COMBINING DOMINANT SPECTRAL FEATURES IN AIRBORNE SWIR AND TIR IMAGERY FOR MINERALOGICAL MAPPING.

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FAGBOHUN BABATUNDE JOSEPH Enschede, The Netherlands, March, 2015

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ABSTRACT

The application of airborne imaging spectroscopy for mineralogical mapping in the past has mostly focused on the use of SWIR airborne data. With continuous development in TIR spectroscopy, it is imperative to examine how the two wavelength ranges complement one another for mineralogical mapping and geologic interpretation. The aim of this research was to examine possible way to optimally combine SWIR and TIR airborne data for mineralogical interpretation and determination of alteration patterns in Yerington district. The Yerington hydrothermal system has an excellent exposure of different hydrothermal alteration zones, therefore it offers a good testing ground for this approach.

A total of 101 rock samples collected Yerington district were analysed for SWIR and TIR active minerals. The dominant SWIR and TIR active minerals were identified. The minimum wavelength position of the spectra was determined. The spectral parameter of minimum wavelength position was chosen it is determined by the dominant mineral in rock samples. By plotting the minimum wavelength positions determined from SWIR against those determined from TIR, mineral associations and assemblages were established. The assemblages established from SWIR and TIR spectral analysis was used as training input to classify airborne data after calculating the minimum wavelength position in each pixel.

The result shows that combination of SWIR and TIR provide complimentary spectral information and can be particular used in tracking alteration intensity in porphyry-epithermal systems. Transition from less pervasive sodic-calcic alteration through sericitic to pervasive advance argillic alteration was identified in the hydrothermal system. Advance argillic, sericitic, sodic-calcic, and skarn hydrothermal assemblages can be readily identified while propylitic and chloritic alteration can be reasonably identified by combination of the two data.

The added value of this research is development of an approach to combine SWIR and TIR airborne data without the use of information from existing alteration maps, rather combination was guided by assemblages established from analysis of rock samples and can therefore be applied as an exploration tool in other porphyry-epithermal-skarn systems.

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LIST OF ABBREVATIONS

ASD	Analytical Spectral Device
ASTER	Advanced Spaceborne Thermal Emission and Reflectance Radiometer
ATCOR	Atmospheric Correction and Haze Reduction
DHR	Directional Hemispherical Reflectance
FTIR	Fourier Transform Infrared
GLT	Geographic Lookup Table
ISAC	In-scene Atmospheric Correction
JHU	Johns Hopkins University
JR	Jurassic
LWIR	Long Wave Infrared (8-14µm)
MCT	Mercury Cadmium Tellurium
MNF	Minimum Noise Fraction
MWIR	Midwave Infrared (3-8µm)
PCA	Principal Component Analysis
SEBASS	Spatially Enhanced Broadband Array Spectrograph System
SWIR	Shortwave Infrared (1.4-3µm)
Т	Tertiary
TIR	Thermal Infrared (consist of MWIR and LWIR)
TR	Triassic
TSG	The Spectral Geologist
USGS	United States Geological Survey
VELC	Virtual Empirical Line Correction

Mineral Aberrations

Alb	Albite	Jar	Jarosite
Act	Actinolite	Kao	Kaolinite
Afsp	Alkali feldspar	Kfds	Potassic feldspar
Alu	Alunite	Mgt	Magnetite
Amp	Amphibole	Mo	Molybdenum
And	Andesine	Mus	Muscovite
An	Anorthite	Olg	Oligoclase
An _{xx}	Plag with xxmol% An	Plag	Plagioclase
Bt	Biotite	Pyr	Pyrite
Bn	Bornite	Pyl	Pyrohyllite
Car	Carbonate	Qtz	Quartz
Сс	Calcitee	Rt	Rutile
Chl	Chlorite	Ser	Sericite
Ср	Clinopyroxene	Smt	Smectite
Dio	Diopside	Sph	Sphene
Epi	Epidote	Spt	Serpentine
Gar	Garnet	Tit	Titanium
Gsl	Grossular	Tml	Tourmaline
Gyp	Gypsum	Verm	Vermiculite
Hal	Halloysite	Ves	Vesuvianite
Hbl	Hornblende		
Ilm	Ilmenite		
IIt	Illite		

1. INTRODUCTION

1.1. Research Background

The formation of ore deposits is usually accompanied by hydrothermal alteration of the host rocks through which ore bearing fluids circulate. The reaction between these circulating fluids and the host rock results in the formation of new mineral assemblages as the reaction attempts to attain equilibrium. Alteration vary in type, however each type and its mineral assemblage depends predominantly on the nature, chemistry, temperature and pressure of the circulating hydrothermal fluid as well as the nature and composition of the rock through which it circulates (Pirajno, 2009). These hydrothermally altered zones serve as fluid path ways through the rock, as such they can serve as a good guide in exploration of ore deposit (Robb, 2005), simply because they extend beyond the ore allowing exploration to be narrowed down to smaller areas.

Spectral remote sensing is an effective method for identification of hydrothermal alteration. It has long been adopted by geologists in mineral exploration (van der Meer et al., 2012) due to its capability to cover large areas when compared with other conventional mapping techniques. Application of remote sensing in alteration mapping began with the use of multispectral images such as Landsat TM and Advanced Spaceborne Thermal Emission and Reflectance Radiometer (ASTER). Alteration mapping using Landsat TM involves the use of band ratios and principal component analysis to delineate alteration zones and lithology types (Abrams, et al., 1983; Chavez, et al., 1991; Green and Lyon, 1984). Ratio of Landsat band 7/band 5 separates argillic from non-argillic bands indicating the presence or absence of hydroxyl absorption bands (van der Meer et al., 2012).

The advent of ASTER in 1999 opened another way for mineralogical mapping using remote sensing images. ASTER has a total of 14 bands, consisting of three bands with 15m spatial resolution in the Visible Near Infrared, six bands in the Shortwave Infrared Region (SWIR) with 30m spatial resolution and five Thermal Infrared (TIR) bands with 90m spatial resolution (Abrams, 2000). ASTER images have been used for both regional lithologic mapping as well as alteration zone delineation by the of use of composites of selective band ratios to identify alteration mineral groups (Kalinowski and Oliver, 2004) as well as resampling spectra from high resolution spectrometer to spectral resolution of ASTER bands 1-9 for mineral identification (Cudahy et al., 2008).

Multispectral images have coarse spectral resolution which makes it impossible to appropriately identify individual mineral. This drawback was solved by the development of hyperspectral sensors. These sensors use several hundred channels enabling identification of individual mineral based on their diagnostic absorption features which are related to vibration of interatomic ions. Spectral features of minerals in the Shortwave InfraRed (SWIR) have been studied (Clark et a., 1990; Hunt, 1977) and this study has been vital to the use of hyperspectral remote sensing in mineral identification and mapping. This region of the spectrum has been extensively used in mapping alteration minerals (Bedini et al., 2009; Kruse, 2012; Lyon and Honey, 1990; van der Meer, 2004).

While SWIR hyperspectral data can provide considerable mineralogical information, some minerals appear featureless or difficult to be uniquely identified using SWIR (Vaughan, et al., 2003). Aside the spectral features exhibited by minerals in SWIR, minerals also exhibit spectral features associated with molecular vibrations in the Long Wave InfraRed (LWIR, 8-14µm) region of the spectrum (Salisbury and Walter, 1989). While SWIR hyperspectral remote sensing has largely been used in mineralogical mapping, the use of hyperspectral TIR remote sensing has been limited. Notable mineralogical mapping with TIR hyperspectral has involved the use of SEBASS dataset (Riley et al., 2007; Riley and Hecker, 2013; Vaughan et al., 2003). Other studies involving the use of SEBASS include discrimination and determination of feldspar chemistry (Cudahy et al., 2000; Hecker et al., 2012b).

Yerington district in Nevada U.S.A is characterized by wide range of alteration types associated with porphyry-epithermal-skarn deposit produced by the intrusion of the Yerington Batholith. Four regions in Yerington district host porphyry copper deposits and associated copper skarn deposits. The alterations types in this region includes phyllic, pottassic, sodic-calcic, advanced argillic, propylitic-actilinolite and skarn alteration types (Barton et al., 2000). Some of this alteration types contain alteration minerals such as feldspar, quartz and garnet which are spectrally difficult to identify in the SWIR. This research explores how SWIR and TIR data can be combined for better mineralogical mapping and alteration zone delineation in the Yerington district. For this research, contiguous scenes of SWIR and TIR airborne data acquired simultaneously were used to map the distribution of minerals the Yerington district.

1.2. Application of Remote Sensing in the Yerington district

Few studies have involved the application of hyperspectral data for mineralogical mapping in Yerington area. Previous application of remote sensing in Yerington area involve the use of Geoscan MkII multispectral image to map surface mineralogy in parts Ann Mason and Buckskin region of Yerington hydrothermal system (Lyon & Honey, 1990). The studies by (Cudahy et al., 2001a) involving the use of few non adjacent scenes of HyMap and SEBASS focused on estimating chemistry of white mica and garnet and the spatial coverage was limited. Other studies in Yerington district focused more on variation in chemistry within a particular mineral species such as differentiation of feldspar chemistry and quantitative estimation of feldspar composition in rocks in Ann Mason area using SEBASS TIR data (Cudahy et al., 2001b; Hecker et al., 2012b). Determination of spatial distribution of minerals and determination of alteration patterns over the entire system using remote sensing and comparison to alteration maps produced through ground sampling is yet to be carried out.

