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ABSTRACT

Over the past decade the field of exploration remote sensing has undergone a fundamental transformation from processing images to extracting spectroscopic mineralogical information resulting in the broader field of Spectral Geology and Remote Sensing (SGRS), which encompasses technologies that contribute to the definition, confirmation, and characterization of mineral deposits. SGRS technologies provide information on the mineralogical and alteration characteristics of a mineral orebody by assisting with the identification of features on the surface, in field samples, and in the subsurface through core spectroscopic measurements and imaging. This contributes mineralogical composition for field mapping and orebody characterization with non-contact, non-destructive measurements at high sampling density that no other technology can accomplish. Application of spectral geology and remote sensing technologies varies depending on the scale of exploration, surface exposure, and alteration type, but may include the use of high resolution satellite multispectral imagery, airborne hyperspectral imagery, surface and core point spectral analysis, or hyperspectral core imaging. SGRS technologies augment human vision by making measurements far beyond the sensitivity of human eyes, providing accurate and densely sampled mineralogical information that contributes to more efficient and accurate field mapping and core logging. When integrated with other exploration data, geologic observation, and engineering and geometallurgical analyses, SGRS data contributes to both upstream and downstream efficiencies. Although the exploration and mining business cycle has impacted expenditures for research and develop of exploration related technologies, SGRS capabilities continue to grow based on demand for new instrumentation and capabilities from the broader geospatial and spectroscopy community.

INTRODUCTION

The last decade has brought significant changes to the field of mineral exploration remote sensing. The title of this paper reflects a transition from a focus on interpretive mapping of geology from imagery to analytics focused identification of mineralogy as an aid to mapping the surface and subsurface. The term “spectral geology” was barely entering the lexicon in 2007; now it is often given priority over “remote sensing”. Geosciences Australia (2014) defines spectral geology as: “the measurement and analysis of portions of the electromagnetic spectrum to identify spectrally distinct and physically significant features of different rock types and surface materials, their mineralogy and their alteration signatures.” Major advances in this area have occurred, especially in spectroscopy of drill core, but also with the launch of advanced commercial imaging satellites and advances in airborne imaging spectroscopy.

As with all other exploration technologies, the commodity price cycle has impacted on the amount of money available for exploration focused research, and this has been a negative impact for several years. Mining and exploration companies have continued to eliminate internal positions for remote sensing and rely on a relatively small number of external consultants. However, a positive attribute of this technology is that demand for geospatial and spectral data continues to grow significantly in fields outside mining and mineral exploration. Petroleum, agriculture, forestry, infrastructure management, wetland and coastal zone monitoring are just a few of the fields that share technology demands with our focus on mineral exploration. This broad base of users has driven improvements in instrumentation and capabilities independent of investment by the mining sector.

Contrary to broad definitions of remote sensing that include RADAR and LIDAR methods, we will focus only on optical remote sensing in this paper, defined as the electromagnetic phenomena in the optical range amenable to spectral geologic analysis. Optical remote sensing covers the range of electromagnetic radiation that can be measured through optical methods, that is with lenses, mirrors, and photon counting detectors. This range is nominally defined as ultraviolet through thermal infrared, but for practical exploration application is defined as visible-near infrared (VNIR) in the range of 400 to 1100 nanometers (nm), shortwave infrared (SWIR) in the range of 1100 to 2500 nm, and long wave or thermal infrared (LWIR or TIR) in the range of 8 to 12 microns (μm).

It is useful to begin with a clear understanding on the contribution spectral geology and remote sensing (SGRS) make to the mineral exploration process. A comprehensive review of exploration methods as applied to discovery case histories is summarized in Sillitoe (1995) and a more general discussion of factors driving exploration success is provided in Sillitoe (2010). An essential aspect of exploration success articulated in these papers is that ore deposits are discovered primarily through detailed mapping and core logging. It is worth emphasizing that although initially the technological tools available may have produced a “discovery hole”, the true definition of a three dimensional ore deposit takes time, and this is time largely contributed through detailed work on the outcrop and in the core...
shed. We can say that mapping and logging have been and continue to be the “bread and butter” of exploration. We assert that the SGRS tools, techniques, and results are entirely focused on mapping and logging. The technology augments geological knowledge and observation by providing unbiased and densely sampled mineralogical information. In mineral exploration, the primary contribution of SGRS is on compositional mapping: the identification and characterization of alteration mineralogy, effectively turning what is often fine grained “white mush” in the hand lens into mineralogy that can be meshed with modern concepts of ore genesis.

One of the most basic rules of exploration is that you rarely find ore without alteration. The lack of consistent alteration logging and mapping is one of the common challenges in mineral exploration, resulting in greater uncertainties in the geological models for targeting. Many factors contribute to this issue such as different levels of field experience amongst the geologists responsible for logging and mapping, complex paragenetic relationships, and alteration of phyllosilicate and sulphate minerals that cannot be distinguished with confidence solely by visual examination. The latter is particularly significant where the mineral species and subspecies of phyllosilicates and/or sulphates reveal a more extensive footprint and zonation in response to the fluid pH and temperature gradient away from the main fluid conduits which can be used as vector towards mineralization, if recognized. The SWIR and LWIR regions are particularly useful for rapid and accurate identification of alteration mineralogy; the VNIR region contributes mainly to identification of iron oxides and sulphates (gossans), and Rare Earth Element (REE) minerals. Portable SWIR spectrometers have been in use for decades in the field and core shed to characterize propylitic, phyllic, argillic, and advanced argillic alteration through general mineral speciation, mineral cation substitution analysis, and mineral crystallinity quantification. LWIR spectroscopy is rapidly evolving, particularly for core analysis, to add potassic, albite, silicic and skarn alteration to the fold.

Our salient objective is to illustrate how SGRS technologies enable economic geoscientists undertake the tasks of field mapping and core logging more accurately, effectively, and efficiently through the addition of data and analyses that stretch their perception of rocks beyond the limitations of human vision.

In this paper, we focus on a number of topics of significant advances in SGRS over the last decade. Most important is the field of spectral core measurements which has evolved rapidly in the last decade. This ranges from augmentation of core logging with point spectroscopy using field portable spectrometers to VNIR-SWIR, and VNIR-SWIR-LWIR hyperspectral core imaging for mineral mapping at sub-millimetre resolution, with concurrent improvements in analytics. The availability of turn-key commercial services for high resolution hyperspectral core imaging, from data collection to data processing and visualization is relatively new, but critical as it has been demonstrated to contribute significantly to exploration success and downstream aspects of mine design and development, and ore control (Harris et al., 2015). The last decade has also brought significant improvements to spatial resolution and spectral coverage of satellite based systems, as well as the introduction of agile satellites that allow significant improvements in coverage opportunities. Airborne hyperspectral systems have seen incremental improvements. However, growing utilization of the technology, especially for targets thought to be unamenable to remote sensing, has shown that the technology can significantly impact the accuracy, time, and cost of field mapping. Our goal is to elucidate the impact these technologies have on exploration, planning, mine development, and downstream ore and process control.

