Geoscience in Support of a Mars Methane Analogue Mission

by

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Abstract

The Mars Methane Analogue Mission, funded by the Canadian Space Agency through its Analogue Missions program, simulates a Mars rover mission whose purpose is to detect, analyse, and determine the source of methane emissions on the planet's surface. As part of this project, both an electromagnetic induction sounder (EMIS) and a high-resolution triangulation-based 3D laser scanner were tested in the field to demonstrate the benefit of including these instruments on future rover missions.

EMIS data was inverted in order to derive information on the conductivity and magnetic susceptibility of the near subsurface. 3D laser scanner data was processed with fracture detection as a goal in order to simplify the search for areas of potential methane seepage. Both instruments were found to be very valuable for future rover missions of this type.

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1 Chapter: Introduction

1.1 Analogue Missions

According to the Canadian Space Agency (CSA), a planetary analogue site is a location on Earth which presents one or more geological, environmental, or biological conditions presumed to be similar to that of a planetary body, either in the present or in the past (Léveillé 2007). An analogue mission is then, according to the National Aeronautics and Space Administration (NASA), an activity located in the field in a remote location with characteristics that resemble the conditions of a real space mission (NASA 2011). The goal of analogue missions can vary from purely scientific, to operational and technical, or a mix of these. Analogue missions can be used to test and improve technology, to train personnel, and to enhance our ability for space exploration, before doing the real thing.

Prominent analogue missions include NASA's Desert Research and Technology Studies (Desert RATS) and NASA Extreme Environment Mission Operations (NEEMO). NASA Desert RATS is a series of missions that, since 1997, has been testing roving and extravehicular (EVA) operations in both Lunar and Martian analogue sites. The NEEMO analogue mission site is located 62 feet underwater off the coast of Florida in the world's only operational undersea laboratory, *Aquarius*. There, conditions similar to real space missions can be recreated such as isolation, reduced gravity, and harsh environments (NASA 2011). In addition to operational goals, analogue mission goals can also be scientific such as the Pavilion Lake Research Project (PLRP), a joint NASA and CSA

effort coordinated from Pavilion Lake, British Columbia. Two-week missions have been held as part of this project every summer since 2004 with the goal of practicing science, such as searching for life, in extreme and gravity-reduced environments (NASA 2011).

1.2 The Mars Methane Analogue Mission (M3)

The recent detection of methane in the atmosphere of Mars at a few tens parts per billion (ppb) (Formisano et al. 2004, Krasnopolsky et al. 2004, Krasnopolsky 2005, Mumma et al. 2004, Mumma et al. 2005) is one of the key drivers for this analogue mission. These observations, which were largely made using Earth-based telescopes, are difficult to make and are therefore not universally accepted. Observational data also suggest that Martian atmospheric methane may vary both spatially and seasonally (Mumma et al. 2009, Villanueva et al. 2009). The observed seasonal and spatial variations of methane in the Martian atmosphere require that both a source and a removal process be present. A potential removal process could be photolysis; however, this process is estimated to take up to several hundred years (Krasnopolsky et al. 2004, Krasnopolsky 2005). More recent removal and more recent sources are therefore hypothesized (Mischna & Allen 2009, Mumma et al. 2009).

At this point, no definitive evidence for past or current life on Mars has been found. Biogenic methane, however, if detected, would be a strong indicator of life processes. In fact, astrobiology continues to be one of the main drivers for Martian exploration with the most recent example being the Mars Science Laboratory rover, also known as Curiosity,

which at this time is currently en-route to Mars with a payload that includes instruments designed to search for life.

On Earth, methane is known to be produced by both biogenic and abiogenic processes. Known terrestrial sources include methanogenesis (the formation of methane by microbes called methanogens), hydrothermal vents, mantle seepage, and serpentinization (the alteration and weathering of olivine to form serpentine). This last process can be both biogenic and abiogenic (Klein & Bach 2009, McCollom & Seewald 2001). Although it remains possible that methane production on Mars is driven by Martian methanogens and therefore biogenic, a potential abiogenic source must also be considered. Based on our current knowledge of the geology of Mars, a probable source of the recently detected methane in the Martian atmosphere is the serpentinization of olivine. The main ingredients required for this process are carbon dioxide and water. Methane production occurs when serpentine, which often contains ferrous iron, releases hydrogen from the oxidation of ferrous iron to ferric iron due to weathering (Klein & Bach 2009). The released hydrogen can then react with dissolved CO₂ to produce methane (Klein & Bach 2009) through the following reaction (McCollom & Seewald 2001):

Although spatial relationships are still being worked out for Martian methane, remote sensing data leads us to believe that the necessary ingredients for the creation of methane

via the weathering of serpentinite (serpentinite is a rock composed of one or more minerals belonging to the serpentine mineral group) on Mars are indeed present. Widely present across the Martian surface are ferric iron-bearing minerals such as hematite, which could result from the production of methane from hydrogen (Bell et al. 1990, Lane et al. 2002). Serpentine has also been detected in a few localities on the planet (Carter et al. 2009).

Funded by the CSA through its Analogue Missions program, the Mars Methane Analogue Mission is a micro-rover mission whose goal is to detect, analyze, and determine the source of methane emissions in a setting simulating as closely as possible the Martian geological environment (Boivin 2011, Cloutis 2011). A first deployment, focusing on instrument testing and science using a test rover, was conducted in June 2011 in the Jeffrey mine, an asbestos mine located in the Appalachian hills of the province of Quebec, Canada (Figure 1.1). In October 2011, an additional trip was made to the mine with the goal of testing a high-resolution (640 by 480 voxels) triangulation-based 3D laser scanner in the field to demonstrate the benefit of adding a 3D laser scanner as a payload on future missions. A second rover deployment, more focused on robotics and technology, occurred in June 2012. This thesis presents data acquired during the first deployment as well as 3D laser images acquired in October 2011.

During the June 2011 deployment, the test rover was only equipped with a video camera for navigation purposes. Although not mounted on the rover at this stage, a suite of instruments were utilized (Cloutis 2011): an ASD point spectrometer (0.35 - 2.5 μm), a

Raman point spectrometer ($100 - 2200 \text{ cm}^{-1}$), a Picarro methane detector, and an Electromagnetic Induction Sounder (EMIS). The long-term goal would be to eventually miniaturize the instruments so they could be mounted onboard future rovers.

The objective of the research project described in this thesis is to demonstrate the value of two scientific instruments in support of a robotic mission aimed at detecting methane on Mars: an Electromagnetic Induction Sounder (EMIS) (Figure 1.2) and a 3D laser scanner (Figure 2.7). As part of this project, the capabilities of the EMIS were demonstrated by:

- (1) Measuring the electrical conductivity and magnetic susceptibility of the geological units present along the rover traverse;
- (2) Determining the locations of major geological contacts.

Along with the in-situ EMIS measurements, laboratory magnetic susceptibility measurements were made on hand samples returned from the mine and compared to the EMIS field results.

The potential of 3D laser imaging was demonstrated by:

- (1) Acquiring detailed images of rock walls exhibiting two different lithologies (peridotite and slate).
- (2) Analyzing high-density 3D point cloud data from the laser scanner. Since methane is likely to be produced in the subsurface and seep to the surface through fractures, edge detection software was also used in an attempt to automate fracture detection.

Both the EMIS and the use of 3D imaging have been suggested in previous studies as scientific instruments for planetary missions. The EMIS has been suggested as a particularly useful instrument for the detection of brine in the near-subsurface of Mars (Samson 2006) and for periglacial studies on Mars (Singleton et al. 2010). Due to the large amount of structural and geographical information easily provided by LiDAR (Light Detection And Ranging), 3D imaging has been suggested as both a scientific tool useful to have on rover missions (Osinski 2010) as well as a tool for autonomous science and navigation (Rekleitis 2009, Barfoot 2010). In this thesis, we examine the strengths and challenges of the EMIS and 3D laser imaging in the context of a methane mission on Mars.

