CHARACTERIZING THE SURFACE MINERALOGY IN THE AGGENEYS SEDEX SYSTEM WITH HYPERSPECTRAL IMAGERY

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February, 2018

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ABSTRACT

The Aggeneys area has economic potential for the exploration of SEDEX deposit. In this area, exploration has been done for targeting the ore bodies (Big Syncline, Swartberg, Broken Hill and Gamsberg) using conventional geological methods. However, these techniques are time-consuming and labor-intensive to explore large areas for these type of deposits. Although this deposit is associated with minerals that can be detected using infrared spectroscopy, there is not much work done yet. In this research, shortwave infrared (SWIR) and thermal infrared (TIR) airborne hyperspectral imagery were coupled with geochemical data to characterize the distribution of surface mineralogy and mineral chemistry and to target the ore bodies of Aggeneys SEDEX system. The SWIR and TIR airborne imagery to radiance-at the sensor were undergone several preprocessing steps. For the SWIR imagery destriping filter, MNF, log residual correction, mean filtering and geometric correction were applied sequentially. For the TIR imagery atmospheric correction and temperature and emissivity, separation were applied. Wavelength mapping and SSEE (spatial-spectra endmember extraction) were used to extract endmembers spectra from the SWIR image, while SSEE was used for the TIR image. Mineral maps of the SWIR and TIR image were generated using linear spectral unmixing method. Geochemical analysis has been done using principal component analysis, Pearson correlation and spatial plots. From the integration of the SWIR and TIR mineral maps with the geochemical analysis result, the ore bodies were located using Mn-garnet, Barite-quartz and Kaolinite as indicator minerals. Finally, a descriptive geological modal of the deposit was created to illustrate the lateral and vertical variation in mineral chemistry and mineralogy.
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1. INTRODUCTION

1.1. Background

Sedimentary exhalative (SEDEX) deposits are stratiform massive sulphide lenses, formed within intracratonic or epicratonic rift basins and are hosted by marine sedimentary rocks (Emsbo, 2009). The deposition occurred during Proterozoic and Paleozoic geological time, and this indicates the formation of these deposits is related to a geological process that operated on a global scale (Machntyre, 1991). Most of these deposits are of middle Proterozoic, and lower-middle Paleozoic age. Proterozoic deposits are large and economically more important than the Paleozoic deposits (Wolf, 1981). The primary ore minerals for these metals are sphalerite and galena, which precipitate on or under the sea floor from hydrothermal fluids (Emsbo et al., 2010).

SEDEX deposits comprise more than 50% of the world’s known resources of lead (Pb) and zinc (Zn) (Robb, 2005). Other than these metals, these deposits contain a significant quantity of recoverable by-products such as copper (Cu), silver (Ag) and gold (Au) (Deb & Goodfellow, 2004). The polymetallic characteristics of these deposits is a crucial quality feature, which generates high income per ton of ore (Mcilroy, 1999).

For exploration of SEDEX deposits several geological criteria and techniques can be used. Studying the genesis whereby secondary minerals are formed is essential as a vector to ore because they are the surface expression of the primary sulfide base metal deposits underneath (de Bruyn et al., 1994). According to Large & McGoldrick (1998), in dolomite-rich sedimentary basins, a number of vectors can be combined to indicate high priority areas such as a change in carbonate composition from dolomite to ankerite to siderite, change in manganese content of dolomite which shows an increasing trend towards the orebodies and others. Similarly, minerals like pyrite and barite which are mainly associated with the host rocks are good indicators of exhalative activity (Machntyre, 1991). Nevertheless, the methods mentioned above are time-consuming and labor-intensive to explore a large area of these type of deposits.

Nowadays, the development of remote sensing imaging spectrometer plays a great role in targeting mineral deposits like SEDEX. These instruments acquire data in contiguous narrow bands and results in data with sufficient spectral resolution for the direct identification of materials based on their diagnostic spectral features (Goetz et al., 1985). Remote sensing techniques reduce the amount of field work and are able to produce a mineral distribution map of a large area quickly by applying classification algorithms. The availability of new sensors operating in the different spectral ranges such as HySpex (visible near infrared (VNIR) and shortwave infrared (SWIR), Hypercam (thermal infrared (TIR) allows combining data for better identification of minerals.

1.2. Research Problem

Previously, exploring and locating the mineral resources of SEDEX deposits were conducted by using conventional techniques such as geological, geochemical and geophysical techniques. These techniques are time-consuming and labor-intensive to explore large areas for these type of deposits. According to Ryan et al., (1986), the ore bodies of the Aggeneys SEDEX system are hosted by quartz-muscovite-biotite-sillimanite schist and locally associated with manganese-rich garnet, iron-bearing minerals and overlain by a barite layer which have potential to be recognized in infrared spectroscopy. Meanwhile, there is not much spectral work
done on SEDEX deposits yet. In this study, characterization of the spatial distribution of surface mineralogy and mineral chemistry of Aggeneys SEDEX system to target ore bodies using mineral spectra will be studied using SWIR, and TIR hyperspectral data. Additionally, the geochemistry and spectroscopy from the groundwork will be combined to understand the spatial distribution of the base metals and geochemical vectors. According to Cudahy (2016), mapping Fe-Mn chemistry of garnet and the presence of a barium (Ba) halo (Stalder & Rozendaal, 2005) could have implications for the exploration of this type of base metal mineralization with IR (infrared) spectroscopy.

1.3. Research Objectives

The main objective of this research is to characterize the distribution of surface mineralogy and mineral chemistry for identification of indicator minerals to locate ore bodies of the Aggeneys SEDEX system using SWIR and TIR hyperspectral imagery.

Specific objectives

1. To produce detailed mineral maps of the study area
2. To investigate variations in mineralogy and mineral chemistry of the deposits
3. To describe mineral zonation of the footwall and the hanging wall
4. To determine the indicator minerals that differentiate mineralized & barren zones
5. To create a descriptive geological model that summarizes the essential characteristics of the mineralization of the Aggeneys SEDEX system

1.4. Research Questions

1. Which infrared (IR) active minerals that occur in the Aggeneys SEDEX system can be detected also with airborne SWIR and TIR imagery?
2. Which of these minerals are spatially associated with the ore zones?
3. What is the spatial distribution of the minerals adjacent to the deposits?
4. Is there any systematic variation in mineralogy and mineral chemistry towards the ore zones?
5. Which minerals can be used as indicator to the mineralized zone?
6. How do the metals contents vary in the different ore bodies?

1.5. Hypothesis

• Using combination SWIR and TIR imagery expected to discriminate/detect the possible indicator minerals to target ore bodies of the Aggeneys SEDEX system
1.6. Thesis structure

The thesis has been structured into 6 chapters. **Chapter 1**, Introduces the research problem, research objectives, research questions, and hypothesis. **Chapter 2**, SEDEX system includes the geology, mineralization, previous works on exploration of SEDEX system using remote sensing techniques and description of the Aggeneys SEDEX system (study area). **Chapter 3**, Methodology describes the data (SWIR, TIR, and Geochemical data) and the preprocessing steps, endmember extraction, mineral mapping, geochemical analysis, data integration and descriptive geological model. **Chapter 4**, present the results of the preprocessing, endmember extraction, mineral mapping, geochemical analysis, data integration and descriptive geological model. **Chapter 5**, discusses the results obtained from this research. **Chapter 6**, conclusion and recommendation.
2. SEDEX SYSTEMS

2.1. Geology and Mineralization

The stratigraphic evolution of the rift basins where SEDEX deposits formed can be divided into rift phase and sag-phase (Emsbo et al., 2010). The rift phase is characterized by continental sediment and the sag-phase results in shallow water carbonate and fine grained elastic sediment (Figure 1). Mafic sills, dykes and related volcanic rocks have a temporal relationship and in few cases, they have also a spatial relationship with the formation of SEDEX deposits (Deb & Goodfellow, 2004).

Figure 1: A schematic cross-section through a rift-controlled sedimentary basin showing the idealized setting of SEDEX deposits (modified after Emsbo et al., 2010).

