# Accepted Manuscript


Issues of Geologically-Focused Situational Awareness in Robotic Planetary Missions: Lessons from an Analogue Mission at Mistastin Lake Impact Structure, Labrador, Canada

I. Antonenko, G.R. Osinski, M. Battler, M. Beauchamp, L. Cupelli, A. Chanou, R. Francis, M. M. Mader, C. Marion, E. McCullough, A.E. Pickersgill, L.J. Preston, B. Shankar, T. Unrau, D. Veillette

| | |
|---|---|
| PII: | S0273-1177(12)00707-7 |
| DOI: | http://dx.doi.org/10.1016/j.asr.2012.11.024 |
| Reference: | JASR 11192 |

| | |
|---|---|
| To appear in: | *Advances in Space Research* |

Please cite this article as: Antonenko, I., Osinski, G.R., Battler, M., Beauchamp, M., Cupelli, L., Chanou, A., Francis, R., M. Mader, M., Marion, C., McCullough, E., Pickersgill, A.E., Preston, L.J., Shankar, B., Unrau, T., Veillette, D., Issues of Geologically-Focused Situational Awareness in Robotic Planetary Missions: Lessons from an Analogue Mission at Mistastin Lake Impact Structure, Labrador, Canada, *Advances in Space Research* (2012), doi: http://dx.doi.org/10.1016/j.asr.2012.11.024

# Issues of Geologically-Focused Situational Awareness in Robotic Planetary Missions: Lessons from an Analogue Mission at Mistastin Lake Impact Structure, Labrador, Canada


| | |
|---|---|
| I. Antonenko | (iantonen@uwo.ca) |
| G.R. Osinski | (gosinski@uwo.ca) |
| M. Battler | (mbattle@uwo.ca) |
| M. Beauchamp | (mbeauch6@uwo.ca) |
| L. Cupelli | (ccupelli@uwo.ca) |
| A. Chanou | (anna.chanou@gmail.com) |
| R. Francis | (rfranci8@uwo.ca) |
| M. M. Mader | (marianne.mader@gmail.com) |
| C. Marion | (cmarion3@uwo.ca) |
| E. McCullough | (emccull2@uwo.ca) |
| A.E. Pickersgill | (aepickersgill@gmail.com) |
| L.J. Preston | (louisa.preston01@googlemail.com) |
| B. Shankar | (bshanka2@uwo.ca) |
| T. Unrau | (troy.unrau@gmail.com) |
| D. Veillette | (dveillet@uwo.ca) |

Centre for Planetary Science and Exploration & Canadian Lunar Research Network
Department of Earth Sciences, University of Western Ontario
London, ON, N6A 5B7 Canada

Corresponding Author:
Irene Antonenko
iantonen@uwo.ca
Fax: 519-661-3198

## Abstract

Remote robotic data provides different information than that obtained from immersion in the field. This significantly affects the geological situational awareness experienced by members of a mission control science team. In order to optimize science return from planetary robotic missions, these limitations must be understood and their effects mitigated to fully leverage the field experience of scientists at mission control.

Results from a 13-day analogue deployment at the Mistastin Lake impact structure in Labrador, Canada suggest that scale, relief, geological detail, and time are intertwined issues that impact the mission control science team's effectiveness in interpreting the geology of an area. These issues are evaluated and several mitigation options are suggested. Scale was found to be difficult to interpret without the reference of known objects, even when numerical scale data were available. For this reason, embedding intuitive scale-indicating features into image data is recommended. Since relief is not conveyed in 2D images, both 3D data and observations from multiple angles are required. Furthermore, the 3D data must be observed in animation or as anaglyphs, since without such assistance much of the relief information in 3D data is not communicated. Geological detail may also be missed due to the time required to collect, analyze, and request data.

We also suggest that these issues can be addressed, in part, by an improved understanding of the operational time costs and benefits of scientific data collection. Robotic activities operate on inherently slow time-scales. This fact needs to be embraced and accommodated. Instead of focusing too quickly on the details of a target of interest, thereby potentially minimizing science return, time should be allocated at first to more broad data collection at that target, including preliminary surveys, multiple observations from various vantage points, and progressively smaller scale of focus. This operational model more closely follows techniques employed by field geologists and is fundamental to the geologic interpretation of an area. Even so, an operational time cost/benefit analyses should be carefully considered in each situation, to determine when such comprehensive data collection would maximize the science return.

Finally, it should be recognized that analogue deployments cannot faithfully model the time scales of robotic planetary missions. Analogue missions are limited by the difficulty and expense of fieldwork. Thus, analogue deployments should focus on smaller aspects of robotic missions and test components in a modular way (e.g., dropping communications constraints, limiting mission scope, focusing on a specific problem, spreading the mission over several field seasons, etc.).

**Key Words**: analogue mission; science operations; situational awareness; geology; robotic data

# 1. Introduction

Historically, robotic missions have been the main method of exploring planetary surfaces – the Apollo program being the one exception – and this trend is expected to continue for the foreseeable future. There are ongoing discussions about the benefits and drawbacks to human exploration (e.g., Glass et al., 2003, and the references therein); however, it is clear that remote data relayed via a robot provides different information than the immersion that field geologists experience on site. As a result, personnel at mission control in a robotic mission have a significantly reduced level of situational awareness than what geologists in the field experience.

This includes a limited understanding of their surroundings, distance to objects, lighting conditions, and so on. This prevents mission control scientists from employing their full range of experience and training and has been shown to affect mission control's ability to conduct comprehensive geological studies (e.g., Yingst et al., 2009, 2011a, b). It is, therefore, important to understand the differences and limitations of robot-collected data and to explore ways to mitigate, or compensate for, their adverse effects.

We observed geologically-focused issues of reduced situational awareness in an analogue robotic rover mission conducted in the summer of 2010. This mission was funded by the Canadian Space Agency and deployed at the Mistastin (Kamestastin) Lake impact structure (Figure 1) in Labrador, Canada (Osinski et al., 2010a). The Mistastin Lake structure represents an ideal scientific lunar analogue site, as it includes both an anorthositic target, similar in composition to the dominant rock type of the lunar highlands (Grieve, 1975; Marion and Sylvester, 2010; Osinski et al., 2010a) and preserved ejecta deposits (Mader et al., 2011). It is a ~28 km diameter, 36 Ma complex impact structure that possesses a large range of impact melt rocks and breccias, which are predominantly generated from the anorthositic target rocks (Marion and Sylvester, 2010).

## 2. Methodology

The purpose of the deployment (the first of 3 conducted by this team), was to simulate a robotic precursor mission in advance of a 7-day human sortie mission conducted in the summer of 2011 (Osinski et al., 2010a). As such, the main goal of this first deployment was to provide reconnaissance of the area and to identify sampling target sites for the human follow-on mission. The intent was to develop a geological understanding of the study area at a variety of scales, including regional, outcrop, and hand sample scales. This understanding needed to be detailed enough to provide context for future sample collection and inform the selection of potential sampling sites.

Three main regions (Figure 2) were selected as target areas during a 2-day site selection workshop (Shankar et al., 2011), where satellite data (8-200 m/pix resolution) and a geologic map (Currie, 1971) were used to represent the kind of data generally available for planetary missions. Suggested traverses were also determined during the workshop, however the resolution of available data was too low for detailed traverse planning to be robust at this stage.

For the deployment, the three target regions were visited over the course of 13 operational days, spanning a 3-week period, with 3–5 days spent on analogue activities at each of the indicated regions. During operations, a field team of 4 geologists simulated the robotic rover at Mistastin Lake. They conducted traverses and collected data, all under the direction of a remote mission control team. Instruments on the simulated rover included a GigaPan robotic camera mount and tripod, a digital SLR camera, a mobile Scene Modeler (mSM) stereo camera (Jasiobedzki et al., 2009; Osinski et al., 2010b), an Optech lidar instrument (approx. range of 1 km), a Bruker X-ray Fluorescence (XRF) instrument (Tracer IV-GEO), and a Noggin-plus ground penetrating radar (GPR) unit (Beauchamp et al., 2011). The field team, acting as robot components, would carry the required instruments to a target and collect any requested data. Typical robot constraints, such as limitations in mobility, reach heights, range of motion, etc. were significantly relaxed for the duration of this deployment, in order to focus on science operations. As a result, the field team flight rules allowed for travelling through dense vegetation, climbing on outcrops, and crossing water. GigaPan, camera, mSM and lidar measurements were acquired at a height of approximately 150 cm, with the instruments either mounted on a tripod or hand-held.

Communications between mission control and the field were limited to twice daily, in order to simulate a mission to the South-Pole Aitken basin on the far side of the Moon (with communications supported by a relay satellite in a polar lunar orbit). Instructions to the field team were uploaded prior to the start of each operational day and collected data was downloaded to mission control at the end of each operational day. Data download volume was limited to ~100 Mb per day, which although small by terrestrial standards, is a factor of 2–5 better than that achieved by the Mars Exploration Rovers (MER) (e.g., Mishkin et al., 2006) and comparable to or greater than the Phoenix Mars Scout mission (e.g., Bass and Talley, 2008).

Operations at mission control were conducted by a team of 10 trained geologists. At the start of the science operational shift, data was downloaded, processed, and analyzed by mission control members working in small teams. Each team selected potential targets (Shankar et al., 2011) for the field team's next steps, based on pre-determined objectives. These potential targets were then assessed and prioritized by the entire mission control team, and the final targets selected. The final task of the science operational shift was to provide the next day's operational instructions for the field team. The science operational process, from data download to instruction hand off occurred within a ~4–5 hour time frame. This is comparable to recent planetary missions (e.g., MER, Phoenix), where the time from data download to integration/validation handoff was 5–6 hours (e.g., Mishkin et al., 2006; Bass and Talley, 2008). The total time for one data cycle (as measured from one data download to the next) was 1 day, again comparable to the MER and Phoenix missions (e.g., Mishkin et al., 2006; Bass and Talley, 2008). After completion of the science operational shift, one or two team members would stay on at mission control for 1-4 hours to conduct strategic planning for the next day's operations.

It is important to note that the mission control team was located at the University of Western Ontario, London, Ontario, Canada, ~2,000 km from the field site (Figure 1). None of the mission control team members had ever been to the field site and so had no a priori knowledge about the mission location (similar to the approach for human missions in Fong et al., 2010), aside from a geologic map (Currie, 1971) and remote sensing data (see Shankar et al., 2011). In some analogue deployments, mission control members work from infrastructure at the field site (e.g., Eppler et al., 2011) In such cases, mission control personnel gain first-hand understanding of the analogue site as they transfer to and from their work space at the start and end of each field day and their situational awareness is supplemented by their personal knowledge of the area. This is experience that mission control members in a purely robotic planetary mission do not have. Thus, in separating the field and mission control teams by such distances in our deployment, we faithfully reproduced this aspect of robotic planetary missions.

# 3. Observations

The mission control team encountered a number of geologically-focused difficulties relating to situational awareness that the field team did not. These can be distilled into 4 main issues relating to 1) scale, 2) relief, 3) geological detail, and 4) time. All of these factors impacted the mission control team's ability to effectively direct the simulated robot. This in turn influenced their ability to interpret the geology of the field site and identify suitable sampling targets, which were the main goals of this deployment. In addition, all 4 of these identified issues are inextricably intertwined, each compounding the difficulties of the others. In contrast, the field team, who also conducted their own investigations outside of the analogue mission, did not experience these kinds of difficulties.