1.3. Problem Statement

Previous work in Yerington area has resulted in the production of geologic maps of the Yerington district and alteration maps for parts of the Yerington hydrothermal system (Barton et al., 2000; Dilles et al., 2000; Dilles & Proffett, 2000). These alteration maps are developed by field observationsampling and analysis of rock samples. Analysis of rock samples to determine alteration types involves either analysis of whole rock chemistry or determination of mineral assemblages. Whole rock analysis involves analysing fluid chemistry and elemental composition to determine change in fluid chemistry as alteration progresses, while mineral assemblage methods usually involves study of thin sections to determine the order of abundance of alteration minerals usually in order of decreasing abundance (Pirajno, 2009). Remote sensing provides an alternative way to mineralogical mapping and alteration determination with the advantage of been able to cover larger areas. While mineralogical mapping has largely been done using SWIR remote sensing in the past, some minerals can be better mapped using TIR remote sensing.

Minerals exhibit spectral absorption features over the entire wavelength regions, but the prominent absorption features of most minerals lie in a particular range of the electromagnetic spectrum (Vaughan and Calvin, 2004). Although SWIR remote sensing has proven to be a reliable method for mineralogical mapping, with the recent development in TIR hyperspectral remote sensing, it becomes imperative to determine how minerals which can be identified with TIR be linked to minerals can be identified using SWIR for better understanding of alteration types. This research examines which minerals can be identified by SWIR and TIR, and how the derived information from both wavelength ranges can be combined for mineralogical interpretation and determination of alteration patterns in Yerington district.

1.4. Research Objective

The general objective of this study is to determine the spatial distribution of minerals using SWIR and TIR airborne data, and to combine this information from both wavelength ranges for mineralogical and alteration pattern interpretation in Yerington district, Nevada

1.4.1. Specific Objectives

- 1. To analyse rock samples collected from the Yerington district to determine SWIR and TIR spectrally active minerals and, the association between minerals identified with both wavelength ranges.
- 2. To determine the spectral characteristic of alteration minerals in the Yerington area in SWIR and TIR airborne data.
- 3. To determine the spatial distribution and patterns of alteration minerals using SWIR and TIR airborne data.
- 4. To relate mineralogical patterns to lithology and determine alteration facies based on their spatial distributions and observed patterns.
- 5. To compare mineral distribution pattern interpreted from integration of SWIR and TIR to distribution pattern in existing alteration maps and those established from rock sample analysis.

1.4.2. Research Questions

- 1. Which minerals can be identified in the SWIR and TIR based on analysis of samples and airborne data from Yerington area?
- 2. How does patterns mapped using SWIR and TIR airborne data compare?
- 3. How can SWIR and TIR airborne data be combined for mineralogical mapping?
- 4. Does the combination of SWIR and TIR airborne data offer additional mineralogical information?
- 5. Which alteration types can be determined from assemblage of alteration minerals mapped by combining SWIR and TIR?
- 6. Is the spatial distribution of alteration minerals and alteration types identified by interpretation of SWIR and TIR data consistent with those determined from samples and existing alteration maps

1.5. Research Hypothesis

Generally, minerals exhibit spectral features over the entire wavelength but depth of spectral features vary between wavelength regions. In principle either SWIR or TIR hyperspectral data can be used discretely to successfully map minerals, however the use of a single wavelength range means some minerals will be inadequately characterized (Vaughan et al., 2003). Most clay minerals have distinctive spectral feature in the SWIR and can easily be characterized in this region, but minerals such as feldspar, garnets, quartz and pyroxene have weak spectral features in the SWIR and are better identified using the TIR wavelength region. Therefore it is expected that there will be spatial relationship between minerals identified using SWIR and TIR which are associated with the same alteration type.

1.6. Dataset

- a. ProspecTIR-VS image (0.4-2.5µm) with 5nm nominal spectral resolution (SWIR)
- b. Spatially Enhanced Broadband Array Spectrograph System (SEBASS)(TIR)
- c. 101 Rock samples collected from Yerington Area in 2009.
- d. Geological maps (Proffett & Dilles, 1984), (Hudson & Oriel, 1979)
- e. Alteration maps: (Dilles & Einaudi, 1992), unpublished maps Dilles (1995, 2001)
- f. Reference Spectral Library (TIR): extracted from

http://speclab.cr.usgs.gov/spectral.lib06/ds231/datatable.html

The airborne dataset for this research was acquired during Joint Airborne Collections using Hyperspectral Systems (JACHS) by SpecTIR (SpecTIR, 2008). ProspecTIR-VS airborne sensor which operates in the VNIR-SWIR having 357 channels and spectral range of 0.4-2.5µm with 0.5nm spectral resolution was used in combination with Spatially Enhanced Broadband Array Spectrograph System (SEBASS). SEBASS is a pushbroom airborne sensor which operates in the Midwave Infrared (MWIR) and Longwave Infrared (LWIR). SEBASS has128 channels in the MWIR (2.5-5.3µm) and 128 channels in LWIR (7.6-13.5µm) (Hackwell et al., 1996; SpecTIR, 2008). The image from ProspecTIR-VS was corrected for atmospheric effects using two atmospheric methods; Atmospheric Correction and Haze Reduction (ATCOR) and Virtual Empirical Line Correction (VELC). The ATCOR corrected image has 178 bands in the Visible-Shortwave Infrared while the VELC corrected image is limited to 82 bands in the SWIR region only.

The survey was carried out between 29th May and 27th June 2008. For this research the images from ProspecTIR-VS and SEBASS LWIR (7.6-13.5 μ m) was used. The images from the two sensors have 4m spatial resolution.

Two Geologic maps, one produced by Hudson & Oriel (1979) at the scale of 1:18000 which covers the Buckskin range and the other by Proffett & Dilles (1984) at scale of 1:24000 which covers the Ann Mason, Blue Hill and MacArthur Area were used. Both maps are published by Nevada Bureau of Mines and Geology. The Maps were digitized and converted into digital format to allow easy comparison of observed patterns to lithologic units.

101 rock samples collected by Hecker (2009) serves as source of ground information. The rock samples are collected from 72 sample locations with multiple samples collected from some sample locations.

1.7. Thesis Structure

The structure of this thesis is given below.

- *Chapter one*: contains background literature regarding the use of remote sensing in mineralogical mapping, the problem to be addressed by this research and the objectives through which the problem will be addressed.
- *Chapter two*: focuses on the study area, in terms of geologic and tectonic history, alteration types and mineralization occuring in the Yerington Hydrothermal system.
- Chapter three: examines the linkage between porphyry-epithermal-skarn systems, alteration types associated with such linked systems as well as minerals which are spectrally identifiable in the SWIR and TIR wavelength region.
- *Chapter four*: contains methods adopted in this research to achieved the research objectives
- *Chapter five.* contains the findings obtained from executing this research. Discussion on the findings is also included in this section.
- *Chapter six*: contains conclusion and recommendation.

2. GEOLOGIC SETTING OF THE YERINGTON HYDROTHERMAL SYSTEM

2.1. Geologic Setting

The Yerington hydrothermal system is located in Yerington, Nevada U.S.A. The hydrothermal system is associated with the formation of porphyry copper deposits, copper skarn deposits and iron oxide-copper-gold lodes. The geologic setting, lithologic description and mineralization presented in this chapter is an excerpt from Dilles et al., (2000), Dilles and Proffet (2000), Hudson and Oriel (1979)

The oldest rocks in Yerington district are intermediate and silicic volcanic rocks of late Triassic or older age, these rocks are intruded by middle to late Triassic plutons (McConnell Canyon Volcanics) and Metavolcanics in the Buckskin Range which strongly resembles the McConnell Canyon Volcanics (Hudson & Oriel, 1979). These rocks are overlain by sedimentary and volcanoclastic rocks consisting of limestone, argillaceous sediments, evaporite tuff and tuffaceous siltstone which lie unconformably over the pre-existing volcanics.

The eruption of Yerington Batholith is preceded by Middle Jurassic igneous activity which is believed to be the initialization of magmatic activity that produced the Yerington batholith. The Middle Jurassic igneous activity produced Artesia Lake Volcanics which are intermediate to silicic rocks overlying the sedimentary and volcanoclastic rocks.

The Yerington batholith is emplaced into the older Artesia Lake Sequence, McConnell Volcanics, sediments and volcanosedimetary rocks. The emplacement of Yerington batholith occurs as three major equigranular intrusions which become progressively smaller and more silicic in composition. The earliest of the intrusions is the hornblende and biotite bearing McLeod Hill quartz monzodiorite emplaced as series of dike-like bodies into the overlying volcanics and adjacent hornfels with steeply dipping contacts. The second phase of intrusion produced the Bear quartz monzonite emplaced into the McLeod Hill body and locally into the Artesia Lake Volcanics. The Bear unit show compositional zoning, ranging from fine grained, graphic-textured granite at the top of the unit to medium-grained, relatively homogenous hornblende quartz monzonite below. The last phase of intrusion produced the Luhr Hill granite resulted in the formation of ore deposits in Yerington area. The emplacement of Luhr Hill granite is also accompanied by the intrusion of granitic porphyry dikes which are closely associated with porphyry copper deposits. The dikes which are compositionally and mineralogically similar to the Luhr Hill granite and they intrude upwards through the cupolas of the Luhr hill granite forming dike swarms (figure 2.2).