**BASICS OF SPECTRAL GEOLOGY**

The methods presented here are a subset of what is commonly referred to as “remote sensing”. Decades of experience have shown that the mission critical information for exploration is derived from the spectral analysis of optical multispectral and hyperspectral data. Moreover, the value and accuracy of the information generated is directly proportional to the spatial and spectral resolution of the data (Coulter et al., 2007).

Spectral geology relies on the collection of multiple spectral bands of reflected or emitted electromagnetic radiation (EMR) between approximately 400 nm and 12 μm. The source of the EMR signal is the sun in the case of airborne and satellite borne instruments, or artificial light (or heat) in the case of portable spectrometers and core scanning instruments. There are obvious limitations for data collected from aircraft and satellites; mainly that the minerals of interest need to be exposed, we need clear skies (although airborne LWIR can be collected by aircraft flying beneath cloud cover), and the atmosphere is optically opaque for some wavelengths. Since we are focusing on the optical wavelengths there needs to be a direct optical path between exposed mineralogy and the sensor making the measurements; this technology cannot penetrate even the thinnest cover. Consideration should be given to the amount of exposure and the character of the outcrop—lichen cover can be a significant problem in many climatic zones; desert-varnish may provide challenges in others. Extent of vegetation cover is always assessed. Full sunlight with high sun angles are the ideal conditions for data acquisition as these maximize the amount of signal on the ground. It is commonly understood that ozone provides protective absorption of UV light, but other gases and vapors (primarily CO₂ and H₂O) selectively absorb light in subsets of the VNIR an SWIR ranges. The interaction between EMR and materials has been studied for many decades and the underlying phenomena are well understood (Hapke, 1993). Within the VNIR range the interaction involves electron transition processes. The interaction in the SWIR is significantly different consisting of molecular vibration processes that create sharp, deep absorptions which are predictable and related to material composition and atomic structure. Further, the position of the absorptions is often directly associated with elemental structural substitutions, which may have been associated with the geochemical characteristics of the ore forming system. There is a transition in the LWIR range from vibration processes to rotational processes (polarization effects). From an implementation standpoint, different instruments are used to measure each of the three ranges as different detector technologies are needed that are
sensitive to each range. The end result is the measurement of a signal that is a spectral fingerprint of the materials being measured, at the spectral and spatial resolution of the instrument utilized. Not all minerals or materials have a unique spectral signature or fingerprint and they may be spectrally unresponsive (i.e. some may be spectrally flat). Typically, the fingerprint of a material varies between the VNIR, SWIR, and LWIR ranges of the electromagnetic spectrum (Figures 1 and 2). Figure 3 shows the qualitative accuracy for a variety of minerals in each of the wavelength ranges. As can be seen in the chart many critical alteration minerals associated with ore deposits are identifiable using spectral geology techniques, most within the SWIR and LWIR ranges. In addition, solid solution substitution in illite, sericite and muscovite (collectively referred to as white mica), as well as alunite, carbonates and chlorite can be measured directly from the shift of the mineral’s respective spectral absorption wavelength (wv) in the SWIR range (Scott et al., 1998, Yang, et al., 2001; Chang et al 2006 and GMEX, 2012). Similarly, mineral crystallinity of white mica and kaolinite can be approximated by a variety of analytical methods.

Figure 1: VNIR-SWIR stacked spectra of important alteration minerals.

Figure 2: LWIR stacked spectra of important alteration minerals.
The principles of spectral geology provide the scientific basis for the scale up in airborne and satellite instruments and scale down in spectral and spatial resolution. The full scale spectral fingerprint measured using lab or field scale “point” analysis (with thousands of bands) is resampled to the spectral bandwidths of a new sensor, with associated compromises in characterizing the fingerprint due to the binning and reduced ability to capture of the distinct details of the spectral signature for any one mineral. This is typically not a problem with hyperspectral sensors with hundreds of bands over the full width of the signal (i.e. 400–2500 nm), but multispectral sensors which are a magnitude smaller in spectral detail with only 10s of bands (e.g. ASTER, WorldView-3) lose sufficient spectral detail so that it is typically not possible to discriminate between mineral species, only broad mineral families. Multispectral sensors which only capture a small portion of the VNIR consequently only have limited compositional mapping capability (i.e. most high resolution satellites such as WorldView-2, Pleiades, RapidEye, etc.). The spatial resolution of spectral and multispectral data has an impact the reliability of the discrimination of different materials due to material mixing issues. Sensor data with a high spatial resolution (i.e. 1 m pixels) will be able to better discriminate surface composition than a sensor with low spatial resolution (i.e. 30 m pixels), due to mixing of spectral signatures from multiple materials in the final signature measured by the instrument for each pixel (Figure 4).
CORE LOGGING WITH SPECTRAL GEOLOGY TOOLS

Over the past decade, systematic spectroscopic core logging has seen increased use because of its non-destructive, objective, consistent, and fast detection of alteration mineralogy. In addition, alteration mineral subspecies and metrics (i.e. mineral chemistry and crystallinity) can also be quantified. This technology has not only provided new knowledge of the geological processes and 3D alteration patterns of volcanogenic massive sulphide (VMS), Carlin, porphyry, epithermal, orogenic and iron oxide copper gold (IOCG) ore systems, but also contributed to exploration successes as well as downstream resource, geometallurgical and geotechnical modelling and mine planning (Harraden et al., 2013, Clark et al., 2015, and Harris et al., 2015 and Astorga et al., 2017).

