Thermal Infrared Sensing for Exploration and Mining – An Update on Relevant Systems for Remote Acquisition to Drill Core Scanning

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ABSTRACT

Thermal Infrared or Long Wave InfraRed (LWIR) sensing using satellite, airborne, field, drill core and laboratory systems is advancing rapidly and is the most critical new frontier in spectral applications for exploration and mining. LWIR can directly distinguish silicate mineralogy, the foundation of Earth’s crust, and can directly detect certain ore systems. Although the technology has existed for some time it has been relatively expensive and data signal to noise was relatively low. Advances over the last decade have resulted in increasing improvements in signal to noise with commensurate higher spectral and spatial resolution, and importantly at lower cost.

Low spatial resolution satellites have provided single or broadband thermal data for decades, and while signal to noise is low, increasingly sophisticated processing techniques such as wavelet transforms can provide new results from historic archives that are important to exploration.

Broadband thermal night-time airborne surveys have provided information that has included mapping under pediment to identify buried faults and shallowly buried siliceous targets.

Intermediate spatial resolution hyperspectral airborne instruments provide better signal to noise, with higher spatial and spectral resolution, but until recently have seldom been employed in operational activities. However, examples include mapping intrusive compositions, siliciclastic and carbonate sedimentary lithologies, and hydrothermal systems.

Outcrop resolution studies involving tripod-mounted thermal scanners have resulted in detailed lithologic and hydrothermal silica mapping. Hand held LWIR spectrometers, widely available for the visible to near infrared VNIR-SWIR, are expensive and rare, and therefore not applied in the general exploration community.

Recently, operational thermal core imaging technology has provided petrographic level information. The ability to map silicate mineralogy, and strong carbonate responses, has significantly increased the reach of hyperspectral alteration mapping. Examples from a variety of deposit types will be presented.

In summary, a discussion of different ore deposit types and the contribution LWIR can make in their understanding of ore genesis, definition, and exploration will be provided. Practical information on how these technologies can be directly applied to other data for a coherent geologic model are discussed.

INTRODUCTION

Thermal infrared or long wave infrared (LWIR) spectroscopy is fundamentally different than visible to near infrared (VNIR) and shortwave infrared (SWIR) spectroscopy because most LWIR systems involve the detection of emitted radiation instead of reflected radiation. Excellent reviews for geologists of thermal infrared systematics are provided by Drury (1993), and Taranik et al. (2009). Most new exploration applications of LWIR are based on using multiple wavelength bands to identify emission features that are diagnostic of specific minerals and rocks. This is the future of the method and goes well beyond the early work in which broad LWIR bands with low signal to noise ratios were only used to detect differences in temperature.

Figure 1 shows the electromagnetic spectrum from visible (VIS) through the thermal infrared (LWIR). The VIS through SWIR portion of the spectrum is typically sourced from the sun due to its high outer surface temperature (as opposed to nuclear reactions in the sun that generate higher-energy, shorter wavelength cosmic rays). In this sense, the sun’s brilliance is due to its behavior as a black body (a near-perfect absorber and emitter of electromagnetic energy). The peak emittance from the sun occurs in the green light region, which is also the wavelength the human eye is most sensitive to; clearly a product of evolution. As wavelengths get longer there is a considerable decrease in emitted solar energy from the sun. In the so-called thermal infrared region of the spectrum, most emitted radiation comes from Earth itself. Because of its lower temperature compared to the sun, Earth emits radiation at much longer (and
therefore lower energy) wavelengths. Many minerals and rocks, especially silicates, preferentially absorb and emit radiation at specific wavelengths in this region. Detection of emitted light at those wavelengths with spectrometers forms a means of mineral identification and mapping.

Figure 1 also illustrates the windows of light transmission through the atmosphere. Many wavelengths of light are absorbed by atmosphere, thus limiting their usefulness in remote sensing, especially with satellites. Fortunately, much of Earth’s peak thermal radiation at normal surface temperatures occurs at wavelengths of 8–12 μm, a region of high Earth atmospheric transmittance, making it possible to use remotely sensed LWIR imagery for mineral exploration and other surface mapping objectives. Atmospheric absorption is less of an issue over short standoff distances (e.g. decimeters), as occurs for field mapping or core scanning.

![Figure 1: The above image shows the energy emitted by the sun at 6000°K versus Earth’s emission at 300°K. This is compared to the transmission of energy through Earth’s atmosphere. This transmission blockage is minimized if the detector is closer to the subject. For core imaging it is not a consideration, but for satellite, and even airborne systems, atmosphere plays a major role in signal attenuation. Please note the significant decrease in the energy available in the LWIR compared to shorter wavelengths.](image)

Energy incident upon a mineral is either reflected or absorbed (an impractical amount for geologic purposes may be transmitted). Emission (e) is proportional to the absorption (p) for a given wavelength (λ) known as Kirchoff’s law:

\[
e \lambda = 1 - p \lambda
\]

Thus energy is conserved and the amount of absorption at specific wavelengths in the LWIR is related to molecular vibration that is related to the crystal structure of the mineral.

Long wave infrared imaging can detect the spectra of many ore-related silicate minerals, including quartz, feldspars, pyroxenes, and garnet, as well as carbonates and sulfates. These minerals can be difficult to detect with visible and SWIR imaging methods, and therefore, LWIR spectroscopy can provide valuable information to complement data on other species such as iron oxides, carbonates, sulfates, phosphates, micas, and hydrous silicates. In situations where samples are too dark at visible to SWIR wavelengths to allow detection of their constituent mineralogy, the same samples show sufficient spectral contrast to enable mineral mapping in the thermal region.

The ability for the LWIR to directly detect quartz and feldspars makes it possible to map not only alteration but the mineralization gangue itself. Airborne LWIR systems, such as the TIMS (Thermal Imaging Multispectral Scanner), have been used to map intrusive rock compositions including leucogranite, granodiorite, diorite, quartz monzonite, and anorthosite (Sabine et al. 1994). More recently, the SiO₂ content of rocks ranging from 50% to over 70% have been mapped with the MASTER (MODIS/ASTER) airborne system in combination with regression statistical processing (Hook et al. 2005). Mineral mapping in both of these airborne studies was made possible by monitoring the wavelength position of emission minimum caused by Si-O bonding in the SiO₃ tetrahedra of silicate minerals. The wavelength position of this minima progressively shifts to lower wavelengths as one moves from low-silica minerals such as olivine through chain silicates (pyroxenes and amphiboles) and sheet silicates (muscovite and biotite) and framework silicates (feldspars and quartz). Other variations in thermal spectral morphology include cation substitution, grain size and crystal anisotropy. These features become particularly relevant at higher spatial and spectral resolution.