After the emplacement of the Yerington Batholith, a series of subareal intermediate to silicic composition lavas, domes ignimbrites and volcanoclastic rocks which form the Fulstone Spring Volcanics are deposited in Early Jurassic period and are preserved in the Buckskin range on the western part of the Yerington district. Fulstone Spring Volcanics consist of the Churchill Canyon Sequence and hornblende dacite porphyry intrusions. The Churchill Canyon Sequence are dacitic to lactitic metavolcanics and crystal rich tuffs, while Hornblende dacite porphyry which appears in the northern part of the Buckskin thrust have texture and composition similar to some of the flows of the Churchill Canyon Sequence. A series of quartz monzodiorite porphyry dikes cut across the Fulstone Spring Volcanics which are commonly emplace along faults which bound and downdrop the Yerington batholith. The base of the Fulstone Spring Volcanics is suggested to possibly be of the same age as the youngest granite porphyry dikes associated with the Luhr Hill Granite because the Fulstone Spring Volcanics includes quartz latite lava flows and dikes, breccia and ignimbrites that are porphyritic in appearance.



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TR-Triassic, JR-Jurassic, T-Tertiary. Grey box marks area covered by airborne data

Following a prolonged period of non-deposition and erosion, a series of Oligocene and early Miocene ignimbrites and some Miocene andesitic lava flows form the Singatse Volcanics which encrust parts of the Yerington batholith and associated dikes in the Yerington district. Singatse Volcanics includes the Mickey pass tuff, Singatse tuff, Hornblende Andesite of Lincoln Flat and some Basaltic intrusions. The Mickey Pass Tuff consist of rhyolitic unwelded tuff, quartz latite ash flow tuff, sedimentary tuff and crystal rich tuff with plagioclase, biotite and augite, while the Singatse Tuff is a quartz latite ash flow tuff. The hornblende Andesite of Lincoln Flat consist of intrusive and volcanic hornblende biotite porphyritic andesites, the phenocryst are embedded in aphanitic groundmass of plagioclase, quartz, biotite, hornblende, magnetite and apatite. The hornblende andesite of Lincoln Flat also intrudes as dike in several part of the system and in some places occurs as hornblende-biotite dacite quartz porphyry dike. These rocks are also present in the Buckskin range. The Basalts are small intrusive bodies of pyroxene-olivine or olivine-clinopyroxene composition.

In terms of structure, the Yerington district was cut by three sets of Cenozoic normal faults that have tilted the Mesozoic rocks to about 70-90°W (figure 2.1). The Yerington batholith is bounded by faults on its north and south sides which drops the batholith down to within 2.5km to around 4 km thereby preserving the mineralized portion of the magmatic hydrothermal system. The faults dip steeply away from the batholith and thus appear as either steep reverse fault, vertical faults or steep normal faults that have been deformed slightly during and after the emplacement of the batholith. Tight non cylindrical fold axes parallel and wrap the Yerington batholith along its southern margin and may have likely been formed during the emplacement of the Yerington batholith.

2.2. Hydrothermal Alteration and Mineralization

Magmatic-Hydrothermal alteration associated with McLeod Hill and Bear intrusions: The intrusion of McLeod Hill quartz monzodiorite and Bear quartz monzonite produced hydrothermal fluids which are considered unrelated to mineralization. Alteration associated with these intrusions predates porphyry dikes which are associated with the Luhr Hill granite. These intrusions are thought to be responsible advanced argillic and sericitic alteration in the overlying Artesia Lake Volcanics. The Bear intrusion also produced low temperature alteration assemblages of k-feldspar, sericite, chlorite and pyrite. The emplacement and crystallization of McLeod Hill and possibly the Bear intrusions are related to the formation of garnet-pyroxene hornfels and pyroxene-plagioclase endoskarn.

Magmatic hydrothermal alteration associated with Luhr Hill granite: The magmatic hydrothermal fluids resulting from the Luhr Hill granite produced series of porphyry dike-centred alteration and mineralization zones.

Magmatic fluids from the Luhr produced potassic alteration, while it is suggested that the mixture of the magmatic fluid with circulating groundwater produced sericitic and advanced argillic alteration. Sodium-calcium alteration is also predominant in Yerington district and it is associated with the Luhr hill intrusion. Sodium calcium alteration represents sodium or calcium metasomatism and it is characterized by addition of sodic plagioclase, actinolite, epidote and sphene to rocks. It is perceived that in all parts of Yerington, hydrothermal alteration progressed from deep potassic alteration to shallow sericitic or advanced argillic alteration.

At Ann-Mason and MacArthur area, propyllitic-actinolite occurs at intermediate depth of 2.5-4.5km. It is characterized by addition of actinolite, epidote, chlorite, minor calcite, hematite, sulphide and magnetite in the mafic mineral sites and by weak alteration of plagioclase to epidote, white mica and clays. *Mineralization Model:* Based on the emplacement, crystallization history and the behaviour of copper, zinc, molybdenum and gold in the Yerington batholith and associated ores, the theoretical model that hypersaline magmatic hydrothermal fluids evolve during crystallization of the batholith is dependable. The ore deposits in Yerington district are located less than 4km depth, however the source granite extends more than 4 kilometre depth which is probably not exposed in most part of the system.

Prominent hydrothermal ores deposits associated with the Yerington Batholith include porphyry copper, copper-iron skarn, iron and copper skarn replacement, copper gold veins deposits. The generic pattern is from copper with or without molybdenum porphyry mineral mineralization in the central part of the batholith with copper skarns localized at proximal distance, while copper-iron replacement of carbonates or low temperature skarn and copper-gold quartz veins lie farther away. The granite porphyry dikes have spatial and temporal relationship with magmatic-hydrothermal fluids, associated hydrothermal alteration and porphyry Cu-Fe±Mo sulphide mineralization. In the proximity of porphyry dike swarms above the Luhr Hill cupolas, the hydrothermal alteration and Cu-(Mo) sulphide mineralization is most intense and resulted in the formation of at least four porphyry copper deposit; Yerington, Ann-Mason, Bear and MacArthur deposits.

Large zones of sodic-calcic alteration underlie the ore zones which are formed either contemporaneously with or after the potassic alteration. The upper part of the ore zone is characterized by sericitic alteration which contains more pyrite than chalcocite and it postdates the underlying potassic alteration. Marginal mineralization to the Yerington Batholith show strong zonation of andradite-diopside skarns typically containing chalcopyrite-pyrite mineralization in the proximity of the batholith and in association with granite porphyry dikes. Large amounts of magnetite and significant chalcopyrite-pyrite mineralization is related to distant mineralization in carbonate rocks. The magnetite-chalcopyrite-pyrite mineralizations are younger than the hornfels and are locally associated with anhydrous diopside andradite skarn but also commonly associated with late hydrous minerals (calcite, chlorite, talc, actinolite with or without epidote).

Veins type deposits which are generally not associated with porphyry dikes occur in the Triassic Volcanics at the eastern margin of the batholith, in the roof Jurassic Artesia Lake batholith or locally within the batholith. Chalcopyrite and pyrite occur within majority of the veins and are more associated with wallrock alteration characterized by alteration in which chlorite replaces the mafic minerals and feldspar altered to potassic feldspar and albite.



Figure 2.2: Pre-tilt conceptual model of the Yerington hydrothermal system (Dilles et al., 2000) Due to Cenozoic faulting and tilting the top of the system is now westward (see figure 2.1).

Alteration Type	Symbol	New (added) and recrystallized minerals ^a	Relict minerals ^b
Pre main stage	ES-1	Grandite and labradorite (An_{50-58}) \pm Dio + Rt	Olg/And + Sph ± Hbl ± Afsp
Endoskarn	ES-2	Olg/And(An_{21-36}) ^c + Dio \pm Hbl+ Tit \pm Qtz (\pm Epi)	
Sodic-calcic	S-1	Olg/And° + Tit +Qtz ± Rt	Olg/And + Sph
	S-2	Olg/(Alb)° + Act +Otz +Tit +Epi (±Pyr)	Olg/And + Sph
	S-3	Olg/(Alb)° + Qtz + Tit + Epi ± Act + (±Chl)	Olg/And + Hbl +Sph ± Afsp
	S-4	Olg/Alb° + Qtz + Sph +Epi +Act	Olg + Sph
Weak sodic-calcic	S-5	Olg/Alb◦ + Qtz + Sph +Epi +Act	Olg + Afsp + Sph
	SW	Epi + Sph ± (Olg)/Alb◦ ± Qtz ±Act ± Bt ± Ser ± Pyr (±Chl ± Rt)	Olg + Afsp + Hbl + Sph (± Mgt)
Potassic	B WB	Afsp + Alb ^d + Bt + Qtz + Cp \pm Bn \pm Mo + Rt \pm Chl ^e Bt + Epi + Qtz +Alb ^d + Cp \pm Bn or Py + Rt \pm Ser ^e \pm Cc \pm Chl ^e Bt + Epi \pm Cp \pm Qtz	Olg + Afsp + Bt Bt ± Olg ± Afsp + Mgt ± Sph (± IIm) Olg + Afsp + Hbl ± Mgt + Sph
Propylitic	PA	Act \pm Bt + Chl + Alb ^d + Epi + Hm + Ser \pm Cc +Rt \pm Pyr + Tml (\pm Cp)	Olg/And +Afsp + Hbl ± Bt + Mgt + Sph
Late stage Chloritic	PC B	Chl + Rt \pm Qtz Chl + Hm \pm Py \pm Ser \pm Cc \pm Alb ^d \pm Epi (\pm Cp \pm Verm) Chl + Alb ^d + Hm + Rt \pm Epi \pm Pyr \pm Ser \pm Cc (\pm Cp \pm Verm)	Alb ± Afsp ± 2nd Bt ± Bt + Mgt ±Epi+Rt (±Cp) Afsp + Mgt ± Olg
Sodic (albitic)	A-1	Olg/Alb ^c + Chl ± Verm + Rt ± sph ± Py ± Qtz	OIg ± 2nd Bt ± Rt ±Cp (± Mo)
	A-2	Alb + Chl + Ser + Rt + Py (±Tml ± Verm)	(±Cp)
	Atm	Alb + Tml + Rt + Pyr ± Chl ±Ser	± Afsp (±Cp)
Sericitic	SQ TBx	Ser +Qtz + Pyr + Rt (\pm Cp \pm Tml) Tml + Qtz +Pyr + Rt \pm Ser (\pm Cp)	(± Cp)
Table 2.1: Hydrot	thermal alterati	on assemblages in Ann-Mason after (Dilles & Einaudi, 1992)	lage and is therefore largely retrograde
^a Minerals in parer	theses occur i	n trace amounts; others listed in order of abundance	
^b Quartz, apatite a	nd zircon are f	oresent as relict minerals in all assemblages	
^c Specifies compos	sitional range f	present in the assemblage ; a sample may content large amount of An content	
^d Albite forms pse	sudomorphs af	ter primary igneous plagioclase	
^e Mineral is comm	only present, b	out textures suggest that it partially or entirely postdates formation of assembl	