The Hylogger hyperspectral core profiler, first developed in the early 2000s, has evolved to include LWIR and is used extensively by the Australian geological surveys and R&D programs to build Australia Auscope National virtual core library and national hyperspectrally derived drill core archive (Schodlok et al., 2016). The most significant technical breakthrough with successful commercial implementation which received rapid uptake by the mineral exploration industry is high resolution hyperspectral core imaging utilizing both whiskbroom and pushbroom hyperspectral cameras. These systems provide non-destructive, automated, objective, semi-quantitative mineralogy for phyllosilicates, sulphates, carbonates etc., along with textural characteristics; whereby the style and intensity of important indicator minerals, mineral chemistry and crystallinity can be mapped at sub millimetre resolution of drill core as well as RC drill chips. In the last decade, hyperspectral core imaging has advanced from small pilot studies of intersections and a few tens to hundreds of metres (Kruse et al., 2012), into thousands to tens of thousands of metres currently being captured and analyzed. The availability of hyperspectral core imaging as a service, either bureau based or on-site mobile lab deployment in the field with automated data collection combined with rapid data processing and visualization capacity, and the opportunity of instrument purchase for extended site operations has enabled application of the technology for the minerals industry (Table 1). Incremental progress has also been made in field portable infrared spectroscopy technology in terms of spectral resolution, signal to noise ratio, instrument portability and accessories for different sample media such as blast hole samples, while more sophisticated semi-automated mineral identification algorithms, spectral libraries, and data visualization software are being made available in the public domain.

Imaging spectroscopy has wide application on sample materials at suitable spatial resolutions for the application. Samples include mineral concentrates, hand samples, run of mine samples, drill chips, rock cuttings and drill core samples. Spatial resolutions are determined through the sample material and the extent of sample coverage required (Figure 5). While many sample materials can be imaged, diamond drill core presents the widest application potential where large sample volumes can be imaged rapidly.

**Figure 5:** Hyperspectral core imaging sample and spatial resolution measurements. Samples from heavy mineral concentrates through drill chip trays and cut and round drill core have been imaged at various spatial resolutions appropriate for the application.
Most commercial imaging options currently measure across the VNIR-SWIR wavelength ranges. These systems allow rock characterization and alteration mapping in many geological environments. Imaging across the LWIR has been a significant advancement in the last ten years and allows near full rock characterization though more complete mineral detection in the drill core. Typical rock forming minerals such as quartz, feldspar, pyroxene, garnet, olivine and carbonate are detected in the LWIR expanding the potential of core imaging to many more geological environments and applications.

Expansion of core spectroscopy capabilities into the LWIR range has improved alteration characterization in porphyry and IOCG deposits through feldspar identification and speciation (Cudahy et al., 2001, Cudahy et al., 2009, Hecker et al., 2010) and skarn alteration characterization through garnet and pyroxene composition changes (Cudahy et al., 2007, Hamilton and Christensen, 2013). Spectral data from the LWIR provides information on carbonate chemistry in orogenic gold, and sediment hosted deposits complimenting and confirming SWIR measurements (Figure 6).

### Integration with Geochemistry

The increased use of systematic infrared spectral mineralogical data has led to an increasing need to integrate results with multi-element geochemical data for more robust alteration interpretation and modelling. Modern geochemical analysis such ICP-MS 4-acid digest whole rock geochemical analysis allows detection of low level ore metals and pathfinders to reveal larger alteration zone temporally and spatially associated with discrete hydrothermal mineralization, metal concentration and metal deployment is complemeted by spectral mineralogical data. As an example, geochemical zoning pattern towards hydrothermal center in the lithocap environment can be significantly enhanced by screening samples with alunite alteration by SWIR analysis (Chang et al., 2011). High resolution hyperspectral imaging provides unbiased, quantifiable and more accurate mineralogical data with improved correlation with whole rock geochemistry (Halley, 2016), whereas the near total mineralogy data derived from hyperspectral VNIR-SWIR-TIR data has demonstrated potential to model elemental geochemistry (Rivard et al., 2016 and Laukamp and Lau, 2017).

### Case Studies

Core spectroscopy using portable spectrometers and hyperspectral core imaging systems has been used successfully for 3D alteration modelling in advanced exploration programs. At Pebble porphyry Cu-Au-Mo deposit in Alaska, the style of mineralization, metal concentration and metal deployment is temporally and spatially associated with discrete hydrothermal alteration zones of potassic, illite, quartz-illite-pyrite, sericite, pyrophyllite, quartz-sericite-pyrite, kaolinite and sodic-potassic assemblages that can be characterized, in part, by variations in phyllosilicate minerals of illite, sericite, kaolinite and pyrophyllite (Harraden et al., 2013, Lang et al., 2013 and Gregory et al., 2013). Integrating geological logging with spectral mineralogical logging is critical to establish such

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*Table 1: Technical specifications of hyperspectral core imaging services.*

<table>
<thead>
<tr>
<th>Company</th>
<th>CoreScan</th>
<th>TerraCore</th>
</tr>
</thead>
<tbody>
<tr>
<td>System</td>
<td>HCl-III</td>
<td>1-Stage (Desktop)</td>
</tr>
<tr>
<td>Spectrometers</td>
<td>3 (VNIR, SWIR-A, SWIR-B)</td>
<td>SWIR</td>
</tr>
<tr>
<td>Spectral Range</td>
<td>450-2500nm</td>
<td>1000-2500nm</td>
</tr>
<tr>
<td>Spectral Bands</td>
<td>510</td>
<td>288</td>
</tr>
<tr>
<td>Spectral Resolution</td>
<td>4nm</td>
<td>12nm</td>
</tr>
<tr>
<td>Spatial Resolution</td>
<td>500μm</td>
<td>30-300μm</td>
</tr>
<tr>
<td>Radiometric Calibration</td>
<td>Spectral reflectance standard, dark current</td>
<td>White reflectance standard, dark current</td>
</tr>
<tr>
<td>RGB Image Resolution</td>
<td>50μm</td>
<td>-</td>
</tr>
<tr>
<td>Laser Height Profile Resolution</td>
<td>20μm</td>
<td>-</td>
</tr>
<tr>
<td>Core Tray Sizes</td>
<td>Up to 600mm x 1500mm (W x L)</td>
<td>Up to 200mm x 300mm x 45mm (W x L x H)</td>
</tr>
<tr>
<td>Scan Rates per Day*</td>
<td>200-500m</td>
<td>50 scans/hr</td>
</tr>
</tbody>
</table>

*Dependent on operational conditions*
Figure 6: Mineral composition changes observed in core imaging data. Illustrated here are examples of composition changes by monitoring wavelength changes of the diagnostic mineral features. These include chlorite and carbonate changes in the SWIR along with garnet composition changes monitored in the LWIR.

relationships and to guide spectral sampling, interpretation and modelling (Figure 7). As an example, in the case of Pebble, relative concentrations of pyrite and textural characteristics observed through conventional logging is required to distinguish pervasive illite of retrograde argillic assemblage from a quartz-sericite-pyrite and quartz-illite-pyrite of phyllic assemblage; and these relationships were incorporated in spectral data interpretation and modelling. The resulting alteration model helped to refine the boundaries between alteration zones that are strongly correlated with copper and gold concentrations (Figure 8).
Figure 7: Strip log of geology-spectral mineralogy-geochemistry-mineralization, Pebble, Alaska, showing strong correlation between alteration domains and Cu-Au concentration. Diamond drill hole location is referenced in Figure 8 (from Harraden et al., 2013).
Figure 8: 3D alteration model, Pebble, Alaska, based on integrating geological logging and 3900 spectral data points collected from 150 diamond drill holes covering all alteration types and mineralization styles across 1700 m vertical range within and immediately surrounding the Pebble deposit (from Harraden et al., 2013).