SEDEX ore bodies are formed in highly restricted basins by the diagenetic process at or below seawater interface and have continuity over a large part of the deposits (Kelley et al., 1986). Intrusive bodies play a great role as a heat source to generate the metalliferous hydrothermal fluids (Deb & Goodfellow, 2004). The ore fluid migrates upwards along a fault and discharges onto the sea floor forming stratiform deposits (Emsbo, 2009). A high speed of the ore-forming fluid and a lack of mixing with seawater facilitates metal transportation and deposition (Sangster, 2002). The orebodies are mainly hosted by marine sedimentary rocks such as dolomitic shale, siltstone, carbonaceous shale, chert and micritic limestone (Kelley et al., 1986). Mineralogically SEDEX deposits comprise galena and sphalerite as major sulfide minerals, although a significant amount of pyrite, pyrrhotite, and chalcopyrite present, while barite is the most abundant sulfate mineral (Maclntyre, 1991; Lyons et al., 2006; Ryan et al., 1986; Kelley et al., 1986). Oxidation of the sulfide
minerals may result in the formation of gossan (iron cap) which mainly contains secondary minerals such as goethite and hematite, quartz, kaolinite, and beudantite (Kelley et al., 1986).

Some of the SEDEX that deposits have undergone intensive metamorphism and structural deformation are categorized under Broken Hill type deposits (e.g. Broken Hill, Australia & Aggeney, South Africa) (Walters, 1998). The distinctive feature of Broken Hill type of deposits is that the ores are associated with banded iron formation (Emsbo et al., 2010; Ryan et al., 1986).

2.2. Exploration of SEDEX using remote sensing techniques

Most of the previous studies used conventional geological methods for exploration of SEDEX deposits. However, little literature is available on mapping and targeting of these deposits using remote sensing imagery. Molan & Behnia (2017), used ASTER and Landsat to predict the potential ore zones of SEDEX mineralization by mapping alteration/weathered products of the host rock (shale unit) and the heat source (monzodiorite unit). The ASTER was used to map jarosite and illite as an indicator of the shale unit and chlorite as an indicator of the monzodiorite unit, furthermore Landsat was used to map iron-bearing minerals which are abundant in the vicinity of the orebodies. Similarly, Rosa et al., (2014), used ASTER to generate priority target areas as reconnaissance exploration of SEDEX deposit. This was achieved by mapping zones of enrichment in ferric iron which is resulted from the weathering of the sulfide ore bodies. Hewson et al., (2005), generated a seamless regional geological map of the Pb-Zn-Ag Broken Hill deposit using ASTER data. Geological units rich in carbonate, MgOH, and AlOH were discriminated using SWIR data and quartz-rich units using TIR data. Studying AlOH and MgOH minerals help to understand the large-scale change in metamorphic grade and metasomatic alteration which plays a great role in prospecting this type of deposits (Hewson et al., 2005). Cudahy (2016) used mid-infrared airborne CO2 laser spectrometer (MIRACO2LAS) and field samples measured using a MicroFT1R™ spectrometer TIR data to identify zones of Mn-rich garnet which are located in the known mineralized areas of Broken Hill.

2.3. Study area

The study area is located in Aggeney in Northern Cape Province, South Africa (Figure 3). The area has a semi-arid climate with sparse vegetation cover. The landscape is characterized by arid plains with outcappings of Precambrian metavolcanic-metasedimentary rocks (Ryan et al., 1986). The terrain has undergone a complex deformation event, which causes ambiguities in correlating the stratigraphic units (Joubert, 1986; Baille et al., 2007). The study area contains strata-bound ore bodies and has economic potential (Ryan et al., 1986). These deposits are a “world-class” Broken Hill-type Pb-Zn-Cu-Ag style of mineralization (Walters, 1998). In the study area, three ore bodies have been discovered. These are known as Broken Hill, Swartberg, and Big Syncline. In addition, similar ore body occurs in the eastern part of the study area called Gamsberg, which is not covered in this study (Figure 3). Although the overall stratigraphic sequence in the vicinity of the ore bodies follows a regional pattern, some units are missing (Figure 2 e.g. amphibolite and gneiss formation) because of the subsequent erosion after deformation (Ryan et al., 1986). The orebodies are associated with banded iron formation (Ryan et al., 1986). Barite lenses overlie the orebodies (Ryan et al., 1986; Stalder & Rozendaal, 2005; McClung et al., 2007) and it’s association indicates high Pb and Cu metal (McClung et al., 2007). Moreover, Mn-garnet is distributed through the ore bodies (Ryan et al., 1986).

For simplification and understanding purpose a conceptual model was created for the Big Syncline ore body (Figure 2), which is relatively the general stratigraphy has been preserved locally. According to Black Mountain Mining, (2014) sustainability report, the Broken Hill deposit started mining since 1980, whereas Swartberg ore body is still being drilled and the Big Syncline development of the ore body postponed for the future.
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Figure 2: Schematic representation of the conceptual mineral deposit model & deformation of the Big Syncline ore body. A & B depicted in a cross-section view, whereas C is plain view (map) after Ryan et al., 1986.

**Unfolded ore body structure**

The original stratigraphy represented by basin floor sediment intruded by granitic batholith & overlying by volcano-sedimentary sequence. The ore body is stratabound & the source of the ore fluid is uncertain.

**Deformation Direction**

(Dynamo thermal metamorphism)

**After Deformation**

The original sequence metamorphose & the subsequent erosion caused the removal of the metamorphic equivalent (metasediment) of the basin floor sediment. In addition, weathering of the sulfide rich ore body resulted in in development of the gossan cap.

Figure 3: Shows location map of the study area (indicated by red star on the google map) and the ore bodies (Big Syncline, Swartberg, Broken Hill and Gamsberg).
3. METHODS AND DATA

In this research, shortwave infrared, thermal infrared, and geochemical data were used to characterize the distribution of mineral mineralogy and mineral chemistry of the Aggeneys SEDEX system. This section introduces the methodology that has been followed in this research and the data. The methodology covers the preprocessing steps (methodology flowchart in appendix I) of the airborne SWIR and TIR images, endmember extraction, and mineral mapping. This section also includes geochemical analysis, integration of the geochemical result and the mineral maps for generating the descriptive geological model.

3.1. Datasets

3.1.1. Airborne data

Shortwave near infrared (SWIR)

The SWIR hyperspectral data were acquired by HySpex airborne sensor. This imaging spectrometer is push broom sensor and has 256 spectral bands between 1000 and 2500 nanometre with a sampling interval of 6 nm and a spectral resolution of 5.6−7.0 nm. In 30 cm GSD (ground sampling distance) the spatial accuracy is better than 2 pixel-size, whereas the spectral accuracy ≤ 1 nanometre. The field of view (FOV) across track is 13.5° and has 320 spatial pixels across the FOV. The sensor equipped with FOV expander lens, this increase the FOV to 27.2° (Köhler, 2016).

The data were collected on 25 July 2015 and 21 August 2015. During the acquisition of the SWIR scenes from August, a FOV expander was mounted and have approximately twice the field of view (with 2.4 m pixel size) (Figure 4) and less gap between the adjacent flight lines than the one from July without FOV expander. For this reason, the images from the two date was used to get continuous coverage of the study area. In total 14 scenes were used, 10 from August and 4 from July. The SWIR data provided was radiance at the sensor (level-1).

Figure 4: SWIR scenes from August with gaps between the flight lines
Thermal infrared (TIR)
TIR data was acquired using Hypercam sensor which was flown along the flight lines with the SWIR HySpex sensors. Hypercam records thermal spectra in 132 bands in the wavelength range between 7800 to 11800 nanometre. The FOV expander was mounted on the sensor and has 24° scanning field of view across track. The delivered TIR data is geometrically corrected and projected into Universal Transverse Mercator (UTM) map projection with world geodetic system (WGS 84) horizontal datum and has 2.4 meter spatial resolution. Unlike the SWIR the TIR data has no gaps between adjacent flight lines and all data that covers the study area were acquired on the same date.