## 3.1. Scale

Estimating scale from the image data returned to mission control proved to be much more difficult than anticipated. This is because images with no known objects for scale can be very difficult to interpret (e.g., Figures 3, 4). The Apollo astronauts also experienced this phenomenon in person, and reported that distances were difficult to judge on the surface of the Moon, because of a lack of familiar objects to provide scale (Mission Operations Branch Flight Crew Support Division, 1969). For this deployment, even when height and distance measurements were available, such as from lidar and stereo data, it was found that the numbers did not convey the sense of scale in an intuitive manner (e.g., Figures 5, 6), and so did not carry the same impact as that experienced by the field team. As a result, mission control members were not able to utilize their considerable geological training in a natural and effortless manner.

For example, Figure 5 shows a comparison of scale, as interpreted by mission control and experienced by the field crew at the Coté Creek site (colour-coded arrows identify the same features in all three parts of the figure). The image and lidar data received by mission control are shown in Figures 5a and 5b respectively. The lidar data indicates that this cliff face is 6 metres at its tallest and the large boulder at top (blue arrow) is 2.5 m tall by 1.5 m wide. With the aid of these measurements, mission control identified a site of interest (red arrow) where additional data was to be collected. Mission control estimated that this target site was less than 2 m above the water line. Based on visual cues (e.g., rocks can be seen just below the creek surface and even protruding above the water line in many places throughout Figure 5a), they determined that the water was shallow. For these reasons, mission control believed that this target site would be accessible to the field team.

The field team, on the other hand, knew intuitively that further data collection at the identified target site was not technically feasible, even before the depth of the water was determined. When the same area is viewed in a personal field photograph (which was not sent to mission control) showing a human for scale (Figure 5c), the size of the cliff is instantly comprehensible and it becomes immediately obvious that the target site cannot be reached by the field team (even ignoring the unexpected depth of the water). As a result, useful data was not acquired at this target of interest and valuable time was lost in the process. Improvements in mission control's situational awareness would have eliminated this site as a potential target, allowing the focus to shift to more technically feasible sites.

It is also worth considering that Figure 5c was taken from a different vantage point than Figures 5a and 5b, providing additional information about the scale (and also the relief structure) of the cliff face. This additional information was available to the field team, who naturally explored the site from a variety of locations during their data collection process. Conversely, mission control was confined to one vantage point. Since the data request/acquisition cycle was very time consuming (using one full day from a very limited number of available days – a maximum of 5 at each of the explored regions), it was not considered efficient to request multiple data sets of the same location from varying angles.

### *3.2. Relief*

One major problem for robotic exploration is that image data tends to flatten features. Humans have a very difficult time reliably determining the relief of complex surfaces from 2D representations (Todd and Reichel, 1989; Koenderink and van Doorn 1995). This is an important issue, since a variety of geological information, at various scales, is interpreted from relief information. Geologists generally acquire relief information by examining areas from multiple angles, distances, and even heights (e.g., Yingst et al., 2011a, b). This approach has also been shown to be effective for depth perception in virtual reality environments (e.g., Creem-Regehr et al., 2005). The value of different viewing angles is illustrated in Figure 5, where Figure 5c is taken from a different vantage point than Figures 5a and 5b, showing how much relief is present in the cliff face.

Understanding the importance of relief information, our mission included a mobile Scene Modeler (mSM) stereo camera and a lidar instrument (Osinski et al., 2010b) in the payload package. Both of these instruments assisted in identifying relief, where regular 2D images made features look completely flat. The lidar instrument provided the ability to measure distance from the rover to an outcrop (up to 1 km away), allowing variations in relief to be ascertained. The mSM camera data were used to build 3-dimensional visual models that could be manipulated, allowing virtual examination from multiple angles. However, our mission control team found that sometimes relief was very difficult to comprehend accurately even with 3D data acquired.

The mSM stereo camera collects a series of stereo images along a continuous scanning traverse and then uses proprietary software to build a high fidelity 3D model of the scene (Jasiobedzki et al., 2009). However, we found that the model occasionally failed to communicate the actual geometry of outcrops as documented in the field. An example of this issue is illustrated in Figure 6. Careful examination of the various features in Figure 6 shows that the stereo model of Figure 6a has been oriented to show a similar vantage point as the field photo of Figure 6b (which was not sent to mission control). Protrusions, fractures, and rocks (yellow arrows) are oriented the same way and have the same relation to other features. However, the large overhang on the right (red arrow) is much less pronounced in the stereo data than in the field photo (which more accurately conveys the true relief, as confirmed by the field team). Additional mSM data of this region are presented in the on-line supplemental material (Supplement A). Supplement A1 shows an animation of the mSM data over a range of different orientations. Supplement A2 shows an anaglyph of the mSM data. In all cases, the overhang is less pronounced than reported by the field team. Discrepancies such as this resulted in mission control sending the field team much more technically challenging requests than would otherwise have been considered. It is worth noting that no high resolution lidar data had been requested for this region. It is possible that such data could have helped in evaluating the true relief of this overhang, thus avoiding such problems.

It was found that the spatial resolution used to acquire mSM images (~2 cm) and lidar data (~2 cm point spacing) at the outcrop scale was not sufficient to distinguish relief at the cm scale. Both the mSM and lidar instruments are capable of acquiring higher resolution data, either by moving closer to the target for mSM or by using the higher-resolution settings of the lidar instrument. Such data was not collected here because the resulting larger data volume and time requirements, along with limitations of the human rover components, were found to be prohibitive. This decision proved to be a problem for the X-ray fluorescence (XRF) spectrometer, a contact instrument that requires a 1 cm square flat area to obtain measurements. The mission control team's ability to obtain quality XRF data, and so assess a site's suitability as a sampling target, was therefore affected by the lack of adequate relief information.

It is important to note that even a 3D data set, like lidar or mSM, can look very flat when displayed statically, which has important implications for how such 3D data needs to be viewed and analyzed. Data cannot simply be printed on paper or displayed statically on a computer screen. Instead, the data needs to be either presented as an anaglyph (which requires 3D glasses to view) or animated. It is known that a series of 2D images displaying different views of an object will acquire the appearance of three-dimensionality when shown in rapid succession (e.g., Wallach and O'Connell, 1953). In a similar manner, adding motion to 3D data helps bring out the inherent relief structure. This phenomenon is illustrated in the on-line supplemental material Supplement B (1–3) where the lidar data of Figure 5b is animated (Supplement B1) and presented as an anaglyph (Supplement B3) to show the spectacular relief of the cliff face, relief that is not obvious in the static images of Figure 5b) and Supplement B2. The software used during this mission allowed the mSM and lidar data to be rotated by hand, and allowed distance measurements between features to be made within each scan, but did not allow the data sets to be integrated together or displayed as automated animations. Hence, comparisons between the 3D and other data were cumbersome (though not impossible) to do, requiring several interactive software programs to be run and manipulated at the same time. The returns on 3D data would be maximized through the use of software packages that can integrate and automate some of these useful features.

### *3.3. Geological Detail*

In robotic explorations, there is always the concern that mission control may miss details of geologic interest that a geologist in the field would not. The field geologist has more ease of motion, is not constrained by the data request/download/analysis cycle, and so can employ their training and experience to quickly gather the required data and make informed assessments (e.g., Yingst et al., 2009, 2011a,b, 2012). In our deployment, it was indeed found that issues of time and data resolution all prevented the mission control team from finding and identifying many details of geologic interest and significance. Furthermore, this was an issue at both at the micro- and macro-scales.

A comparison of the micro-scale geologic detail seen by mission control and the field team is illustrated in Figure 7. Both parts of the figure show close-up images of a 'fresh', clean surface of granodiorite, one of the major target rocks of the Mistastin Lake impact structure (Currie, 1971). The two images are from different areas, but at both locations the surface is relatively devoid of lichen and the effects of weathering. In both images, large cm-sized potassium feldspar phenocrysts can be seen. However, these phenocrysts are much more spectacularly illustrated in the field photo (Figure 7a), and notable reaction rims (Currie, 1971) are clearly evident. In contrast, a similar surface identified by mission control is not as optimal (Figure 7b). It is not as smooth, shows some effects of weathering, and has minor lichen present. This surface is, therefore, not as ideal for XRF data collection as the one found by the field crew, and the quality of the XRF data suffered as a result, thereby impinging on the mission goal of identifying suitable sampling locations.

Mission control never saw the spectacular surface identified by the field team, because it was beyond their field of view. This ideal exposure consisted of a flat smooth area approximately 1 by 0.5 m, located on the horizontal surface above the cliff face in Figure 6 (just above the people in Figure 6b). Because of its location, it is not clear if mission control would have ever discovered this ideal surface. Meanwhile, the field team identified this spot easily during a quick survey of the site.

Similar issues were also observed at the macro scale. Figure 8 shows the regional geology at the Mistastin River/Rim site, looking southward across a small narrow lake. Mission control identified the southeast shore of this lake (red arrow in Figure 8) as an area of interest on the first day, and requested a high resolution image of this region. The resulting data, which was collected two days later, is shown in Figure 8a. As it turns out, the lighting and location of data collection proved to be less than optimal. The image data shows only the rock underfoot and the distant horizon, with the region of interest obscured in shadow. Re-acquiring this data from a better location and with better lighting was given a low priority, due to time constraints. Meanwhile, the field team identified an optimal vantage point and lighting conditions on their first day's hike, prior to beginning mission activities at this site. They acquired this spectacular photograph (Figure 8b), which beautifully shows the detailed geology of this area.

### *3.4. Time*

Many of the situational awareness issues addressed so far were also found to be intimately related to the inherent time requirements of conducting robotic missions. The gathering of data in a robotic mission depends on data cycles. While a human field geologist may take 5 minutes to (1) see an outcrop, (2) approach it for a closer look, (3) view it from another side, and (4) take an even closer look, this same sequence of events consumes 4 data cycles for a robotic mission. When the length of a data cycle is controlled by communication limitations (e.g., for Mars or the far side of the Moon), this simple geologic process can take days, as it did for our analogue mission. In such a situation, the time required for a rover to collect the data is irrelevant, so long as it is less that the time to the next data upload, and the need for multiple data cycles to achieve what a human would do intuitively becomes the rate determining factor. Not surprisingly, our remotely-directed exploration occurred slowly. Because our analogue mission was constrained to only 13 operational days, this slow rate was frustrating and so attempts were made to cut steps. However, such corner-cutting itself often resulted in a less than effective use of time.

In addition, gleaning information from the returned robotic data was found to be much more time consuming than interpretations in the field. It took time for mission control to download the data. Interpretation of the data was much less intuitive and took longer, since many of the scientists' acquired field skills could not be applied as effectively to the remote data. The data had to be discussed, the next targets identified and prioritized, and the data for those finally requested. All these steps resulted in a very time-consuming data analysis process. A similar result was observed by Yingst et al. (2012). In contrast, a field team can absorb and process visual information intuitively. They automatically modify their distance to an object of interest, view it from multiple angles and at different heights, all to optimize the quality of their observations. Decisions are made quickly, whether as a group or unilaterally, and then followed up on instantly (e.g., Yingst et al., 2011a). This was also observed in this deployment, where the field team observed and interpreted more geology than mission control, both while gathering data as mission robot components and during out of scenario periods.

Almost all of the examples discussed so far have illustrated the issue of limited time, in one way or another. Figures 5 and 6 illustrate how non-intuitive numerical values of scale can be. In both figures, the scale of the outcrops is conveyed much more intuitively and, therefore, quickly by the presence of a human figure. The numerical scale, meanwhile, must be measured from the data and then digested by the interpreter, taking much more time to accomplish the same result.