Figure 9: 3D alteration model derived from integrated geology, high resolution hyperspectral core imaging data, geochemistry and CSAMT, Alturas high sulphidation deposit, Chile (from Astorga et al., 2017).
The Pebble case history suggests that the broad hydrothermal system of this giant porphyry deposit could have been defined by less drilling at wider spacing with an integrated approach combining spectral mineralogy and mineral chemistry with traditional core logging and lithogeochemical data sets (Harradon et al., 2013). In addition, the resulting robust, integrated 3D alteration model such as Pebble provides key information on the volume, geometry and spatial relationships of alteration zones which are critical for more robust resource modelling, geometallurgical domain definition and life of mine planning with optimized metallurgical process designs, geotechnical, and value/cost driven financial models.

One of the challenges of alteration mapping with the aid of field portable infrared spectrometers is sample representation with a spot field of view of approximately 1 to 2 cm in diameter. In highly heterogeneous and/or less understood hydrothermal systems, an initial orientation study may be required to spectrally characterize different alteration styles, assemblages and intensity in order to establish the utility of the spectral tool and an effective sampling protocol and data interpretation-integration strategy. As demonstrated by Pebble case history, an interactive approach combining geological visual observation with spectral analysis is critical for successful field implementation.

High resolution hyperspectral core imaging has made significant contribution to logging and 3D alteration modeling in several advanced porphyry and epithermal exploration projects (Clark et al., 2015 and Astorga et al., 2017). At Alturas, a recent discovery of breccia hosted high sulphidation gold deposit in the El Indio belt, Chile, a total of 15,403 metres from 41 core holes were scanned on site during the field season. Semi-quantitative

![Figure 10](image)

Hand specimen photograph (top) and mineral classification map (bottom) from Corescan data for selected hand specimens collected at the Orange Hill deposit. Data collected at 500-micron spatial resolution.

**Figure 10:** Hyperspectral mineral classification maps, Orange Hill porphyry copper deposit, Alaska, showing alteration patterns at hand sample scale mimic alteration mapped across several hundred metres hill side outcrops (from Kokaly et al., 2016).
spectral mineralogy of clay alteration assemblages coupled with textural characteristics were mapped at 0.5 mm resolution at the deposit scale. Near real time data processing and on-site visualization capacities enabled the field geologists and management to promptly utilize the high quality mineral mapping images as well as the numerical logs of mineralogy and mineral composition indices. This has led to more consistent and objective logging of alteration (Zhou et al., 2017) and improved understanding of alteration paragenesis (Figure 9), which in turn, helped to construct a high impact 3D alteration model (Astorga et al., 2017).

Hyperspectral core imaging alteration patterns at drill core and hand sample scales have been recognized to mimic alteration patterns at outcrop to deposit scales (Figure 10, Kokaly et al., 2016). Systematic SWIR analysis of clay alteration assemblages as well as the numerical spectral indices of mineralogical composition and crystalinity from microscopic to drill hole and deposit scales also revealed cryptic alteration zoning patterns as vector towards mineralization in a wide range of deposit types, and allowed to refine empirical models for targeting from deposit to district and regional scales (Zhou et al., 2017). In porphyry systems, zonation of white mica chemistry variation associated with phyllic alteration has been demonstrated as an important proxy to fluid pH chemistry (Dilles et al., 2012 and Halley et al., 2015). As an example, white mica of phyllic alteration at Yerington, Nevada is found to be phengentic in composition (wv > 2215 nm) in the albite zones at depth, and changes inward and upward to become paraganitic (wv <= 2195 nm) in topaz zone and advanced argillic zone of the most acidic part of the system at shallow levels, with potassic white mica (wv = 2200 – 2205 nm) spatially associated with mineralization (Figure 11). Late stage illite of argillic alteration is found to be phengentic. In addition, illite, smectite and kaolinite of argillic alteration is feldspar destructive, while earlier, higher temperature white mica of phyllic alteration remains intact. This new insight allows geoscientists to use textural characteristics to guide logging and spectral sampling of phyllic alteration and map white mica chemistry to assist targeting.

The addition of the LWIR for drill core imaging expands the application across a significantly larger geological environments and deposits types. While the detection of the major rock forming minerals in the LWIR increases the geometallurgical

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**Figure 11:** Typical cross section of porphyry copper deposit, showing 1) distribution of hydrothermal alteration gauge and sulphide minerals, and 2) generalized contours of ALOH 2200 nm absorption wavelength of white mica of phyllic alteration, measured in SWIR spectral instruments (from Halley et al., 2015).
applications, alteration mapping and rock type characterization capabilities are also improved. An example of the LWIR core imaging data across an iron skarn deposit in northern Sweden is illustrated in Figure 12 (Ojala et al., 2007). The skarn is developed at the interface between greenstone rocks and porphyritic granite intrusions. The iron skarn of the Masugnsbyn area comprises magnetite units associated with amphibole-pyroxene-serpentine and minor pyrite. The LWIR maps the skarn mineralogy as well as differentiating the greenstone and intrusive units in the drill core. Magnetite is mapped only by elevated reflectance values and indicates the possibility of mapping metals in the drill core even though there are no distinct characteristic features in this wavelength range (Huntington and Schodlok, 2016).

A detailed geometallurgical modelling program was undertaken at the La Colosa project in Colombia. Hyperspectral core imaging provides the proxy data with sufficient spatial coverage to develop a comminution (ore crushing) model for the project. Approximately 140 km of drill core were subjected to hyperspectral imaging to provide a comprehensive project dataset from the available sampled materials. These data have been integrated with other analytical measures, most notably ICP analysis but also Equotip, sonic, and pXRF data. Selected pilot samples were used to provide a reference dataset for modelling using the core imaging dataset as a proxy to predict comminution behavior across the project area. Modelling of the parameters indicates spatial coherency of the data supporting the modelling application results (Figure 13). These data allow thoroughput modelling to define hard and soft material distributions within the project. The spatially coherent datasets have been used to inform plant and optimization allowing better economic planning to be developed for the prospective deposit.