Digital elevation model (DEM)
LiDAR (Light detection and ranging) data were collected from the study area and the DEM was generated from the mass point data. The spatial resolution is 1 meter and projected into UTM map projection with WGS 84 horizontal datum.

3.1.2. Ground spectra
VNIR-SWIR
The BGR has collected field samples from the study area in 2014 field campaign. In total 40 samples collected from four traverses across the Aggeneys ore formation. Two of the traverse covers part of the east, and west Big Syncline and the other two covers part of the north and south Swartberg. Among these, 30 samples were measured in BGR, Hannover laboratory (Germany). The spectra were collected using TerraSpec Halo mineral identifier which operates in VNIR-SWIR wavelength region (350-2500 nm) (https://www.asdi.com/products-and-services/terraspec/terraspec-halo-mineral-identifier). The instrument has internal reference and mineral identification software. This spectrometer identifies near infrared active minerals in a matter of a second, and it is designed to facilitate mineral exploration (Shankar, 2015).

3.1.3. Geochemical data
In total 40 samples were analyzed at Hanover by BGR and provided for this thesis work. The samples were analyzed using X-ray fluorescence (XRF) and X-ray powder diffraction (XRD) analytical techniques, to determine elemental and mineralogical composition respectively. The XRF analysis was made for Major, Minor and Trace elements. Whereas the XRD analysis result includes silicate (Quartz, Muscovite, Kaolinite, Plagioclase, K-feldspar, Sillimanite, and Garnet), sulfate (Barite, Gypsum, and Jarosite) and oxide minerals (Magnetite, Hematite, Goethite, Rutile). For further analysis, only particular elements and minerals were selected to achieve the objectives.

3.2. SWIR image processing
3.2.1. Preprocessing
Destriping filter
The SWIR images contain considerable levels of noises, such as striping which reduced the quality of the imagery. Since the striping artifacts introduce a noise in the subsequent processing steps a destriping filter algorithm in HypPy3 software package (Bakker, 2012) was used to remove them. The software allows the user to control the destriping process to confirm the trustworthiness of the result. This can be done in two steps, one for inspection of the bad pixels then followed by replacing the bad pixels. As a first run, a destriping filter was applied on the radiance data without replacing the bad pixels to assess the bad pixels based on the mean and the standard deviation values from the resulting offset image (Figure 5). Since standard deviation and the mean values of a central pixel is assumed to be similar to its neighboring pixels.
By evaluating the offset image, it is easy to know how the statistics of each pixel differ from the neighboring pixels. Some of the bad pixels have low mean and high standard deviation and the others have the reverse. To replace all bad pixels, there are no common threshold values because of the unpredictable nature of the radiance values. However, considering only standard deviation values, the bands in the shorter wavelength have higher standard deviation than the longer wavelength. To overcome this problem, the data was spectrally subsetted into two wavelength ranges. These are from 1040 to 2012 nm excluding the first 13 bands with not a number (NaN) values (Figure 5) and from 2018 to 2492 nm.

After spectral subsetting, the destriping filter was run using the default threshold values (Mean = 1000 and Standard deviation = 500) for each spectrally subsetted images without replacing the bad pixels in order to determine the threshold values to replace them. By keeping the mean value higher than all the pixels mean values, a standard deviation 1000 and 150 were used for spectrally subsetted shorter wavelength and longer wavelength image respectively. Then destriping filter was run for the second time and the bad pixels that have a standard deviation above the threshold were replaced by the average value of the 9 neighboring pixels.

![Offset Image](image)

Figure 5: The offset image is showing the bad pixels based on the deviation of their statistics from the neighboring pixels. The dark areas are bad pixel with NaN value, and the red circle indicates the bad pixels, the black arrow shows increasing band number, X shows the pixel location and 1-13 shows the bands that are excluded from further processing.

**Minimum Noise Fraction (MNF)**

Individual bands of the destriped SWIR images were evaluated manually to check their quality and then some of the bands contain a significant amount of noise. Consequently, MNF transformation applied to maximize the signal-to-noise ratio of the images (Green et al., 1988). A forward MNF transformation was applied to the destriped SWIR data to filter out the noisy MNF components and to sort out according to the image quality. Since the first 13 bands with NaN values were excluded before applying the destriping filter, only bands from 14 - 256 were transformed into MNF components. The inherent dimensionality of the data was assessed by visual inspection of the individual MNF bands which contains more information and then the first 30 bands selected to inverse transform into the original coordinate system.

**Log residual**

Converting the radiance to reflectance is the most critical step. Since the SWIR data has wavelength calibration issues, in-scene statistics based atmospheric correction preferred to retrieve the relative reflectance. Log Residuals correction was applied to the SWIR data in HypPy3 software to transform the
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Radiance image to Pseudo-surface reflectance. This method removes albedo and atmospheric effects from the data by normalizing the spectra of the pixel first (with upper convex hull) then divided by a mean spectrum of the entire image (Bakker, 2012). In HypPy3 Log residuals interface there are two options to convert the radiance into Pseudo-reflectance. These are the KWIK residuals and Log residuals. The Log residuals method was selected which use the geometric mean rather than arithmetic mean (KWIK residuals). The default value for the number of standard deviation (Number of stddev’s=3.0) was used which is one of the parameters to calculate the statistical least upper bound (SLUB) spectrum (spectrum constructed from pixels that have higher brightness). Then the program runs to create albedo and pseudo-surface reflectance images.

**Mean filter**
Mean filtering was applied to the atmospheric corrected SWIR image to remove random noises. This filters both the spatial and the spectral information in 3-dimension (Bakker et al., 2014). Fast mean 1+5+1 neighborhood was selected to replace the pixel value with the average of the seven neighborhood pixel values. This 7-element kernel has less smoothing effect on the data and it preserves the spectral detail (Bakker et al., 2014). As shown in Figure 6, the kernel consists of 1 central pixel, 4 direct spatial neighbours and 2 direct spectral neighbours.

![Figure 6: 7-element filter kernels, x and y are the spatial dimensions (rows and columns) in the image; λ represents the spectral dimension. Modified after (Bakker et al., 2014).](image)

**Geometric correction**
Geometric correction of the Pseudo-reflectance images has been done in ENVI software using the GLT (geographic lookup Table) files provided for each SWIR scene. The GLT file has a fixed pixel size with a 2.4-meter spatial resolution where each pixel of the SWIR images coincide with based the sample numbers and line numbers. It has also a predefined projection which is UTM zone 34 South (Datum WGS-84). In order to maintain a transparent edge in the adjacent overlapping scenes during mosaicking, the default background value (DN value= 0.0) was used. Afterward, all the SWIR scenes were mosaicked in ENVI software. During mosaicking the SWIR scenes from July were placed below the scenes from the August to fill the gaps.

3.2.2. **Endmember extraction**
Wavelength mapping (Van Ruitenbeek et al., 2014) was applied on atmospheric corrected SWIR scenes in HypPy3 software to get an overview of the dominant absorption features and spectral diversity of the area. This method provides as a first assessment of the spatial distribution of the minerals and mineral assemblage possibly present in the SWIR data by mapping the wavelength position of the deepest absorption features (Van Ruitenbeek et al., 2014) and helps to collect endmembers. Since the SWIR data was acquired at
different dates, the wavelength mapping was applied to each scene separately to avoid variation in the depth of the deepest absorption features of minerals between overlapping scenes. The wavelength maps were generated from 2145 to 2225 nanometre wavelength region were created to enhance the spectral contrast. Pure spectra were collected manually from the highlighted wavelength regions of the wavelength maps. In addition, to include endmembers that have the diagnostic spectral feature at longer wavelength than the selected wavelength region and to account for other endmembers that were missed during the analysis in the selected wavelength region, the spatial-spectral endmember extraction (SSEE) method was applied. The collected endmembers were compared with the United States Geological Survey (USGS) spectral library taking into account the wavelength shift caused by sensor wavelength calibration problems to identify the mineralogy.