Figures 5 and 6 also demonstrate how a limited amount of scale and relief information can result in mission control selecting inappropriate target sites, thereby wasting data cycles and time. Since the data request/acquisition cycle is very time consuming, it was often considered inefficient to request additional data sets of the same location, in order to observe the area of interest from other viewing directions or distances. Had more time been available, multiple data cycles could have been executed, resulting in more information, and from a variety of locations, improving the target selection results and geologic interpretation of the region. Yingst et al. (2009) observed this same phenomenon, where lack of data at multiple scales resulted in reduced contextual information and an inability to constrain geological hypothesis for the region of study. The trade-off between the time required to collect additional data versus the potential time wasted by non-optimal decisions due to insufficient data needs to be carefully considered, as it can significantly affect the best achievement of mission goals.

The time involved in remotely locating and observing important geological details is illustrated in Figures 7 and 8. At the microscopic scale, mission control took several days to acquire a non-optimal view (Figure 7b) of the phenocryst texture of the target rock, while the field team discovered a spectacular exposure (Figure 7a) of this texture in a quick survey of the site. Figure 8 illustrates that the time required to collect useful information on geologic detail can also be considerable at the macroscopic scale. Mission control identified the area indicated by the red arrow as a target of interest on the very first day of the deployment. Because of time constraints, a high resolution image of the area was not acquired until 2 days later. The resulting data, however, was collected under non-optimal lighting conditions and from an unfortunate vantage point, resulting in the area of interest being obscured by shadows and the foreground (Figure 8a). Time constraints again were responsible for giving a low priority to the re-acquisition of this data, and so it was not obtained. Meanwhile, the field team acquired a spectacular photograph (Figure 8b) of the target of interest on their first day's hike around the Mistastin Lake Rim site, prior to the start of operations here. They intuitively identified the optimal vantage point and lighting conditions to show off the beautiful structures and linear orientations of the rock.

One additional aspect observed during the deployment involved the time lost due to miscommunications between mission control and the field team. In some cases, it appears that mission control's instructions to the field team were not clear, resulting in either data of the wrong resolution, from the wrong instrument, or even of the wrong area being collected. Several such incidents produced squandered data cycles and wasted time. This issue has broader considerations, outside the confines of this deployment structure. In a standard robotic scenario, a science team would be responsible for directing which data should be collected, but these directions would then be translated to the robot by an engineering team. Miscommunication between the science and engineering teams could result in similar problems and a subsequent waste of time.

# 4. Discussion

From these initial studies, it is clear that the geologically-focused situational awareness issues of scale, relief, geologic detail, and time are very complex, and that they are all inextricably intertwined. These issues can seriously impede the ability of the mission control science team to interpret the geology of a region effectively and to direct further data collection in an efficient manner (Yingst et al., 2009, 2011a,b), the two main goals for this deployment. This finding shows that even for a pre-cursor robotic deployment, designed simply to reconnoiter for a human follow-on mission, situational awareness issues are of significant scientific concern. It is not clear that these types of issues can be addressed with more or better instrumentation. Alternative solutions and mitigation options need to be considered.

### 4.1. Scale

It is clear that scale is much more difficult to determine in remote data. In our case, this was found to apply even when numerical dimensional information was provided. The numerical data was found to be non-intuitive and therefore took much longer to interpret. The presence of humans or known objects in the scene allows for a more intuitive and, therefore, faster interpretation of scale. This issue is of great concern in robot-driven planetary exploration, where humans or common objects of known size are not present. The issue is further complicated by the fact that familiar geologic features cannot be relied upon to provide indications of scale, because extraterrestrial features may have vastly different scales than their Earth analogues. This fact was effectively demonstrated in our deployment, where the stunted trees of the northern Labrador proved to be ineffective indicators of scale for the mission control team members, who are much more familiar with the larger trees common at more southern latitudes.

One solution to the scale issue may be to develop and employ extensive training programs in scale interpretation for mission control team members. Such training would work towards instilling a more intrinsic sense of scale from numerical values, thereby improving on the speed and functionality of this process. Mission control members did not undergo any such training prior to the deployment, because the value of such training had not been appreciated. Personnel trained in such techniques would be able to make much better use of the 3D data collected by the field team. In particular, as suggested by Osinski et al. (2010b), lidar data has great potential as a science tool and so should be utilized much more in this capacity, in addition to its current use for rover navigation. Science team members that are trained to fluidly interpret scale from numerical lidar data may help to significantly alleviate this problem.

Another option for this issue would be to attempt to mimic the quick and intuitive interpretation of scale experienced by geologists in the field. It should be possible, through the use of software, to generate intuitive scale-indicating features (such as humans, pens, or coins, which are generally more meaningful to humans than numerical scale bars – see Figures 5 and 6) from the numerical dimensional data and automatically embed appropriately sized representations of these beside their corresponding feature of interest in the image data. Such a solution would of course consider the distance to each feature of interest within the scene and adjust the local auto-generated scale object accordingly, based on available distance information (from lidar or other 3D data). Techniques employing similar concepts were developed for commercial aviation more than a decade ago (e.g., Foyle et al., 1996). It is important to stress that such a solution would take advantage of the already extensive training that field geologist have, thereby minimizing the need for additional training.

It is also important to consider that scale issues can be better understood with data from a variety of distances and vantage points. However, in this deployment, the limited number of data request/acquisition cycles (no more than 5 per landing region) meant that data from multiple vantage points was not generally acquired. Mission control did not consider obtaining additional data from a different location or angle to be an efficient use of an entire data cycle. This assumption should be explicitly evaluated in future missions on a case-by-case basis, to determine if more data is indeed necessary for an accurate interpretation of scale. Since not enough of this kind of data was acquired during our deployment, additional work is necessary to explore the criteria requirements for such evaluations.

### *4.2. Relief*

As noted above, determining relief from remote data also proved to be more difficult than anticipated. Even with the availability of 3D data, relief information was not always interpreted accurately. One solution could be to collect data from multiple vantage points, thus forcing the robot to mimic typical field geologists techniques (e.g., Yingst et al., 2011a). Collection of data from multiple vantage points is also the principle behind the mSM stereo camera (Jasiobedzki et al., 2009). However, as was shown in Figure 6, even this approach does not guarantee accurate communication of relief. Further development of these technologies may mitigate this issue.

It would have been very useful to spend more time on data acquisition in general around areas of interest, in order to collect more relief information. Time should be taken to move the robot around the target, collecting data from a variety of viewing directions. This would help to develop better situational awareness of the target area in all respects, not just regarding relief. Such activity should not automatically be considered a waste of time. It should be considered a necessary step for providing invaluable relief information, from which geological understanding and further targeting will follow. The cost/benefit analysis of such an activity needs to be carefully considered on a case-by-case basis, to determine if the outlay of time is justifiable with respect to anticipated improvements in relief and general situational awareness. Areas where variable relief may have a significant impact on geologic interpretation or further targeting activities are prime candidates for such additional data acquisition. More research is needed to evaluate exactly when such data is cost effective, since not enough relief data was collected during this deployment to make this assessment.

The resolution of collected mSM and lidar data proved to be insufficient for identifying suitable targets for X-ray fluorescence (XRF) spectrometer measurements, which require a 1 cm square flat area. Higher resolution data could have been collected and may have helped alleviate this problem. However, this would have required more bandwidth to transmit, which is generally limited in planetary exploration scenarios (e.g., Mishkin et al., 2006; Bass and Talley, 2008), and was not available in our deployment. Use of effective compression algorithms would be highly desirable in such cases.

Collection of 3D data in and of itself is not sufficient to provide relief information. The data must also be displayed correctly, since static displays of 3D data (even on a computer screen and projected onto a 3D space) still appear flat and lose much of their relief information (e.g., Figure 5 and Online Supplement B). Therefore, software tools that either animate the data or display it as an anaglyph need to be employed, so that the relief information can be interpreted by the human brain/eye combination (e.g., Wallach and O'Connell, 1953). It is worth noting that software must support hands-free rotation and movement of the 3D data model, and not just allow for manual manipulation of the data, since some analysis may need to take place when hands are occupied by other activities. Currently, work on 3D visualization is being done (e.g., Rauschecker et al., 2006; Creem-Regehr et al., 2005) in the Virtual Reality community, opening up interesting solutions to this problem.

### 4.3. Geologic Detail

A number of geologic details, at both the macro and micro scales, were missed due to operational decisions, based on the time required to collect more and better data (higher resolution, smaller scale of focus, better vantage point, proper illumination, etc.). Missed geologic details, therefore, appear to be a serious operational problem for robotic planetary missions. Geologists tend to move around when conducting field observations. They conduct a preliminary survey of a field area before zooming in on targets of interest. Identified targets are then observed from a variety of look directions and distances to obtain as much information as possible (e.g., Glass et al., 2003; Yingst et al., 2011a). When this process is not simulated in robotic missions, geologic detail can be missed, as we observed, and this can have a significant impact on achieving mission goals.

Clearly, operational processes need to be developed that better model effective field techniques. It may be beneficial for a robot to conduct a quick reconnaissance of an outcrop or smaller-scale target of interest, prior to more detailed data collection, to aid in the planning of further data acquisition. Factors such as sun angles and orientation of features should also be noted to help optimize subsequent data collection. Again, such activity should not be considered a waste of time or robot resources, but rather an important step towards a thorough and accurate geologic understanding of the region. Such an operational model requires a lot more time to execute effectively, a factor that needs significant consideration.

### 4.4. Time

All of the geologically-focused issues encountered were compounded by time constraints. This is an inescapable factor of robotic exploration. It has been shown that humans are 1–2 orders of magnitude more productive per unit of time than robots when it comes to planetary exploration (Glass et al., 2003). Interpretation of non-intuitive data takes longer. The data request/acquisition cycle is very time consuming, since communications may be limited such as for a mission on the far side of the Moon. This means mistakes are very costly, and so decisions about next steps are more carefully considered. All these factors combine to make robotic missions slow processes that span months to years (e.g., Mishkin et al., 2006).

Robotic analogue missions, in contrast, are generally conducted on short timelines, lasting only days to weeks, due to the difficulty and expense of fieldwork. As a result, analogue missions do not tend to explore the kind of long term operational model that appears to be required to optimize geologic science results in robotic missions. Instead, time constraints may be used to justify scaling back on data acquisition, because each data request/acquisition cycle is so costly, using a large portion of available mission time. Thus, additional data sets of the same site of interest are given low priority. High quality data of systematically increasing resolutions, necessary for targeting and to provide context, are not obtained. This approach can result in non-optimal decisions, which themselves waste time, and so needs to be reconsidered.

In order to properly model the operational time scales of geologically productive robotic missions, it seems clear that the analogue mission design needs to be reconsidered. It is important to recognize that robotic missions work slower, but last longer. These aspects of robotic missions need to be embraced and planned for during planetary deployments. They also need to be included in the test aspects of analogue missions. It must, however, be acknowledged that analogue missions cannot realistically be run for time durations that are comparable to actual planetary robotic missions. Instead, analogue deployments will need to focus on smaller aspects of operations and test components modularly, possibly “green carding” aspects outside of the test parameters. Examples of this approach could include dropping communications fidelity constraints and operating with live communications, providing multiple views of a target of interest in one data cycle, limiting the scope of the exercise to a very specific problem, such as locating an optimal sampling target in one limited outcrop, spreading out a mission over several field seasons, etc.

### *4.5. Data Bandwidth Considerations*

A recurring theme for addressing the geologically-focused issues we encountered appears to be the collection of more or better data (higher resolution, smaller scale of focus, different observation angle, etc.). The problem with more data for each feature of interest is that, in robotic planetary exploration, limited bandwidth is often a consideration (e.g., Mishkin et al., 2006; Bass and Talley, 2008). Thus the desire for more and higher quality data must be balanced by the total quantity of data that can be returned to mission control.