COMBINING DOMINANT SPECTRAL FEATURES IN SWIR AND TIR AIRBORNE IMAGERY FOR MINERALOGICAL MAPPING.

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Figure 2.3: Maps of Alteration zones covering parts Ann Mason, Blue Hill and MacArthur area of the Yerington district.(Dilles & Einaudi, 1992), unpublished maps (Dilles, 1995, 2001) Geologic map in background for orientation

3. GENETIC RELATIONSHIP BETWEEN PORPHYRY-EPITHERMAL-SKARN-SYSTEM

3.1. Linkage between Porphyry-Epithermal-Skarn System

Porphyry systems are generally considered an upright cylinders consisting of coaxially distributed alteration zones, silicate and sulphide mineralization centre on felsic stock usually of porphyritic texture (Sillitoe, 1973). The mineralization zone with potassic alteration is enveloped by zone of sericitic, propylitic and advanced argillic alteration, with the formation of hypogene advanced argillic alteration coming at the waning stage of the porphyry system. The epithermal mineralization accompanies advanced argillic alteration, silicification, propylitic alteration and have been proven not to be fringe products of mineralization in propylitic altered rocks(Sillitoe, 1973).

Several examples of spatially associated porphyry and epithermal ore deposits have been identified, some of which genetic linkage have been proven while for others their genetic linkage remain contentious (Beaudoin et al, 2005; Duuring et al., 2009; Hedenquist & Arribas, 1998; Heinrich et al, 2004; Sillitoe & Hedenquist, 2003). In areas where the two deposits are linked, it implies a physical and chemical link between the deposits. While the possibility of volatile phase separation from a single magma chamber at depth which is then transported as a whole to epithermal environment is considered (Hedenquist & Arribas, 1998), alternatively fluid may separate into two phases at the source or during ascent in which the less viscous and more buoyant phase are transported to the epithermal environment (Heinrich et al., 2004 and cited works)

Detailed study of porphyry system indicated that early potassic alteration formed from hot (>400 ° C) hypersaline fluid of magmatic origin whereas sericitic alteration are produced by less saline fluid of possible mixture of meteoric and magmatic fluid (Dilles et al., 2000; Hedenquist & Arribas, 1998). Sericitic-clay-chlorite alteration is typical and overprints potassic alteration as observed in most porphyry style deposits (Hedenquist & Arribas, 1998) and are interpreted as the linking channel ways for gold transporting vapour derived fluid for epithermal deposit (Heinrich et al., 2004). The advanced argillic alteration which produces the epithermal deposits forms from extremely acidic fluids that were progressively neutralised by wallrock interaction away from the flow channel. However, not all porphyry system evolve to the stage where they form an overlying epithermal environment, despite the susceptibility of most porphyry system to develop an extensive lithocap of hypogene advanced argillic alteration due to vapour saturation from hypersaline fluid, although there is also the argument that the epithermal zone might have been eroded away during uplift in systems where they are absent (Pirajno, 2009; Sillitoe, 1973).

Additionally, where mineralizing pluton is emplaced in the region of carbonate rich sedimentary rocks, skarn are formed as a result of contact metamorphism. Two main categories of skarn are recognised based on the rock replaced (Einaudi, 1982); exoxkarn are formed when the rock replaced are carbonate rich rocks, whereas the replacement of intrusives or aluminous rocks result in the formation of endoskarn.

3.2. Alteration Types and Mineral Assemblage in Porphyry-Epithermal-Skarn System

Hydrothermal alterations can be described in terms of their chemistry or mineral assemblage. Studying hydrothermal alteration associated with a deposit provide an insight into the genesis as well as spatial and temporal transition between different parts of the system (Hedenquist & Arribas, 1998; Pirajno, 2009). The following alteration types and their mineral assemblages are commonly associated with porphyry-epithermal-skarn system.

- Potassic alteration: It occur predominantly in the basal part on porphyry-epithermal mineralizing system(Hedenquist & Arribas, 1998; Pirajno, 2009; Sillitoe, 1973). It results from the introduction of potassium into alumina-silicate rocks, leading to replacement of calcium and sodium by potassium (Beane & Bodnar, 1995). Hornblende and plagioclase are replaced by hydrothermal potassium feldspar. Common assemblages include K-feldspar, biotite, quartz, chlorite and vary proportion of other minerals such as albite, sericite, magnetite, apatite, anhydrite and occasionally rutile (Pirajno, 2009).
- Phyllic alteration: It occurs widely in porphyry-epithermal system where in some cases overprints potassic alteration (Beane & Bodnar, 1995; Hedenquist & Arribas, 1998; Pirajno, 2009). This alteration type grades into potassic alteration by increasing amount of k-feldspar and also into advanced argillic by increasing amount of clay (Pirajno, 2009; Sillitoe, 1973) and has been interpreted as link between porphyry deposit and epithermal deposit (Hedenquist & Arribas, 1998). This alteration type is characterized by quartz, sericite and pyrite (QSP), additionally k-feldspar, kaolinite, calcite biotite, apatite, anhydrite and rutile may be associated with QSP (Pirajno, 2009). Presence of increasing amount of topaz, tourmaline and quartz indicate a transition from phyllic towards greisen type of alteration.
- Propylitic alteration: In this alteration type, biotite and hornblende are altered to chlorite which is commonly associated with hematite. Anorthite component of the original plagioclase is converted to epidote, calcite and sericite while albite content is preserved (Beane & Bodnar, 1995).
- Argillic alteration: This alteration type is characterized by the presence of montmorillonite, illite, chlorite, kaolinite group clays and minor sericite but also k-feldspar (albite) may remain unaltered (Pirajno, 2009).
- Advance argillic alteration: This alteration type differs from intermediate argillic alteration in that there is complete destruction of feldspars and iron bearing silicates (Beane & Bodnar, 1995). It usually consists of dickite, kaolinite, pyrophyllite, barite, alunite and diaspore. Topaz, tourmaline and amorphous clay may also be present (Pirajno, 2009).
- Skarn alteration: Alteration of carbonated rocks adjacent to mineralizing pluton produces assemblage of garnet, epidote, clinozoisite, clinopyroxene, wollastonite, diopside, tremolite-actinolite, phlogopite, biotite and andradrite (Pirajno, 2009). Exoskarn which are commonly associated with porphyry copper deposit are divided into calcic skarn which consist of garnet, clinopyroxene and wollastonite minerals formed when the rock replaced is non magnesian limestone, while magnesian skarn result from replacement of dolomitic rock and are characterized by assemblage of fosterite, talc, tremolite, and serpentine (Einaudi, 1982).

Although there are transitional types and continua in many alteration process, these are best describe as endmembers for conveniences(Pirajno, 2009).