### 3.2.3. Mineral mapping
Linear Spectra Unmixing was applied on the SWIR imagery using the endmembers that were collected from the imagery. This method was used to determine the abundance of the minerals in each pixel of an image. The accuracy of this method depends on the quality of the endmember spectra provided by the user (Boardman, 1993). The presence of the endmember spectra in the image and the abundance in each pixel are the most important points to be considered before using this method (Boardman et al., 1995). Since the possible pure pixel endmembers were collected from the image, this method can be appropriate. All the collected endmember spectra were used to unmix the mosaicked SWIR data and to get the individual abundance images. After evaluating the root mean square (RMS) error that was calculated by the unmixing algorithm, a shadow endmember spectrum was included to reduce errors introduced by the topographic effect. Subsequently, the unmixing was run again, now including the shadow endmember in the procedure. To illustrate the spatial distribution of the minerals, the abundance images were displayed as an RGB color composite.

### 3.3. Ground spectra analysis
TerraSpec Halo mineral identifier was calibrated, before starting measuring the field sample spectra. Considering the small field of view of the instrument, a number of measurements were taken based on heterogeneity (mineral diversity) of the rock samples (appendix II). The collected spectra of each sample were interpreted using Spectral Geologist software version 5.03. The algorithm matches only for minerals that have a diagnostic feature in the SWIR wavelength region. Nevertheless, most of the samples are rich in iron oxides (hematite and goethite); therefore, the spectra were manually inspected in the VNIR wavelength region to crosscheck with the automatic interpretation of the software. Finally, the samples spectra were used to validate the SWIR mineral map.

### 3.4. TIR image processing

#### 3.4.1. Preprocessing
**Definition of the sensor in ATCOR4**
ISAC of ATCOR4 (Atmospheric and topographic correction) (Richter, 2016) was used for atmospheric correction of the TIR images. The Hypercam sensor is not defined as a standard hyperspectral sensor in ATCOR4. To include this new airborne sensor, the sensor parameters (e.g., sensor total FOV, number of across-track pixels), wavelength file, and calibration file were provided to the software. The wavelength file was prepared as ASCII file and contains band number, central wavelength, and bandwidth in three columns. Since Hypercam is an FTIR system, the resolution is wavenumber; consequently, the bandwidth is variable.
after converting to nanometres. The wavelength file was used to generate spectral response curve for each thermal band and to calculate the blackbody function which is used for temperature retrieval.

**In-Scene Atmospheric Compensation (ISAC) and unscaled ISAC surface emissivity**

Atmospheric modelling based atmospheric correction did not work well for the TIR data, possibly because of wrong input parameters. For this reason, ISAC was used to remove atmospheric contributions from the TIR radiance data and retrieve surface radiance. This method does not require meteorological data. Since the TIR data was acquired in the same date, the atmospheric parameters considered to be homogeneous throughout the study area. However, this method works well when there is sufficient spread in surface temperature throughout the scene (Young et al., 2002). In ISAC method some of the pixels in the scene assumed to be with high emissivity (blackbody) close to 1; therefore, to search the blackbody pixels, at-sensor radiance converted into brightness temperature (Young et al., 2002). The wavelength with the most blackbody pixels is selected as a reference temperature. A scatterplot of measured at-sensor radiance versus blackbody radiance (Planck function radiance) is generated to determine the path radiance (intercept) and atmospheric transmittance (slope) by fitting straight line on the upper edge of the cluster. Because of the assumption (reference temperature is not the true surface temperature) both quantities may be negative in some channels, as a result, the compensated spectra are unscaled (Young et al., 2002).

The algorithm used the unscaled surface radiance \( L^{(u)}_{\text{surface}} \) and the brightness temperature image in the reference channel \( T_{\text{ref}} \) to calculate the unscaled ISAC surface emissivity as follow:

\[
\epsilon_{\text{ISAC}}(\lambda) = \frac{L^{(u)}_{\text{surface}}(\lambda)}{L(\lambda, T_{\text{ref}})}
\]  

### 3.4.2. Endmember extraction

For the extraction of endmembers, spatial-spectral endmember extraction (SSEE) method was used. Since the area is dominated by quartzite and schist (contain a significant amount of quartz), the quartz will affect the spectra contract considering the whole image. Consequently, SSEE method was selected to enhance the spectral contrast of low contrast endmember spectra by analyzing part of the scene at a time based on user-defined window size (Rogge et al., 2007). A subset size window (2X the square root of the no of bands= 24) and the default Singular Value Decomposition (SVD) were used to retain more endmembers. Spatial averaging (threshold =1) was applied to increase the signal to noise ratio (SNR) of spatial adjacent and spectrally similar endmembers. To reduce the processing time, the mosaicked TIR image was spatial subsetted into two and the method was applied on both images separately. After extracting the image endmembers, the spectra were matched with Johns Hopkins University Spectral Library (JHU) spectral library using spectral analyst in ENVI software.

### 3.4.3. Mineral mapping

The abundance of the TIR active indicator mineral (barite and spessartine) was expected to be small within a pixel (2.4 m). For this reason, to determine the fractional abundance of all endmembers within each pixel spectral linear unmixing method was preferred. First, the algorithm was run using pure pixel endmembers and then by evaluating the RMS error missing endmembers (unknown and mixed endmembers) were included. The output presented as RGB color combination of the fractional abundance images of each endmember.
3.5. Geochemical data analysis

3.5.1. Pearson correlation and Principal component analysis

The correlation between elements (Cu, Pb, Zn, As, Ba, Co, Cr, Mo, Ni) were investigated using Pearson correlation and principal component analysis in SPSS software. A normality test was applied to the variables to check whether they are normally distributed or not. After evaluating the numerical (Skewness & Kurtosis z-value) and visual outputs (Histogram, Box plots & Normal Q-Q plots), the data were not normally distributed. A Log transformation (Log10) was applied to all variables, and then the data were approximately normally distributed. For further analysis, the Log transformed data was converted back to the original units to make the result understandable.

Pearson correlation was performed to estimate the association between two elements. The relationship between the base metals with individual elements were analysed from the resulting correlation coefficient matrix table based on the predefined level of significance.

The elements were subjected to principal component analysis to understand multivariance correlation and to predict the relationship between the elements in terms of mineralization trend. The components with the largest variance (high eigenvalue) have been chosen by looking the scree plot (Figure 7) and the first four components were considered for further analysis. The output pattern matrix was evaluated to find which elements correlated with each component based on the score and the magnitude of loadings (above 0.5 considered as the statistically significant correlation value).

Figure 7: Scree plot showing components number and their corresponding eigenvalue.

3.5.2. Spatial plot

Spatial plot of the concentration of the indicator minerals and the base metals in relation to lithology was generated to understand their association with ore bodies. All the samples from the Big syncline and Swartberg were exported into ArcMap. Then, the indicator minerals (Barite, Garnet, Hematite, and Muscovite) and the base metals (Cu, Pb, and Zn) plotted on the georeferenced geological map from Ryan et al. (1986). Although most of the samples laid on the Aggeneys ore formation (ore host formation), it was necessary to make a differentiation of the lithologies within the Aggeneys ore formation to study the association in detail. Consequently, the samples lithological description was used as a base and their spatial extent extrapolated. This has been done based on the assumption that all the samples are representative and they have been collected when new lithology was encountered. Afterward, the individual concentration of
the indicator minerals and the base metal plotted on the digitized lithological map. In addition, to determine the variation in base metals content across the ore bodies a ternary plot was generated using GeoChemical Data toolkit (GCDkit) software.

3.6. Data integration
The SWIR and TIR mineral maps were exported to ArcMap to evaluate the spatial association of the indicator minerals. The spatial association of the indicator minerals from the integrated mineral maps were compared with the geochemical spatial plot, to investigate whether the anomalous concentration corresponds to those areas. Furthermore, the existing geological map was used as a base to check whether the geological boundaries on the geological map and ore bodies location matches with the result. Then the approximate location of the ore bodies were demarcated on a hill shaded DEM (1m spatial resolution) and the mineral zonation of the foot wall and the hanging wall were studied.