One solution may be to develop software tools that manage the data on the robot and return only selected data. In the case of the mobile Scene Modeler, this may mean building the model on the robot and returning only the model, but not the original data. For the issues of spatial resolution, one approach may be to collect all data at very high resolutions, but return only sub-sampled, lower resolution data in the first pass, and then allow mission control to request the higher or full resolution data for small selected regions of interest (e.g., Litwin and Maki, 2005). This scheme, however, is contingent upon nearly continuous and speedy communications with the robot, since delays in the data request/delivery cycle would negate any benefits of this scheme in comparison to collecting the high resolution data for an area of interest only when it is requested.

### *4.6. Data Fusion*

Another aspect of data management that needs to be addressed is the way in which data from various instruments is interrelated. Generally, each instrument has a specific data type, which is managed and displayed by a separate software tool. This can make interpretation difficult. For example, image and lidar data provide different, but complementary, information. However, it can be difficult to see correlations between the data elements if one has to manually correlate corresponding features from data sets displayed side by side. If, instead, the data is fused, with one set overlaid on top of the other (e.g., Norris et al., 2005), commonalities and differences are instantly visible. In this way, more information can be gleaned, allowing synergies between the data to be displayed and analyzed.

Software tools and techniques that can fuse such disparate data sets quickly and effectively, displaying them in an intuitive manner (e.g., 3D and panoramic representations), need to be developed and employed. Such tools should also have the functionality of communicating data collection requests clearly between the science team and the engineering team (e.g., Norris et al., 2005). Science team members want to be able to make data selection decisions using the same tools that they use to display and manipulate their fused data sets. Using those same tools to present their data acquisition requests should help to minimize miscommunications with the engineering team, which is responsible for converting those requests into instructions for the robot.

## 5. Conclusions

Robotic planetary exploration is a slow process, lasting months to years, and takes longer to achieve results than with humans in the field. Human exploration, on the other hand, is decidedly faster, but requires consumable resources to sustain the astronauts and so typically cannot have as long durations as robotic missions (unless architecture for an extended-stay human mission is in place). For this reason, robotic missions will always have a place in any planetary exploration program, and so their limitations need to be addressed, understood, and, if possible, mitigated for.

We observed a number of geologically-focused issues during a robotic analogue mission to the Mistastin Lake impact structure in Labrador, Canada. Results suggest that problems of geologically-focused situational awareness fall into a number of categories, including scale, relief, geological detail, and time. These categories are all inextricably intertwined and significantly affect the ability of the mission control science team to conduct geologic investigations and achieve mission goals. Furthermore, situational awareness issues are of substantial scientific concern, even for robotic reconnaissance in preparation for human deployment.

Several suggestions for how to mitigate these effects have been presented. Incorporating known objects that convey scale information intuitively, such as humans, pens, or coins, could be used to help address the non-intuitive nature of numerical values in scale interpretations. Collecting data from multiple vantage points (including view angle and distance) would help with interpretations of relief. In addition, 3D data must be viewed in motion (e.g. using software that allows rotation about 3 axes) or as anaglyphs, since 3D data will otherwise appear flat. In fact, all the data needs to be viewed in a more dynamic way, allowing all the various data sets to be fused and analyzed interactively. Software tools that integrate this aspect with the task of communicating science team requests to the robot engineering teams are highly desirable.

One of the most important mitigating suggestions is an operational one. Time needs to be allocated to the collection of specific types of data that are often overlooked, typically due to time constraints. These include cursory preliminary surveys, multiple observations of the same region from various vantage points, and progressively higher resolution data sets for targets of interest. Such data collection models the techniques generally employed by field geologists. However, as we discovered, there is a danger that these can be given low priority in robotic exploration because they may be perceived to be an inefficient use of robot time and resources. It is important to be mindful of such pitfalls, and to recognize that this kind of data collection can be an absolutely necessary step for the thorough and accurate geologic interpretation of a region.

Finally, the different timelines of robotic missions need to be recognized and embraced. Robots take longer than humans to complete tasks, but robotic missions last months or years (not days or weeks). Analogue deployments need to consider this aspect in their testing methodologies, if they are to accurately model planetary missions. It may be beneficial to consider smaller aspects of an analogue mission and test components in a modular way.

**Acknowledgements:** Funding from the Canadian Space Agency (CSA) is gratefully acknowledged. Genevieve Dubreuil-Laniel, Timothy Haltigin, David Gingras, Luminita Ilincalgnat, and Eric Martin, all from the CSA, are thanked for their support throughout. Ho-Kong (MDA) and Chris Shaver (UWO) are thanked for their efforts in the field.

# References


Bass, D.S., and Talley, K.P. Phoenix surface mission operations process, J. Geophy. Res. 113, E00A06, doi:10.1029/2007JE003051, 2008.

Beauchamp, M., Osinski, G. R., Unrau, T., Marion, C., Mader, M.M., Antonenko, I., and Barfoot, T. Ground Penetrating Radar (GPR) Investigations of the Mistastin Lake Impact Structure: A Case for GPR on the Moon, 42nd Lunar and Plan. Sci. Conf., Abst. #2147, 2011.

Creem-Regehr, S.H., Willemsen, P., Gooch, A.A., Thompson, W.B. The influence of restricted viewing conditions on egocentric distance perception: Implications for real and virtual indoor environments, Perception 34 (2), 191–204, 2005.

Currie K.L. Geology of the resurgent cryptoexplosion crater at Mistastin Lake, Labrador, Bulletin of the Geological Survey of Canada 207, Ottawa: Geological Survey of Canada, 62 p., 1971.

Grieve R. A. F. Petrology and chemistry of the impact melt at Mistastin Lake crater, Labrador, Geol. Soc. of America Bull. 86, 1617-1629, 1975. Eppler, D.B., Ming, D.W., and the Desert RATS Science Operations Team. Planetary surface science operations for human missions: The 2010 Desert Research and Technology study, 42nd Lunar and Plan. Sci. Conf. Abst. #1811, 2011.

Fong, T., Abercromby, A., Bualat, M.G., Deans, M.C., Hodges, K.V., Hurtado, J.M., Landis, R., Lee, P., Schrckenghost, D. Assessment of robotic recon for human exploration of the Moon, Acta Astronautica 67, 1176-1188, doi:10.1016/j.acta.astro.2010.06.029, 2010.

Foyle, D.C., Andre,A.D., McCann, R.S., Wenzel, E., Begault, D., and Battiste, V. Taxiway navigation and situational awareness (T-NASA) system: Problem, design philosophy, and description of an integrated display wuit for low-visibility airport surface operations, SAE Transcactions: Journal of Aerospace 105, 1411-1418, 1996.

Glass, B., Briggs, G., Jaspar. J., and Snook, K. Evaluation of human vs. teleoperated robotic performance in field geology tasks at a Mars Analog Site, in Proc. 7th i-SAIRAS-03, 1, 2003.

Jasiobedzki, P., Ng, H., Bondy, M., and Mcdiarmid, C.H. CSM2: a mobile system for detecting and 3D mapping of chemical, radiological, and nuclear contamination, in: SPIE Volume 7305, Sensors and Command Control Communications and Intelligence (C31) Technologies for Homeland Security and Homeland Defense VIII, Orlando, Florida, 2009.

Koenderink, J.J. and van Doorn, A.J. Relief: pictoral and otherwise, Image and Vision Computting 13 (5), 321-334, 1995.

Litwin, T.E. and Maki, J.N. Imaging services flight software on the Mars Exploration Rovers, in Systems, Mand and Cybernetics, 2005 IEEE International Conference, 895-902, doi: 10.1109/ICSMC.2005.1571260, 2005.

Mader, M.M., Osinski, G.R., Marion, C. Impact ejecta at the Mistastin Lake impact structure, Labrador, Canada, 42nd Lunar and Plan. Sci. Conf., Abst. #2505, 2011.

Marion, C.L. and Sylvester, P.J. Composition and heterogeneity of anorthositic impact melt at Mistastin Lake crater, Labrador, Planet. and Space Sci. 58, 552-573, doi:10.1016/j.pss.2009.09.018, 2010.

Mishkin, A., Limonadi, D., Laubach, S.L., and Bass, D.S. Working the Martian night shift. The MER surface operations process, IEEE Robotics and Automation Magazine 12 (2), 46-53, 2006.

Mission Operations Branch Flight Crew Support Division. Apollo 11 Technical Crew Debriefing, NASA Manned Space Centre, Houston, TX, 1969.

Norris, J.S., Powell, M.W., Bona, M.A., Backes, P.G., and Wick, J.V. Mars Exploration Rover operations with the Science Activity Planner, Proc. 2005 IEEE Internat. Conf. on Robotics and Automation, Bacelona, Spain, 4618-4623, 2005.

Osinski, G.R., Antonenko, I., Barfoot, T., Ghafoor, N., Jolliff, B.L., and Sylvester, P. An analogue mission in support of MoonRise and other sample return missions to the South Pole–Aitken basin, LEAG 2010, Abstract #3047, 2010a.

Osinski GR., Barfoot, T.D., Ghafoor, N., Izawa, M., Banerjee, N., Jasiobedzki, P., Tripp, J., Tichards, T., Auclair, S., Sapers, H., Thomson, L., Glemming, R. Lidar and the mobile Scene Modeler (mSM) as scientific tools for planetary exploration, Planetary and Space Science, 58, 691-700, doi: 10.1016/j.pss.2009.08.004, 2010b.

Rauschecker, A.M., Solomon, S.G., and Glennerter, A. Stereo and motion parallax cues in human 3D vision: Can they vanish without a trace? Journal of Vision, 6, 1471-1485, doi: 10.1167/6.12.12, 2006.

Shankar, B., Antonenko, I., Osinski, G. R., Mader, M.M., Preston, L., Battler, M., Beauchamp, M., Chanou, A., Cupelli, L., Francis, R., Marion, C., McCullough, E., Pickersgill, A., Unrau, T., and Veillette, D. Lunar Analogue Mission: Overview of the Site Selection Process at Mistastin Lake Impact Structure, Labrador, Canada, 42nd Lunar and Plan. Sci. Conf., Abst. #2594, 2011.

Todd, J.T. and Reichel, F.D. Ordinal structure in the visual perception and cognition of smooth surfaces, Psychol. Rev. 96, 643-657, 1989.

Wallach, H. and O'Connell, D.N. The kinetic depth effect, Journal of Exploration Psychology, 45, 205-217, doi: 10.1037/h0056880, 1953.

Yingst, R.A., Schmidt, M.E., and Lentz, R.C.F. Observations of a potential Mars analog at the microscale using rover-inspired methods: A 10-sol observation of Fort Rock tuff ring, J. Geophys. Res., 114, E06004, doi:10.1029/2008JE003223, 2009.

Yingst, R.A., Cohen, B.A., Crumpler, L., Schmidt, M.E., and Schrader, C.M. Testing Mars-inspired operational strategies for semi-autonomous rovers on the Moon: The GeoHeuristic Operational Strategies test in New Mexico, Mars, 6, 13-31, doi:10.1555/mars.2011.0002, 2011a.

Yingst, R.A., Schmidt, M.E., Lentz, R.C.F., Janzen, J.L., and Kuhlman, K.R. A Mars-oriented image database of hand lens-scale features and textures: The 1996 Skeiðarársandur Jökulhlaup example, in Garry, W.B., and Bleacher, J.E., eds., Analogs for Planetary Exploration: Geological Society of America Special Paper 483, p. 301-315, doi:10.1130/2011.2483(20), 2011b.

Yingst R.A., Cohen, B.A., Ming, D.B., Eppler, D.B. Comparing Apollo and Mars Exploration Rover (MER) operations paradigms for human exploration during NASA Desert-RATS science operations, Acta Astronautica, doi:10.1016/j.actaastro.2011.10.001, 2012.