Thermal inertia mapping is another thermal technique that has been employed for mapping surface geologic materials (Kahle et al., 1981). Estimation of thermal inertia requires a minimum of two flights taken at different times over a 24-hour period (preferably just after midnight (hottest) and after midnight (coolest)). This method is challenging because the images must be accurately rectified, daytime albedo calibration is required, and considerable processing can be required. In addition, the thermal inertia of some rocks overlap, but some materials have distinctive thermal inerts (e.g., sand dunes, with low thermal inertia). One example of the application of thermal inertia mapping to mineral exploration involved the detection of base metal deposits in India in high grade metamorphic terrane (Ramakrishnan et al., 2013). ASTER LWIR data with 90 m pixels were employed producing 1:100,000 scale maps. Correlation of low thermal inertia areas with mineralized rock was good, but the ore conveniently occurred in country rock with a consistently higher thermal inertia. Thermal inertia differences are not as great between rock types as they are between consolidated and unconsolidated rock. This technique has the ability to map eluvial/bedrock interfaces and could be a proxy for seismic refraction. Therefore, thermal inertia mapping can be useful for mineral exploration in shallow pediment and lateritic environments.

Another temperature mapping technique useful to exploration is the use of pre-dawn broad band thermal for mapping subtle near surface variations related to deeper features. For example, Loughlin (1990) examined gold targets in Nevada and mapped silica bodies such as jasperoids that retain more heat (i.e. high thermal inertia) relative to the surrounding geology. This technique can also look several meters into the pediment. Bedell
(pers. comm.) used this technique in Nevada and drilled a radianc anomaly in pediment (a buried resistant positive topographic feature) and hit the target at a depth of 30 m. Buried fault systems have also been detected based on the differences in moisture content of soils. This broad band method, which examines relative radianc anomalies, could be considered a type of unconstrained thermal inertia mapping.

Another region of the thermal spectrum of potential interest is the middle infrared (MIR) that ranges from about 3 to 7 µm. Because this wavelength region is shorter than that of the main LWIR region (8 to 12 µm), sources of radiation include both Earth and the sun. The MIR is being actively used by astronomers to look at planetary and asteroid surfaces (e.g., Reddy et al., 2015). It has also been used by the petroleum industry, because many organic compounds have significant features in the MIR (e.g., Cataldo and Iglesias-Groth, 2010). In addition, sulfates (Lan, M.D., 2007), carbonates, and hydrous minerals have features in the MIR. This is a possible future area of research interest, but currently the importance to mineral exploration is minimal, because most of the mineral species of interest are also detectable in the SWIR spectral region at lower cost.

In summary, thermal spectroscopy can play an important role in future exploration because of its ability to detect many silicate minerals that do not have distinctive spectra at shorter wavelengths. In the past, low signal to noise ratios and the high cost of cooled detector arrays were factors that limited field applications. Considerable improvements in technology have been made in recent years, with the result that better thermal systems are becoming available for satellite, airborne systems, hand-held instruments, and drill core scanning applications.

This paper reviews a range of thermal infrared systems and their application at spatial scales ranging from regional (satellite imagery), project-scale (airborne imagery), through to mine-scale (outcrop scanning) and core scanning. Drill core scanning will be an increasingly important source of exploration data, and high-resolution mineral mapping will also be useful for metallurgical studies and mine planning. Because of the increased spatial resolution of new systems, a brief section on spectral petrology will focus on applications at a hand specimen scale, with discussion on where the science is headed. Lastly, a discussion of what LWIR data can contribute to the exploration, development and understanding of different deposit types will be presented.

### LWIR IMAGING SYSTEMS RELEVANT TO MINERAL EXPLORATION

Commercially available thermal data range from very coarse satellite data with 120 m pixels down to high spatial resolution core scanning at 0.0004 m pixels (0.4 mm) (Table 1). Although other systems have been built for military and government research purposes this section will focus on systems that have been available for exploration. Other important factors include weight and cost of the detectors. For technical specifications of the systems discussed below, please see Table 1.

Thermal infrared imagery was first used to identify anomalies in the mid-wave infrared spectrum due to their capability to map large variations in temperature and materials. Initial development of LWIR imaging systems consisted of only one thermal band, and were focused on the detection and evaluation of atmospheric gases particularly cloud temperature and water vapor concentrations. Other impetus included detecting man-made phenomena, such as jet and missile exhaust, and natural events such as volcanic eruptions and fires. Once multiple band long-wave sensors became available, they were soon exploited by geologists. Laboratory measurements in the 1960s began to show the importance of the long-wave region in geology for detecting and mapping silicates, carbonates, sulfates, and phosphates, making long-wave sensors very complementary to visible and short-wave sensors (e.g. Lyon and Green, 1975; Taranik et al., 2009).

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Years Active</th>
<th>Utilization</th>
<th>Band</th>
<th>Wavelengths (µm)</th>
<th>Average Bandwidth</th>
<th>Spatial Resolution</th>
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<tbody>
<tr>
<td>ASTER</td>
<td>Currently Operational</td>
<td>Spaceborne</td>
<td>5</td>
<td>8.125 - 11.65</td>
<td>0.85 µm</td>
<td>90 m</td>
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<td>LANDSAT 7</td>
<td>1978 - 1983</td>
<td>Spaceborne</td>
<td>1</td>
<td>10.4 - 12.6</td>
<td>2.2 µm</td>
<td>120 m</td>
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<tr>
<td>LANDSAT 5</td>
<td>1982 - 1993</td>
<td>Spaceborne</td>
<td>1</td>
<td>10.4 - 12.5</td>
<td>2.1 µm</td>
<td>120 m</td>
</tr>
<tr>
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<td>1984 - 2013</td>
<td>Spaceborne</td>
<td>1</td>
<td>10.4 - 12.5</td>
<td>2.1 µm</td>
<td>120 m</td>
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<tr>
<td>LANDSAT 7</td>
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<td>2.1 µm</td>
<td>120 m</td>
</tr>
<tr>
<td>LANDSAT 8</td>
<td>Currently Operational</td>
<td>Spaceborne</td>
<td>2</td>
<td>10.6 - 12.51</td>
<td>0.59 µm</td>
<td>120 m</td>
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<td>Geocam AMIS MK4I</td>
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<td>Airborne</td>
<td>6</td>
<td>8.54 - 13.29</td>
<td>0.53 µm</td>
<td>3 - 20 m</td>
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<tr>
<td>TMS</td>
<td>Currently Operational</td>
<td>Airborne</td>
<td>6</td>
<td>8.2 - 12.2</td>
<td>0.4 µm</td>
<td>50 m at 20 km</td>
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<td>MASTER</td>
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<td>7.7 - 13</td>
<td>0.4 µm</td>
<td>5 - 50 m</td>
</tr>
<tr>
<td>TMS</td>
<td>Currently Operational</td>
<td>Airborne</td>
<td>1</td>
<td>8.5 - 14</td>
<td>5.5 µm</td>
<td>25 m at 20 km</td>
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<tr>
<td>SEBASS</td>
<td>Government Only 2005 - Present Commercially</td>
<td>Airborne</td>
<td>128</td>
<td>7.8 - 13.4</td>
<td>43.75 nm</td>
<td>1 - 3 m</td>
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<td>Specian (ORST)</td>
<td>Currently Operational</td>
<td>Airborne</td>
<td>54</td>
<td>8 - 12</td>
<td>48 nm</td>
<td>304 pixel swath</td>
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<tr>
<td>Iron (TSIR-1000)</td>
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<td>8 - 11.5</td>
<td>250 nm</td>
<td>600 pixel swath</td>
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<td>Currently Operational</td>
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<td>125</td>
<td>7.6 - 11.5</td>
<td>40 nm</td>
<td>320 pixel swath</td>
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<tr>
<td>Hylirgic-3</td>
<td>Currently Operational</td>
<td>Tensile</td>
<td>210</td>
<td>6 - 14.5</td>
<td>40 nm</td>
<td>18 x 8 mm</td>
</tr>
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</table>