**Future Trends**

In the next decade, hyperspectral logging will be more comprehensively incorporated into project workflows. This will be on the application side. Advanced data science such as machine learning is one of the emerging tools for analyzing and integrating high dimensional and very large volume of hyperspectral core imaging data with other geoscience data sets. It will also transgress the sampling process where it will be integrated with other analytical methods. This will allow the dataset to become the fundamental base layer utilized in core logging.

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**Figure 12:** Drill hole intersection through an Iron Skarn intersection from the Masugnsbyn area, northern Sweden. The ore zones are mapped by pyroxene, amphibole in associate with magnetite, which are mapped using the LWIR.
The addition of other important mineral wavelength ranges in the infrared will continue to expand the mineral detectability enhancing lithologic and alteration mapping. As the LWIR is utilized across more deposit styles so will new understandings of the extent and understanding of the mapped alteration systems. Some work is being expanded through the mid-wavelength Infrared (MWIR, 0.3–0.8 μm) providing other mapping capabilities for specific geological environments.

Advances will be made in the handling and the ability to query the drill core images allowing more geologically significant data to be easily extracted for the core images. Automation of consistent extraction of alteration textural attributes from hyperspectral core images will further improve logging consistency and efficiency. Consistent and reliable datasets of similar quality will allow information to be integrated into geological and mining models. Geological models will be continually updated and improved throughout the life span of a project or mine with these data combined with new levels of thinking and understanding which can be easily translated through these data. Most significantly, spectral analysis of core aids visual core logging through unbiased identification of minerals. The direct measurement of the material being explored or mined makes this technique ideal as a reusable dataset that can be continually queried for different problem solving or applications. Once this non-destructive sampling has been implemented a record remains for additional work where it can be reused and queried throughout the life span of the project.

**SATELLITE IMAGERY**

The decade between 1997 and 2007 saw a transition from the use of the Landsat Thematic Mapper (TM/ETM+) series of satellite images as the primary regional mapping tool for exploration to the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) system. Whereas the TM/ETM+ imagery allowed very generalized mapping of terrains that “might” be altered, ASTER allowed mapping of broad alteration mineral families that targeted terrains that “possessed alteration mineralogies”. Most of the decade after 2007 saw ASTER as the front line tool for general alteration mapping from space, even more so since the global archive of precision terrain corrected ASTER data became available free from the USGS. Since 2007, development of many new satellite sensors has continued improvements in spatial and spectral resolution and data quality from geological mapping prospective, and one in particular, WorldView-3 (WV-3), that provides alteration mapping capabilities similar to ASTER but with much higher spatial resolution and data quality.

Since 2007 several new high resolution satellite data sets...
became available, including Worldview-1, GeoEye-1, Worldview-2, and Pleiades. This has significantly increased the coverage of high resolution satellite data archive globally. Satellite images with sub-metre resolution such as Pleiades provide outcrop details for lineament analysis (Zhou et al., 2017). The latest satellite imaging systems have been designed to be highly agile with rapid pointing capabilities using gyros rather than the limited fuel supplies of older generation satellites. Landsat-8 Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) provides continuity of the Landsat mission through replication of the same band configuration as Landsat-7 plus two additional 30 VNIR bands: a coastal blue band and a new near infrared band to monitor cirrus clouds, and one additional TIR band of 100 m resolution resampled to 30 m resolution. It is important to note that Landsat-8 data is of significantly better quality and clarity due to the 12 bits dynamic range vs 8 bits for Landsat-7. With currently free on-line searchable global data available through NASA and United States Geological Survey (USGS) data portals, Landsat (1984–current) and ASTER (2000–2007) remain as the most cost effective (i.e., free) remote sensing reconnaissance alteration mapping tools especially in arid to semi-arid terrains. In recent years, government regional to continental scales (1:50K to 1:2.5M), GIS compatible ASTER surface mineralogy maps, utilizing thousands of ASTER scenes, have been released to the public (CSIRO, 2012; Mars, 2013, 2014; Rockwell et al., 2015; Cudahy, 2016).

**WorldView-3**

The most significant technical advance in satellite technology for geological mapping over the last decade is Digital Globe’s WV-3, launched in 2014. WV-3 is the first satellite borne commercial hi-resolution VNIR-SWIR multispectral sensor. It has a 0.31 m panchromatic band, eight 1.24 m VNIR bands, eight 3.7 m (7.5 m for commercial use) SWIR bands, and twelve 30 m CAVIS bands (Figure 14). Real time, pixel based atmospheric measurements through the CAVIS bands enable improved atmospheric correction through Digital Globe’s ACOMP algorithm, and an annual vicarious calibration program is in place to compensate post launch radiometric drift.

WorldView-3 has a high degree of aiming flexibility; it has the capability of bi-directional scanning, is highly agile with rapid retargeting at a rate of 3.5 deg/s using control moment gyros with viewing angles of +/- 45 deg off-nadir. Its revisit frequency (at 40 deg latitude) is less than one day and is capable of acquiring up to 680.00 km² of imagery per day, with a predicted performance of ≤3.0 m autonomous geo-location accuracy. The satellite can effectively point sideways and sweep multiple image swaths along the orbital path as it passes over a target area of interest, and can collect an image over 66.5 km x 112 km (5 strips) contiguous area in a single pass. This is critical for areas with problematic cloud coverage allowing the satellite to image targets of opportunity when cloud cover permits.