Figure 1.1: Google Earth image of the Jeffrey Mine in Asbestos, Quebec

Figure 1.2: Data being taken 10 m behind the rover showing the EMIS sitting in its non-conductive sled during June 2011 deployment. The instrument height while in the sled is 0.25 m above ground.

1.3 Jeffrey Asbestos Mine: Geological Background

In order to fulfil the CSA objective that site selection and traverse planning be done in such a way that mimics a realistic Mars mission, remote sensing data was used prior to the first mine visit in order to map out the regional fault responsible for the presence of chrysotile, a serpentine mineral, in the Jeffrey mine. Located in the Appalachian hills, the Jeffrey mine is the largest open pit asbestos mine outside of Russia. It is approximately 700 m deep and $2 \text{ km} \times 1 \text{ km}$ wide. The mine opened in 1879 and has since produced about 28 million tonnes of material. The interior of the pit is accessible through a system of spiralling roads which can be seen in Figure 1.3. The interpreted version of Figure 1.3 is Figure 3.1.

Most asbestos mines in Quebec lie on a large-scale regional fault called the Saint-Joseph fault (Turcotte et al. 1989, Tremblay et al. 2009). It was determined that the best roving direction would be perpendicular to the fault direction. The majority of the work involving remote sensing data was done using a combination of Google Earth data, Landsat 7 data, and a digital elevation model (DEM) of the area in order to map the regional fault and compute an approximate strike for the fault at the location of the Jeffrey asbestos mine. In order to determine the strike, Landsat 7 data and a DEM (both orthorectified and projected in the Lambert conformal conic projection) were used in combination with ArcGIS. Figure 1.4 is a true colour Landsat 7 image of the Thetford Mines area with the location of the Jeffrey Mine indicated in red.

Figure 1.3: Photo of the open pit Jeffrey Mine.

Thetford Mines Region Landsat True Colour
Lambert Conformal Conic

Figure 1.4: Landsat 7 true colour image of the Thetford Mines area showing the location of the Jeffrey Mine.

In order to enhance the visibility of the fault, a false colour image was created by mapping Landsat 7 band 6 to the colour red, band 4 to green, and band 3 to blue. This false colour image makes the location of the asbestos mines which lie on this fault more apparent by making them dark purple (human developments are seen as light purple) (Figure 1.5). Using data available on Geobase¹, a DEM for the region was also acquired (Figure 1.6). Using this DEM, an aspect map was created in order to help visualise the location of the fault. An aspect map uses data from a DEM to compute the orientation (specifically the slope direction) of a surface on the ground and maps this direction to a colour. This allows one to easily visualise the location of hills and other topographic features, and can be used to enhance the topographic expression of a fault line (Figure 1.7). From the aspect map, it can be seen clearly that the fault is striking in the northeast direction, which is consistent with geological observations reported in the literature (Turcotte et al. 1989, Tremblay et al. 2009). To further constrain the location and orientation of the fault, the DEM was also used to compute a shaded relief (hillshade) map (Figure 1.8). A hillshade map allows one to easily visualise differences in elevation by digitally computing the shadows that would be caused by changes in topography assuming a specific azimuth for the sun, in this case 315 deg (northwest direction). This direction was chosen since it is approximately perpendicular to the predicted fault direction and is therefore the direction in which the fault will be most enhanced. Finally, the hillshade map was superimposed with the false colour Landsat image in order to further enhance topography as well as provide context (Figure 1.9). From this image, it is now possible to interpret the location of the fault. The COGO Reporting tool in ArcGIS

¹ <http://www.geobase.ca/>

was then used to calculate the approximate strike direction of the fault at the location of the mine. This angle was found to be ~ 20 deg. This information could then be used to help determine a suitable roving location such that the rover would traverse perpendicular to the fault.

Thetford Mines Region Landsat FalseColour Lambert Conformal Conic

Figure 1.5: Landsat 7 false colour image of the Thetford Mines area.

Thetford Mines Region DEM

Figure 1.6: DEM mosaic of the Thetford Mines area. Grey shades correspond to elevation in metres relative to mean sea level.

Thetford Mines Region Aspect

Legend

Flat (-1)
North (0-22.5)
Northeast (22.5-67.5)
East (67.5-112.5)
Southeast (112.5-157.5)
South (157.5-202.5)
Southwest (202.5-247.5)
West (247.5-292.5)
Northwest (292.5-337.5)
North (337.5-360)

50 25 0 Kilometers

Figure 1.7: Aspect map of the area. The colours represent angle of strike in degrees.

Thetford Mines Region Hillshade

Legend

Value

50 25 0 Kilometers

Figure 1.8: Hillshade map of the area. Dark blue regions are shaded regions based on a sun azimuth of 315 deg.

Figure 1.9: Superimposed hillshade (Figure 1.8) and false colour image (Figure 1.5) with fault location indicated by a dotted line.

Jeffrey mine is cut across by the major regional fault identified on Figure 1.9. The two main rock types exposed in the mine are peridotite (serpentinite bearing) and slate, separated by a shear zone which has been heavily metamorphosed and is characterised by the presence of schist. The peridotite-shear zone-slate contacts are the expression of the regional fault in the mine (Boivin et al. 2012).

Due to the lack of availability of detailed remote sensing data for the accurate location of structure and geology within the mine, digital photographs were taken during the mine visit in an attempt to replicate short-range remote sensing data which would have been captured during descent by a spacecraft landing on Mars. These photographs (such as Figures 1.3 and 3.1) were used as the primary source of information for roving site selection, together with logistical factors such as the availability of a scientifically interesting area which would not be in active production during times of planned rover deployment. Figures 1.3 and 3.1 clearly show interesting structures within the mine, especially the transition between peridotite, a ~25 m wide shear zone, and slate. This transitional area was determined to be a possible site of methane production and was therefore selected as the primary roving site.

The presence of serpentinite in the form of chrysotile (asbestos) makes the Jeffrey Mine a likely location for methane production to occur and therefore an excellent mission analogue site. Furthermore, magnesium carbonate (another weathering product during methane production via the weathering of serpentinite) is present at the site. Magnesium

carbonates have been detected on Mars in close proximity to serpentinite (Ehlmann 2008, Ehlmann 2009) and in areas of enhanced methane production (Mumma 2009).

The roving site within the mine is located at the base of Figure 3.1 where a spiralling road meets the peridotite-shear zone-slate contacts where serpentinisation is prominent and weathering of the serpentinites is thought to occur. This site was selected due to the presence of the appropriate mineralogy as well as joints and fractures in the rock wall which would provide a path for methane seepage. Near the shear zone, the peridotite is chrysotile-bearing and schistose as well as heavily fractured and jointed. The rocks within the shear zone are very soft and are characterised by an overall talc-like texture. The slate wall is jointed and faulted.

2 Chapter: Background and instrumentation

2.1 The Electromagnetic Induction Sounder

2.1.1 Underlying theory

Electromagnetic (EM) induction is a geophysical technique by which subsurface conductors can be investigated remotely with the use of a time-varying electromagnetic field, called the “primary field”, emitted by a transmitter. Instruments making use of this technique can either be “frequency-domain” systems or “time-domain” systems. A frequency-domain system emits one continuous sinusoidal waveform while a time-domain system periodically switches the primary field on and off and senses the decay of the response (Telford et al. 1990).

The concept of EM induction is illustrated in Figure 2.1. The transmitter of an EM system generates a primary field (by passing an alternating current of a specific frequency through a coil) which propagates in the subsurface. When a subsurface conductor is subjected to the primary field, eddy currents are induced in the conductor according to Faraday’s law. According to Ampere’s law, these currents in turn generate a “secondary” electromagnetic field which can be sensed by a detector located on or above the ground (Grant & West 1965). Both the primary and secondary fields (the “total” field) are then sensed by inducing a current in the receiver coil. Electronics attached to the receiver can then isolate the secondary field from the total field by comparing a reference signal from the transmitter to the signal recorded at the receiver, allowing the instrument to remotely gain information about the subsurface.