# Figure Captions

**Figure 1.** Location of the field site at Mistastin (Kamestastin) Lake impact structure, Labrador, Canada (55.88° N, 63.31° W) (yellow star) and mission control at the University of Western Ontario, London, Ontario, Canada (red star). These two locations are separated by approximately 2,000 km. (Earth Image courtesy of Blue Marble Next Generation, NASA Earth Observatory, compiled using NASA World Wind source code, displayed using Geosoft Dapple open source software).

**Figure 2.** Google Earth© image of the Mistastin Lake impact structure, Labrador, Canada. The proposed rim location is shown by the dashed yellow line. Various field sites discussed in the text are indicated by letters; A) Mistastin River/Rim site, B) Coté Creek site, C) Discovery Hill site.

**Figure 3.** Field photograph showing an outcrop at the Mistastin River/Rim site. The reader is encouraged to estimate the size of the foreground outcrop and then refer to Figure 4, where the same area is shown with a person for scale.

**Figure 4.** Field photograph showing the same area as in Figure 3, taken from the same vantage point, but with a person for scale. Note how the addition of a human figure makes the interpretation of scale immediate and intuitive.

**Figure 5.** Comparison of scale, as interpreted by mission control and experienced by the field crew. **a)** Section of rover image data received by mission control, showing the northeast bank of Coté Creek. **b)** Robot-collected lidar data received by mission control, showing the same area as in a). The lidar data indicates that the cliff is 6 m tall and that the large rock at the top of the cliff (blue arrow) is 1.5 m high and 2.5 m wide. The mission control team selected what they believed was a reasonably accessible target of interest (red arrow), based on the available data. **c)** Personal photograph taken by the field team (but not sent to mission control), showing approximately the same area as seen in a) and b). The large rock at the top of the cliff is again indicated by a blue arrow, and the red arrow shows the selected target of interest. Note how the inclusion of a field member in the photo communicates the scale of the cliff more instantly and effectively than a numerical value. It also immediately demonstrates that the selected sampling site is not accessible to the field team, even if the water depth was not a factor.

**Figure 6.** Comparison of relief, as interpreted by mission control and experienced by the field crew. Arrows identify the same features in the two images. **a)** Section of mobile Scene Modeler (mSM) 3D data received by mission control, showing an outcrop at the Mistastin River/Rim site. The 3D model has been oriented to show the same view as seen in b). **b)** Field photograph (not sent to mission control) showing the same area as a), but with people for scale. These images demonstrate how the overhanging rock (red arrow in both images) appears to protrude much less in the mSM 3D model than in the field photograph. Stereo data can also yield heights and distances. The red line on image a) is 1.6 m long (measured from mSM data), about the same length as the person at that location in photograph b). However, the human figure conveys a much better sense of scale than the numbers do.

**Figure 7.** Comparison of the micro-scale geologic detail seen by mission control and the field team at the Mistastin River/Rim site. **a)** Personal field team photograph of a “fresh” granodiorite surface, showing beautiful potassium feldspar phenocrysts with notable reaction rims. This surface is located on the horizontal surface above the cliff face seen in Figure 6. Mission control never saw this surface because it was not in their line of sight. Meanwhile, the field team identified this spot easily by a quick survey of the site. **b)** The mission control team did discover a relatively ‘fresh’ surface of similar material, but this exposure was less than optimal and not as ideal for XRF data collection.

**Figure 8.** Comparison of the macro-scale geologic detail seen by mission control and the field team at the Mistastin River/Rim site. The red arrow shows the same location in both images. **a)** Image data of the south-east shore of a small narrow lake obtained by mission control on the 3rd day of the deployment. Note how the target of interest (red arrow) is obscured by shadow and foreground rock. Re-acquisition of this data was given low priority due to time constraints, and so was never obtained. **b)** Field photograph of the same area as in a). Note how the rock structures and lineations are clearly seen in this photo, which seems to have been taken at an optimal angle and with ideal lighting conditions. The field team collected this photograph on their first day’s walk around, prior to the start of mission operations at this site.

# Issues of Geo-Focused Situational Awareness in Robotic Planetary Missions: Lessons from an Analogue Mission at Kamestastin Lake Impact Structure, Labrador, Canada.