3.7. Descriptive geological model
A schematic abstraction of the ore bodies of the Aggeneys SEDEX system was created in ArcMap. This model was done by reviewing previous works and summarizing the characteristic of the ore bodies in terms of mineralogy and mineral chemistry. The vertical and later variation in the base metals concentration while approaching the ore zones and their association with other metals were determined from statistical correlation plotted on the integrated mineral maps from SWIR and TIR data. Since most of the field samples were collected from the Aggeneys ore formation, there is lack of geochemical data from lower and upper part of the stratigraphy; consequently, the geochemical characteristics of the metals mainly focuses the ore formation.
4. RESULTS

This section presents the results of SWIR and TIR pre-processing steps, endmember extraction, mineral mapping, field samples spectral analysis and mineral map validation. Furthermore, geochemical data analysis, integration and descriptive geological model result are included at the end of this chapter.

4.1. SWIR image processing

4.1.1. SWIR preprocessing

Destriping filter

The result of the destriping filter of the SWIR data was assessed by visual inspection of each band. The bad pixels flagged in step 1 were cross-checked with the processed data to see whether they are really replaced in step 2 with a selected threshold value. On both spectrally subsetted image, the threshold work to some extent to replace the bad pixels that were detected in step 1 (Figure 8). Although the procedures followed replaced some of the bad pixels, still there are remnant striping artifacts which are clearly visible in MNF transformed components (Figure 9). However, these striping noises were slightly smoothed due to the interpolation of the neighboring pixel values, which makes them less pronounced in the processed image.

![Figure 8: SWIR band 194 of flight line 14 displayed in grayscale. (A) before and (B) after destriping filter. The red arrow show vertical striping noise at X=142.](image)

MNF

The MNF transformed SWIR data as shown in Figure 9, can be categorized as noise-free, noise plus signal and noise dominated MNF bands. MNF band 1-11 except 5 contain most of the information in the data and they are not degraded by noise. MNF component 12-30 clearly shows the vertical striping artifacts were not totally removed from the SWIR images after applying destriping filter. Although these vertical striping artifacts slightly affect the image quality, these MNF bands contain signal. However, MNF band 31-243 are dominated by random noise that degrades the signal content of the image. They are excluded from inverse transformation by spectral subsetting to the first 30 MNF bands.
CHARACTERIZING THE SURFACE MINERALOGY IN THE AGGENEYS SEDEX SYSTEM WITH HYPERSPECTRAL IMAGERY

Figure 9: MNF bands were sorted by decreasing the signal to noise ratio. MNF band 1-11 except 5 have a high signal, 12-30 shows vertical striped/noise plus signal and above 30 are noise dominated and excluded from further processing.

Log residual and mean filter
The Log residuals correction generated albedo and pseudo-surface reflectance images. Spectra from the pseudo-surface reflectance images show the feature in the water bands (1334-1424 nm, 1814-1874 nm, 1886-1916 nm, and 1988-2000 nm) are much deeper and contain residual atmospheric artifacts (blue box shown in Figure 10 C and D). In some cases, the spectral shape is inverted in these water bands. On the other hand, in the wavelength region from 2100-2400 nm, where most the clay minerals, carbonate, and sulfate show diagnostic absorption feature (Clark et al., 1990), the spectral shape is well-preserved. Nevertheless, there is a slight shift in the wavelength of the minimum absorption features compared to typical laboratory spectra. Example kaolinite spectrum, the first and the second deepest absorption feature shifts from 2203 nm to 2200 nm and from 2164 nm to 2162 nm respectively (Figure 10 D).

The result of the mean filter shown in (Figure 10 C), the random noise removed from spectral without modifying the overall spectral shape. At around 2000 nm and 2400 nm, the spectral show significantly reduced spikes compared with the one without a mean filter.
CHARACTERIZING THE SURFACE MINERALOGY IN THE AGGENEYS SEDEX SYSTEM WITH HYPERSPECTRAL IMAGERY

Figure 10: Shows kaolinite spectra were collected from flight line 14 (pixel coordinate 286950.846 E and 6767658.452 N) of an average 4x4 pixels (A); (B) Radiance at the sensor spectrum; (C) After Log residual atmospheric correction; (D) Mean filtered spectrum (the arrows show the removal of the spikes); (E) Zoom in Kaolinite features, to show the wavelength positions of the features.

4.1.2. Endmember extraction

The image endmember library a collection of endmembers from the wavelength map interpretation and SSEE method. The wavelength map in Figure 11, orange colors indicate pixels with kaolinite/halloysite/white mica1, whereas yellow and cyan colors indicate pixels with white mica 2 and alunite respectively. Since the spectra collected from wavelength map that covers 2300nm to 2400 nm are mixed, SSEE method was used to extract pure pixel endmembers. However, the collected endmember shows a was a mix of spectral features of two amphibole mineral, these are tremolite and riebeckite. In addition, shadow endmember was collected from shadow area by handpicking because the reflectance is not absolute, it is not recommended to use a constant zero reflectance shadow endmember.

As shown in Figure 12, in total seven endmembers were collected and six of them compared with USGS library spectral, these are alunite, white mica (white mica 1, and white mica 2), halloysite, kaolinite, and tremolite- riebeckite. Alunite shows diagnostic features at 2161 nm and 2197 nm. The two varieties of white mica classified based on the shift in wavelength of the diagnostic absorption feature. The deepest absorption feature of white mica 1 and white mica 2 is positioned at 2201 nm, and 2195 nm respectively. Kaolinite show strong doublet features, one at 2198 nm and the other at 2162 nm. Similarly, halloysite (kaolin group mineral) show absorption feature at the same wavelength; however, halloysite shows weaker feature at 2162 nm. Tremolite- riebeckite show mixed diagnostic features of tremolite (at 2300 and 2384 nm wavelength) and riebeckite (at 2345 nm wavelength).
Figure 11: Wavelength map for the wavelength range between 2150-2220 nm. The colors correspond to the wavelength range (for details see main text above)

![Wavelength map and reflectance spectra for different minerals.](image-url)
4.1.3. Mineral mapping

From the spectral unmixing result, fractional abundance of each pixel containing the selected endmembers was discriminated and minerals that have similar spectral classified as one group. Figure 13 shows, a color composite image of the fractional abundance image of the white mica group (1 + 2), kaolinite group (kaolinite + halloysite) and amphibole group (tremolite-ribeckite) displayed as red, green, and blue (RGB), respectively. The kaolinite group and white mica group are in close association in most part of the area. From the RMS error image (Appendix III) some of the pixels were wrongly classified as amphibole group which are indicated by black arrow in mineral map. This implies missing of spectral endmembers to classify those pixels.

4.2. Ground spectra analysis and mineral map validation

From the automatic interpretation of the field samples spectra, muscovite, illite, and kaolinite are the most abundant minerals in the samples (Appendix II). In addition, the samples contain minor amount of halloysite, gypsum, montmorillonite, jarosite, Fe-chlorite, and opal. The SWIR mineral map was validated using the field sample spectra as shown in Figure 13.

The field samples spectra were confirmed that the areas mapped as white mica group are mainly muscovite and illite, whereas areas covered with kaolinite group are kaolinite and halloysite. However, the presence of amphibole minerals could not be validated, since these minerals were not detected by TerraSpec Halo mineral identifier in any of the samples.
Figure 13: The abundance images displayed as Color composite of R: white mica group, G: kaolinite group, B: amphibole group. The box symbol shows samples used to validate the SWIR mineral map and the arrow shows pixels wrongly classified.
Figure 14: Shows continuum-removed spectra for some of the samples were used for validation. (A) and (B) are muscovite rich schist, (B) muscovite rich gneiss, (D) Kaolinite rich schist and (E) kaolinite associated with quartzite (see appendix II for the other samples spectra).
4.3. TIR image processing

4.3.1. Preprocessing

In-Scene Atmospheric Compensation (ISAC) and unscaled ISAC surface emissivity

The atmospheric correction and surface emissivity were simultaneously done and resulted in unscaled surface emissivity (equation 3.1). After obtaining the unscaled surface emissivity of the TIR data, the output was evaluated based on known surface material (quartz-rich area) (Figure 15 A and B). The output emissivity image provided more information compared to the radiance data. The emissivity color composite image in Figure 15 (B) show clear spectral contrast (represented by color brightness) between the quartz-rich (yellow) and quartz poor area (blue).