Alteration Type	Mineral Assemblage
Potassic	K-feldspar, biotite, sericite, chlorite, quartz, anhydrite, hematite, actinolite
Sodic, Sodic-Calcic	Albite, actinolite, epidote Clinopyroxene(diopside), chlorite, scapolite
Propylitic	Epidote, chlorite, calcite, albite, sericite, clay, pyrite, actinolite
Phyllic	Sericite, quartz, pyrite, chlorite, biotite, rutile, chalcopyrite
Intermediate Argillic	Kaolinite/Dickite, Sericite (illite-smectite), montmorillonite, feldspar,
	quartz, pyrite, calcite, epidote
Advanced Argillic	Quartz, kaolinite/dickite, pyrophyllite, alunite, diaspora, rutile, zunyite,
	alumino sulphate-phospahte, native sulphur, pyrite, hematite
Skarn Clinopyroxene, wollastonite, garnets, actinolite/tremolite, ve	
	pyroxene, epidote, serpentine-talc, calcite, chlorite, illite-smectite, nontronite

Table 3.1: Summary of alteration types, mineral assemblages modified after (Thompson & Thompson, 1996) and (Pirajno, 2009). Key minerals in bold letters

3.3. SWIR Spectrally Identifiable Minerals Associated with Porphyry-Epithermal-Skarn System

The spectral description given in this section is based on the review of the work of Clark et al., (1990) and examination of spectral information provided by Pontual et al (1997) in spectral interpretation field manuals. Many Minerals show diagnostic absorption in the region of 0.3-3 μ m which is as a result of vibrational overtones, electronic transitions, charge transfers and conduction processes (Clark et al., 1990). These diagnostic absorption features are related to OH (~1.4 μ m), H₂O (~1.4 μ m and ~1.9 μ m), AlOH (~2.16-2.22 μ m), FeOH (~2.23-2.295 μ m), MgOH (~2.3-2.36 μ m) and CO₃ (~2.3-2.35 μ m) occur at characteristic wavelength bands (Pontual, Merry, & Gamson, 1997). For the sake of consistency, description and characteristics of mineral spectra given below are in micrometre (μ m) since the unit of airborne data is micrometre.

Sericite group: Illite $(Ca_{0.05}Na_{0.03}K_{0.61})(AI_{1.53}Fe^{+3}_{0.22}Fe^{+2}_{0.03}Mg_{0.28})(Si_{3.4}AI_{0.6})O_{10}(OH)_2$ Muscovite $K_2AI_4[Si_6AI_2O_{20}](OH,F)_4$

This group of minerals are characterized by absorptions related to H_2O and OH vibrations. Absorption at ~1.400µm indicates the presence of OH while the absorption at ~1.900µm indicates the presence of molecular water (Clark et al., 1990). Their diagnostic absorptions occur at ~2.200µm and it's related to AIOH vibrations, additional absorption is observed at ~2.350 and 2.450µm (Clark et al., 1990; Duke, 1994). The change in chemistry within the sericite is manifested spectrally as a shift in the position of AIOH absorption wavelength position (Duke, 1994; Swayze et al., 1992). The shift in AI-OH absorption wavelength in sericite results from substitution of FeMg₋₁ for AI in the octahedral site and Tschermak substitution which involves substitution of Al₂Si₋₁(Mg,Fe)₋₁ in the octahedral tetrahedral site (Deer, 2003), this provides a means to determine variation in the chemistry of sericite from spectral data using depth of AIOH absorption and absorption wavelengths between 2.190-2.202µm are categorized as normal potassic sericite, AI-OH absorption in the range of 2.210-2.215µm are categorized as tending towards phengite, while at AIOH absorption at ~2225nm are classified as phengite (Pontual et al., 1997). Differentiation between illite and muscovite is usually based on the depth of ~1.900µm which is shallow in muscovite when compared with illite (figure 5.1A and figure 5.1B).

Smectite Group: Montmorillonite $(\frac{1}{2}Ca, Na)_{0.7}(AI, Mg, Fe)_4[(Si, AI)_8O_{20}](OH)_{4.1}H_2O$ Smectites similar to sericites have absorption related to the presence of OH and H₂O but there are little differences between the two groups. Similar to sericites, smectites have absorptions at ~1.400µm, ~1.900 µm, and ~2.200µm, however the ~1.400µm and ~1.900µm feature is much wider in smectites (figure 5.1C) giving the absorption features asymmetrical shape (Pontual et al., 1997). Additionally the double absorption features at 2.350µm and 2.450µm present in sericite is absent in smectites (Clark et al., 1990).

Kaolinite Group:KaoliniteAl₄[SiO₁₀](OH)₈HalloysiteAl₄Si₄(OH)₈O₁₀8H₂ODickiteAl₄[Si₄10](OH)₈

This group of minerals show doublet absorptions related OH and AIOH near 1.400µm and 2.200µm (Clark et al., 1990). Kaolinite has doublet absorptions at ~1.389µm and ~1.410µm and another doublet at ~2.162µm and 2.206µm related to AIOH vibrations with the 2.206µm absorption having greater depth than the 2.162µm absorption (figure 5.1E). The H₂O related absorption at ~1.900µm is subtle and may be absent in highly crystalline kaolinite. In dickite the doublet near 1.400µm which occur ~1.384µm and ~1.418µm is more pronounced likewise is the ~1.9µm absorption related to H₂O, the doublet related to AIOH vibration occur at ~2.178µm and ~2.206µm with the two absorptions features having relatively the same depth. In Halloysite the OH doublet occurs at ~1.389µm and ~1.410nm but could shift slightly to higher wavelength with increasing hydration, the AIOH doublet occur at ~2.166µm and ~2.206µm. The

effect of hydration on AIOH absorption feature is a decrease in depth of the \sim 2.166µm absorption with increasing hydration (Pontual et al., 1997).

Chlorite Group: Mg Chlorite, Mg-Fe Chlorite, Fe Chlorite (Mg,AI, Fe)₁₂[(Si,AI)₈O₂₀](OH)₁₆

The chlorite group of minerals contain AI, Mg and Fe in varying proportions which influences the position and shape of the spectral features of the chlorite endmembers. The Fe content influences the position of MgOH and FeOH absorption wavelength which causes shift in the position of these absorption bands. For Mg-Chlorite the FeOH and MgOH absorptions occur at ~2.245µm and 2.325µm,

in the case Mg-Fe Chlorite, the FeOH and MgOH absorptions occur at 2.254µm and 2.347µm, while for Fe-Chlorite the FeOH and MgOH absorption occur at 2.261µm and 2.355µm. Additionally the Mg-chlorite has a shoulder at 2380nm which makes it distinctive (Pontual et al., 1997).

Carbonate Group: Calcite CaCO₃

Dolomite CaMg(CO₃)₂

The absorptions in carbonates are associated with planar CO_{3}^{-2} ion with the band position varying with composition as observed between calcite and dolomite (Clark et al., 1990). Carbonates typically show five absorptions, two prominent absorptions lie at longer wavelength and are more intense than the three at shorter wavelength (Hunt, 1977). The positions of CO_{3}^{-2} absorptions in calcite are at ~1.880µm, ~1.992µm, ~2.156µm and ~2.340-2.345µm. In dolomite the absorptions are at ~1.865µm, ~ 1.940µm, ~2.140µm and ~2.320-2.328µm although due to water the ~1.940µm might be absent in some cases (Pontual et al., 1997).

Sulphate: Alunite (K,Na)Al₃(SO₄)₂·(OH)₆ Jarosite KFe₃(SO₄)₂(OH)₆

Alunite exhibit double absorptions associated with OH vibrations at ~1.40 μ m (Clark et al., 1990), the position of the doublet absorption near 1.40 μ m may vary with composition (Pontual et al., 1997). The next absorption feature whose position can also vary occurs between 1.700-1.800 μ m. The main alunite feature in the SWIR is a broad absorption produced by AIOH vibrations which lies at ~2.160-2.170 μ m with minor shoulders ~2.0 μ m, ~2.050nm and 2.200 μ m (figure 5.1D) (Pontual et al., 1997). The variation in the position of this feature in alunite is influenced by the chemical composition (presence of Na, K or NH₄ in alunite chemistry).

Jarosite is characterized by diagnostic absorptions occurring at ~1.844-1.855µm associated with OH vibrations, ~2.262-2277µm associated with FeOH with a shoulder occurring at 2.206µm.

Epidote: Ca₂Fe⁺³Al₂O·OH·Si₂O₇·SiO₄

In the visible region, epidote is dominated by Fe³⁺ ligand field transition with bands ~0.366µm, ~0.457µm, ~0.473µm and ~0.616µm, the three bands at ~1.357µm, ~1.409µm and ~1.548µm are probably due of OH vibrations (Clark et al., 1990). Subtle absorption occur at ~1.830nm and ~1.947µm (figure 5.2A and 5.2D) which persist even in mixed spectral (Pontual et al., 1997). Prominent absorptions occur at ~2.256µm and ~2.339µm which are attributed to combination of OH stretches and FeOH bending (Clark et al., 1990; Pontual et al., 1997).

Pyrophyllite: Al₄[SiO₈O₂₀](OH)₄

Pyrophyllite is characterized by single sharp absorption band related to OH vibrations in visible region at ~1396nm. The AIOH absorption which is also a sharp absorption occur ~2.166 μ m, additional absorption occur at ~2.319 μ m (Clark et al., 1990; Pontual et al., 1997). The other absorptions at 2.066 μ m and 2.078. μ m are sometimes not resolvable (Clark et al., 1990).

$\textbf{Tourmaline:} \quad (Na,Ca)(Mg,Li,AI,Fe^{+2})_3AI_6(BO_3)3Si_6O_{18}(OH)_4$

Tourmaline is characterized by four distinctive absorptions at ~2.205 μ m, ~2.249 μ m, ~2.299 and at ~2.369 μ m which is related AIOH, FeOH and MgOH vibrations (figure 5.1F).