## Colour Figures for Electronic Publication

**(Black and white figures for hardcopy publication follow)**

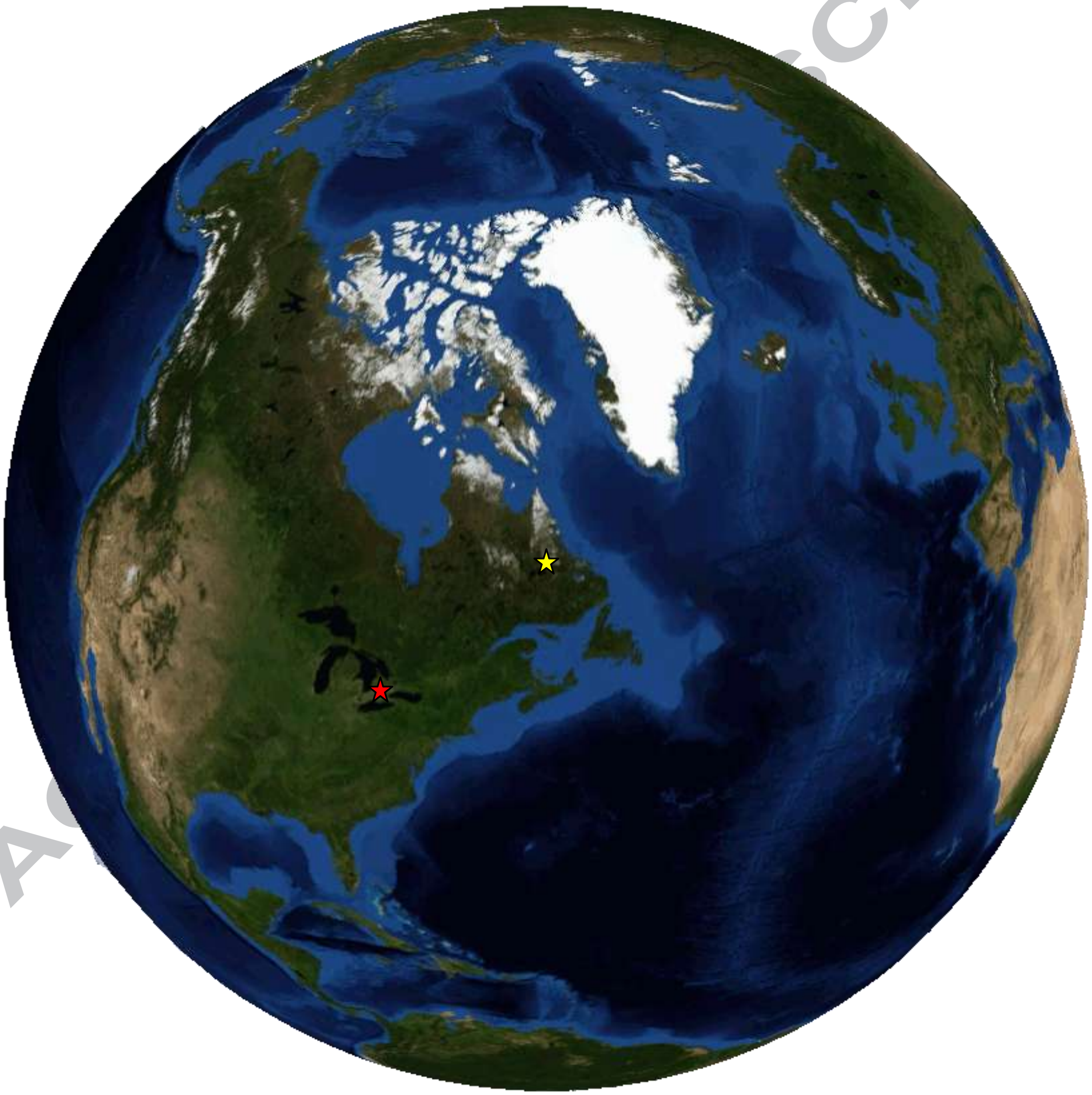

**Figure 1**

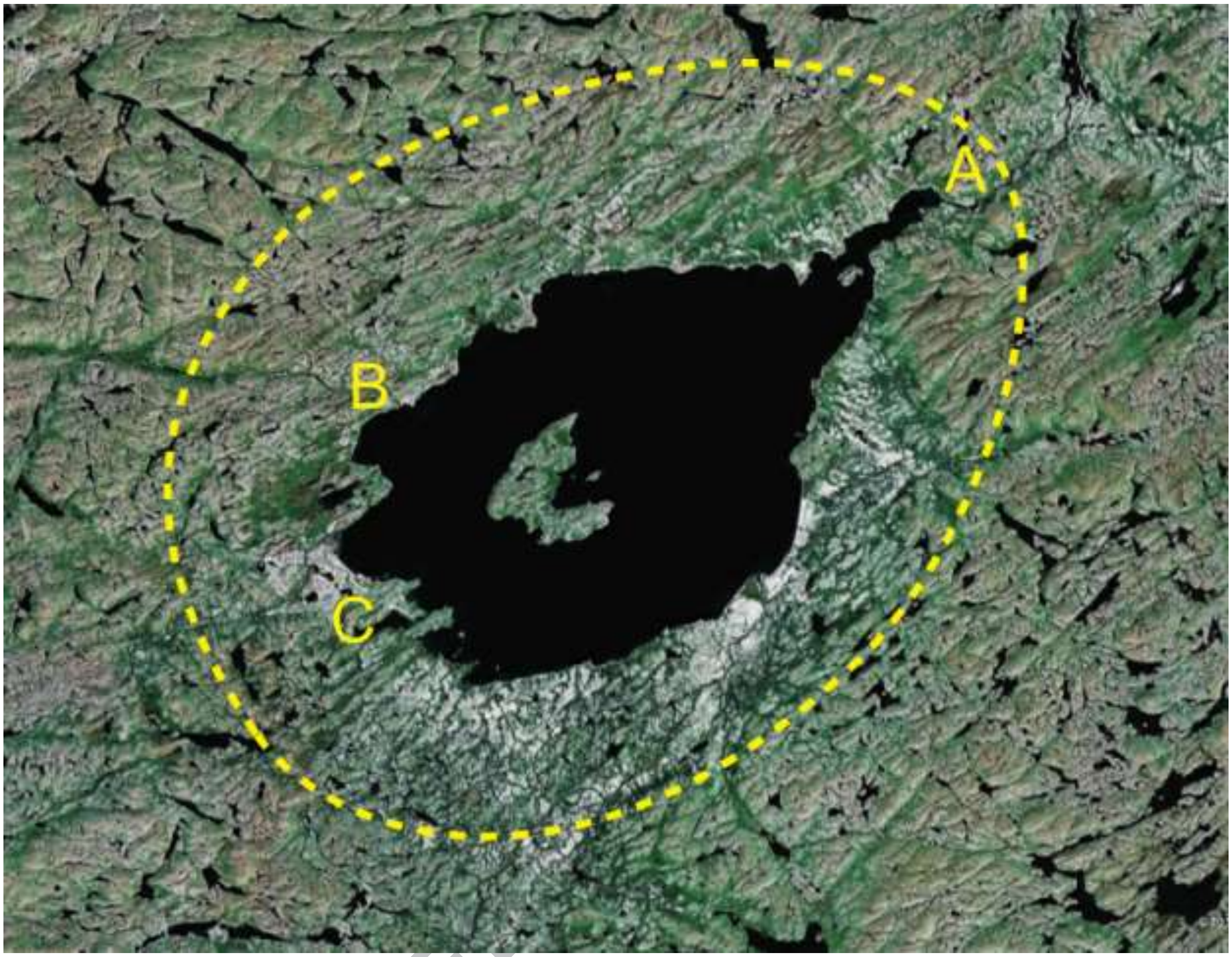


**Figure 2**

**Figure 3**

**Figure 4:**

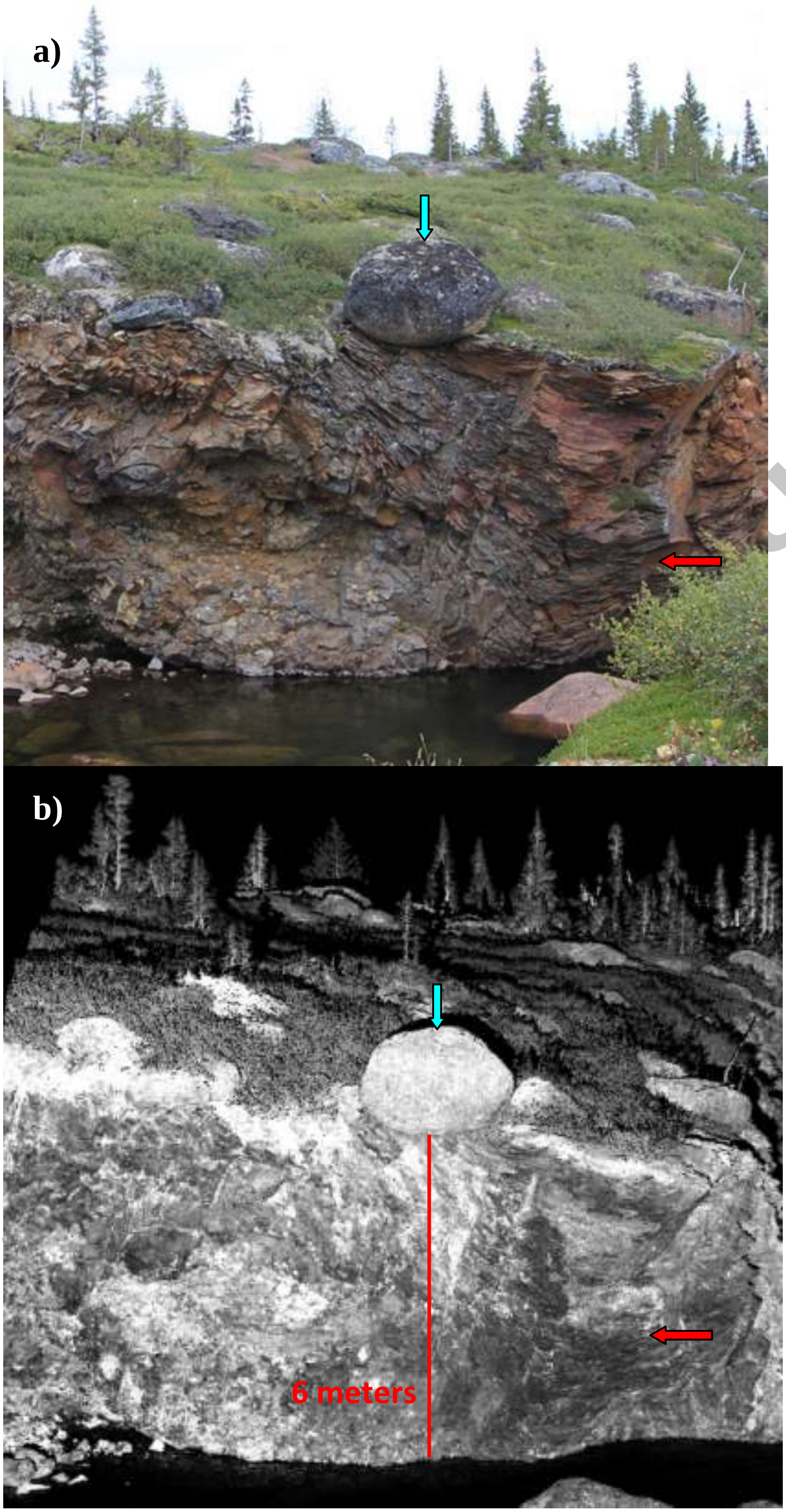


Figure 5

Figure 5c