The strength of the eddy currents induced in a subsurface conductor by a time-varying electromagnetic field are directly proportional to the frequency of the inducing field; this implies that eddy current induction is frequency dependent. However, if the frequency used is very high, a saturation effect takes place which prevents making the secondary response very large by using very high frequencies. For geophysical applications, the frequency used is usually in the kHz range (Grant & West 1965).

Figure 2.1: Dualem-2 EM system showing electronics (green) as well as the primary field (red) generated at the transmitter, propagating through a subsurface conductor, and inducing eddy currents (purple) and a secondary field (grey) sensed by two orthogonal receivers.

If we model the subsurface conductor as a simple circuit with a resistance R and inductance L in series, the secondary response is a complex function which depends on the induction number, defined as $\omega L/R$, where ω is the transmitter frequency. The secondary response can be represented mathematically by both a “real” component, called the “in-phase” component because it is in phase with the primary field, and an “imaginary” component whose phase is shifted by 90° from the real component, called the “quadrature” component (Grant & West 1965). In this model, the response function can therefore be written as $(P+iQ)$ where P represents the in-phase component and Q represents the quadrature component. Figure 2.2 shows P and Q with the amplitude (P^2+Q^2) and the phase angle ϕ versus the induction number $\omega L/R$. At low induction number, we can see that the response is 90° out-of-phase (and therefore in quadrature) with the primary field and that its amplitude is small. In this region, the quadrature component recorded by an EM system is proportional to apparent conductivity, while the in-phase signal is proportional to magnetic susceptibility (Callegary et al. 2007, Holladay 2012). This greatly simplifies data processing. As the induction number increases, the response becomes much larger and in phase with the primary field, with maximum response eventually being reached (Grant & West 1965).

Figure 2.2: Response function of a loop (Grant & West 1965). The dotted line labeled ϕ corresponds to the phase angle while the dotted line labeled $(P^2 + Q^2)^{1/2}$ corresponds to the amplitude.

For solid bodies, the secondary response remains similar to that of a circuit as long as the transmitter-receiver pair is located far enough away from the conducting body. This ensures that the whole body is subject to the same strength of the primary field and consequently that the receiver is influenced equally by all parts of the conducting body. For solid bodies, the induction number is a function of the frequency of the primary field, the distribution of the primary field over the conductor, the conductivity of the conductor, and the thickness of the conductor (Grant & West 1965). Since the response of a solid body is typically anisotropic, it is advantageous to measure the secondary field in two directions. This can be done by using two orthogonal receivers instead of one. In the system shown in Figure 2.1, the transmitter coil and one of the receivers are oriented vertically (in the Z-direction) thus having horizontal windings. This configuration is called the horizontal co-planar (HCP) orientation. The configuration involving the vertical transmitter and the horizontally oriented (X-direction) receiver coil is called the perpendicular (PRP) orientation. Both of these configurations have different depths of exploration into the subsurface. The PRP orientation has a depth of exploration of 0.6 transmitter-receiver lengths while the HCP orientation has a depth of exploration of 1.5 transmitter-receiver lengths.

2.1.2 Use and Applications of Electromagnetic Induction

The method of electromagnetic induction is particularly well suited to determining the presence of conductors located at shallow depth (< 300 m) and is used extensively for the detection of base-metal deposits. The method was developed in the 1920's in regions such as Canada, Scandinavia, and the United States, where conductors would often be in sharp contrast to resistive host rock. In the Canadian Shield, for instance, we might expect conductivities in the range of 0 - 0.2 mS/m for granite and 0 - 0.01 mS/m for gneiss, whereas the conductivity of ore bodies can reach much higher values (Telford et al. 1990). The EM method was later adapted for airborne use. Different EM systems employ different transmitter frequencies depending on the application.

Electromagnetic induction has previously been suggested as a useful method to determine the location of subsurface ice (Singleton et al. 2010) and near-surface briny water (Samson et al. 2008) on Mars. This includes the development of new sensors (Huang et al. 2005) and the use of existing sensors (Samson et al. 2006). Here, a similar sensor to the one used by Singleton et al. (2010) is used to show that electromagnetic induction is also useful in the determination of geological contacts in a Mars-like setting which can help in the determination of fractured areas where methane seepage would be more likely to occur from the subsurface.

2.1.3 Specifications of the Dualem-2

The instrument used for this research project was the Dualem-2, a frequency-domain electromagnetic induction sounder (EMIS) produced by Geosensors Inc. of Toronto, Ontario², and marketed by Dualem Inc. of Milton, Ontario³. The Dualem-2 comprises a rigid cylinder containing one vertical transmitter loop with windings oriented in a plane parallel to the ground surface (Z-direction) and two receiver loops, one also oriented in the Z-direction and one with vertically oriented windings (X-direction), plus electronics and an external user interface (Figure 2.1). The transmitter operates at 9 kHz. The transmitter and the receivers are separated by a distance of 2 m. The secondary fields recorded at the receivers are decomposed by the internal processor into components in phase and in quadrature with the primary field. The data recorded by the receiver oriented in the X-direction probes the subsurface to a depth of approximately 1.2 m, while the data recorded by the receiver oriented in the Z-direction investigates to a depth of approximately 3 m (Dualem Inc. 2002). Specifications for the Dualem-2 are shown in Table 2.1.

² <http://www.geosensors.com/>

³ <http://www.dualem.com/>

		Dualem-1s	Dualem-2
Transmitter frequency	[kHz]	9	9
Components	-	1 transmitter	1 transmitter
		2 receivers	2 receivers
Transmitter-receiver separation	[cm]	66	200-210
Mass	[kg]	3	10
Power	[W]	2.75	3.00
Survey height above surface (sled)	[m]	0.25	0.25
Accuracy	[10 ⁻³ SI]	0.01	0.02
Depth of exploration	[m]	0.6 (PRP)	1.2 (PRP)
		1.5 (HCP)	3.0 (HCP)

Table 2.1: Instrument specifications for the Dualem-1s used by Singleton, et al. (2010) and the Dualem-2 used in this research project.

Two different survey types can be conducted with the EMIS. The first is the horizontal survey as seen in Figure 2.3 where the EMIS is dragged along a traverse. During a horizontal survey, data is being acquired continuously throughout the traverse at a set sampling frequency. This survey type is used to acquire a horizontal profile of both the in-phase and quadrature responses. The second survey type, referred to as a vertical sounding, consists of taking multiple EMIS measurements at different instrument heights above ground at a given location. This allows us to characterize the conductivity and magnetic susceptibility gradients, and also helps to further constrain any models derived from the data. Vertical soundings typically produce more reliable conductivity and susceptibility values than a horizontal survey (Holladay 2012). One sounding, however, only samples a single location and it is therefore very time consuming to cover a large area with vertical soundings.

Data from both survey types can be inverted in order to extract information about layering in the subsurface. In the case of a horizontal survey, inversion is used to remove the air layer between the instrument and the ground as well as to gain information on subsurface layering if it is present. If it is anticipated that at a particular location two layers are present, inversion can be used in an attempt to derive information about the conductivity and susceptibility of each layer separately as well as the thickness of the shallowest layer. Vertical surveys can be inverted in order to determine conductivity and magnetic susceptibility profiles as a function of depth. Since the results of a vertical sounding are typically more reliable than those of a horizontal sounding, it is advantageous to conduct vertical soundings along a horizontal survey traverse in order to

compare both results. The vertical sounding results can also be used to constrain parameters, such as layer thickness, when inverting a horizontal survey.