Amphibole: Actinolite/Tremolite Ca₂(MgFe⁺²)₅[Si₈O₂₂](OH,F)₂

Hornblende NaCa₂(MgFe⁺²)₅AlSi₇O₂₂(OH)₂

Actinolite is characterized by four absorption bands due to OH linked with Mg₃, Mg₂Fe, MgFE₂ and Fe₃ (Clark et al., 1990). These absorptions occur at ~1.399µm, ~2.117µm, ~2.314µm and ~2.384µm. The ~2.117µm absorption is absent in tremolite which enables differentiation actinolite from tremolite while the occasional presence of a shoulder at ~2301 enables differentiation of actinolite from hornblende (Pontual et al., 1997). Spectrally, hornblende is very similar to other amphibole particularly actinolite, having absorption features at ~2.117µm, ~2.314µm and ~2.384µm (figure 5.2C).

3.4. TIR Spectrally Identifiable Minerals Associated with Porphyry-Epithermal-Skarn System

The description given in this section is of emissivity spectra of minerals which are based on examination of emissivity spectra of minerals after converting United States Geological Survey (USGS) (Clark et al., 2007) and Johns Hopkins University (JHU) (Salisbury & D'Aria, 2001) hemispherical reflectance spectral libraries into emissivity using Kirchhoff's law, hence spectral feature described are emissivity low in the spectra. The description of these spectra features in reflectance spectral is provided by Salisbury et al., (1991). Conversion of spectral measured in hemispherical reflectance is necessitated in other to facilitate comparison of laboratory derived spectral to that of remotely sensed data which is usually in emissivity since currently used algorithms rely on identifying minima band position, depth of minima and shape for identification and classification. Converting TIR spectra to emissivity enable identification of emission minimal (Reststrahlen feature) diagnostic for minerals.

Most minerals have a broad feature between 2.5-5.5µm, although few minerals have features within this range which can be used to identify the presence even in mixed spectral.

Quartz: SiO₂

Quartz show spectral features related to Si-O-Si stretching vibrations which is the dominant vibration type in silicate minerals. Quartz has characteristic double spectral feature at ~8.3µm and ~9.2µm which are approximately of the same depth, the depth of the spectral features may vary with spectral contrast which is influenced changing particle size (Salisbury et al., 1991). Additionally weak doublet occurs at ~12.5µm and 12.7µm (figure 5.4A). The ~9.2µm feature usually is the position of emissivity minimal in quartz spectra and the position vary from 8.8-9.25µm as determined from reference library.

Feldspars:	Microcline	KAISi ₃ O ₈
	Albite	NaAlSi ₃ O ₈
	Andesine	(Na,Ca)AI(AI,Si)Si ₂ O ₈
	Oligoclase	(Ca,Na)(AI,Si) ₄ O ₈

Microcline display four spectral features between 8-12µm associated with Si-O-Si stretching, the spectral features occur at ~8.5µm, ~9.1µm, 9.4µm and ~9.8µm. The deepest feature varies between the 9.4 µm and 9.8 µm feature. Albite is characterized by four spectral features between 8-12µm. The first occurring at ~8.4µm, the second spectral feature which is subtle is centred at ~9.2µm, this is followed by a doublet ~9.6µm and ~9.9µm with the ~9.6µm feature occurring as the deepest spectral feature in albite spectrum. Beyond 12µm albite has four weak spectral features $\sim 12.6\mu$ m, $\sim 13.0\mu$ m, $\sim 13.3\mu$ m and $\sim 13.8\mu$ m (figure 5.5C). Andesine has five spectral features between 8-12µm in which the depth and intensity of the spectral features decreases with increasing wavelength. The features occur at ~8.4µm, ~8.7µm, ~9.2µm, ~9.6µm and at 9.9µm. Andesine is spectrally similar to albite but they differ in the depth of the features which is more pronounced in albite. The deepest feature in andesine occurs at ~9.6µm for pure andesine, but when mixed with quartz, the presence of quartz might result in the ~8.4µm or ~9.2µm becoming the deepest feature. Beyond 12µm, there are weak features ~12.5µm, ~12.9µm and ~13.0µm. Oligoclase has a spectral

feature at ~8.6µm and another feature at ~9.6µm which can sometimes form a weak doublet resulting in ~9.6 µm and 9.8µm features

Garnet:	Grossular	Ca ₃ Al ₂ (SiO ₄) ₃
	Andradite	Ca ₃ Fe ⁺³ ₂ (SiO ₄) ₃

In grossular, the first spectral feature occur at ~6.2 μ m, the main spectral feature occur ~10 μ m due to Si-O-Si stretching, the position of this spectral feature ranges from 10-10.5 μ m which can sometimes be a doublet depending on the composition. A doublet feature characteristic of garnets occurs at 11.6 μ m and 11.9 μ m in grossular (figure 5.5E). Andradite display a weak spectral feature at ~6.4 μ m, the spectral feature associated with Si-O-Si stretching vary between 10.1-10.4 μ m. Doublet spectral feature also occur with the position varying from 11.6-11.9 μ m and 11.9-12.3 μ m (5.5D).

Carbonate Calcite CaCO₃

Dolomite CaMg(CO₃)₂

The spectral features observable in carbonates are predominantly due fundamental internal molecular vibrations of CO₃ ions, these features occur near 7 μ m, 11.3 μ m and near 14 μ m (Salisbury et al., 1991). The near 7 μ m feature was found to occur at ~6.4 μ m in both calcite and dolomite. The next feature occurs at ~11.1 μ m for dolomite and ~11.3 for calcite (figure B.5B), the near 14 μ m feature occurs at ~14.0 μ m in calcite and at slightly lower wavelength than 14 μ m in dolomite (13.75 μ m).

Vesuvianite: $(Mg,Fe^{+2},AI)_3(AI,Si)_4O_{10}(OH)_2 \cdot 4H_2O$

Vesuvianite is characterized by a deep narrow spectral feature at ~9.7 μ m associated with Si-O-Si stretching and a weak spectral feature at ~10.9 μ m. Other weak features occur at ~11.2 and ~12.6 μ m (figure 5.6A).

Serpentine Mg₃Si₂O₅(OH)₄

Serpentine uniquely characterised by a single prominent feature in the TIR which is centred at ~9.5 μ m and weak shoulder feature at ~9.1 μ m

Amphibole:	Actinolite	$Ca_2(MgFe^{+2})_5[Si_8O_{22}](OH,F)_2$
	Hornblende	NaCa ₂ (MgFe ⁺²) ₅ AlSi ₇ O ₂₂ (OH) ₂

Actinolite and hornblende have five spectral features between 8-12 μ m occurring at ~8.7 μ m, ~9.2 μ m, ~9.6 μ m, ~10 μ m and 10.9 μ m. The ~10 μ m spectral feature is the deepest feature in both minerals but generally deeper in actinolite than in hornblende. The spectral feature at ~9.6 is subtle and broad in hornblende, where as it occur as sharp narrow feature in actinolite. Actinolite has additional spectral feature at ~13.2 μ m which is absent in hornblende.

Epidote: Ca₂Fe⁺³Al₂O OH Si₂O₇SiO₄

Epidote has double spectral feature in the MWIR region at ~3.4 μ m and 4.1 μ m. This is followed by weak doublet at 5.1 μ m and 5.4 μ m. In the TIR, epidote is characterized my three main features between 8-12 due to Si-O-Si stretching occurring at ~9.3, 10.3 and 11.3 μ m. The ~9.3 μ m feature shows band shift. The 10.3 μ m feature is the deepest feature in epidote, addition subtle feature occur at 11.6 μ m which can sometimes be absent. Beyond 12 μ m, doublet feature occur at ~14.5 and ~15 μ m with the ~15 μ m feature been deeper than the ~14.5 μ m

Sericite and smectite:	Muscovite	$K_2AI_4[Si_6AI_2O_{20}](OH,F)_4$
	Illite	$(Ca_{0.05}Na_{0.03}K_{0.61})(AI_{1.53}Fe^{+3}_{0.22}Fe^{+2}_{0.03}Mg_{0.28})(Si_{3.4}AI_{0.6})O_{10}(OH)_2$
	Montmorillonite	(½Ca,Na) _{0.7} (Al,Mg,Fe) ₄ [(Si,Al) ₈ O ₂₀](OH) _{4.} nH ₂ O

Muscovite has its first TIR feature at \sim 6.5µm which is present in most clay minerals, the diagnostic feature of muscovite is a doublet at \sim 9.1 and 9.4µm associated with Si-O stretching (Farmer & Russell, 1964; Vedder, 1964). These spectral features are also present in illite but the spectral features in muscovite are relatively deeper

compared to illite particularly the ~9.4 μ m feature. Also muscovite has additional spectral feature at 11.7 μ m and 12.6 μ m which is absent in illite.

Montmorillonite is spectrally similar to illite in shape and depth of spectral features but the position of spectral features vary slightly in montmorillonite as it occurs at \sim 8.9µm and \sim 9.3µm, the \sim 9.3 being the position of emissivity minimal.

Kaolinite: Al₄[SiO₁₀](OH)₈

The spectral features of kaolinite in TIR lies mainly between 8-12 μ m. Kaolinite like other clays have its strongest spectral feature at ~9.4 μ m, additional features can lie at ~8.85 μ m and 9.9 μ m. Weak spectral feature can sometimes be present at ~11 μ m associated with OH stretching (Farmer & Russell, 1964; Vaughan et al., 2003).

Alunite: (K,Na)Al₃(SO₄)₂ (OH)₆

Alunite has a spectral feature in the MIR at ~5.0 μ m. In the TIR region, the first spectral feature occurs at ~7.9 μ m which show positional shift possibly related to variation in composition, next feature is doublet at ~8.5 μ m and ~8.9 μ m, the 8.5 μ m is relatively narrow compared to ~8.9 μ m (figure 5.5F). Additionally a broad feature whose position vary from 13.7-14.4 μ m also occur in alunite.