| Table 1: LWIR systems. |

Following the initial understanding of the importance of the thermal range on mineral identification, the past 50 years has seen expansive development and increased capabilities of thermal sensors. In the late 1970s, the first thermal measurement of outcrops was performed using the Daedalus 24-channel scanner in the East Tintic mining district in Utah (Kahle and Rowan, 1980). The positive results from this mission led to the development of the airborne TIMS in 1981 (Taranik et al., 2009). The Landsat Multispectral Scanner (MSS) was also equipped with thermal capabilities during this time, and has continued to evolve with each subsequent Landsat mission, such as the Landsat Thematic Mapper 4-5 (TM), Landsat 7 Enhanced Thematic Mapper Plus (ETM+), and the Landsat 8 Thermal Infrared Sensor (TIRS).

Following the successful TIMS development, the Jet Propulsion Laboratory for NASA began development of the Advanced Spaceborne Thermal Emission and Reflection Radiometer
(ASTER) in collaboration with the Japanese Space Agency and the Ministry of Trade and Industry of Japan in 1988. ASTER utilized five channels within the thermal region, and was launched aboard the Terra payload in 1999 (Yamaguchi 1998). To validate the ASTER datasets, NASA developed the MODIS/ASTER Airborne Simulator (MASTER) which began flying in 1999. Additionally, MASTER provides calibration datasets for ASTER, as well as providing an alternative to the TIMS system (Hook et al., 2001). The development of airborne thermal systems continued with the development of the Spatially Enhanced Broadband Array Spectrograph System (SEBASS) in 1995, a true hyperspectral LWIR instrument, although it was reserved mostly for government research and development use until its first commercial flight in 2005 (Collins, 1996; Cudahy et al., 2000; Taranik et al., 2009).

Since the 1970s many advancements in our understanding of the thermal region and its utilization have taken place with the aid of research and increased spectral and spatial resolutions. Additionally, the increased signal to noise ratio has been an important development because of the relatively low energy levels associated with thermal emission compared to energy levels associated with reflected solar radiation. Detectors with useful signal to noise require cooling. Although uncooled thermal detectors exist, the noise is considered by these authors to be so great that it renders these instruments of no practical use in studying mineralogy. Sensors such as Specim’s OWL have not only increased the use of thermal in airborne surveys with higher signal to noise, but have been invaluable in the development of core imaging systems and the application of outcrop mapping.

Very little is published on geological applications of the Landsat single thermal band unless it is for geothermal work or for simply demarcating gravel versus bedrock. Warner and Chen (2007) normalized thermal data to suppress solar heating and topography in daytime Landsat TM thermal imagery resulting in a superior classification of maps (also employing VNIR–SWIR bands) used to distinguish bedrock versus spectrally similar gravels. More thermal information can be obtained with thermal inertia data that require day-night image combinations, but because of orbital configurations, it can be difficult to obtain day and night images in the same 24-hour period. Optimal thermal contrasts are provided when one of the images is acquired in pre-dawn hours and the other image is acquired in the afternoon. Older Landsat satellites should be re-tasked to maximize the potential for acquiring this type of data.

ASTER has five thermal bands designed to measure and map quartz, silica content and carbonate. This is an obvious option for exploration, as the ASTER global data archive comprises multiple coverages (~6) of Earth’s land surface at <80° latitude. Since early 2016, it is now freely available via the web sites https://gbank.jsi.jp/madas/map, and https://asterweb.jpl.nasa.gov/data.asp.

As shown in Figure 1 there is less energy available at longer wavelengths and therefore the pixel (sample size) is larger to compensate, and therefore the VNIR has 15 m pixels, the SWIR has 30 m pixels, and the LWIR has 90 m pixels. For a practical review of remote sensing systems and associated signal to noise levels for geologists, see Bedell (2004). Figure 2 is an example of processing thermal data over the Klondike mining district in northern Nye County Nevada. These large pixels accurately map silica rich lithology and mesothermal quartz veins.

Figure 2: ASTER image using the thermal bands to map silica in the Klondike Mining District, northern Nye County, Nevada. The geologic map is from Bonham and Garside (1979) and the black-line grid has 1 km spacing. The blue to red-colored pixels denote increasing amounts of silica mapped with ASTER. Note the blue unit is the Ordovician Palmetto Formation and contains chert and argillite. The ASTER image clearly depicts the chert rich lithologies. In addition, the ellipse shows an area of intense quartz veining and silicification in the hanging wall of a thrust (see red ellipse).

Airborne thermal systems provide better exploration project resolution data for geologic studies because of the increased signal to noise ratio as well as improved spatial and spectral resolution compared to satellite systems. Important studies used
to map intrusive rock compositions include Sabine et al. (1994) using TIMS and Hook et al. (2005) using MASTER. Mapping of alteration is demonstrated by Taranik et al. (2009) using MASTER and SEBASS imagery.

(a)

Several studies have employed airborne detectors and mounted them into various configurations to scan outcrops and pit-walls (e.g. Ramanaidou et al., 2002; Fraser et al., 2006; Kruse et al., 2012) but these have been restricted to the VNIR through SWIR. These examples mounted the imaging systems into a van which drove into the mine open pit and then scanned walls. The same could be accomplished with a TIR instrument and has been done using SEBASS.

Figure 3 shows an example of outcrop scale mapping done at the University of Nevada Reno. This image from an outcrop in Death Valley California shows how expressive the lithologic contrast can be in the TIR relative to visible photography.

Eventually these systems will be deployed in drones, but the current cost is prohibitive, even for the less expensive SWIR instruments. Quality LWIR systems are about ten times the cost of SWIR detectors; therefore, their use in exploration will be limited for the immediate future.

THERMAL CORE LOGGING

There are currently three systems that have been actively using the LWIR for core scanning over recent years. The current HyLogger-3 system is developed by CSIRO and being commercialized by Corescan Pty Ltd. It is a line profiler only but has been providing useful data the longest and has substantial literature relevant to mineral exploration. It is being commercialized by Corescan Pty Ltd. The University of Alberta system was developed for academic and some commercial work, and some important theses relevant to mineral exploration have been done with this system. Thirdly, the TerraCore commercial system is available globally and offers a variety of portability such that it can be moved to remote sites. All three systems will be described with mineral exploration examples and references to the literature.