The Dualem-2 can be set to operate in “continuously recording mode” with the instrument taking measurements at a preset sampling frequency. This greatly simplifies surveying since the EMIS can be mounted on a non-conductive sled and dragged across the ground surface along a traverse line without having to stop to record data. This was the primary way the instrument was used during this research project. When conducting a survey, pitch and roll of the instrument can cause error in measurements and should be kept as close to zero as possible. For this purpose, an arrow which should be kept pointing up is printed on the side of the instrument. Pitch and roll estimates are also indicated on the handheld user interface. In the sled, the EMIS is locked in position eliminating the need to adjust pitch and roll for each measurement assuming the ground surface is relatively flat. The Dualem-2 also measures Wide Area Augmentation System (WAAS) corrected GPS data (but not differential GPS) making mapping very straightforward. The GPS is accurate between approximately 1-3 m, depending on the number and locations of available satellites as well as whether or not a WAAS fix was achieved.

In addition to GPS, the Dualem-2 outputs 4 different data streams which are the in-phase and quadrature data for both the HCP and PRP orientations. As previously noted, at low induction number, the quadrature component is proportional to apparent conductivity in that direction while the in-phase component is proportional to magnetic

susceptibility in that direction. This means that quadrature data is reported directly in mS/m while in-phase data is presented in 10^{-3} SI susceptibility units. No further processing is required to obtain observed conductivity or magnetic susceptibility values. Table 2.2 shows an example of Dualem-2 output data.

Station	Line	ZCond	ZSusc	XCond	XSusc	Temp (K)	Pitch [deg]	Roll [deg]	GPS Time	Latitude	Longitude	Altitude [m]
10	1	5.50	17.51	6.60	-35.15	303.6	1.90	6.40	49719000	45.773112	-71.957882	-69.1
20	1	5.50	21.19	6.00	-29.45	303.6	6.50	5.60	49720000	45.773112	-71.957882	-69.1
30	1	3.80	27.01	5.20	-21.99	303.6	1.90	6.80	49721000	45.773112	-71.957882	-69.1
40	1	3.70	28.53	7.50	-30.92	303.6	4.50	4.20	49722000	45.773112	-71.957882	-69.1
50	1	4.10	26.98	10.80	-39.49	303.6	-6.80	2.60	49723000	45.773123	-71.957873	-68.6
:	:	:	:	:	:	:	:	:	:	:	:	:

Table 2. 2: Example of Dualem-2 output data. ZCond and XCond are HCP and PRP conductivity, respectively, while ZSusc and XSusc are HCP and PRP magnetic susceptibility, respectively. Station number increases for each measurement taken. Note that stations 10-40 were taken at the same GPS location while the instrument has moved for station 50.

2.1.4 Preliminary instrument field testing

In April 2011, a small EMIS test survey was run in Vincent Massey Park near Carleton University in Ottawa in order to become familiar with fault detection and identification prior to going to the mine (Figure 2.3). The survey was conducted by running 6 parallel NE-SW lines spaced approximately 1 m apart and perpendicular to the Gloucester regional normal fault (Adams 1994) with a Dualem-2 instrument set to record data once every second. The traverse lines were approximately 50 m long with a single line taking less than a minute to complete. The western side of the fault is known to have over 30 m of overburden mostly made up of clay and till while the eastern side has approximately 2 m of overburden before reaching limestone (Michel 2011). Since clays range in conductivity from 10-1000 mS/m and limestone ranges in conductivity from 0-0.02 mS/m (Telford et al. 1990), we expect to see a conductivity contrast between both sides of the fault. Indeed, the EMIS was successfully able to detect a resistivity contrast between the two sides of the fault as can be seen in Figures 2.4 and 2.5 which are Inverse Distance Weighting (IDW) interpolations of observed HCP and PRP conductivities, respectively. The western side of the fault has an average apparent conductivity of approximately 12 mS/m for both HCP and PRP orientations, while the eastern side has an average apparent conductivity of approximately 2.5 mS/m for the HCP orientation and 4 mS/m for the PRP orientation, separated by a 3 m wide fault zone. The PRP data slightly overestimates the conductivity of the limestone unit which is located 2 m below ground, because the depth of exploration for the PRP orientation is only 1.2 m and therefore mostly the overburden is sensed. Magnetic susceptibility was not plotted due to the fact

that no discernible difference in susceptibility was observed between the two sides of the fault.

As a means to estimate instrument error, six repeated base station measurements were conducted and the standard deviation of the base station measurements for both quadrature and in-phase data in the HCP and PRP orientations were computed. Instrument error is estimated to be ± 0.3 mS/m for the quadrature (observed conductivity) data and $\pm 0.09 \cdot 10^{-3}$ SI for the in-phase (observed magnetic susceptibility) data.

Figure 2.3: EMIS survey in Vincent Massey Park, Ottawa, Ontario. The 2 m long EMIS is sitting in a sled and dragged along a profile line.

Figure 2.4: Map of observed HCP conductivity over Gloucester fault in Vincent Massey Park. The fault zone is located in the light blue area where a transition between relatively high and low conductivity occurs.

Figure 2.5: Map of observed PRP conductivity over Gloucester fault in Vincent Massey Park. The fault zone is located in the light blue area where a transition between relatively high and low conductivity occurs.

2.2 Magnetic Susceptibility Measurements of Hand Samples

Multiple hand samples of the different geological units investigated during the June 2011 rover deployment were collected. These samples were then taken to the laboratory operated by Dr. Richard Ernst at the Geological Survey of Canada in Ottawa and volume magnetic susceptibility measurements were taken using a Sapphire Instruments SI-2B magnetic susceptibility meter (Figure 2.6). The SI-2B is an alternating current susceptibility bridge which measures the magnetic response of a sample inserted into a coil and subjected to a field of 24 A/m. Measurements were taken using a frequency of 19 kHz in two perpendicular directions in an attempt to minimise the effect of anisotropy. Measurements were also taken at 830 Hz on a random selection of samples in order to investigate any possible frequency dependence. Samples were broken into small pieces (on the order of 2.5 cm in diameter) and placed onto a diamagnetic sample holder before being inserted into the instrument. The instrument assumed a sample volume of 11 cm³ and results were corrected for actual volume to yield the magnetic susceptibility of the samples. Sample results were then compared to EMIS magnetic susceptibility results.

Figure 2.6: The SI-2B magnetic susceptibility meter. The sample is inserted into the coil while sitting on a diamagnetic holder (not shown).

2.3 3D Laser Scanner

2.3.1 Background

More and more, laser imaging is emerging as a tool for rock mass characterization (Mah et al. 2011, Mah et al. 2012). In time-of-flight (TOF) LiDAR systems, the length of time between the emission of a laser pulse and the detection of its reflection is calculated in order to determine distance to the target. TOF LiDAR systems have a target-camera distance between 2-800 m with accuracy ranging from the sub-millimeter range to about 1 cm depending on the system (Blais 2004). Triangulation-based laser scanners are usually shorter range systems when compared to LiDAR systems and generally operate at a distance less than 10 m from the target. These systems project a laser beam onto the target and the diffusely reflected beam is focused onto a detector array. Since the geometries of the emitted and reflected beam paths are known, they can be triangulated to calculate distance to target at sub-millimeter accuracy (Mah et al. 2011). Both triangulation-based systems as well as LiDAR systems produce high-density point clouds where a single image can contain millions of points. Here a triangulation-based 3D laser scanner was used to image rock walls.

2.3.2 Technology Potential for Planetary Rover Missions and Current Use

3D laser imaging has recently been used extensively in space applications. It has been used for remote inspection of the space shuttle's thermal shield (Gregoris et al. 2004) as well as for autonomous satellite rendezvous (Allen et al. 2008). It has also been suggested for use in rover navigation (Dupuis et al. 2008). 3D data acquired by LiDAR is now being suggested not only as an engineering tool, but one for scientific exploration. Recently, its use has been suggested to help locate ground ice (Barfoot et al. 2010) as well as a scientific tool to explore the terrain on planetary bodies (Osinski et al. 2010).