Chlorite: (Mg,AI, Fe)₁₂[(Si,Al)₈O₂₀](OH)₁₆

Chlorites have one main spectral feature in TIR occurring at ~9.7 μ m with the presence of shoulder features on both side of the 9.7 μ m feature. The shoulder features occur at 9.3 and 10.3 μ m respectively. In intermediate chlorites the 10.3 μ m is absent.

Pyroxene:	Augite	(Ca,Na)(Mg,Fe,AI,Ti)(Si,AI) ₂ O ₆		
	Hedenbergite	$CaFe^{+2}Si_2O_6$		
	Diopside	MgCaSi ₂ O ₆		

Augite and hedenbergite generally have their most intense spectral feature at ~8.9 μ m, followed by a doublet at ~10.5 μ m and ~10.8 μ m. Additionally, there is the presence of a feature ~5.6 μ m. For diopside deepest feature occur ~10.3 μ m which is the first of a doublet, the second occurring at ~10.8 μ m. Other features which occur in other pyroxenes also occur in diopside at ~8.9 μ m and ~5.6 μ m.

4. METHODOLOGY

Understanding of alteration patterns and distribution of alteration minerals involves identifying both SWIR and TIR active minerals in rock samples collected from the study area, establishing a relationship between SWIR and TIR identified minerals and subsequently implementing the association determined from rock samples analysis on airborne data.





4.1. Laboratory Spectroscopy

4.1.1. Dataset and Instruments

For this research 101 rock samples collected in 2009 from Yerington area served as the major source of spectral information to identify minerals and to establish association between minerals active in both wavelength ranges. The instruments used for spectral analysis of samples are the FieldSpec Analytical Spectral Device (ASD) which operates in the Visible to Shortwave InfraRed and the Bruker Vertex 70 Fourier Transform Infrared (FTIR) spectrometer which operates in the Near Infrared to the Thermal Infrared, analysis was carried out at University of Twente ITC Faculty spectral laboratory.

The FieldSpec ASD operates between 350-2500nm spectral range, with 3nm spectral resolution at 700nm and 10nm resolution at 1400/2100nm, the sampling interval is 1.4nm at VNIR and 2nm at SWIR regions (ASDInc, 2013). For this research an average of 50 spectra was chosen for each spectral measurement.

Characteristics			
Spectral range	350-2500nm		
Spectral	3nm at 700nm		
Resolution	10n at 1400/2100nm		
Sampling	1.4nm at 350-1000nm		
Interval	2nm at 1000-2500nm		
Light Source	Internal lamp (contact probe)		
Channels	2151		
Detectors	VNIR- 512 element silicon array		
	SWIR 1-Graded index InGaAS Photodiode, TE Cooled		
	SWIR 2- Graded index InGaAS Photodiode, TE Cooled		

Table 4.1: Summary of ASD specification (ASDInc, 2013).

The Bruker FTIR spectrometer works in the 10000-600 cm⁻¹ (1.6-16.7µm) spectral range. It measures through a modified integrating sphere with a sample port of 30mm which enables hemispherical reflectance measurement (Hecker et al., 2011). For comparison with remote sensing data, emissive or directional hemispherical reflectance (DHR) measurement geometry with integrating sphere is required (Salisbury et al., 1991). The integrating sphere is a 150nm diameter block of aluminium blasted with glass pearls before being gold-coated by galvanization to a thickness of 3µm to create highly-diffuse reflecting surface. The sphere is connected to the spectrometer's external ports through a connecting funnel.

Component	SWIR/TI	Description	Cooling	Range (cm-1)	Range (µm)
	R				
Source	TIR	Globar source 150	Water cooled	10000-600	1.6-16.7
		W(external)			
Beamsplitter	TIR	Ge on KBr Splitter	n/a	7800-370	1.3-27.0
Detector	TIR	MCT midband	Liquid	10000-600	1.6-16.7
		detector (on	nitrogen		
		integrating sphere)	-		

Table 4.2: Specification of UT-ITC thermal infrared spectrometer used for directional-hemispherical reflectance measurement. Modified after Hecker et al., (2011).

The Mercury Cadmium Telluride (MCT) detector is positioned at the top such that the folding mirror restrains and prevents the reflection from directly entering the detector. To reduce the effect of CO_2 and water on the measurements, a hygroscopic was placed continually inside the instrument compartment and nitrogen gas is continually passed through the interferometer compartment. This flows to the integrating sphere through the connecting funnel during measurements.

4.2. Measurements, Data Correction and Interpretation

4.2.1. SWIR Measurement, Data Correction and Interpretation

SWIR measurement was done using the ASD. Measurements with the ASD was carried out on 101 rock samples, targeting fresh surface in the samples as much as possible and also capturing variation observed in the samples. For samples which show a lot of variation in appearance, multiple measurements were taken from such samples.

Splice correction was applied on the spectral measurements obtained using the splice correction algorithm in ViewSpecPro software, after which the corrected spectra were converted to ASCII format which is compatible with other software. Splice correction is done to correct for slight offset in spectral resulting at the splice point between detectors (ASDInc, 2008). The derived spectra are then interpreted using The Spectral Geologist (TGS) software and Spectral Analyst in ENVI. The dominant SWIR active minerals in the spectra were interpreted using The Spectral Assistant (TSA) and Auxillary Match (AuxMatch) algorithms in TSG. The AuxMatch algorithm allows matching of mixed spectral with a library which contains mixed spectra of minerals. ENVI Spectral Analyst tool was also used for spectral matching against USGS spectral library. The spectral absorption (including the main and additional) features used for interpretation are H_2O , OH, AIOH, FeOH, MgOH and CO₃. In addition to identifying to mineral identification, the wavelength position of the deepest absorption feature between 2.1 and 2.4 μ m was also determined.

4.2.2. TIR Measurements, Data Correction and Interpretation

TIR measurement was done using Bruker FTIR spectrometer. At the start of each day's measurement, the detector is filled with Nitrogen liquid and allowed to cool for at least thirty minutes. Nitrogen gas setted at 100L/h was used continually to purge the entire system. Substitution method of measurement was adopted which involves measuring a reference material (gold plate) and then followed by measurement of the sample. For each sample, gold plate is measured once after system purge of two minutes, the gold plate is replaced by the sample followed another two minutes of system purge which precedes eight repeated measurements of the sample. The eight spectrums for each sample was later average into a single spectrum. The sample is placed on a material covered with aluminium foil to prevent reflectance from other sources, the aluminium foil covered material along with the sample on it is then placed on a laboratory jack (figure 4.1). The sample is aligned as much as possible to cover the whole 30mm sample port except in few cases of samples with irregular geometry.

Each measurement cycle takes approximately forty minutes. The measurement was done on same surface as the SWIR measurement was done except for few samples for which the shape is not proper alignment under the aperture. Recorded spectral measurement is between 4000-625 cm⁻¹ (2.5-16 μ m). The ratio of reference measurement and sample measurements convert the spectrum to reflectance percentages. The external globar source was left running for two weeks of the entire measurement but nitrogen purge gas is turned off at night.

Because a small fraction of incoming energy is reflected off the edge of the sphere, rather than the sample itself, correction for background radiation was applied to both gold plate and sample measurements before a ratio of the two is performed (Hecker et al., 2011). This is done by measuring an empty sample port and the subtracting the empty measurement from gold plate and sample measurements. Opus converter algorithm in HypPy software was used to extract the reference and sample measurements including the empty port measurements which are used to generate reflectance spectra of the samples. More detailed description of the procedure of correction can be found in Hecker (2011). The laboratory spectral measured in hemispherical reflectance were further converted into emissivity using Kirchhoff's law which proves that the addition of reflectance and emissivity of a material to be equal to one with the assumption that transmission is negligible, thus emissivity can be calculated by subtracting the reflectance measured from one using the formula

$$(\varepsilon = 1 - r)$$

4.1

To interpret spectral measurements from samples, TIR spectral library from United States Geological Survey (USGS) and Johns Hopkins University spectral libraries were also converted to emissivity using Kirchhoff's law. Matching of reference spectra against measured spectra was done using ENVI spectral analyst algorithm. For mineral identification, both the spectral absorption features in the MWIR and TIR regions were used, additionally the wavelength of minimum position in each sample spectral between 8.0 and 11.7µm was determined.

4.3. Preprocessing of SEBASS data

Due to the presence of striping in the apparent emissivity data provided, the original radiance data had to be reprocessed into emissivity while introducing destriping into the processing chain to eliminate the striping in the image. The processing adopted is similar to that adopted by Hecker (2012a) which involves spectral subsetting, bad pixel detection, destriping, atmospheric correction and emissivity calculation but with the exclusion of the normalization step which more suitable when dealing with relatively small homogeneous area.