The derived surface emissivity spectrum inverted below 8-micrometer spectral region. However, the spectrum shows consistent shape above this wavelength region except for a few surface materials (e.g. dark areas) that show inverted spectra. Moreover, most of the atmospheric noises were removed in the emissivity spectrum (e.g. quartz spectrum (Figure 15 D)).

![Image](image_url)

Figure 15: Shows the original radiance image and emissivity image of flight line 25 displayed as RGB (11.07 µm, 9.59 µm, 9.01 µm) and average quartz spectrum from pixel coordinates 287601.6 E and 6764688.0 N.

4.3.2. Endmember extraction

Several pure and mixed candidate image endmembers were obtained from the SSEE methods. All the candidate endmembers were compared with JHU spectral library (Figure 16). The ten endmembers are albite, quartz, mixed quartz, spessartine (mixed with clay), gypsum, barite mixed with quartz (barite-quartz), vegetation and...
three unknown spectra with no match with the library spectral (unknown 1 to 3). Although spessartine and barite have mixed spectrum, these endmembers are important indicator minerals to target the ore bodies. Moreover, *mixed quartz* spectrum endmember included in the collection to see if its spatial distribution has implication to differentiate the geological units in further mineral mapping.

*Quartz* has a broad doublet features at 8.4 µm and 9.1 µm with an emissivity peak at 8.6 µm; *mixed quartz* has similar feature with quartz except the 8.4 feature is shorter and there is additional feature at 8.1 µm; *albite* has twin feature at 9.6 µm and 9.9 µm and a small feature at 8.65 µm; *gypsum* (selenite) show deep narrow spectral feature at 8.6 µm; *barite* (mixed with quartz) has a large feature at 8.8 µm and a small feature at 8.1 µm; *spessartine* shows a wide feature at 10.2 µm and a small feature at 11.2 µm. *Vegetation* (blackbody) show nearly constant high emissivity spectrum throughout the wavelength region, whereas unknown 1, unknown 2 and unknown 3 shows a deep spectral feature at 9.1 µm, 9.6 µm, and 9.2 µm respectively. However, from a visual comparison of unknown spectra with library and field samples spectra. Unknown 1, unknown 2, unknown 3 slightly matches with biotite, sillimanite, and olivine respectively.
Figure 16: The TIR image endmember spectra (black) and corresponding JHU reference spectra (red). Subfigure G shows unknown image endmember spectra of unknown composition as well as a vegetation spectral (cyan color).

4.3.3. Mineral map

The result of the TIR mineral mapping is shown in Figure 17 and Figure 18. The RMS error of the classification is shown in Appendix III.

The mineral map in Figure 17 shows the fractional abundance image of *albite*, *quartz* and *mixed quartz* displayed as RGB. Areas covered with albite and mixed quartz shown with magenta color and areas dominated by *mixed quartz* and with a lesser amount of *albite* shown with light purple color. The minerals shows distinctive pattern as indicated by box A (*albite*) and B (*mixed quartz*). Box A shows outcrop stratigraphically below box B (ridge). The RGB color composite also shows a match with geological boundaries (Figure 22).

The mineral map in Figure 18 shows the spatial distribution of the *spessartine*, *barite-quartz*, and *Gypsum* highlighted as RGB respectively. Since these minerals are less abundant with a pixel, the RGB color combination image does not stand out. The arrows indicates areas dominated a mix of *spessartine* and *barite-quartz*. 
Figure 17: The abundance images displayed as Color composite of R: albite, G: quartz, B: mix quartz.
Figure 18: The abundance images displayed as Color composite of R: spessartine G: barite-quartz, B: Gypsum. The black arrows showing areas a mix of spessartine and barite-quartz.
4.4. Geochemical data analysis

4.4.1. Pearson correlation and Principal component analysis

Pearson correlation

From the Pearson correlation result as shown in Table 1, As, Ba, Co, Mo correlated with base metals at significance levels of \( p \leq 0.05 \) and \( p \leq 0.01 \). Pb shows the highest correlation with As \( (r = 0.86) \) and slightly correlated with Ba \( (r = 0.35) \). This shows Pb occurs in close association with As and Ba.

Cu shows highest correlation with Mo \( (r = 0.76) \) and shows less correlation coefficients with Co \( (0.48, ) As \( (r = 0.39) \) and Pb \( (0.33) \). The occurrence of Cu and Pb is slightly related; however, Zn doesn’t show significant correlation with either of the elements.

Table 1: Correlations among the elements, the yellow and green colors shows high and very high correlation respectively.

<table>
<thead>
<tr>
<th></th>
<th>Cu</th>
<th>Pb</th>
<th>Zn</th>
<th>As</th>
<th>Ba</th>
<th>Co</th>
<th>Cr</th>
<th>Mo</th>
<th>Ni</th>
</tr>
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<tbody>
<tr>
<td>Cu</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pb</td>
<td></td>
<td>(0.33^*)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zn</td>
<td>(-0.07)</td>
<td></td>
<td>(0.22)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>As</td>
<td>(0.39^*)</td>
<td>(0.86^{**})</td>
<td></td>
<td>(0.04)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ba</td>
<td>(-0.13)</td>
<td>(0.35^{**})</td>
<td>(-0.05)</td>
<td>(0.40^{**})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Co</td>
<td>(0.48^{**})</td>
<td>(0.17)</td>
<td>(0.03)</td>
<td>(0.47^{**})</td>
<td>(0.04)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cr</td>
<td>(-0.23)</td>
<td>(0.07)</td>
<td>(0.24)</td>
<td>(-0.11)</td>
<td>(-0.13)</td>
<td>(-0.23)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mo</td>
<td>(0.76^{**})</td>
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<td>(0.22)</td>
<td>(0.44^{**})</td>
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<tr>
<td>Ni</td>
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<td>(0.29)</td>
<td>(0.58^{**})</td>
<td>(0.14)</td>
<td>(0.29)</td>
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</table>

\(^*p \leq 0.05; **p \leq 0.01\)

Principal component analysis

The principal components 1,2,3 and 4 accounted for 80.07% variability in the data. The eigenvalues for these components are 3.02, 1.66, 1.26 and 1.16 respectively. To examine the elements that contribute to the components in a meaningful way a threshold value above 0.5 used.

The first principal component is correlated with Cu, Mo, and Co. All these elements increases with this component and they are affected by the same factor. Cu component loading is very strong with 0.92 value and followed by Mo with 0.72. Based on their contribution to the component, the first principal component is primarily a measure of Cu.

The second principal component correlated with Pb, As, and Ba. These elements contribute positively to this component. Although Pb and As are not loading significantly in the first principal component, their component loading is very high (were enriched) in the second principal component with 0.97 and 0.90 respectively.

In the third principal component, Cr and Zn are in association and increases with increasing this component. Both Cr and Zn almost contribute similar component loading with 0.74 and 0.75 respectively.
In the fourth principal component, Ni and Co are in association and negatively affected the component (removed from the environment). Ni strongly affects the component with component loading -0.95.

Table 2: Principal component analysis result is showing the component loading of each element in the first four components. Green and red colors shows a group of elements significantly contributing positively and negatively to the component respectively.

<table>
<thead>
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<th>Principal component</th>
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</thead>
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<tr>
<td>Cu</td>
<td>0.92</td>
</tr>
<tr>
<td>Mo</td>
<td>0.72</td>
</tr>
<tr>
<td>Co</td>
<td>0.57</td>
</tr>
<tr>
<td>Pb</td>
<td>0.07</td>
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<tr>
<td>As</td>
<td>0.16</td>
</tr>
<tr>
<td>Ba</td>
<td>-0.43</td>
</tr>
<tr>
<td>Zn</td>
<td>0.06</td>
</tr>
<tr>
<td>Cr</td>
<td>-0.25</td>
</tr>
<tr>
<td>Ni</td>
<td>0.07</td>
</tr>
<tr>
<td>Eigenvalue</td>
<td>3.02</td>
</tr>
<tr>
<td>% Total variance</td>
<td>33.57</td>
</tr>
</tbody>
</table>

4.4.2. Spatial plot
The ternary diagram as shown in Figure 19, most of the samples from Swartberg contain more Pb than Zn metal, whereas samples from Big syncline contain more Zn than Pb. Over all Cu is less abundant in all samples.