HyLogger

The current HyLogger-3 system developed by CSIRO is an integrated hyperspectral VNIR-SWIR-TIR line profiler with sub mm resolution visible imaging for spatial reference. Hylogger technology is recently licensed to Corescan Pty Ltd to provide commercial services globally. This system operates in line profile mode taking a spot sample approximately every 1 cm. Capable of scanning up to 1 km of core per day it can measure all the drill core collected from a given deposit enabling 3D characterization of a range of ore quality properties (Haest et al., 2012a, 2012b) from both wall rock and from veins of at least 5 mm width. The system provides a profile of spectra along the crest or middle portion of the core. The more spectral features that are detected and analyzed the more detailed information that can be obtained. This is described for additional carbonate features near 14 µm that helps classify specific carbonate species in the Roseberry volcanogenic massive sulfide (VMS) deposit in Tasmania (Green and Schodlok, 2016). The profiler saves time, money, and data volume relative to imagers and is a follow on to several programs at CSIRO that employed airborne profilers for hyperspectral and laser thermal detection (e.g. Whitbourn, 1997). Because of the relatively large footprint of Hylogger-3 compared to core imagers (e.g. <1 mm) and because this is not an imager, information related to textural relations is
relatively poorly captured but spatial context can be interpreted given its position along a given core and using the associated high resolution visible core imagery. There is associated literature associated with the HyLogger-3 given in a 2016 special issue of the Australian Journal of Earth Sciences (Vol. 63 Issue 8) as well as earlier work on the TIR module for mapping plagioclase compositions associated with Archean gold deposits in Kambalda, Western Australia (Cudahy et al. 2009).

UofAlberta Thermal Imaging System

The University of Alberta employs a SisuROCK imaging work station that includes the SPECIM HS thermal camera with a range of 7.4–12.1 µm across 32 bands at nominally 150–250 nm (0.15–0.25 µm) band width. The SWIR is 1.90–2.36 µm with a 6 nm (0.006 µm) band width.

Case Study: Kimberlite Dilution Snap Lake, NWT, Canada

In a study by Tappert et al. (2015), short-wave infrared (SWIR, 1.90–2.36 µm, nominally 6 nm bandwidth) and long-wave infrared (LWIR, 8.1–11.1 µm, 150–250 nm nominal bandwidth) hyperspectral images were collected from two kimberlite drill core of the Snap Lake mine (NWT, Canada). The nominal pixel size of the SWIR and LWIR imagery was 0.28 x 0.28 mm and 1.1 x 1.1 mm, respectively. Obtaining accurate crustal dilution data from kimberlites is very important because the presence of crustal rocks can affect diamond grade. This is typically achieved using linescan data (visual counts of crustal xenoliths >1 cm) but errors in such estimates arise in part from the alteration of xenoliths and from the presence of xenoliths too small to be identified visually. At Snap Lake, granite is the main dilution component in the ore body.

A detailed description of the data preprocessing and subsequent determination of spectral endmembers can be found in Tappert et al. (2015). Prior to endmember extraction the data were processed using the Spectral Analysis in Wavelet domain (SAW) tool (Rivard et al., 2008) used to isolate mineral spectral features from the spectral continuum, and to minimize noise. Spectral endmembers were then used to define four compositional classes: undiluted kimberlite, micro-diluted kimberlite, macro- and micro-diluted kimberlite, and crustal rocks. Subsequently the SWIR and LWIR imagery was classified and the percentage of each class was compared primarily to linescan data and drill core logs. Here macro-dilution refers to the presence of crustal xenoliths greater than one millimeter in size, and micro-dilution refers to the presence of fine-grained xenoliths less than one millimeter in size. This size cutoff is determined by the pixel size of the LWIR imagery. The Spectral Angle Mapper (SAM) tool was then used to classify each pixel.

Spectral Classes for Diluted Kimberlite

Two subclasses of LWIR spectra were collected from diluted kimberlite (Class 2-1, 2-2) that differ in their peak location near 9.8 µm (Figure 4). Peaks at these wavelengths are attributed to the vibrations of the Si-O-Si bonds of many different minerals and consistent with the presence of serpentine-bearing clays. Antigorite: (Mg,Fe)3Si2O5(OH)4, Mg-clay (sepiolite: Mg4Si4O9(OH)2·6H2O), phlogopite (KMg3AlSi3O10(F,OH)2), and talc (Mg3Si4O10(OH)2) documented in these rocks from Raman spectroscopy. At Snap Lake, these alteration minerals develop extensively around the granite xenoliths and are indicative of crustal contamination. The difference between the Class 2-1 and Class 2-2 spectral groups is explained by bulk chemistry or varying amount of granite, a higher SiO2 resulting in a shorter wavelength peak as seen in Class 2-2.

Figure 4: SWIR and LWIR spectral endmembers: (1) kimberlite, (2) diluted kimberlite, and (3) crustal rocks. Care should be taken when directly comparing these wavelet spectra to traditional reflectance spectra because the removal of the spectral features from their location observed in reflectance spectra.

The spectra of these two subclasses are very similar in the SWIR but there are important differences: the features at 1.911 and 2.320 µm in the Class 2-1 spectrum are shifted to 1.909 and 2.318 µm in the Class 2-2 spectrum. These small shifts are approaching the spectral resolution limitations of the SWIR instrument, but they are significant when combined with the results obtained from the LWIR instrument. They are best explained by differences in the relative abundance of Mg-bearing phyllosilicates and Mg-bearing clays.

Mg-bearing phyllosilicates, like serpentine and chlorite, produce an absorption feature at 2.326 µm, whereas Mg-bearing clays, like sepiolite and talc, produce an absorption feature at 2.315 µm (e.g., Hunt and Salisbury, 1970; Clark et al., 1990; Clark et
al., 2007). This higher abundance of Mg-bearing clays inferred in Class 2-2 can also be correlated to a higher SiO₂ content in these rocks, which is consistent with the results observed in the LWIR.

Spectral Classes for Crustal Rocks

Three subclasses of spectra relating to crustal rocks (e.g., granite, amphibolite, and chert/opal) were identified in the LWIR. Class 3-1 spectra represents and observed spectral features at 8.8 and 9.7 µm result from the presence of feldspar, illite, and quartz. Class 3-2 spectra represents amphibolite xenoliths, and the amphibolite kimberlite host rock. Features at 9.2 and 10.5 µm, and a weak inflection at 8.8 µm, are consistent with the presence of abundant feldspar and amphibole. Class 3-3 spectra, has a peak at 8.8 µm, and can be attributed to the presence of amorphous silica. The SWIR analysis was based on imagery that did not contain Class 3-2 or Class 3-3 spectra. The Class 3-1 SWIR spectra contain several absorption features (1.913, 2.105, 2.199, 2.249, and 2.342), consistent with the presence of potassic dioctahedral micas (e.g., illite and/or muscovite). Primary muscovite is present in the granite, but muscovite and/or illite formed by the alteration of feldspar.

The SWIR and LWIR classified images had similar abundances (Figure 5) for each class. Differences of 7% in the extent of Class 1 and Class 2-1 between the SWIR and LWIR are best explained by the different sensitivity of the SWIR and LWIR wavelengths to specific minerals, and to differences in the spatial resolutions of the two spectral cameras.

Implications

Valuable information emerges from the classified imagery of kimberlite drill core (Figure 5). A high degree of mixing can be seen between the kimberlite and the crustal rocks, as indicated by the presence of abundant Class 2-1 and Class 2-2 spectra, particularly in the middle core section. This is a good example of how reflectance and emissivity spectroscopy can be used to identify micro-dilution (Class 2-1) which is not possible using visual linescan techniques. Without the compositional map of the core, several thin sections would need to be analyzed to determine the extent of this unit.