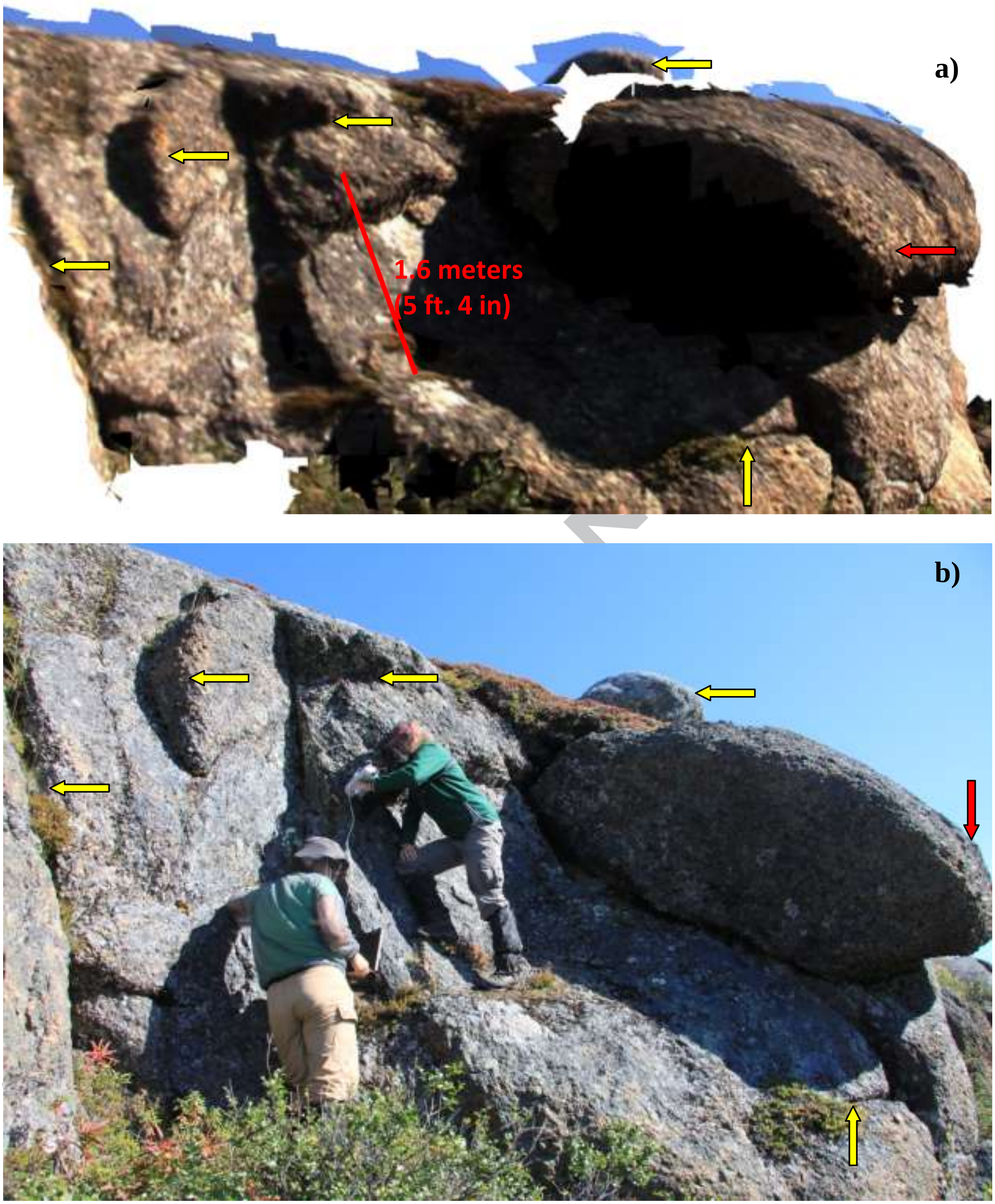


**Figure 6**


**Figure 7**

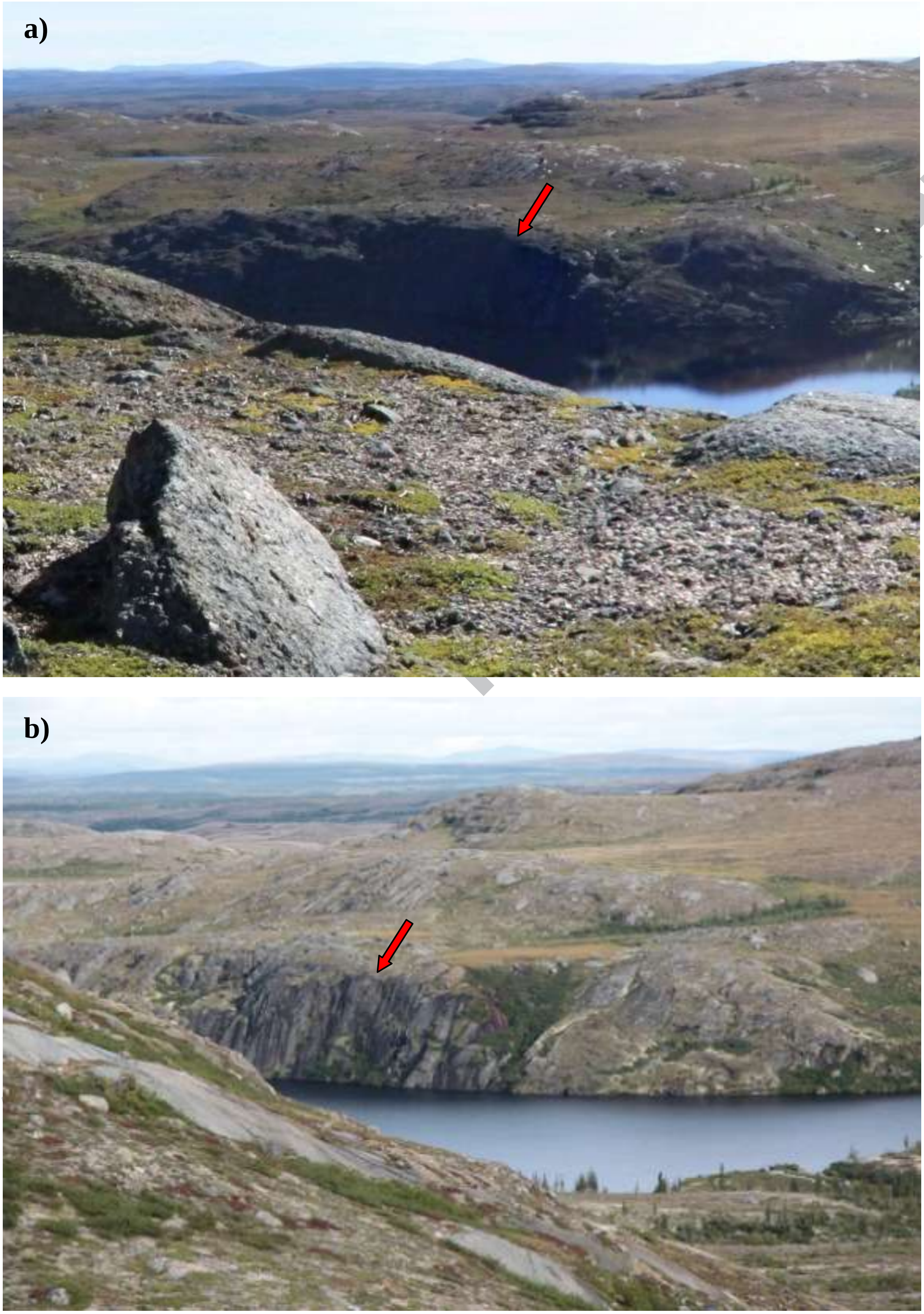


Figure 8

# Black and White Figures
# For Hardcopy Printing

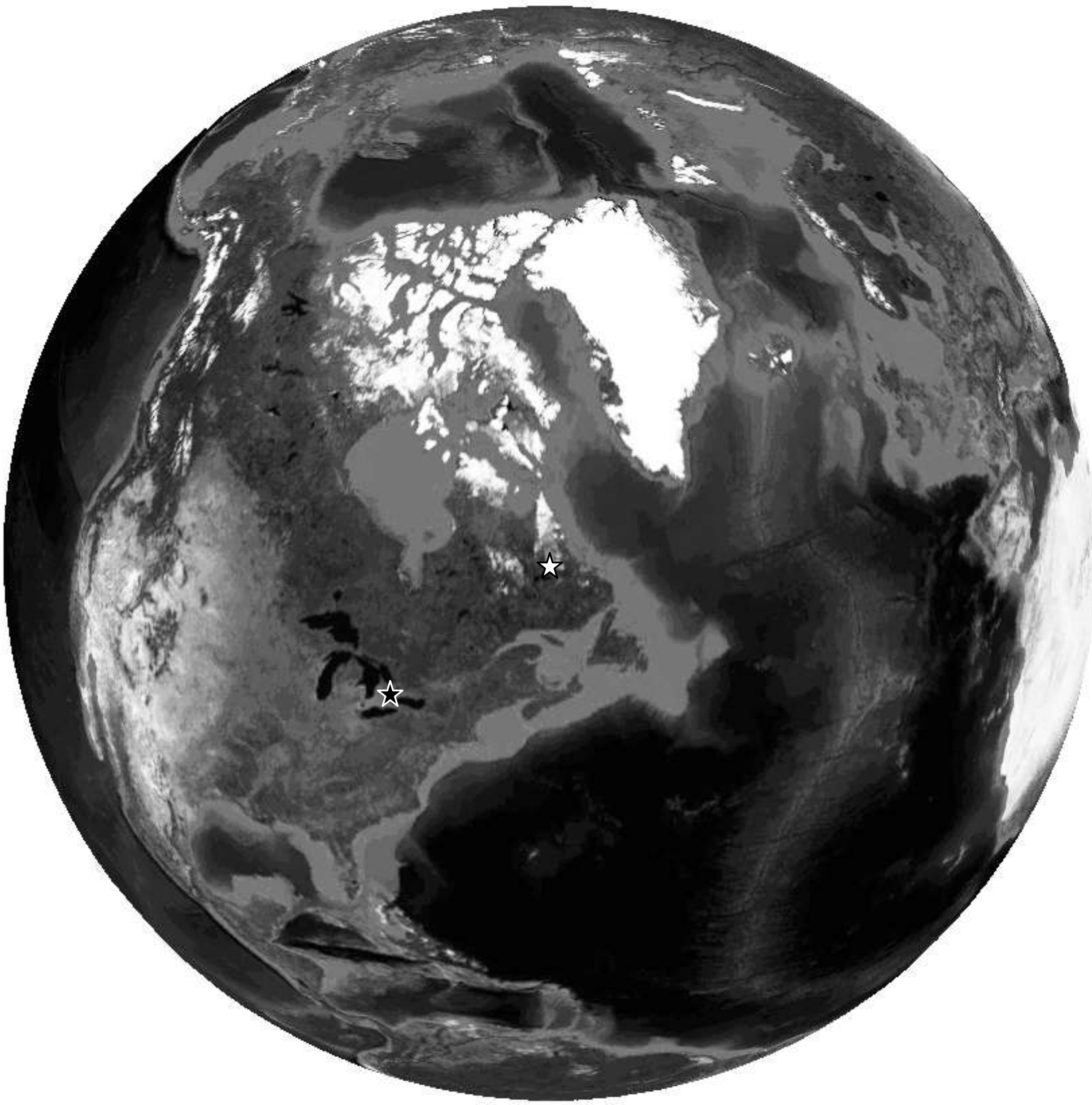

**Figure 1**

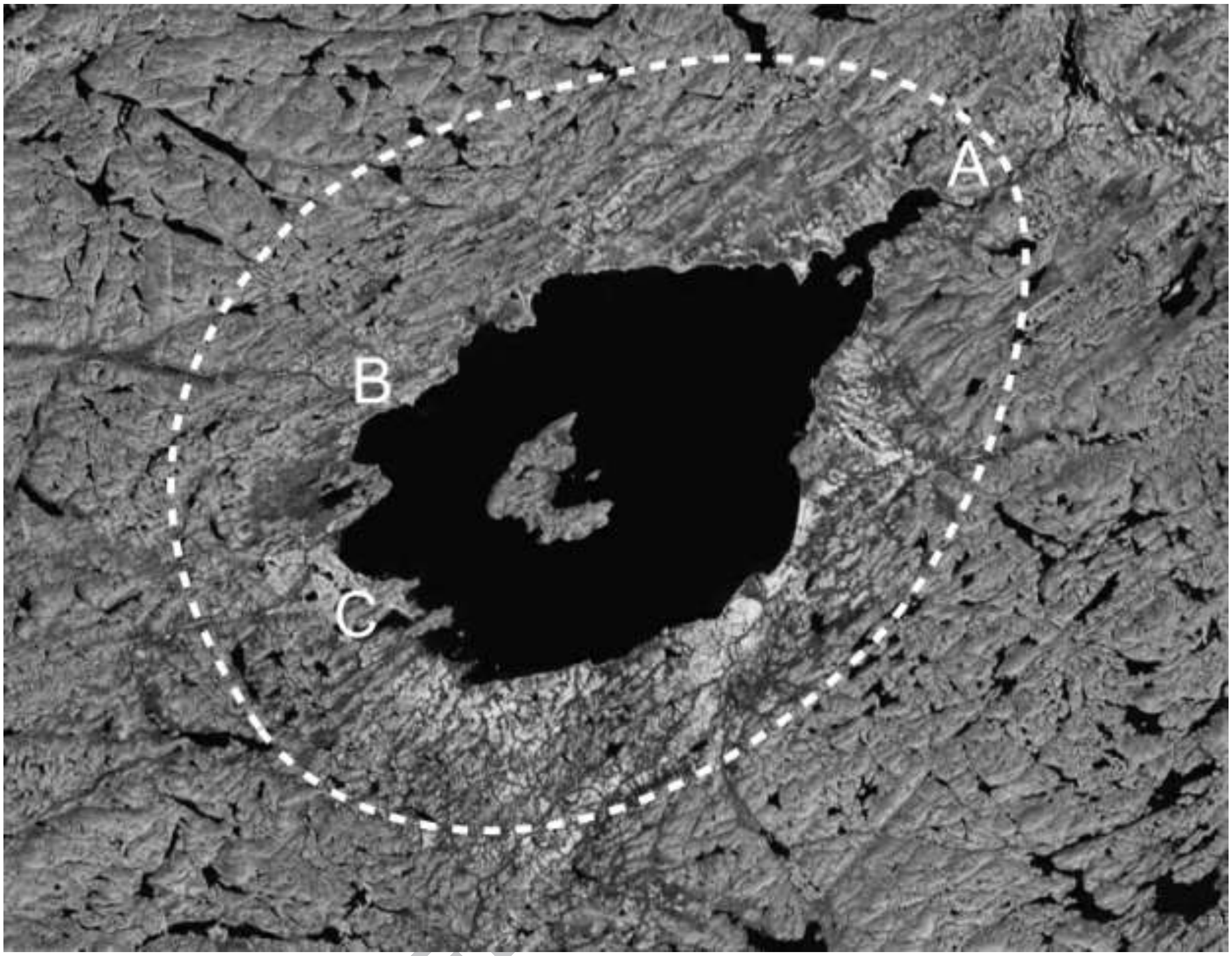


**Figure 2**

Figure 3

Figure 4:

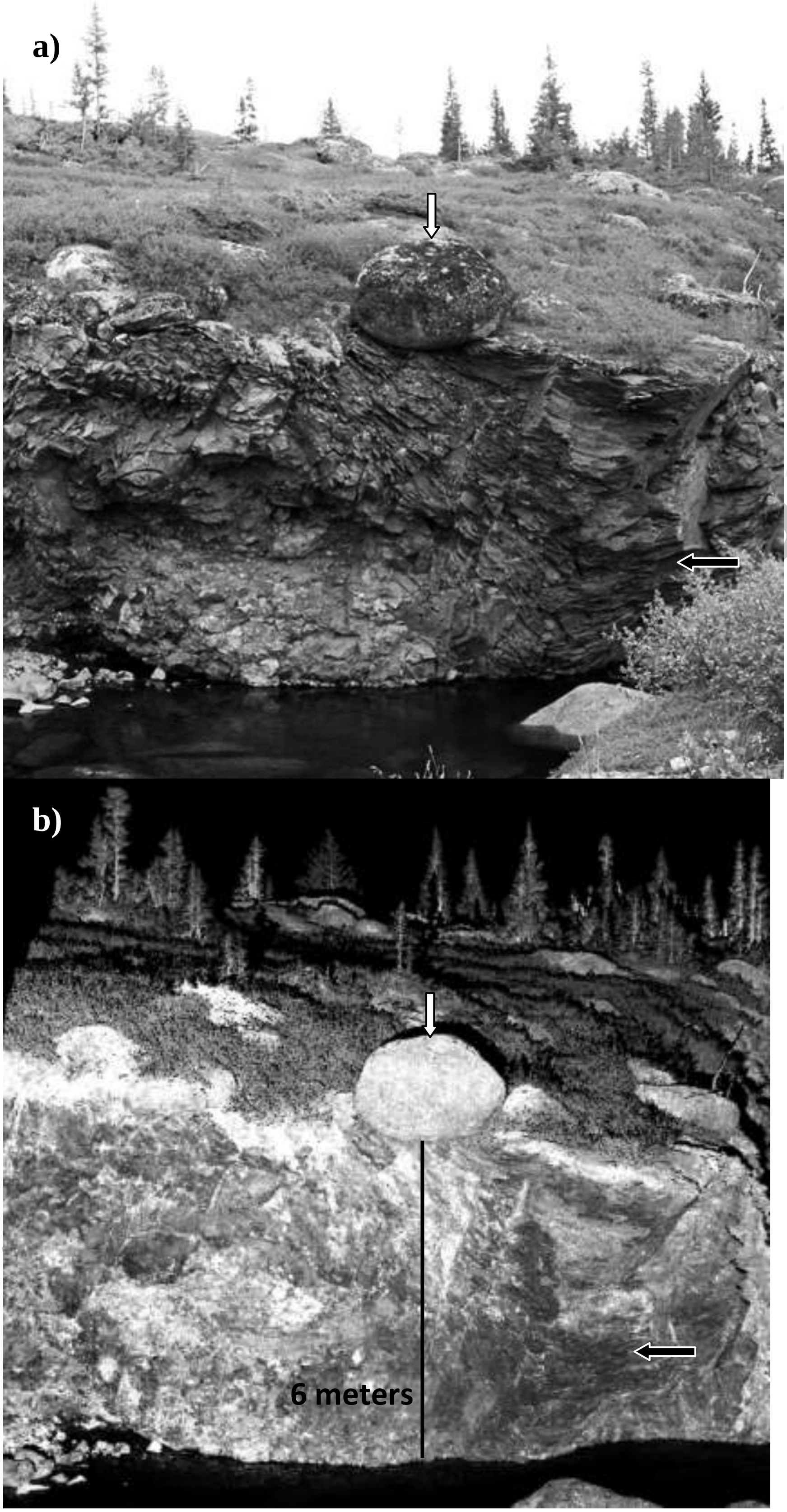


Figure 5


Figure 5c

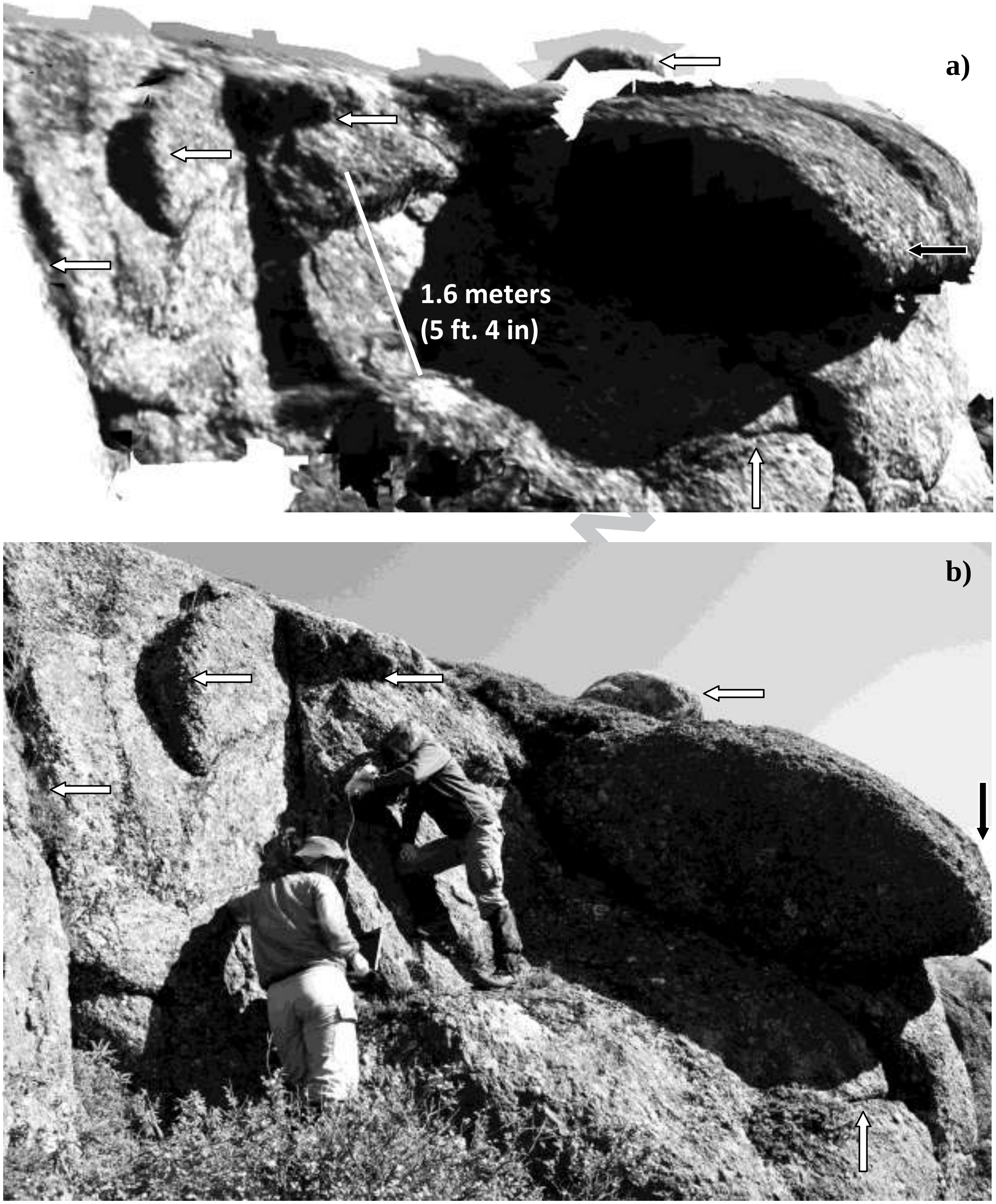


Figure 6

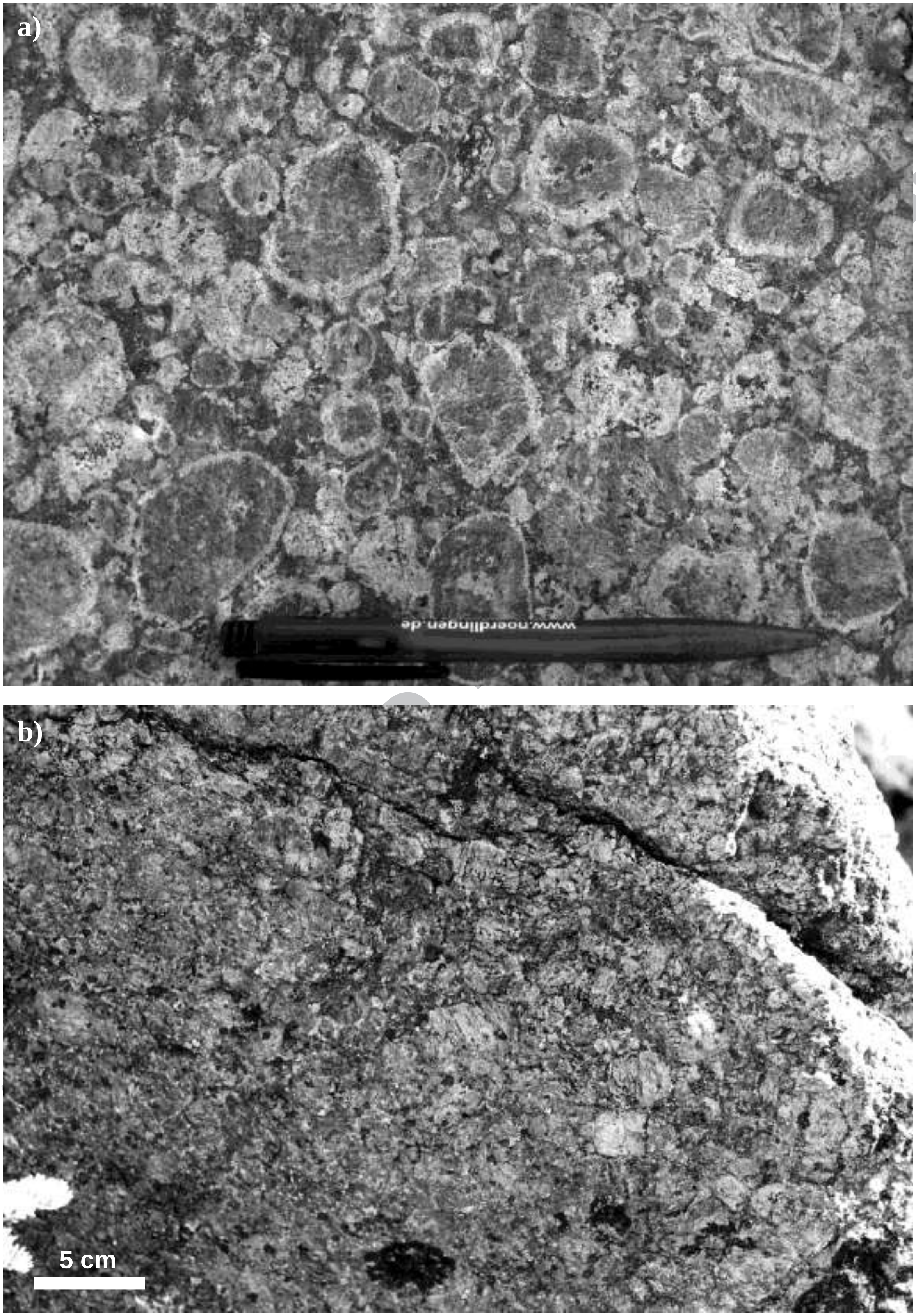


Figure 7

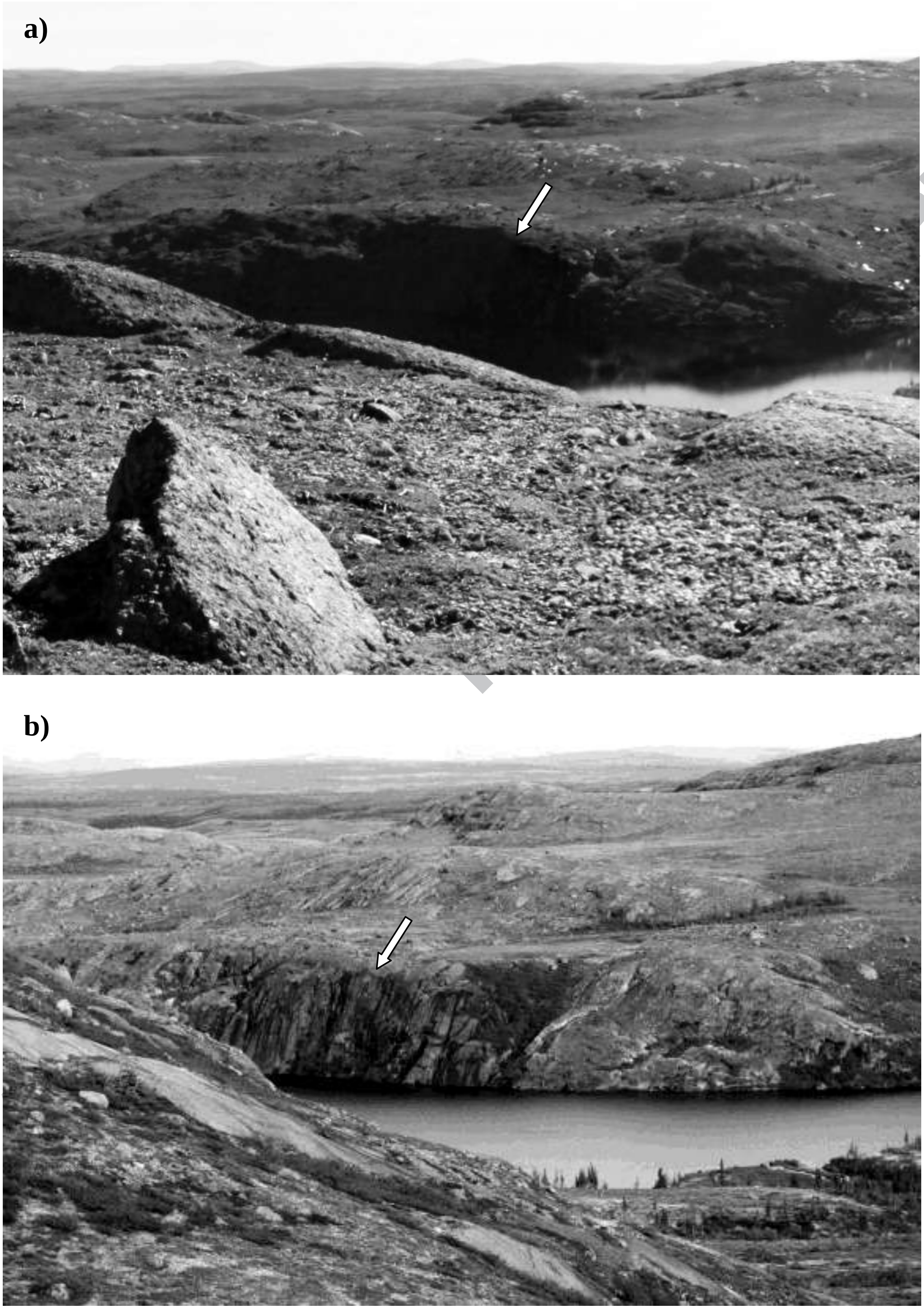


Figure 8