2.3.3 Instrument specifications

The instrument used in this research project is the Konica Minolta VIVID 9i non-contact 3D digitizer (Figure 2.7). Its specifications are listed in Table 2.3. The VIVID 9i has three interchangeable lenses (tele, middle, and wide) which each providing a different focal point. Here, the middle lens was used, which is optimal for capturing a scene from $165 \times 124 \times 42$ mm to $823 \times 618 \times 1100$ mm. The point cloud produced by the instrument is composed of elements called voxels which are simply volumetric image elements defined by a point in 3D space (x, y, z). Although taken to the field for this project, the VIVID 9i has been designed as a laboratory instrument and encounters difficulty operating in direct sunlight. To overcome this problem, a shadow can be cast on the area being imaged. Imaging on a cloudy day is also recommended while keeping in mind that the instrument should not be exposed to rain. The VIVID 9i is also capable of

acquiring a 640×480 pixel 2D colour photograph that can be superimposed on a point cloud. It does not measure the intensity of the reflected laser signal.

Figure 2.7: The VIVID 9i 3D laser scanner being used in the field at the Jeffrey asbestos mine.

Measuring Method	Triangulation
Lenses	TELE Focal distance $f=25$ mm
	MIDDLE Focal distance $f=14$ mm
	WIDE Focal distance $f=8$ mm
Scan Range	0.5 to 2.5 m (In Extended mode)
Scan Method	Galvanometer-driven rotating mirror
Laser Class	Class 2 (IEC60825-1), Class 1 (FDA)
Accuracy	± 0.05 mm (Using TELE lens at distance of 0.6 m, with Field Calibration System, Konica Minolta's standard, at 20°C)
Precision	0.008 mm (Using TELE lens at distance of 0.6 m, Konica Minolta's standard, at 20°C)
Ambient Lighting Condition	Office environment, 500 lx or less
Number of Output Voxels	640 x 480
Power	Commercial AC power, 100 to 240 V (50/60Hz), rated current 0.6 A (at 100 VAC)
Dimensions	221 (W) x 412 (H) x 282 (D) mm
Weight	Approx. 15 kg (with lens attached)

Table 2.3: Specifications for the Konica Minolta VIVID 9i.

2.3.4 Surface Orientation and Edge Detection

In order to visualise the surfaces represented by the 3D point clouds provided by the laser scanner, a program developed by Lai (2012) at Carleton University was used. First a triangular mesh is calculated using the Delaunay triangulation method (Lee 1980). An example mesh is seen in Figure 4.15 and Figure 4.16. The program uses the HSV (Hue Saturation Value) colour model for the strike and dip of each triangular element before converting to the standard RGB colour model for display (Lai 2012). In the HSV model, the Hue (H) is represented by an angle from 0° to 360° , making it ideal for representing strike (Figure 4.17). Figures 4.18 and 4.21 are examples of a strike image produced by this program. In the HSV model the Value (V) is represented by a value between 0 and 1 where 0 is black and 1 is white. This is then mapped to an angle between 0° and 90° for visual representation of dip (Figure 4.19, Figure 4.22). When both H and V vary, strike and dip can be represented in a single image such as Figure 4.20 and Figure 4.23. This program does not make use of Saturation (S) which is kept constant at a value of 1.

In addition to using this visualisation program, fracture detection was attempted using edge detection software within MATLAB's image processing toolbox. Sobel edge detection was applied to both 2D photographs of the rock wall taken by the laser camera as well as to a 2D image visually representing dip angle on a triangulated surface. Sobel edge detection is a non-linear edge detection method based on the Sobel operator. It computes an approximation to the gradient of the intensity of the image by using a 3×3

moving window. When the change in gradient is deemed abrupt enough, an edge is detected (Peli 1982, Kittler 1983).

3 Chapter: Field Data Acquisition

3.1 EMIS Surveys

During the June 2011 deployment, two EMIS survey types were conducted: horizontal surveys (Boivin et al. 2012) and vertical soundings.

Horizontal surveys were conducted with the EMIS mounted on a non-conductive sled such that the height of the instrument is 0.25 m above ground level (Figure 1.2). The EMIS sled was dragged along a traverse and data was automatically taken at 1 second intervals. Originally, it was planned for the EMIS to follow the rover track. This proved to be problematic, however, since the rover moves at a pace of only a few cm per minute and paused for long periods of time at each rover station so that data could be acquired. Because of this, the rover did not cover enough ground to cross all of the geological units, traveling only ~50 m in one day. In order to overcome this, EMIS data was collected separately from the rover operations. The EMIS was deployed on three different levels in the mine, one of these being the level of the rover deployment (Figure 3.1). Horizontal surveys were conducted multiple times on each of the traverse levels such that data could be compared to verify consistency and repeatability. A summary of horizontal surveys conducted is presented in Table 3.1.

Traverse Name	Mine Level	Traverse Length (m)	Start Position (lat, lon)	End Position (lat, lon)	Date Acquired
ASBELE11	Rover Level	50	45.772902 N -71.058057 W	45.773598 N -71.957638 W	14/06/2011
ASBELE12	Rover Level	~200	45.773273 N -71.957735 W	45.773130 N -71.957882 W	14/06/2011
ASBELE13	Rover Level	250	45.773112 N -71.957882 W	45.775083 N -71.956035 W	15/06/2011
ASBELE14	Rover Level	275	45.773083 N -71.957852 W	45.774955 N -71.956163 W	15/06/2011
ASBELE21	Level 2	390	45.773302 N -71.957852 W	45.775585 N -71.957257 W	16/06/2011
ASBELE22	Level 2	390	45.773087 N -71.960405 W	45.775585 N -71.957277 W	16/06/2011
ASBELE31	Level 3	380	45.773240 N -71.960355 W	45.776148 N -71.958137 W	16/06/2011
ASBELE32	Level 3	380	45.773242 N -71.960445 W	45.776782 N -71.956783 W	16/06/2011

Table 3. 1: Summary of conducted horizontal surveys in the Jeffrey Asbestos mine. Traverse length for survey ASBELE12 is approximate due to poor GPS data during this survey.

A total of 7 vertical soundings were conducted with the help of a wooden frame at the level of rover deployment with two soundings each in the peridotite and slate units, and 3 soundings in the shear zone. A total of 7 heights were sampled per sounding: 0.25 m, 0.5 m, 1.0 m, 1.6 m, 1.0 m, 0.5 m, and 0.25 m above ground level. Data for vertical surveys were taken manually at each height, with data taken at each height twice; once on the way up and once on the way down the frame. A summary of vertical soundings conducted is presented in Table 3.2.

Sounding Name	Mine Level	Sounding Position (lat, lon)	Date Acquired
ASBEL1S1	Rover Level	45.774983 N -71.956118 W	15/06/2011
ASBEL1S2	Rover Level	45.774950 N -71.956158 W	15/06/2011
ASBEL1S3	Rover Level	45.774737 N -71.956383 W	15/06/2011
ASBEL1S4	Rover Level	45.774295 N -71.956730 W	15/06/2011
ASBEL1S5	Rover Level	45.774148 N -71.956922 W	15/06/2011
ASBEL1S6	Rover Level	45.773377 N -71.957682 W	15/06/2011
ASBEL1S7	Rover Level	45.773228 N -71.957877 W	15/06/2011

Table 3.2: Summary of conducted vertical soundings in the Jeffrey Asbestos mine.

Figure 3.1: Interpreted version of Figure 1.3 showing geological units (dashed lines), EMIS horizontal traverse locations (coloured lines), and vertical sounding locations (red dots).

