumptions and will most likely be looking for remnant biosignatures, thus requiring a different analytical suite. There is no *a priori* reason other analytical techniques could not be used in the same manner, so this decision making methodology could be used in other contexts.

These methods have a number of advantages over the standard sampling metholodogy of taking samples back to institutional laboratories, especially in the context of life detection, where changes over the course of even the days or weeks before analysis could severely affect the results. Additionally, assuming that all samples are partioned appropriately while performing in-field analysis, samples can still be retained for return to an institutional laboratory if they show particularly interesting results and would benefit from more extensive analysis.

Our expedition also has implications for robotic planetary missions. We have shown that with careful planning of experimental sequences and shared resources, multiple analytical techniques can be used synchronously and rapidly to provide information that improves further sampling. In the context of future biomarker detection missions, such as the ExoMars or Mars 2020 rovers, instruments may face severe limits on their operation and the ability to increase their science return within those limits will be of extreme importance. Decision making as described here can help to increase science return. Future human planetary missions will also need robust decision making tools, though their sampling limitations will likely be reduced as compared to robotic missions.

The developments presented here are appropriate to the context of Icelandic lava fields, but may need to be modified for other analogue sites. For example, the analogue sites of Iceland are less remote than those such as the Haughton impact crater or remote regions of the Atacama desert, and it may be much more challenging to assemble a fully equipped field lab in some of these other analogue sites. Testing these methods in a variety of analogue sites will increase their robustness under varying levels of infrastructure and demonstrate their applicability to planetary missions.

The feasibility of implementing fluorescence microscopy with nucleic acid staining, ATP bioluminescence assay and qPCR as a set of quick-turnaround life detection techniques in the context of a field campaign at a Mars analogue location has been demonstrated. With the use of a field laboratory such as that described here, these methods can be used and extended to increase the science return of terrestrial planetary analogue expeditions. Preliminary results from the expedition suggest that the diversity of microbes in extreme environments is a complex problem and further analogue investigations are required in order to enable the full exploitation of data from future planetary exploration missions. They also show that more comprehensive methods are required to assess the environmental homogeneity of sampling areas.

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8 Abbreviations

ATP, adenosine triphosphate; Cq, quantification cycle; DNA, deoxyribonucleic acid; EDTA, ethylenediaminetetraacetic acid; FIM, Fimmvörðuháls; FM, fluorescence microscopy; HEI, Heimaey; qPCR, quantitative polymerase chain reaction; RLU, relative light units; Tris, tris(hydroxymethyl)aminomethane; UV, ultraviolet.

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