![Figure 14: Spectral band configuration of Worldview-2 and -3, ASTER and Landsat-8 (from Baugh, 2015).](image)

Compared to ASTER, WV-3 provides significantly improved mineral mapping at deposit and district scales. This is attributed to its higher spatial resolution, improved spectral band configuration, higher signal to noise ratio (SNR), as well as more accurate radiometric calibration and atmospheric correction. The high spatial resolution of the WorldView-3 sensor has resulted in a significant increase in information content in imagery relative to its lower spatial resolution cousin ASTER. The impact of spectral mixing in a given pixel is much less than what is observed with ASTER because of its improved spatial resolution. This allows improved discrimination of compositional geological information from the surface, with resulting improvements in data quality and mapping capability (Kruse, et al., 2016, Swayze, et al., 2014). Small outcrops with sparse vegetation can be difficult to resolve at ASTER 15 m VNIR and 30 m SWIR resolution due to spectral mixing. These areas become more mappable at WV-3 1.2 m VNIR and 7.5 m SWIR resolution. However, WV-3 SWIR spectral resolution is similar to that of ASTER and mapping of mineral species will still not be possible without additional ground-derived a priori knowledge (Kruse, et al., 2016).
In a series of recent studies, WV-3 data were collected over a variety of regional deposit settings, as well as for an active mine. Results were also examined over Cuprite, Nevada, a common SGRS reference site, and WV-3 data was compared to that previously published by Swayze et al. (2014) to assess data quality (Figure 15). Spectral data collected by Swayze in the field were compared to in-scene spectra derived from WV-3 imagery with the standard calibration applied. Overall, there was an excellent correlation of key spectral features, with some differences in general shape of parts of the reflectance curve to be expected from spatial mixing when comparing point analyses against pixel spatial resolution for the WV-3 data (Figure 16). The strength of the signal of the data was also assessed in the study and found to be very good. The good correlation between spectral features of WV-3 to field spectral measurements gives a positive preliminary indication of data quality of the sensor for
mineral mapping applications.

At Copper Basin area at Battle Mountain, Nevada, the impact of the higher spatial resolution of WV-3 at mapping was compared against ASTER data (Figure 17). An examination of an alteration index for WV-3 data at Battle Mountain also demonstrates how effective WV-3 is at highlighting the presence of argillic alteration in red in Figure 18.

Figure 17: Comparison of ASTER and WV-3 Resolutions Impacts for Muscovite Index – Battle Mountain, Nevada.

Figure 18: Mapping of argillic alteration (in red) at Battle Mountain, Nevada using WV-3 data.
The effectiveness of WV-3 as a mapping tool for very small gossans was assessed in a Ni-Cu prospect hosted in Archean norites and ultramafics amongst granitic and metamorphic rocks in southwestern Greenland. The site was challenging for satellite-data collection because of the high latitudes and potential low signal level due to low solar angle, and the challenge of mapping predominately dark, mafic rocks. Not only were the results acceptable indicating high SNR for WV-3, but the data were very effective in mapping very small gossans at surface due to the high spatial resolution (Figure 19).

Lastly, an examination of alteration mapping capabilities of WV-3 data in the pit at the Kalgoorlie mine in Australia shows a high level of detail highlighted; even composition differences from different stockpiles are visible (Figure 20).

Figure 19: Gossan mapping at Maniitsoq, Greenland, using WV-3 data. Four different data products highlight both 1) subtle and 2) prominent gossans at two sites. WV-3 products are: A) True colour, B) Ferric iron index; C) Gossan-1; and D) Gossan-2.

Figure 20: Composition mapping at the Kalgoorie Superpit, Australia, using WV-3 data.
Currently, there is not a large archive of SWIR data from WV-3 which primarily acquires imagery as requested by individual customers, but as data acquisitions increase and broader areas of exploration interest are archived the impact of these data on the success of geological mapping and mineral exploration will increase and cost of the data will decrease.

**Future Trends**

Satellite Earth Observation (EO) imagery is Big Data, in fact it is the original Big Data. NASA alone stores nearly 10 petabytes of EO data and adds almost 6.5 terabytes of data each day (Berrick, 2016). The question for the future is how existing government and commercial EO data can be used most effectively for exploration and what new data will provide greater capabilities for mapping surface mineralogy. Currently much of the available reconnaissance-scale remotely sensed data is free, but is not accessible in a globally integrated and transparent manner. Semi-automated processing commercial imagery from multispectral satellite sensors such as WV-3 is starting to be implemented. Data suppliers such as DigitalGlobe, and software and solutions providers such as Harris (ENVI) are providing subscriptions to their large data repositories, and providing processing capabilities using developed algorithms through geospatial Big Data technologies, (i.e. GBDX, Harris GSF) and this trend will only continue.

Perhaps the most significant innovation on the horizon is the launch of a moderate resolution (30 m/pixel) hyperspectral satellite covering the VNIR to SWIR range, EnMAP (DLR, 2017). This satellite sensor has been in development for many years by the German Aerospace Center (DLR) and is anticipated to be in orbit in 2019. The primary technological delay of the project has been the lack of detector arrays for the SWIR range that permit a practical swath width for global mapping. The availability of reliable, commercially available, SWIR arrays with a width of 1k has only become a reality in the last few years, allowing an image swath of 30 km to be collected. The design of EnMAP was one of the motivating factors for making these arrays available to the non-military/intel community. It is anticipated that EnMAP will become the tool of choice for reconnaissance scale exploration as it will allow definitive alteration mineral mapping and solid solution characterizations to be made, as opposed to the generalized alteration mapping capabilities of ASTER.

The future of commercial high resolution hyperspectral imagery from space remains in limbo. The US Air Force Research Laboratory's Artemis sensor that was flown experimentally on TacSat-3 proved that space based hyperspectral imagery at approximately 5 m resolution is an achievable goal (Wikipedia, 2017). There have been initiatives to launch an Artemis like instrument for combined military, intelligence, and commercial applications (i.e. HySpecIQ, NorthStar), but funding has been lacking and potential restrictions on commercial availability of high resolution hyperspectral data from space need to be resolved.

**AIRBORNE HYPERSPECTRAL IMAGING**

Airborne hyperspectral imagery has been collected since the 1980s with instruments designed and operated by the Jet Propulsion Laboratory (JPL) for research applications; and since the late 1990s with commercially designed and operated sensors (Agar and Coulter, 2007). Airborne hyperspectral systems effectively acquire a full spectrum for each pixel because of the large number of bands, resulting in a spatial-spectral data cube (Figure 21). When acquired for mineral exploration the data are utilized primarily to map the surface expression of alteration mineralogy. The method works best in arid to semi-arid regions but can sometimes be useful in lightly forested and tundra settings as long as bare outcrop is exposed at individual pixel resolution. Exploration surveys are typically flown at 2 m to 5 m ground resolution (Figure 22), but can currently be flown at resolutions as high as 0.5 m. Based on a photogrammetric rule of thumb: “Map Scale = Raster resolution (in metres) \* 2 * 1000” (Nagi, 2010), this results in nominal mapping scales of 1:4,000 for 2 m resolution to 1:10,000 for 5 m resolution data. This is a major advantage of airborne surveys: the mapping scale of measurement can be selected to match the necessity in the field.