Information about the contacts between the different compositional units is also captured by the classified images. For example, gradational contacts are observed between the undiluted kimberlite, diluted kimberlite, and crustal rocks in the middle section. Such a transition would suggest that the units were emplaced at approximately the same time. In comparison, sharp contacts may indicate the presence of faults or a temporal or compositional disconnect between the emplaced units.

At Snap Lake, the entrainment of crustal material, particularly granite, into the kimberlite has resulted in the formation of distinct compositional units that are captured using hyperspectral imaging. The imaging system allows more quantitative assessment of dilution relative to the line scan system with a sample every cm. The resulting compositional maps can aid in the production of more detailed drill core logs to accurately describe kimberlite dilution. Here the SWIR and LWIR analysis resulted in very similar assessments of class abundance and distribution in part because the dominant crustal component, namely granite, has altered to mineral products with SWIR signatures.

![Image of classified maps](https://via.placeholder.com/150)

**Figure 5:** Dilution maps obtained from the analysis of LWIR and SWIR imagery. Top: photo of three core lengths. Below are pairs of LWIR and SWIR image maps for the top, middle and lower core lengths seen in the photo.

**TerraCore**

TerraCore offers a full range of imaging from VNIR-SWIR-LWIR in locations worldwide. The system is available directly through them and their partners ALS Global. The systems are scalable from tabletop SWIR to portable two spectrometer swappable mobi systems to the full three spectrometer system. The LWIR instrument is the SPECIM OWL with an 8–12 µm range 84 bands at 100 nm and spectral sampling per band of 48 nm.

Two resolutions are available depending on application. The normal resolution scans a whole core box at a time with 1 mm pixels. This takes about 3 minutes per box. A typical core box has four rows. The high-resolution system scans two rows at a time at 0.4 mm.

An example of the different resolutions of the system are shown in Figure 6. The higher spatial resolution shows more detailed fine-scale bedding than the standard 1 mm pixel scan. This can have important implications for studies where the modeling of porosity and permeability are concerned but the speeds and costs will be considerably different.
Case Study: Reduced Intrusion Gold System Nevada, USA

A reduced intrusion gold system called the Everson Deposit in NW Nye County Nevada is within a Renaissance Gold Project called Buffalo Canyon, most recently described by Quillen et al. (2016) in preparation for a M.Sc. thesis. The project is a complex series of intrusions and mineralization including Jurassic, Cretaceous and Oligocene overprints dated by LA-ICPMS U-Pb dating of zircons. This complex area describes how useful high resolution spectroscopy can be in sorting out the phases, and in particular, what is important to vectoring towards mineralization.

The country rocks are greenschist grade Triassic metasediments and volcanics that have a pyrrhotite bearing biotite hornfels overprint (undated). This is overprinted by a Jurassic sodic-calcic alteration dated by metaluminous, biotite-pyroxene diorite stocks 159.59±4.5 Ma and porphyritic granodiorite dikes dated at 159.38±0.94 Ma. A later Cretaceous event including peraluminous, ilmenite bearing, equigranular granite dated at 78.9±1.8 Ma and coarse grained leucogranite dikes and plugs dated 81.05±0.44 Ma. Mineralization appears to be Oligocene associated with quartz-tourmaline veins.

One core drill hole is on the edge of the deposit and was scanned by TerraCore at 1 mm spatial resolution to aid the thesis investigation. The core hole went through four intervals of anomalous gold mineralization. The data processing employed by TerraCore is to first create a Self Organizing Map (SOM) to define endmembers of the hyperspectral data which are viewed and manipulated on the cloud using IntelliCore © TerraCore. Assays are viewed downhole with the endmembers displayed. A useful first approach is to see which endmembers correlate with mineralization. Often the endmembers are mixtures so by analyzing the mixtures and searching for specific minerals, one can often find better definition of the mineralization and associated alteration. In this case quartz and tourmaline correlated with mineralized intervals.

Figure 6: Drill core 102 mm across scanned at different spatial resolutions in the LWIR and in the visible for comparison.

Figure 7: (a) SOM image of drill core approximately 6.3 cm wide (2.5 inches). The pink represents one class member of a SOM and relates to a quartz vein. The spectra to the right shows the spectra of the pixel defined by the orange cross and the yellow is from an in-house spectral library. (b) is the same specimen using feature extraction 2.340 µm to find schorl tourmaline. The rock image on the left is about 12 mm across and includes the area within the orange cross. The spectra in that cross is shown as the cyan spectra on the right compared to library spectrum in magenta.

In addition to the drill core a suite of hand specimens was run through the TerraCore system. An example of a Cretaceous peraluminous leucogranite hand sample is shown in Figure 8. The thin section shows a chlorite-albite-epidote-sphalerite-apatite assemblage and the SEM shows a Kspar matrix, with quartz, apatite, ilmenite and titanite. Examples of SOM endmembers include quartz-orthoclase in the thermal and chlorite in the SWIR. It is interesting to compare resolution with speed. Significantly more detail is obtained with optical methods and SEM but the overlapping information is corroborative.

Minerals identified with the thermal spectrometer include quartz, orthoclase, albite, plagioclase (not albite), biotite, and tremolite. This is in addition to the minerals found using predominantly the SWIR which include tourmaline, montmorillonite, chlorite, and illite-smectite.
additional data useful for the interpretation of ore systems. Light in the thermal region involves excitation of fundamental vibration modes of silicates and thus the information gained from spectroscopy in the 8–12 µm region complements that obtained at shorter wavelengths involving overtones and combination tones (e.g. Jones and Raschke, 2012).

Given the longer wavelengths there will be a theoretical minimum grain size at which the technology can reliably provide accurate spectra. At 12 µm it is logical that one would need at least a two to three times larger grain size for the spectra to be reliable. Ramsey and Christensen (1998) demonstrated that incoherent volume scattering of grains less than about three times the wavelength produced significant changes in spectral morphology. This study assessed thermal radiation of up to 25 µm wavelength, and found that below 60 µm spectra were significantly attenuated.

**Chemistry**

It is well established in the spectroscopy literature that cation and anion substitution can be detected in the spectra for many mineral species. There are many examples of this in the SWIR but not many studies have been carried out in the thermal.

Plagioclase has been studied by Cudahy et al. (2001) with SEBASS airborne imagery and correlated with XRD. The study was based on the classic porphyry district at Yerington, Nevada and demonstrated it is possible to distinguish anorthite (Ca endmember) from albite (Na endmember) and intermediate-composition members. Plagioclase undergoes significant crystal structure modification from Na-rich albite to Ca-rich anorthite. Understandably there is a corresponding change in spectra given structural changes in the lattice parameters. This is documented in spectral libraries derived from laboratory conditions.

Olivine, on the other hand, has one crystal structure for Fe-rich fayalite to Mg-rich forsterite, but the unit cell parameters change. In the thermal part of the spectrum the emittance bands shift to shorter wavelengths with decreasing Fe/(Fe+Mg) (Koike, 2003). Similar shifts in the thermal for Fe/(Fe+Mg) were found in pyroxenes (Chihara et al., 2002).