Data from the EMIS was downloaded onto a laptop at the end of each day. Data was then imported into MATLAB and plotted. Since the quadrature signal recorded is proportional to apparent conductivity and the inphase signal is proportional to magnetic susceptibility, preliminary data processing is not required and a plot can be generated within minutes of acquiring the data.

3.2 Hand Sample Data

Laboratory magnetic susceptibility measurements were done on nine hand samples from the mine. Two samples were taken from the peridotite unit, three from the shear zone, two from the slate unit, and two from the gravel road. Two pieces from each sample were analyzed, yielding a total of 18 susceptibility values. All samples were acquired on June 15th 2011. A summary of hand sample results is shown in Table 4.3.

3.3 Laser Imaging Survey

Laser scans were taken along the rock wall of the rover-level traverse at six different stations in five different locations (Figure 4.8). Stations were chosen such that relevant features would be clearly visible in the data in order for fracture detection to be attempted. Settings for each scan are shown in Table 4.4. Data was recorded on a field laptop connected to the laser scanner and was later brought to the lab for processing (Figure 2.7). Data was acquired over two days due to rainy weather.

4 Chapter: Results

In this section, data from the horizontal and vertical EMIS surveys, analyses of hand samples, and 3D laser images are presented and discussed. The EMIS data presented is either observed or inverted data. Observed data is data that was measured in the field and underwent no processing. Data was then inverted in order to extract results about layering in the subsurface. As this project is within the context of an analogue mission, data is compared to expectations based on geological context in order to assess the feasibility of using these methods on rover missions in which little or no prior information about the geology is known.

4.1 Horizontal EMIS Surveys

Horizontal EMIS surveys can be used to quickly assess both the conductivity and the magnetic susceptibility of the near subsurface (see section 3.1). This survey type is used for quick and simple contact detection and domain identification. Where multiple subsurface layers are present, data can be inverted in order to derive information about individual layers. Due to the presence of a gravel road on the traverse paths, all data was inverted using a 2-layer model in order to characterise the geological unit under the road.

A total of four traverses were conducted at the rover level and two traverses were conducted on both levels 2 and 3 (Table 3.1, Figure 3.1). An example HCP observed

conductivity data can be seen in Figure 4.1 for all three rover levels with matching contacts indicated by dotted lines. Comparing Figure 4.1 to Figure 3.1, it can be seen that the EMIS was able to successfully identify contact locations and to discriminate between geological units.

Looking closely at Figure 4.1, it can be seen that both the peridotite and slate units have low and uniform conductivity while the shear zone is characterised by a much higher average conductivity and has larger variability. Lows in conductivity within the shear zone are interpreted to coincide with resistive granitic dykes. Notable features include a dip and subsequent large spike in conductivity located in the shear zone at all three levels right before the transition into slate. This feature is interpreted to be due to a granitic dyke passing through the shear zone at all three levels.

Figure 4.1: Observed HCP conductivity data for all three surveyed mine levels. Contact locations are identified using dotted lines and are labelled. HCP conductivity was chosen for this example due to the larger DOE achieved by this configuration, although the PRP configuration provided similar results. Plotted are rover level traverse 3, level 2 traverse 1, and level 3 traverse 1.

4.1.1 Rover Level

A total of one short “rover traverse” (ASBELE11) and 3 long survey traverses (ASBELE12 - ASBELE14) were conducted at the rover level. The rover traverse was conducted behind the rover along its path and data for this traverse was acquired at a spacing of 2.5 m between stations. This was done such that data would be taken at every rover station (every 5 m) as well as at the half-way point between rover stations. All three long traverses are along the same line and cover the same contacts except for ASBELE12 which does not continue into the slate unit. Figure 4.2 shows observed HCP conductivity data of two long traverses (ASBELE13 and ASBELE14) as well as the rover traverse with geological contacts shown. ASBELE11 was not plotted due to large GPS error for this traverse, making feature matching more difficult to visualise.

It is clear from both Figure 4.1 and Figure 4.2 that both the peridotite and slate units are lower conductivity regions with little variation and that the shear zone is of much higher observed conductivity and is prone to high variations in conductivity. Comparing the three traverses plotted in Figure 4.2, it can be seen that instrument repeatability is very high with all the same features being detected in each of the traverses with similar magnitudes. Slight misalignment of features is due to inaccuracies in GPS.

Figure 4.2: HCP conductivity of two long (ASBELE13 and ASBELE14) and one short (ASBELE11) traverses at the rover level. Black dots correspond to the discrete measurements made every 2.5 m along the short rover traverse. Locations of geological contacts at this level are indicated.

Figure 4.3 is the observed ASBELE14 conductivity and magnetic susceptibility data in both the HCP and PRP configurations. Note that as a matter of convention, all DualEM instruments record HCP susceptibility as positive and PRP susceptibility as negative. From Figure 4.3 it can be seen that observed conductivity is very consistent between the two configurations and that both can be used to discriminate between geological units. It is worth noting that in the HCP orientation, magnetic susceptibility seems to follow the conductivity trend whereas in the PRP orientation susceptibility follows the opposite trend (high susceptibility when conductivity is low and low susceptibility when conductivity is high). This is due to anisotropy in magnetic susceptibility of these units. Although susceptibility seems to be capable of discriminating between geological units, the distinctions are not as clear as with conductivity.

Figure 4.4 shows the 2-layer model (layer 1: gravel; layer 2: bedrock) produced by inversion of the observed data. Inputs used for inversion include all HCP and PRP data for both conductivity and susceptibility as well as sensor height and transmitter-receiver separation. The final model is created by conducting a series of 1D inversions at every data point. Each individual result is then stitched together. We can see that, in this model, the thickness of layer 1 varies laterally but does not surpass 1 m which is within our expectations for the thickness of the gravel road. Apart from anomalous spikes near the beginning of the traverse, the model features a consistently variable conductivity for the gravel road and low and uniform susceptibility. Comparing Figure 4.4b to Figure 4.3a we see that the spikes, which occur in both layer 1 conductivity and magnetic

susceptibility, seem to coincide with spikes in observed HCP susceptibility (dips in PRP susceptibility). The conductivity spikes in Figure 4.4b seem to be, then, artifacts of the inversion modeling process. The 2-layer model reproduces with high fidelity lateral variations of physical properties through the different geological units (compare Figure 4.4c to Figure 4.3a). Since the gravel road is composed of similar material throughout the traverse while the underlying geology is changing, the overall inversion results are reasonable.

Figure 4.3: Observed conductivity and magnetic susceptibility data for rover level ASBELE14 in both HCP and PRP orientations.

Figure 4.4: Resulting inversion model for ASBELE14 data showing both conductivity and magnetic susceptibility. Large spike in both conductivity and susceptibility truncated at the beginning of the traverse in the Physical Properties plot for clarity.

4.2 Vertical EMIS Soundings

Vertical soundings are used to characterise the conductivity and magnetic susceptibility gradient at a specific location and are described in Section 3.2. A total of 7 vertical soundings were conducted at the rover level and then inverted once for susceptibility and once conductivity, independently from each other. Table 4.1 shows a summary of the results from the magnetic susceptibility inversions and Table 4.2 shows the results from the conductivity inversions. In Table 4.1 and Table 4.2, RMN is the normalized root-mean-square error. This type of normalization assumes that errors correspond to a constant percentage of the input amplitude. It allows a dataset that has strong and weak responses to be inverted so that all the observed data are fitted equally well (Holladay 2012). It is worth noting that the operator conducting these soundings was wearing steel toe boots and that this could potentially be a source of error. As an example, Figure 4.5 shows the inversion susceptibility results for Sounding 2 and Figure 4.6 shows the corresponding conductivity results.

Looking at Table 4.1 we see that overall, the thickness of layer 1 is within expected values and compares well with horizontal survey results. Inversion results where the thickness of layer 1 was estimated to be larger than 2 m, such as for soundings 4 and 5, are unable to properly distinguish between the two layers since these thicknesses are larger than the depth of exploration of the EMIS. Also worth noting is the prediction that the gravel road is very highly susceptible when compared to the bottom layer which

contradicts the horizontal survey inversion results. Hand sample results will be used in Section 4.3 to clarify this result.