Figure 19: Ternary plot showing the variation in Cu, Pb and Zn content of the field samples. Red show Swartberg samples and black dot show Big Syncline samples.
In most of the samples, garnet and barite are not common and it hard to relate to the lithologies and the base metals concentration. However, with the available samples, barite and garnet show relationship with Pb and less with Cu and no relation with Zn. The presence of hematite and muscovite don't show a significant relationship between the base metals and the lithologies.

The spatial plots in Figure 20 and Figure 21 shows the variation in concentration of the base metals (Pb, Zn & Cu) and the indicator minerals (barite, garnet, hematite, and muscovite) in relation to lithology. The spatial plots of the western part of the Big Syncline and Northern part of Swartberg the reader can refer appendix IV.

Figure 20 shows spatial plots of the samples from the east part of Big syncline. The concentration of the base metals and the indicator minerals except for barite show anomalous concentration in schist. Cu shows spatial association with Pb, whereas Zn doesn't show relationship with these metals. Garnet shows a spatial relation with Pb; however, the other indicator minerals do not show a spatial association with base metals.

Figure 21 shows spatial plots of the samples from the South part of Swartberg (appendix II). Hematite, barite, muscovite shows a spatial association with Pb and have an anomalous concentration in schist. Pb and Zn show low concentration across the lithologies.

Figure 20: Spatial plots for samples from the eastern part of the Big syncline. The circle shows areas with high base metals concentration.
Characterizing the surface mineralogy in the Aggenys Sedex system with hyperspectral imagery.

Figure 21: Spatial plots for samples from the southern part of the Swartberg (lower ore body). The circle shows areas with high base metal concentration.
4.5. **Data integration**

The coincidence of geological boundaries with the mineral distribution pattern was evaluated. However, there is a slight mismatch in most part of areas, this may be a result of scale difference or inaccurate delineation of the geological boundaries.

The result of the integration of SWIR and TIR mineral maps with existing geological map is shown in Figure 22. The TIR mineral map shown in (A), the magenta\((\text{albite + quartz})\) and the red\((\text{albite})\) color correspond to the augen and pink gneiss formation in the geological map shown in (C), whereas the blue\((\text{mixed quartz})\) and purple\((\text{mixed quartz + albite})\) color matches with white quartzite unit. The green color\((\text{quartz})\) represents the schist units, these are sillimanite quartzite schist, undifferentiated schist, and aluminous schist.

The SWIR mineral map shown in (B), the red color\((\text{white mica group})\) doesn’t show a clear geological contact except it shows lower abundance in the augen and pink gneiss formation. The green color\((\text{kaolinite})\) matches with the magnetite-rich gossans in Big synclinal; however, it shows the irregular distribution in augen and pink gneiss formation, quartzite unit, sillimanite quartzite schist and aluminous schist. The blue color\((\text{amphibole group})\) mainly correspond to augen and pink gneiss formation.

The result of the integration of TIR mineral maps, SWIR mineral map with the spatial plot of Pb concentration is shown in Figure 24 and the location of the samples is shown in Figure 23. In location 1, 2 and 3, high Pb content corresponds with the presence of barite-quartz and spessartine in (A); mixed quartz, albite, and quartz in (B); kaolinite group, white mica, and amphibole group in (C). On the other hand, the absence of spessartine in (A) and kaolinite group (C) in location 2 samples shows relatively low Pb concentration.
Figure 22: Geological boundaries overlaid on TIR and SWIR mineral maps. (A) TIR mineral map RGB color composite, R: albite, G: quartz, B: mixed quartz. (B) SWIR mineral map RGB color composite, R: white mica group, G: kaolinite group, B: amphibole group. (C) Geological map.
Figure 23: TIR mineral map RGB color composite of R: spessartine, G: barite-quartz, B: Gypsum showing the location of the samples.

Figure 24: Integration of TIR mineral maps and SWIR mineral map with the spatial plot of Pb concentration. (A) TIR mineral map RGB color composite of R: spessartine, G: barite-quartz, B: Gypsum; (B) TIR mineral map RGB color composite of R: albite, G: quartz, B: mixed quartz; (C) SWIR mineral map RGB color composite of R: white mica group, G: kaolinite group, B: amphibole group and (D) Pb concentration spatial plot. The black dots shown in A, B and C are the field samples location.
The TIR mineral map (Figure 18), SWIR mineral map (Figure 13) and the spatial plots were used to locate the ore bodies in ArcMap. Areas indicated by arrows (mix of quartz-barite and spessartine) from the TIR mineral map, the presence of kaolinite group mineral (SWIR) and areas with high base metal concentration shown by circle in Figure 20 and Figure 21 were used delineate the possible ore body locations (Figure 25). The ore bodies distribution integrated with hill shaded DEM to understand their orientation. The Big syncline orebodies were mainly distributed on the southern limb and trending to north-east direction, whereas the Swartberg ore bodies scattered on relatively low topography and strike to south-east direction. The broken hill orebody is laid on the along a crest and strike to north-east.

![Possible ore body locations on a hill shaded DEM](image)

Figure 25: Possible ore body locations are shown on a hill shaded DEM

### 4.6. Descriptive geological model

The idealized setting of the Aggeneys SEDEX system shown in Figure 26 illustrate the early stage deposition of ore and the parent rocks. The basin floor sediment assumed to be the oldest unit and intruded by granitic batholith. The units are displaced by syn-sedimentary fault and this acts as a path way for migration of the ore forming fluids. The ore fluids discharged on basin floor and forming stratiform deposits (within clay rich formation 2).

Figure 27 **A, B** and **C** shows original stratigraphy, after metamorphism/ deformation and after erosion/weathering respectively. Cross section **A** is representation of the Aggeneys system at basin scale whereas cross section **B** and **C** are representing only the eastern part of the Big Syncline. After metamorphism as shown in **B**, the metamorphic equivalent of original sedimentary rocks were formed and the ore body deformation. The erosion/weathering as shown in **C** caused removal of the fold (syncline) limbs and development of gossan cap on ore body.

Figure 28 shows cross section of the Big Syncline ore bodies, mineralogical variation across the stratigraphy and metal variation near to the ore bodies. The base metal variation from west (Swartberg) to east (Big Syncline) also shown in this model. The minerals are from the spectroscopy result and literature review (indicated by asterisk).
Figure 26: Generalized schematic diagram illustrating Aggeneys SEDEX deposit formation modified from (Robb, 2005).

Figure 27: Shows modification of the original stratigraphy and ore body through time. (A) cross-section view of the original stratigraphy and ore body orientation, (C) cross section view of eastern part of the Big syncline after deformation and metamorphism, (D) after prolonged erosion and weathering.
Figure 28: A descriptive geological model showing the variation in mineralogy and metal across the stratigraphy. The minerals are from spectroscopy, and the one with an asterisk are from Ryan et al., 1986. The base metals variation from east to west also shown here.
5. DISCUSSION

Log residual atmospheric correction was able to extract well the mineralogical features that were not coinciding with atmospheric absorption. However, mineralogical features in the atmospheric absorption were difficult for interpretation because of the presence of atmospheric artifact and inverted spectral were introduced by the algorithm.

For SWIR mineral mapping, linear spectral unmixing was used to determine the fractional abundance the endmembers per pixel. The result of this method mainly depends on the quality of the endmembers provided by the user. In order to get better classification, one should consider the presence and quality the endmembers and the abundance in each pixel. For this reason, endmembers collected from the image were used for the classification. Minerals that have similar spectrum were grouped as one endmember, e.g. halloysite + kaolinite (kaolinite group) and white mica 1 + 2 (white mica group).