LWIR imaging of garnets have also been useful at the Yerington porphyry system in the associated skarn, whereby the spectra act as a proxy for Fe/Ca ratios (anraditic to grossular) to vector mineralization (Cudahy et al., 2001). In addition, Mn substitution in garnets have been found to be a vector at the Broken Hill deposit in Australia. In this case Mn-rich spessartine garnets are proximal to mineralization relative to the more distal Fe-rich almandine garnets (Cudahy et al. 1999 and Hewson et al. 2001).

Future work will continue to define chemical changes that can be detected in spectra and applied to exploration.

**Grain Size**

Grain size can be an important petrographic parameter and spectroscopy can give clues beyond laborious measurements of grain boundaries. Data suggest that spectral features can vary in depth and shape with grain size and in the LWIR can also be

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**SPECTRAL PETROLOGY**

High-resolution LWIR spectrometers can now be used with spatial resolutions as low as 0.4 mm to analyze hand specimens, drill core and other small samples to augment petrographic descriptions. By providing information on mineral composition and crystallographic states, LWIR spectroscopy aids in the identification of mineralogy, alteration, and lithology, to provide

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**Figure 8:** Images of sample RBCQ021A/B (a) SEM backscatter image with Kspar matrix, quartz, apatite, ilmenite, titanite. The image is about 175 µm across. (b) photomicrograph of a thin section of chlorite-albite-epidote-sphalerite-apatite. The image is about 800 µm across. (c) thermal spectra showing quartz and orthoclase features taken from the blue SOM classification. The pink represents an endmember with mixed phyllosilicate and feldspar. The image is about 10 cm across at the base. (d) The same sample as in (c) but this endmember is chlorite.

In summary, there was considerable confusion by multiple groups of geologists who thought that the pre-Jurassic hornfels was a vector to mineralization. Others thought the Jurassic sodic-calcic event was important. The spatial association with Cretaceous intrusions was the preferred candidate until recently. The Oligocene seems the most likely because it cuts an Oligocene quartz monzonite dike dated to 25.66±0.26 Ma. Greenschist metamorphism followed by four intrusive events makes for a very complicated series of superimposed mineralogy that only detailed petrographic relationships can unwind.

This study showed that by simply looking at spectral endmembers down the drill hole in conjunction with assays that one could quickly determine what mattered in these complex overlapping systems.

Assays provide trace element geochemical signatures that overlap because samples are taken over larger intervals (typically 1 m), but high-resolution spectroscopy provides distinctive phase and textural relationships at a resolution relevant to determining ore genesis. These data provide a rapid assessment as to what is controlling the mineralization and what the true vectors are relative to other techniques.
The SWIR (reflection) and LWIR (emission) are fundamentally different so rules can only be shared between the spectra with caution. For reflectance data (visible – SWIR) grain size has a nonlinear effect on continuum values consistent with optical theory. Grain size effects the relative proportions of volume scattering to the total observed reflectance. A decrease in grain size translates into an increase of the relative proportion of volume scattering (Shkuratov and Gruyko, 2005).

Work done on olivine by Lindsay et al. (2013) show theoretical parameters for emission spectra changes according to grain size. The longer wavelengths associated with thermal part of the spectra obviously limit the size of the grains that can be imaged. In the 8–13 µm region, for very small grain sizes (approximately 3 times the wavelength) the increase in grain size has a marked shift.

Carbonates make a good comparison because they have diagnostic features in the SWIR and LWIR. A study using synthetic, chemical grade, and natural calcite and dolomite shows an increase in feature depths with finer grained samples in the LWIR. In addition, there are documented wavelength shifts with grain size (Zaini, et al., 2012). Drill core studies on carbonates for mineral exploration include Green and Schodlok (2016), in which they relate carbonate species to VMS mineralization.

Glotch et al. (2004) found differences in thermal spectra of hematite if it was secondary after magnetite. Goethite was found to have changes in spectral shape as the temperature of dehydroxylation increased. These are important conclusions and demonstrate that LWIR analysis can show evidence of protolith and temperature of formation, critical to the understanding of ore genesis.

Recent work by Browning (2016) using the high resolution TerraCore system with a 0.4 mm pixel shows important grain size variations for petrologic features. Through the use of endmember mapping, two distinct responses were recognized, both of which mapped areas of calcite. In Figure 9, the blue spectra map calcite grains within the core, while the green spectra are mapping an area of calcite cementation. This spectral distinction is believed to be related to crystal grain size. These results provide information on porosity and permeability characteristics that are critical in studies of hydrothermal mineralization, oil and gas fields, and hydrogeology.

These data indicate that algorithms to define grain size may be more productive in the LWIR than the VIS-SWIR, including feature magnitude, shape and spectral shifts.

![Figure 9](image)

**Figure 9**: The drill core is 102 mm (4 inches) wide and the image is comprised of 0.4 mm pixels. The black circular features are billets used to sample for XRF, XRD and other studies typical of the oil and gas industry. The far-right image shows calcite grains in blue and calcite cement in green.

**Crystal Orientation**

As the spatial resolution gets higher, the importance of crystal orientation is amplified. Hand held spectrometers cover a large enough area in a single reading that they are likely to capture multiple orientations from a typical rock. Core scanning now must strongly consider orientation effects particularly when invoking unmixing models to determine mineral abundances. Quartz is an anisotropic mineral, and each mid-infrared (7–15 µm) reflectance spectrum collected from an individual quartz crystal (see Figure 10) is strongly influenced by its orientation. As a result, quartz reflectance spectra contain features that systematically change with orientation though for many forms of analysis a general representation can be used for quartz. However, with proper spectral and spatial detail, the latter to minimize the effects of spectral mixing, one could exploit the spectral differences resulting from orientation to extract textural information from imagery as illustrated in Tappert et al. (2013).

Optical mineralogy which is the backbone of modern day petrology, demonstrates crystallographic anisotropy in the VIS. For the LWIR there is significant data in the synthetic crystal literature for anisotropic emission features and related phenomena for micro-lasers, optical switches, and micro-transistors. Practical mineralogy is just starting to investigate these LWIR attributes and will be important in the future for many geologic applications.
Mineral Abundance Determination

Mineral abundance determinations are important for exploration and production, but also to simply map rock type. The simplest approach would be to count pixels for each classification (minerals or mixtures) as a type of modal analysis. The challenge of distinguishing domains (geologic boundaries) can be addressed in a variety of ways with image processing techniques such as cluster analysis and edge detection. However, such algorithms could only be productively applied after interactive supervised classification by a geologist. Once domains are established then a more automated approach can ensue within the same geologic domain.

Mixtures present another level of difficulty. The easiest method would be to take the dominant mineral and simply count that pixel for a single mineral. This is probably not a bad proxy for many practical applications. However, end members probably include a number of mixtures and this will be related in part to abundance. If an endmember can be reliably used to label a range of mineral mixtures, this approach might work for many applications. The challenge lies in determining the relative abundance of the minerals captured by a given endmember.