As with any airborne data acquisition the benefits of hyperspectral imagery must be offset against acquisition costs. Historically, hyperspectral imagery has largely been considered primarily useful for exposed porphyry and high sulphidation epithermal systems. These are still the dominant targets but experience has shown that many of these systems, although exposed or in some cases barely daylighting, are not well understood solely on the basis of traditional alteration mapping by visual means. Broad alteration patterns for porphyry systems are better understood and mapped with hyperspectral imagery given the density of sampling and synoptic viewing perspective. High sulphidation systems are often complex and present the problem of having “too much alteration” that requires detailed field mapping to define paragenetic relationships. Hyperspectral imagery can significantly improve the quality and efficiency of field alteration mapping for high sulphidation systems by providing a highly detailed alteration mineralogy base map. The applicability of hyperspectral imaging to other ore deposit models has been proven through numerous non-disclosed commercial surveys. Low sulphidation systems (particularly in the Sierra Madre) and Carlin systems are known to have many ammoniated alteration minerals which are easily identified by spectroscopic methods (Ridgeway, 1991; Ridgeway et al., 1991; Godeas and Litvak, 2006; Mateer, 2010; Browning, 2014). In low sulphidation systems adularia may be ammoniated producing an identifiable fingerprint for buddingtonite (generalized ammoniated K-feldspar), which has been verified in commercial surveys. In at least one case, results of an airborne hyperspectral survey when integrated with regional gravity, indicated that ammoniated illite was associated with a possible deep seated structure sub-parallel with the Carlin trend (Peloton, 2016; and unpublished report). Even subtle alteration associated with low temperature sediment hosted deposits has been shown to be mappable by hyperspectral methods through clay crystallinity metrics (Coulter, 2015).
Although some explorationists have concerns about the complexity, logistics and costs of airborne hyperspectral, the actual issues are typically less than most traditional geophysical surveys and are more analogous to aerial photography. All of the major hyperspectral contractors ship the necessary equipment by commercial carrier for integration at or near the survey location. The aircraft required are normally twin engine turboprops (for safety and fuel availability considerations) with a standard aerial photography belly port. These type of aircraft are available in most countries or through global providers. The surveys operate at high fixed altitude (typically 6,000 ft to 15,000 ft AGL) in either pressurized or unpressurized mode with oxygen for the crew if needed. The survey operations are much lower risk than draped surveys at low altitude using rotary or fixed wing aircraft. Global historical weather records and local liaisons allow survey companies to offer “all in” costing for survey completion without clients negotiating standby days.
Airborne hyperspectral imagery operates similar to hyperspectral core imaging (in some cases with identical cameras). There are two notable differences: 1) only part of the VNIR-SWIR range can be collected due to atmospheric absorption of light; and 2) data acquisition must be done under full sunshine and clear skies. Figure 23 illustrates the wavelength limitation as a function of atmospheric transmission in the VNIR to SWIR range. It is important to note that a critical SWIR region around 1400 nm that is useful for mineral mapping is atmospherically opaque. For alteration mineral mapping we typically utilize only the VNIR between 400 nm and 900 nm and the SWIR between 2100 nm and 2400 nm. High resolution VNIR-LWIR hyperspectral imagery is currently only commercially available from airborne platforms. LWIR data is collected with a separate sensor. Fixed wing aircraft are the platform of choice due to stability and operating costs.

Figure 23: Transmission of sunlight in Earth's atmosphere.

Figure 24: Flight line map of USGS hyperspectral survey of Afghanistan (218 flight lines) (Kokaly, et al., 2008).
Over the last decade hyperspectral camera technology has seen incremental improvements. The standard SWIR swath width of 384 pixels (pushbroom systems) or 512 pixels (whiskbroom systems) has been in place for many years. Recently systems have become available with 600–1024 pixel swath width which has the potential to lower survey operating costs.

Perhaps the most significant improvements have been in the area of improved geometric correction and data processing/management capabilities that have allowed very large surveys with hundreds of flight lines to be flown and nearly seamless image mosaics to be created. The USGS organized the first full country hyperspectral survey in 2007 covering 483,000 km² of Afghanistan at a nominal resolution of ~30 m per pixel (Figure 24); generating 800,000,000 pixels of spectral data (~20 GB of raw data) (Kokaly, et al., 2008). The Moroccan Office National des Hydrocarbures et des Mines (ONHYM) was not far behind acquiring regional hyperspectral imagery over the Moroccan Anti-Atlas terrain in 2009 and 2013 (ONHYM, 2016a, 2016b). Although smaller areas than Afghanistan (approximately 10,000 km² per survey), the imagery was collected at 4–5 m resolution resulting in a combined pixel count similar to the USGS Afghan project (Figure 25). A primary goal of all of these government funded projects was to stimulate mineral exploration. Commercial exploration surveys are not conducted at these scales, but are typically higher spatial resolution to meet the needs of detailed field mapping. Commercial surveys generally range from 100 km² to 1,000 km² at resolutions of 2–3 m.

The ability to efficiently process hyperspectral imagery from large surveys has dramatically improved due to advances in computer technology. Improvements in processor speed have had an impact, but improvements in solid state drive (SSD) costs, speed, and capacity have had a game-changing impact. As illustrated in Figure 21, hyperspectral imagery is collected and stored as a data cube. When processing and analyzing these data, the data cube must be traversed in three different directions depending on whether spatial or spectral dimensions are needed for processing. With conventional hard disk storage, data access that does not mesh with physical record storage creates a significant bottleneck—in general, processing of hyperspectral data is highly IO bound. Whereas processing on spinning disks required reorganization of the data cube for spatial or spectral analysis, SSDs allow a large hyperspectral data cube to be traversed in any dimension with little to no penalty. The availability of consumer grade SSDs up to 2 TB (in 2017) for relatively low cost (<US $600 for 2 TB) makes analysis of very large surveys practical on a desktop or laptop PC. For comparison, a 1 TB SSD dropped in price from US $2 million in 2003 to <US $300 in 2017 (Storagesearch, 2017).