The spatial distribution of the minerals from the SWIR mineral map shows white mica group is the most abundant on the outcrop of the study area then followed by kaolinite group and amphibole group minerals. In most part of the area, kaolinite group occurs in association with white mica group and has irregular distribution throughout the area. This indicates the formation of kaolinite group minerals has a strong genetic relationship with the presence of white mica group minerals. Kaolinite can be formed as a retrograde product of muscovite or as a recent weathering product of plagioclase (Cudahy, 2016).

Although the ISAC unscaled surface emissivity is vital to study mineralogical related features, it has some drawbacks. For instance, some of the pixels and the spectral region below 8 µm shows inverted spectrum. In the first case, since ISAC spectrum is pixel-dependent, the inverted spectrum may happen for pixels that have brightness temperature outside of the selected reference channel. In the second case, the spectrum in the atmospheric water vapor region (below 8 µm) is inverted because the spectral region didn’t involve in the maximum brightness search (Young et al., 2002). In addition, ISAC assumes that the atmospheric parameters are homogeneous throughout a flight line, at-sensor radiance has a linear relationship with at-surface radiance (Young et al., 2002). For this reason, it does not correct the reflected downwelling radiance.

For TIR mineral mapping, spectral linear unmixing was used to get the abundance image the endmembers. The overall RMS error of the classification is lower because the endmembers provided were enough to classify the entire image. The abundance images displayed as an RGB color composite to see patterns related geology of the area. The RGB color combination of albite, quartz, and mixed quartz shows a distinctive pattern. Albite mainly occurred at the base of the outcrops and mixed with mixed quartz in most part of the area. Quartz covers most of the low-lying areas, on the contrary, the mixed quartz distributed along the ridges (competent layer). The spatial distribution of the three mineral implies that these minerals are representing geological units situated in different stratigraphic position.

The RGB color combination of spessartine, barite-quartz, and gypsum were used to highlight the possible locations of the ore bodies. The distribution of a mix of spessartine with barite-quartz in few areas of the Big Synclinal, Swartberg, and Broken Hill shows an indication of the bodies locations. The distribution of barite-quartz does not show a pattern alone because of the presence of quartz, whereas gypsum mainly occurred in the Broken Hill mining areas and this may be a result of oxidation of the sulfide.
Principal component 1, 2 and 3 indicates the nature of Cu, Pb and Zn mineralization in the study area respectively. Moreover, the strong association of the Pb with Ba and As, Cu with Mo and Co and Zn with Cr may indicate that they are originated from the same source or ore-forming fluid.

According to Ryan et al., 1986, the ore host formation and aluminous schist contains a significant amount of quartz, muscovite, sillimanite, biotite, and k-feldspar. Due to the presence of similar mineralogy in the two formations, these units were not able to differentiate them based on their composition using spectroscopy. However, areas where the stratigraphy is well preserved (e.g. Big Synclinal), the ore host formation is younger than aluminous schist, and this stratigraphic position can be used to distinguish them.

The variation of the base metal concentration with the indicator minerals was investigated. The spatial association of barite-quartz and spessartine with elevated Pb concentration implies that there is a relationship with the mineralization. While approaching the ore zones of Broken Hill-type deposits, the garnet composition becomes Mn-rich (spessartine) (Cudahy, 2016). Similarly, Manganese rich garnet and barite are in close association with ore bodies (Ryan et al., 1986). In SEDEX system the oxidation of ore bodies may result in the formation of gossan and contains minerals such as goethite and hematite, with minor quartz, kaolinite, and beudantite (Kelley et al., 1986). The distribution kaolinite group minerals in ore formation may relate to the mineralized zone. This secondary mineral is good indicator minerals for exploration (Emsbo et al., 2010). Even though the white mica group is associated with high base metal concentration, the composition variation is not investigated in this study. However, a number of studies showed that the shift in the wavelength of white micas in relation to hydrothermal mineralization processes (van Ruitenbeek et al., 2005; Yang et al., 2011). Moreover, in Broken Hill and Swartberg, albite and amphibole group minerals are closely associated with ore bodies. Ryan et al., 1986, confirmed that these minerals are among the most common minerals dispersed throughout the Broken Hill ore body.

The ore bodies were targeted using a mix of spessartine with barite-quartz and kaolinite group as main indicator minerals. The ore bodies are distributed as discontinuous lenses along the strike of the ore formation. Relative to the Big synclinal ore body, the stratigraphic position of Swartberg and Broken Hill ore bodies with the underlying formations is not clear. Metamorphism and deformation might have obscured the details of stratigraphy. All the ore bodies are closely associated with barite-quartz, spessartine, white mica group, kaolinite group, quartz, mixed quartz, amphibole group and albite. However, the Swartberg northern ore body (upper ore body) less associated with kaolinite group, white mica group, and albite. Based on the spectroscopy result, there is no clear difference in mineralogical association of the ore bodies.

The descriptive geological model helps to understand the spatial distribution of the ore bodies after deformation and the associated gossan after weathering, which has great implication in exploration. Furthermore, this schematic abstraction help to understand the change in the Aggeneys SEDEX system through time.
6. CONCLUSION AND RECOMMENDATION

- In this research, the integration of SWIR and TIR imagery shows a great potential to characterize the surface mineralogy on the outcrops of Aggeneys SEDEX system. From the SWIR mineral mapping result, the spatial distribution of white mica group, kaolinite group, and amphibole group minerals was successfully mapped. Additionally, the TIR mineral mapping result shows minerals such as quartz, mixed quartz, plagioclase, barite-quartz, spessartine, and gypsum. With these results, objective 1 was reached.

- The SWIR and TIR integration result was able to distinguish most the geological units in the study area. However, the ore host formation and the aluminous schist could not be differentiated because of their similarity in mineralogical composition.

- Investigation of the ore host formation helped to understand the distribution of the minerals around the ore bodies. Barite-quartz, spessartine, white mica group, kaolinite group, quartz, mixed quartz, amphibole group and albite are the most common minerals associated with the orebodies. Regardless of the variation in abundance of these minerals in each ore bodies, there is no clear mineralogical variation spectrally detected between the ore bodies (part of objective 4 was achieved).

- In the Aggeneys SEDEX system, barite-quartz, spessartine, and kaolinite were used to differentiate the mineralized and barren zone (objective 2 was achieved).

- The geochemical analysis evaluation shows that there is metal zoning between the ore bodies. The Swartberg ore body is rich in Pb, whereas the Big Synclinial is rich in Zn. Pb is closely associated with Ba and As, while Cu with Mo and Co. However, Zn does not show association with any of the metal. The principal component analysis result has implication on the mineralization of the area. The metals comprise a group, Pb with Ba and As, Cu with Mo and Co and Zn with Cr. With these results, part of objective 4 was achieved. In addition, the geochemical plot shows that the presence of barite and garnet in the ore formation correspond to high Pb concentration.

- The foot wall of the mineralization consists of Mn-garnet, mixed quartz, albite, and amphibole group. The hanging wall consists of kaolinite group which associated with gossan cap. However, quartz and white mica group occur on the foot wall and hanging wall of the ore bodies (objective 3 was reached).

- The result of the descriptive geological model shows the formation of the Aggeneys SEDEX deposit and the change through time. Moreover, it shows how the mineralogy and mineral chemistry varies in the deposit. (objective 5 was achieved).

The following recommendations are forwarded:

- In a similar style of mineralization, barite, Mn-garnet, and kaolinite minerals can be used for targeting the ore body.
- Combining VNIR data (to map the gossan cap) and mapping the shift in the wavelength of white mica may help to improve the targeting of orebodies.
7. APPENDICES

Appendix I. Flow chart illustrating methodology
Appendix II. Field samples and spectral geologist software interpretation of the measured spectra.

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Appendix III. SWIR and TIR unmixing RMS Error

In areas highlighted with white color the unmixing didn't work well
Appendix IV. Geochemical spatial plot for samples from west part of Big syncline and North part of Swartberg

West part of the Big Syncline
North part of the Swartberg (Upper ore body)