Studies done in the VIS-SWIR have found that the spectral response of mineral mixtures can be highly non-linear and requires a complex convolution (e.g. Mustard and Sunshine, 1999). However, in the thermal part of the spectrum, Ramsey and Christensen (1998) were able to deconvolve 70 mineral mixtures (with 2-15 end members) with a linear mixing model. This work was done at a variety of size fractions. The accuracy fell off rapidly with size fractions below 40 µm. This study suggests that simple linear models may be sufficient for unmixing thermal data, but more work is needed to assess mixing over a broader range of mineral mixtures.

In summary, thermal spectral petrology will have grain size limits for extremely fine-grained rocks, but it can potentially be more informative and offer complementary information to shorter wavelengths. The textural context is essential to effective geologic interpretation. Thermal imagery at scales that allow rapid determination of mineral species that can evaluate detailed sedimentary facies, breccia matrix, vein textures and many other features demonstrate the importance of this data in future exploration and development.

LWIR BY DEPOSIT TYPE

Table 2 is a summary of mineral families that can be detected in the VNIR, SWIR, or LWIR. This is a useful proxy reference for considering which spectral data would be most helpful for a given deposit type.

Ore deposits can be divided into magmatic, hydrothermal, basinal brines, or lateritic groups. Each one of these carries a breadth of deposit types and we will discuss them broadly in the context of what LWIR can do to help determine which mineral families or specific species.

Magmatic deposits range from mafic to felsic. Mafic magmatic deposits include Ni-Cu-(PGE) with mafic silicates that include olivine, pyroxenes and calcic plagioclase, all of which are more diagnostic in the LWIR than at shorter wavelengths. These ores are associated initially with sulfide immiscible melts but ultimately ore formation is controlled by temperature, viscosity and the volatile content of the melt (Arndt et al., 2005), and therefore getting at the specific cation substitution of a mineral species becomes important. This cation substitution is documented in olivine’s LWIR response with a shift to shorter wavelengths with decreasing Fe(Fe+Mg) (Koike, 2003). Similar shifts in the thermal for Fe/(Fe+Mg) were found in pyroxenes (Chihara et al., 2002). Shifts in LWIR emission spectra of plagioclase feldspar mineralogy are documented by Cudahy et al. (2001).

 Kimberlites are also associated with similar mafic mineralogy as well as high temperature garnets. Lamproites are ultrapotassic and may include potassic silicate minerals such as leucite and sanidine. These are all responsive in the LWIR relative to shorter wavelengths. An example was provided in the previous section under core logging that used SWIR and LWIR for quantifying crustal contamination and determined quartz and feldspar abundances using LWIR (Figures 4 and 5).

Felsic magmatic deposits include reduced intrusion gold systems such as described by Thompson and Newberry (2000) that are enriched in Sn, W, Bi, Mo, Ag, U and Pb, Zn, Cu. Important ore mineralogy includes quartz, tourmaline, Kspar, and albite. Micas and amphiboles are important alteration facies. The hydroxyl bearing minerals are easily defined by SWIR observations but the more proximal silicate mineralogy is best defined by the LWIR. The case study presented in this paper employing the TerraCore thermal core logging system provides examples
Porphyry Cu-Mo-Au-W-Sn deposits include an enormous volume of rock ranging from intermediate to felsic in composition. Mineralization can encompass a wide range of pH and sulfur and oxygen fugacity environments that can include both high to low sulfidation assemblages. The magmatic to hydrothermal transition is well documented in porphyry districts (e.g. Muntean and Einaudi, 2000) that can include altered rock volumes exceeding 10 km$^3$ (Seedorf, et al. 2005). The ore is most often associated with hypogene potassic alteration that includes Kspar and quartz. Feldspars can also include plagioclase particularly when dealing with more mafic or sodic host rocks. More distal alteration assemblages can usually be mapped with the SWIR; however, quartz is invariably important in most assemblages and can only be directly detected in the LWIR.

Table 2: Summary of Mineral detection capabilities for several regions of the infrared. These include the VNIR, SWIR and the LWIR (after Harris, 2015).

Red – Minerals that are well characterized in the infrared region.
Yellow – Minerals that can be identified in the infrared region. These minerals may not have high contrast responses or are not easily distinguished from some minerals if the system measurement resolution is low.
Grey – Non-diagnostic responses observed for these minerals across the specific infrared regions.
White – Uncertain responses for these minerals across these regions of the infrared.

(Figures 7 and 8). Other granite related deposits (e.g. Cerny et al., 2005) not only include the classic Sn, W, Bi deposits but also rare earth deposits, related veins and greisens, as well as pegmatites. This covers an enormous plethora of complex districts such as Cornwall, UK, with a mineralogy too complex to review here. However, many styles of granitic mineralization are related to the type of intrusion, ranging from peralkaline to peraluminous. Therefore, the composition of feldspars and their abundance relative to quartz is an important part of the classification system. The mineral potential is itself defined at the magmatic stage as this is where saturation of ore minerals is attained (Cerny et al. 2005). In conclusion, LWIR will be a very useful tool in the definition and exploration of granite related mineralization because it can be used to detect and map silicate mineralogy abundances and compositions (e.g. Sabine et al. 1994 and Hook et al. 2005).
Skarns are a variant of magmatic systems and can be related to magmatic deposits of intermediate to felsic composition as well as porphyry copper deposits. Skarns are defined by the presence of calc-silicate minerals which are predominantly detected in the LWIR. Meinert et al. (2005) reviews skarn mineralogy families by grouping them into garnet, pyroxene, olivine and pyroxenoid all of which are best detected in the LWIR relative to shorter wavelengths. The skarn at Yerington shows Fe/Ca ratios in garnets detected by LWIR vector mineralization (Cudahy et al., 2001). The other families include amphibole, epidote and carbonate all of which have significant SWIR features, but also have complimentary spectra in the LWIR.

Epithermal systems have been well imaged using the VNIR and SWIR in terms of iron oxide and the argillic alteration surrounding the deposit, particularly the acidic high sulfidation systems. High sulfidation systems are easy to vector spectrally in the SWIR because clays are highly expressive and usually provide distinct information for temperature and pH. For intermediate and low sulfidation systems the more neutral pH propylitic assemblage is not as easy to define. This alteration is more subtle, and the full range of mineralogy is important to navigate vectors to ore. For instance, epidote has been found to be an important phase in the propylitic assemblage proximal to the ore body in the Midas low sulfidation gold and silver system in Nevada (Leavitt et al., 2001), and at the intermediate sulfidation silver and gold, Comstock Lode, also in Nevada (Hudson, 2003). Epidote and other propylitic phases can be detected in the SWIR but more features in the LWIR might help the vectoring process. Most importantly, the proximal gange mineralogy of quartz and Kspar can be detected that can help define ore directly. The spectral geology literature has many examples of mapping alteration around high to low sulfidation epithermal systems in the VNIR-SWIR, however the LWIR is more uniquely capable of detecting proximal indications of ore by mapping quartz and Kspar.