Since the inversion results were derived independently from one another, the magnetic susceptibility and conductivity results for a single sounding will have different predictions for the thickness of layer 1. Although the conductivity inversions produced generally higher predictions for the thickness of layer 1, values for thickness were reasonable for both inversion types (with the exception of soundings 4 and 5 of the susceptibility inversion as previously noted). The conductivity results (Table 4.2), however, seem to be unable to distinguish between layers 1 and 2. The calculated conductivities for both layers are very similar (in several cases, of the same order of magnitude). Sounding 5 indicates that layer 1 (the gravel road) is much more conductive than layer 2 (bedrock). This results clashes with both expectations and the overall results from the horizontal surveys and sample data must be used to make an accurate prediction.

Sounding	Geological Unit	Layer 1 Susceptibility (10^{-3} SI)	Layer 1 Thickness (m)	Layer 2 Susceptibility (10^{-3} SI)	RMN
1	Slate	19.5	0.3	0.8	0.05
2	Slate	37.4	0.4	1.6	0.08
3	Shear Zone	23.0	0.9	1.4	0.07
4	Shear Zone	42.7	15.1	0.3	0.12
5	Shear Zone	43.6	6.6	1.2	0.30
6	Peridotite	20.9	0.6	2.3	0.24
7	Peridotite	13.5	0.9	0.3	0.02

Table 4.1: Magnetic susceptibility inversion results for the vertical soundings. RMN is the normalized root-mean-square error.

Sounding	Geological Unit	Layer 1 Conductivity (mS/m)	Layer 1 Thickness (m)	Layer 2 Conductivity (mS/m)	RMN
1	Slate	1.8	1.5	18.6	0.37
2	Slate	1.8	1.3	22.2	0.05
3	Shear Zone	5.0	1.0	6.2	0.20
4	Shear Zone	12.5	1.0	62.2	0.02
5	Shear Zone	31.9	0.7	3.4	0.01
6	Peridotite	12.0	0.7	11.2	0.09
7	Peridotite	5.3	1.3	6.0	0.07

Table 4.2: Conductivity inversion results for the vertical soundings. Poor conductivity results in soundings 1 and 3 could possibly be caused either 2D or 3D effects. RMN is the normalized root-mean-square error.

Figure 4.5: Inversion susceptibility results for Sounding 2. Here IPZ and IPX data stand for observed HCP and PRP susceptibility data, respectively, while IPZ and IPX models are the inversion models produced for both HPC and PRP, respectively.

Figure 4.6: Inversion conductivity results for Sounding 2. Here SigZ and SigX data stand for observed HCP and PRP conductivity data, respectively, while SigZ and SigX models are the inversion models produced for both HPC and PRP, respectively.

4.3 Hand Sample Magnetic Susceptibility

Nine samples were taken at 8 locations along the traverses in order to validate magnetic susceptibility results from the EMIS. Two measurements were taken for each location in the mine representing a geological unit while four measurements were taken on samples from the gravel road. As the EMIS is measuring physical properties in the subsurface and the samples, with the exception of the gravel road, were taken on the rock wall, comparisons are expected to be somewhat crude.

Table 4.3 lists the magnetic susceptibility of all hand sample measurements. We can see that samples from a common location yield similar results. The gravel road measurements reveal comparatively very high magnetic susceptibility for all samples which agrees with EMIS vertical sounding results. This result explains why it is more difficult to discriminate between geological units using the EMIS horizontal survey magnetic susceptibility results as such a highly susceptible road partially masks contributions from the underlying layer. In this setting, the magnetic susceptibility inversion results for the horizontal surveys are not very accurate, while the vertical sounding results are much more representative of reality.

Figure 4.7 compares susceptibility measurements from hand samples with rover level traverse 2 observed EMIS susceptibility data. Samples from both the peridotite and slate units yielded lower magnetic susceptibilities than measured by the EMIS, however both units were much lower in susceptibility than the shear zone, which was on average

high in both the sample and EMIS results. The shear zone was also very variable in both results which indicates that susceptibility trends seen with the EMIS are also present in the samples (Boivin et al. 2012).

Sample	Susceptibility (10^{-3} SI)	Sample	Susceptibility (10^{-3} SI)
Peridotite 1a	0.27	Peridotite 1b	0.41
Peridotite 2a	0.63	Peridotite 2b	0.46
Shear Zone 1a	14	Shear Zone 1b	24
Shear Zone 2a	74	Shear Zone 2b	64
Shear Zone 3a	0.70	Shear Zone 3b	0.66
Slate 1a	0.30	Slate 1b	0.32
Slate 2a	0.24	Slate 2b	0.29
Gravel a	92	Gravel c	86
Gravel b	65	Gravel d	75

Table 4.3: Magnetic susceptibility of hand samples. Note the very high results for the gravel road.

Figure 4.7: HCP susceptibility (solid line), hand sample susceptibility results (coloured dots), and Layer 1 vertical sounding susceptibility results (red pluses).

4.4 Laser Imaging

In addition to EMIS data, high-density 3D laser images of the rock face were acquired at rover level. Data was acquired at 6 locations, 5 of which were visited by the rover during deployment (Figure 4.8). In acquiring the images, an attempt was made to pick locations where fractures were present; however, it was not always possible to locate a prominent fracture. For this reason, no scans were taken in the shear zone since it is mainly composed of rubble and more difficult to access.

Despite a maximum range of 2.5 m according to the manufacturer's specifications (Table 2.3), outdoor lighting conditions made it impossible to achieve a focal distance of more than 1 m without sacrificing point cloud concentration, that is, the number of voxels per area. To achieve a balance between focal distance and field of view, the middle lens was used. The field of view for the scenes in this survey ranged between 179×131 mm to 479×337 mm (Table 4.4). Since the scanner is not meant for use in direct sunlight and so as to not 'blind' the scanner, a shadow was cast of the scan area using an umbrella as well as jacket. Despite this effort, some sections of scanned scenes suffered from relatively poor coverage. These areas, however, were purposefully limited to the least interesting portions of a particular scene so as to insure targeted features received the most coverage.

Figure 4.9 shows the scan location for Station 2 and indicates the exact area of the scan. The colour digital photograph taken by the laser scanner is shown in Figure 4.10.

We can see a very bright area on the right of the image where the scanner was being 'blinded' by sunlight which causes the scanner to produce a lower point cloud density in that region. Figure 4.11 is a plot of the point cloud produced for Station 2 with each voxel plotted as a small coloured circle where the colour is determined by target-camera distance (Z value). Holes in the data can be seen on the right of the scan area. The feature of interest located at the center of the scan, however, is well covered. Likewise, Figure 4.12 shows the scan location for Station 6 and Figure 4.13 is the colour photograph taken by the scanner. Blinding of the scanner can also be observed in this image. The point cloud can be seen in Figure 4.14.

Site	Geological Unit	Laser Intensity (0 - 255)	Gain	Noise Filter	Distinctive Feature	Image Dimension (mm)	Number of Voxels	Point Cloud Concentration (voxels / mm ²)
1	Peridotite	25	0	No	Fracture	479 × 337	56835	0.4
2	Peridotite	25	0	Yes	Fracture	472 × 339	52944	0.3
3	Peridotite	255	0	Yes	Fracture	229 × 165	44322	1.2
4	Peridotite Boulder	25	0	Yes	Chrysotile vein	230 × 163	49427	1.3
5	Peridotite Boulder	25	0	Yes	Chrysotile vein	176 × 131	39398	1.7
6	Slate	25	0	Yes	Relief	251 × 175	56248	1.3

Table 4.4: Laser scanner settings and image characteristics for all six scan sites.