Figure 25: Flight line footprint map of OHNYM 2009 hyperspectral survey of the Sirwa area (284 flight lines).
**Case Studies**

Examples are provided here to illustrate the usefulness of mineral mapping in various geologic settings. The first example is a classic use of hyperspectral imaging to map tertiary epithermal alteration assemblages. Figure 26 shows alteration mapping in the area of the Chimberos silver mine in Chile (pit is in the northeast corner). This is part of a large survey covering the La Coipa mine region flown for Kinross Gold in 2009. The Chimberos area is part of the larger Esperanza epithermal alteration zone. At the time of the survey conventional alteration mapping of the area was spotty and rational for drilling was based on surface geochemical anomalies rather than detailed regional geologic mapping. Prior to acquisition of the hyperspectral imagery the Kinross exploration staff estimated that it would take several months to produce a generalized alteration map via field work assisted by a field spectrometer. The hyperspectral alteration map allowed a detailed geologic-alteration map to be produced in several weeks. It is important to recognize that a hyperspectral alteration map is not an end product in itself; field observations of texture, lithology, stratigraphy, and structure are needed to complete the picture, but the hyperspectral alteration map provides densely sampled unbiased mineralogical information that is often difficult to visually identify in the field. An illustration of this is shown in Figure 27 which is enlarged to the natural mapping scale of the data. Of particular importance are areas with alunite-dickite-kaolinite zoning. The presence of dickite zones is often a strong indicator of potential precious metal mineralization (Sudo and Shimoda, 1978); dickite and kaolinite are visually indistinguishable (in many cases illite, kaolinite, and dickite are indistinguishable visually) but easily mapped with hyperspectral data.

![Figure 26](image1.png)

**Figure 26**: Overview of epithermal alteration south and west of the Chimberos silver mine, Chile (pit in NE corner of image).

![Figure 27](image2.png)

**Figure 27**: Enlargement of area highlighted in Figure 26 to illustrate data at optimum mapping scale.
Figures 28 and 29 show the Tidili alteration zone within the ONHYM survey of the Anti-Atlas terrain in Morocco. It is of particular interest because the rocks are Neoproterozoic age (~650 my). The alteration mineralogy contains relatively high temperature clays—primarily pyrophyllite, dickite, and paragonitic (high aluminum) illite (Figure 29). Field observations found epithermal geomorphology with silicified ribs and knobs (Figures 30 and 31). The area was designated for high priority follow-up (ONHYM, 2016a).

**Future Trends**

Airborne hyperspectral imagery is a mature technology. As such the future trends are primarily focused on improved data quality and acquisition cost reduction. Although left largely unmentioned in this section airborne LWIR hyperspectral acquisition with high signal to noise has been available utilizing the SEBASS instrument. However, the narrow swath width (128 pixels), high operating cost, and limited (by government restriction) geographic deployment areas made this instrument impractical for exploration. It can be flown at the same time (in the same aircraft, but with a different boresight), as the VNIR-SWIR instrument, or separately. In general, an acquisition of VNIR-SWIR-LWIR with SEBASS is 3–4 times the cost of VNIR-SWIR alone. The designers of SEBASS have improved the swath width limitation a successor instrument called Mako which will potentially be utilized on proof of concept missions.

**Figure 28**: High and low temperature alteration minerals for the Tidili system in Morocco.

**Figure 29**: High temperature alteration minerals for the Tidili system in Morocco.
for exploration in the summer of 2017. Operating costs, however, are still significantly higher than VNIR-SWIR due to aircraft and crewing requirements. The introduction of 1K element swath width SWIR sensors holds the promise of survey cost reductions as the number of flight lines required for a survey will be reduced by a factor of slightly more than two.

Ground or mobile vehicle based hyperspectral outcrop imaging (e.g., as shown in Figure 10) combined with cost effective 3D georeferencing capacity will be complimentary to airborne
surveys. This is particularly of interest for geological mapping of hill sides in high relief terrains in remote regions such as Alaska (Kokaly et al., 2016), open pit highwalls for precision mineralogical bench mapping, and possibly in regions where frequent cloudy conditions restrict data collection windows and flexible tasking within days is required.

A final issue on future trends for airborne hyperspectral needs to be addressed: UAV implementation. UAV implementations are challenging as a stable platform is needed for pushbroom cameras, SWIR and LWIR sensors are relatively heavy, and high end GPS-INS equipment is required to measure aircraft attitude (Goossens, 2015). The nature of pushbroom hyperspectral cameras makes them highly sensitive to aircraft roll. In order to correct for this either gyro roll stabilization is needed or a high end GPS/INS that samples attitude and roll rates greater than the rate of roll in the operational platform—these requirements are weight incompatible with small commercial drones. In addition, a full VNIR-SWIR camera and ancillary equipment have a value in excess of US$250k and cannot be insured due to the high risk of UAV loss. UAVs suffer from crashes at approximately 100 times that of pilot operated aircraft (Susini, 2015), making the loss of a UAV and hyperspectral package highly likely (or even a given) over even a medium term operational program.

CONCLUSIONS
Spectral geology has played an increasingly important role in the advances in geoscience and exploration successes by improving mapping and logging accuracy and consistency leading to more robust alteration modelling for targeting as well as resource modelling, geometallurgy and other downstream applications, and by refining hydrothermal alteration footprint models with improved understanding of the control of and vectors to mineralization of many deposit types.

Very significant progress has been made in high resolution VNIR-SWIR hyperspectral core imaging over the last decade with commercial services that combines automated, rapid data collection with near real time data processing and visualization capacity. This has led to successful field implementations of deposit scale spectral logging of important indicator minerals of phyllosilicates, sulphates and carbonates, coupled with textural characteristics at sub-millimetre resolution in porphyry and epithermal projects. Extension of spectral coverage into the LWIR in hyperspectral core imaging systems enables the detection of hydrothermal and rock forming silicates such as quartz, skarns and feldspars and their sub species. This is a step change of infrared spectral technology towards near total mineralogy that will impact field application in established and new applicable deposit types such as IOCG and skarns.

Improvements in satellite spatial resolution and spectral coverage have brought ASTER-like basic alteration mapping capability from reconnaissance scale to project scale with the SWIR capable WV-3 system. The agility of several new satellites, including WV-3, allow multiple swaths to be collected in a single orbit pass allowing large areas to be collected under similar illumination conditions. Reconnaissance scale hyperspectral imagery from space will likely be available by the end of the decade.

Airborne hyperspectral imagery continues to be used for high spatial resolution prospect to district scale alteration mapping but, through improvements in GPS/INS technology, to be able to acquire nearly seamless regional to country scale surveys. The introduction of 1K SWIR arrays promises improvements in efficiency and accompanying lower survey costs. Advances in computer technology, particularly low cost high capacity SSDs, makes processing and analysis of large surveys significantly faster and cheaper.

Integrating spectral geology with field mapping and logging is key for successful field applications. Spectral geology and geochemistry are complimentary and cross validating for more robust and cost effective alteration mapping, logging and modelling.

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¹ Contrary to accepted publication protocol, Wikipedia is used as a reference as most original source material on TacSat-3 has been redacted—see Wikipedia for links to archived copies of original sources.