Iron oxide copper gold (IOCG) deposits and their variants are related to crustally derived granitoids and extensive alkali metasomatism. Most of the phases in these deposits can be detected well in the VNIR through SWIR but the thermal can offer complimentary spectral data. One place that LWIR could contribute is in the proximal alteration and mineralization that is dominated by Kspar, whereas the sodic calcic alteration that might be expressed in plagioclases is often deeper in the system and more distal (Williams et al. 2005).

Carlin type gold deposits are formed by large volumes of fluid circulating in permeable rocks over a long period of time with highly undersaturated fluids with respect to gold. Siliceous jasperoids are a common association with these deposits but may be the distal manifestation of such systems. Within the orebodies themselves there may be very little silica. Relevant mineralogy within the ore bodies include iron oxides and clays detectable at shorter wavelengths. However, because of the nature of formation of these deposits, permeability is very important. Dirty carbonates with siliceous clastic grains make preferred host rocks because they provide a framework of permeability after some of the carbonate is dissolved. Examples of high resolution carbonate mapping with thermal spectra, such as shown in Figure 6, may be relevant to core logging of Carlin deposits, as the mineralization can be strongly controlled by lithology. In addition, dikes of varying composition may be relevant to the genesis as well as the precipitation of ore because when the fluid encounters iron it will precipitate gold by the process of sulfidation (e.g. Cline et al. 2005). These magmatic dikes, that can be mafic to felsic, should be detectable in the LWIR.

Orogenic gold is associated with quartz veins that can be directly detected with LWIR (Figure 2). Although quartz veins are usually obvious visibly, the thermal would be most useful in quantifying abundance in disseminated and stockwork systems. Importantly, accurate mapping of quartz directly (and carbonate) can make it much easier to build quantitative distribution maps that are important for resolving structural controls necessary for predictive exploration. In addition, orogenic deposits are typically hosted in metamorphosed host rocks that often respond in the thermal part of the spectrum.

Volcanic massive sulfide deposits form from hydrothermal vents on the ocean floor. Active black smokers on the ocean floor have temperatures of up to 400°C, and therefore quartz solubility can play a role (Hannington et al., 2005). Such high temperatures can create green schist alteration, iron-rich olivine, calcic-plagioclase and epidote. Many VMS deposits are in older shield rocks and have been metamorphosed. With the Mg flux created in their formation, a classic “head frame rock” is cordierite, a Mg-silicate that is proximal to mineralization. Cordierite and other Mg-silicates are detectable with LWIR. Therefore, LWIR can play a significant role in mapping and exploring for VMS deposits.

Banded iron formation (BIF) is composed of hydrous iron oxides and hematite as thinly banded chemical muds. The associated granular iron formation (GIF) is composed of coarser sand sized granules with cross bedding indicative of a higher energy environment. In this instance the high spatial resolution core logging of grain size, as shown in Figure 6, is highly applicable. These deposits are often low grade and their economics depend on volume and consistent ore mineralogy; thus, LWIR could be very useful in ore control.

Basinal brine deposits include Mississippi Valley-type (MVT) and sedimentary exhalative (SEDEX) deposits and are not obviously associated with igneous activity. They form at lower temperatures 90-200 deg. C (Leach et al. 2005) and so their mineralogy is not strongly advantageous to LWIR detection, although it can be complimentary to SWIR for carbonates, sulfates, and phosphates. However, metamorphosed equivalents such as the Broken Hill deposit in Australia have abundant LWIR detectable mineralogy such as garnets, quartz, and pyroxenes. Mn substitution in garnets detected by LWIR are a Mt.

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deposits, but will also offer important adjunct data to VNIR and SWIR.

Lateritic deposits are an important source of many minerals formed during intense weathering, but laterites can also conceal underlying bedrock-hosted mineral deposits. Spectroscopy is an excellent tool in these terranes, as many minerals can still be found spectrally that relate to the protolith, or to the alteration, and mineralization itself. LWIR is only an advantage relative to other spectral regions dependent on the original mineralogy.

In summary, research has just begun to determine how thermal imaging can be used to map many deposit types. Given the ability to uniquely detect silicate mineralogy and provide information on cation substitution, crystal orientation, and grain size information, the future literature will be replete with examples using the high spatial and spectral resolution LWIR systems.

**DISCUSSIONS AND CONCLUSIONS**

Spectroscopy in the LWIR region is becoming a standard exploration tool and important future developments will improve the ability to detect minerals directly associated with ore and to map silicates that are the framework of Earth’s crust. Increased spatial and spectral resolution and decreasing costs will drive the applications. Although exploration will be an important user, the most important applications may be at the outcrop scale in the production phase of mining to define metallurgy and ore streams.

Reference libraries are an important tool, but optimal results come from libraries derived by the instrument being used, ideally from the specific deposit being worked on.

LWIR libraries include the John Hopkins initially under the direction of spectral pioneer John W. Salisbury and then added to at the US Geological Survey ([https://speclib.jpl.nasa.gov/documents/jhu_desc](https://speclib.jpl.nasa.gov/documents/jhu_desc)). Another important library is derived from the University of Arizona ([http://speclib.asu.edu/libmaker.php](http://speclib.asu.edu/libmaker.php)). These libraries were primarily built for planetary sciences. The CSIRO in Australia also have a LWIR library and is very much driven by ore deposit research (Schedlok et al., 2016; [http://www.csiro.au/en/Research/Mining manufacturing/CSIRO-Chile/Noticias/HyLogging](http://www.csiro.au/en/Research/Mining manufacturing/CSIRO-Chile/Noticias/HyLogging)). Considerable, site specific data is now being generated from portable field instrument and scanning of samples and core.

As with all exploration data, spectral data can be leveraged when integrated with other datasets. Contiguous and continuous coverage provided by satellite or airborne systems can be integrated with other spatially comprehensive data (e.g. potential field surveys) and spatial probability methods can be employed such as weights of evidence, fuzzy logic, neural nets or expert systems. Thermal inertia-related mapping would be very well integrated with gravity or seismic refraction or reflection that also can see the bedrock pediment interface.

Pit wall mapping can be integrated into 3D pit models and is especially powerful when linked with LIDAR surveys so detailed geomorphology is also expressed. Silicic units that are typically harder than other units should be easily detected with the LWIR data.

Drill core logging is a key component of resource modeling. The distribution of metals in many ore deposits is erratic in nature, especially for gold deposits. It is useful to pick a proxy to align the block model and see the overall system. Frequently associated elements like Fe or As are commonly used as they have stronger signal to noise and better spatial coherence. The problem with using chemical distributions alone is that these elements can go into different mineral phases that may not be related to the mineralization, but instead related to the protolith, such as shales. By mapping specific minerals that have specific chemistry and atomic structure there is a much better chance of accurately mapping the ore body itself, particularly when using mineralogy that is part of the ore assemblage, such as quartz, and not the alteration.

In summary, there is much to gain from LWIR as applied to ore deposits and exploration in the immediate future. Technology will drive the price of detectors down and services for airborne and core logging surveys will decrease because of the increased demand and volume. Thermal imaging may be the more expensive option in the world of spectral geology, but if it can find the unique solution or provide rapid answers then it is highly applicable to practical exploration and mining.

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