Figure 4.8: Locations where 3D laser images were acquired at the rover level in the Jeffrey Mine. The 4th location in the peridotite unit consisted of a large boulder where two separate scans were taken (one high and the other low on the boulder).

Figure 4.9: Photo indicating the scan location and size of the image acquired at Station 2.

Figure 4.10: Digital colour photograph for Station 2 taken by the laser scanner. Bright area on the right of the image is due to sunlight 'blinding' the scanner. Image dimension is 472×339 mm.

Figure 4.11: Point cloud for Station 2 in two orientations. Voxels are plotted as small circles with colour representing target-camera distance (Z value) where red is closer and blue is farther away. All units are in mm. The left plot and Figure 4.10 are in the same orientation.

Figure 4.12: Photo indicating the scan location and size of the image acquired at Station 6.

Figure 4.13: Digital colour photograph for Station 6 taken by the laser scanner. Image dimension is 251×175 mm.

Figure 4.14: Point cloud for Station 6 in two orientations. Voxels are plotted as small circles with colour representing target-camera distance (Z value) where red is closer and blue is farther away. All units are in mm. The first plot is in the same orientation as Figure 4.13.

Figures 4.15 to 4.23 show outputs from the program developed by Lai (2012) to enhance visual perception of images. Looking at Figures 4.18 and 4.21, we see that these images enhance flat areas very well while fractured areas look more chaotic. As the dip image was found to most clearly represent fractures, this type of image was further processed in an attempt at simple fracture detection.

Figure 4.15: Triangular mesh generated from the 3D point cloud showing zoom area.

Figure 4.16: Zoomed in version of area indicated in Figure 4.15 to show triangular mesh elements. Triangles conform to the topology of the surface according to Delaunay triangulation. Larger triangles are found in areas of lower point cloud concentration.

Figure 4.17: HSV colour scale used in the strike and dip images. For the strike images (Figure 4.17, Figure 4.21), only the H value varies, with colour ranging between 0° and 360° . For the dip images (Figure 4.19, Figure 4.22), only the V value is changed between 0 and 1 and then mapped to an angle between 0° and 90° . In the combined strike and dip images (Figure 4.20, Figure 4.23), both values vary.

Figure 4.18: Strike image of Station 2 according to the scale in Figure 4.18.

Figure 4.19: Dip image of Station 2 where black areas have close to 0° dip and light areas approach 90° dip in accordance with the HSV scale in Figure 4.18.

Figure 4.20: Combined strike and dip image of Station 2 according to the HSV scale in Figure 4.18.

Figure 4.21: Strike image of Station 6 according to the scale in Figure 4.18.

Figure 4.22: Dip image of Station 6 where black areas have close to 0° dip and light areas approach 90° dip in accordance with the HSV scale in Figure 4.18.

Figure 4.23: Combined strike and dip image of Station 6 according to the HSV scale in Figure 4.18.

As shown by the flowchart in Figure 4.24, Sobel edge detection was attempted on the 2D colour photos (such as Figure 4.10) produced by the laser scanner with limited results (Figure 4.25). Another approach, in which the dip image serves as a pre-conditioning step before the application of edge detection, was more successful as can be seen in Figure 4.26 which is the result for Station 2 (Figure 4.19). Figure 4.26 can easily be used to identify locations in the image where fractures are present. Edge detection simplifies the task of identifying fractures in an image and can be a powerful tool for rover-based planetary exploration missions. Not all scenes are well suited for this method, however, as can be seen in Figure 4.27 which is the result for Station 6. Station 6 (Figures 4.38 and Figure 4.13) is located in the slate unit and although expressing a large amount of relief, this unit is not home to much fracturing and detected edges therefore do not correspond to fractures.

Figure 4.24: Flowchart indicating the process of simple fracture detection via edge detection.

Figure 4.25: Sobel edge detection results using the colour photo in Figure 4.10 as an input (blue branch in the flowchart presented in Figure 4.24). Although fracture locations can be identified, they are not well delineated in this image.

Figure 4.26: Edge detection results using the Station 2 dip image in Figure 4.19 as input (red branch in the flowchart presented in Figure 4.24). Fracture locations are much clearer than in the previous example (Figure 4.25).

Figure 4.27: Sobel edge detection results from the Station 6 dip image (Figure 4.22). Due to a lack of fractures in this scene, these results are not as conclusive at the Station 2 results.

5 Chapter: Conclusions and Recommendations

In this project, research focused on two different instruments in the context of an analogue mission whose goal was the detection of methane. An EMIS was presented as a potential tool for geological contact and fault detection with the idea that these areas would be more likely to harbour fractures from which methane could potentially seep. Additionally, 3D laser imagery was used alongside edge detection in order to specifically identify fractured areas which could then be further analysed for methane seepage.

During the deployment in the Jeffrey Mine, the EMIS proved that it is a rugged instrument well suited to field use in an analogue mission setting. It has no moving parts and can be controlled from a simple-to-use hand-held device. It produces stable results (with noise estimated to be ± 0.3 mS/m for conductivity and $\pm 0.09 \cdot 10^{-3}$ SI for magnetic susceptibility) which are easy to interpret and minimal processing is required. Simply plotting instrument HCP or PRP quadrature or in-phase output against distance clearly shows the locations of geological contacts between units with differing conductivity and/or magnetic susceptibility. This could be done, directly in the field, a few minutes after data acquisition. Later, detailed analysis can be done through data inversion to extract more detailed information about subsurface properties. The EMIS could therefore become part of a set of tools designated for the purpose of autonomous science. Since no data processing is required to analyze observed data and since the data sets generated by the EMIS are very small, control software on the rover could make autonomous decisions without having to wait for command and control from earth-based scientists. For

instance, a decision flowchart could be: is the new observation equal to the previous observation within a certain tolerance? If it is, continue roving. If it is not, move back a certain distance, select a finer spatial sampling, and acquire new data.

During the reconnaissance phase of an exploration mission, the EMIS could also simply be mounted on a rover and used for the purpose of real-time geological change detection as the platform is moving. The instrument could be always turned on and a georeferenced database of subsurface electromagnetic properties (electrical conductivity and magnetic susceptibility) could be built over time. During a more complex mission, the EMIS could be mounted on a “scout” rover preceding the “main” rover with the purpose of detecting regions with changes in electromagnetic properties. This information could then be relayed to the ‘main’ rover which could modify its course or slow down its speed to examine in more detail the anomalous region.

Were the EMIS to be mounted on a rover, electromagnetic interference and vibrations would be issues which would require careful attention. Preliminary tests would involve mounting the EMIS on a rover that is not moving as well as taking data in the same position but with no rover. Afterwards, while the EMIS is mounted on the rover, other instruments would be turned on one by one and EM noise measured by the EMIS. Tests could then be conducted with the instruments off, but with the rover moving, and finally with the rover moving and the instruments on. When EM noise is characterized in detail (amplitude, frequency), then magnetic signature control strategies can be implemented to subtract it out of the data.

When considering the results achieved using 3D laser imaging, it becomes clear that having such a capability would be a tremendous asset to any rover mission. Although full point clouds can be very large files, with the minimal processing presented here, it would be feasible to have a rover with 3D imaging capabilities process the large point cloud data on the fly and only return the much smaller strike, dip, or combined strike and dip images to Earth for interpretation. Although more work needs to be done, it would also be possible to use high density 3D imagery for the purpose of autonomous navigation as well as autonomous science.

Full capability 3D laser scanning systems such as the triangulation camera used here as well as LiDAR systems use large amounts of power which makes rover integration a challenge. However 3D data can also be extracted and processed from stereo cameras which are often mounted on rovers or from structure-from-motion software which can extract 3D information from 2D video (Ullman 1979, Koenderink 1991). The methods described here are applicable to any point cloud data, irrelevant of the sensor used.

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