Spectral subsetting. Application spectral subsetting was done in two phases, before correction for striping and secondly before calculation of emissivity. The last four bands (125-128) of SEBASS generally show significant amount of striping, introducing these bands into the processing chain will introduce noise into the data (Hecker, 2012a), and these bands has also been reported to contain no significant information for mineralogical mapping (Cudahy et al., 2000), as such these bands were removed. Correction was performed separately on each flightline so as to give optimal result. After correction for bad cells, striping and noise, some bands were found to contain a residual atmospheric effect which affects emissivity calculation. These bands occur at both ends of the spectral, and are therefore removed before emissivity calculation

Destriping and Removal of bad cells: Bad cell detection and destriping was achieved using pushbroom plugger and destriper algorithm (Mason, 2000). The algorithm assumes average ground composition for each flightline, such that all columns in a particular band should have the same average radiance value. Where the mean and/or standard deviation of a single column differ by more than three standard deviations from that of all other columns, the detector cell is flagged as a bad cell and its values replaced by interpolation of the neighbouring cells. Once the bad cells are removed, each image band was destriped by normalizing the response of all cells of the same wavelength band. The mean and standard deviation of individual image column is calculated for each wavelength band, likewise the mean and standard deviation of the entire image band (μ_{total} and σ_{total}) is also calculated which is then used to calculate new radiance value for each pixel (Hecker, 2012a; Mason, 2000).

$$\mu_{x} = \frac{1}{n} \sum_{y=1}^{n} Rad_{x,y} \qquad \sigma_{x} = \sqrt{\frac{\sum_{y=1}^{n} (Rad_{x,y} - \mu_{x})^{2}}{n}} \qquad 4.2$$

$$\mu_{total} = \frac{1}{mn} \sum_{x=1}^{m} \sum_{y=1}^{n} Rad_{x,y} \qquad \sigma_{total} = \sqrt{\frac{\sum_{x=1}^{m} \sum_{y=1}^{n} (Rad_{x,y} - \mu_{total})^2}{mn}} \qquad 4.3$$

Where μ_x and σ_x are the mean and standard deviation of individual image column, μ_{total} and σ_{total} are the mean and standard deviation of an entire image band, x and y are column and row numbers, m and n are the total number of rows and $Rad_{x,y}$ is the original radiance value for pixel x, y before destriping. The new radiance is then calculated after destriping

$$Destriped_Rad_{X,y} = \left(Rad_{x,y} - \mu_x\right) \frac{\sigma_{total}}{\sigma_x} + \mu_x$$

$$4.4$$

Because bad cell and destriping algorithm assume average composition across all image columns, surface features which are not related to geology such as buildings, agricultural fields and water bodies were masked out from the processing allowing only bare ground to go into the calculation of statistics. Vegetation has significant effect on spectral features of underlying geology and when in excess the variation in the radiance of underlying rocks are difficult to detect (Vaughan et al., 2003), hence area with much vegetation needs to be excluded from the calculation.

Noise reduction: Noise reduction was achieved through Minimum Noise Fraction (MNF) transformation. MNF was applied on each flight scene. MNF which is similar to Principal Component Analysis (PCA) but depends on signal-to-noise ratios and thus invariant under scale changes to any band. MNF generates new eigenvectors from the data but differs in that the resulting components show steady decrease in information contained (Green et al., 1988). Usually MNF partitions the data space into two parts, one part with large eigenvalues and coherent eigenimages and the other part with near-unity eigenvalues with images which are noise dominated (Kruse et al., 1997). Examinations of the results MNF forward transform show that first 40 components contain information related to surface materials. A threshold of 40 MNF components was chosen to prevent noise going into the subsequent processing steps and also preserve sufficient spectral information. The 40 components were then used for inverse MNF transform which transform the selected 40 MNF components back into image space. *Atmospheric correction and T*_E*S*: To correct for atmospheric effects, the In-Scene Atmospheric Compensation (ISAC) was applied (Johnson 1999; Young 2002). The correction was implemented in Exelis visual information

(ISAC) was applied (Johnson, 1998; Young, 2002). The correction was implemented in Exelis visual information solutions ENVI software. The ISAC correction applied is based on (Young, 2002) model of radiance reaching a single pixel of SEBASS sensor which is expressed as

$$L(\lambda) = \varepsilon(\lambda)B(\lambda,T)\tau(\lambda) + L_{u}(\lambda) + [1-\varepsilon(\lambda)]L_{d}(\lambda) + \tau(\lambda)$$
4.5

Where λ is the wavelength, $\epsilon(\lambda)$ is the surface emissivity spectrum, $\tau(\lambda)$ is the transmissivity spectrum of the atmosphere for the path between the surface and the sensor, $L_u(\lambda)$ is the upwelling atmospheric radiance for the same path and $L_d(\lambda)$ is the hemispherical downwelling radiance from the entire sky, $B(\lambda,T)$ is the planck radiation function.

ISAC compensates for atmospheric effects by empirically estimating atmospheric properties from the image scene based on statistical information it extracts from the scene to be corrected. It has the advantage of not requiring meteorological information or complicated radiative transfer modelling (Hecker, 2012a).

ISAC assumes uniformity of atmosphere across a flightscene and that a blackbody is present within the scene. This involves determining a reference wavelength from the data which is then used to determine the atmospheric properties of the scene. There reference wavelength can either be the wavelength which has the brightest temperature in most pixels or the wavelength with the brightest temperature in the entire data. In the case of the wavelength with the brightest temperature in most pixels, the algorithm determines the wavelength which often has the maximum brightness temperature for most pixels, this wavelength is adopted as the reference wavelength. Atmospheric compensation is then calculated from only pixels which has the brightest temperature at this wavelength (this is referred to as most-hits) (Young, 2002). Alternatively, the wavelength with the maximum value of brightness temperature found throughout the input wavelength can be adopted as the reference wavelength. At each wavelength the reference blackbody radiance values is plotted against the measured radiances. A line is fitted to the highest points in the plotted data, the fit is weighted to assign more weight to regions with dense sampling (Exelis Visual Information Solution, 2013; Young, 2002). The use mosthits was underperforming for some flightscenes due to the fact that the wavelength for which the temperature is highest is not usually the same for all pixel (Young, 2002), thus temperature for each pixel was calculated using the maximum value of brightness temperature found throughout the input wavelengths. The atmospheric upwelling and transmission are then derived from the slope and offset of the line fitted for the plot of brightness temperature against radiance at the reference wavelength.

After atmospheric correction using ISAC, temperature-emissivity separation ($T \in S$) was applied using the emissivity normalization (ENorm) procedure. The ENorm calculates temperature for each pixel assuming constant emissivity for the band and the maximum temperature calculated is set as the pixels's temperature. Once the temperature is determined, the emissivity and Planck curve are calculated using a constant emissivity value of 0.96 (Hecker, 2012a; Kealy & Hook, 1993; Vaughan et al., 2003). Division of the original spectrum by Planck curve gives a separated output of emissivity and temperature.

Planck curve gives a separated output of emissivity and temperature. Due to the presence of residual atmospheric effects spiking is introduced into the data particularly around 12µm which tend to influence emissivity calculation, the wavelength from which emissivity was calculated was reduced to 8-11.7µm which is the range for which most mineral have their diagnostic TIR features.


Figure 4.2: Flowchart of SEBASS pre-processing (Modified after Hecker, 2012a)

4.4. Geometric Rectification

In addition to ProspecTIR-VS and SEBASS data provided, geographic location file for each flight line of each dataset was also provided. For ProspecTIR-VS flightscenes, the geographic location files were provided as geographic lookup table (GLT) files, each GLT file contains map locations for every pixel in the image for which it is associated. The GLT files were used to georeference 11 flightlines where was subsequently mosaicked using nearest neighbourhood resampling without application of feathering and linear stretching while retaining 4m pixel size. For the SEBASS dataset, the geographic location files were provided as geometry files, the geometry files were used to build GLT files which was subsequently used to georeference SEBASS flightlines. 33 SEBASS flightlines were georeferenced and mosaicked using nearest neighbourhood resampling and output pixel size of 4m. No feathering and linear stretching was used while mosaicking.

4.5. Mineralogical Mapping

To determine the spatial distribution of minerals in the study area, two approaches were considered;

- I. Combining the two dataset and analysing the combined data.
- II. Analyse each data independently and combining the results.

4.5.1. Principal Component Analysis

Reduction of dimensionality of hyperspectral data is one way to use hyperspectral data efficiently and also reduce the effect of Hughes phenomenon (Pal, 2012). Hughes phenomenon relates to the dimensionality of hyperspectral data which results in decreasing accuracy with increasing number of features given as input training data for classification beyond a particular threshold (Melgani & Bruzzone, 2004). Principal component analysis (PCA) is one of the commonly adopted methods for dimensionality reduction in remote sensing image processing (Richards, 2013; Rogge et al., 2007).

PCA involves transformation of multivariate data into new coordinate system. In the case of remote sensing images, the multiple variables are the different wavelengths of hyperspectral image. In PCA each pixel is represented in a vector space with as many axes or dimensions which equal the number spectral component associated with the pixel. Each pixel plot as a point in the vector space with coordinates which corresponds to its brightness value in the spectral components (Richards & Jia, 2006).

Mathematically the position of pixel points in spectral space is described by column vectors, the components of which are the individual spectral responses in each band. In a spectral space containing large number of pixels with each pixel described by its appropriate vector \mathbf{x} , the mean position of the pixels is defined by the expected average value of the pixel vector \mathbf{x} , this is mathematically presented by Richards (2013) as

$$m = \varepsilon \left\{ x \right\} = \frac{1}{\kappa} \sum_{k=1}^{K} X_k$$
4.6

Where *m* is the mean pixel vector and X_k are individual vectors of total number K, and ε is the expectation operator. While the mean vector determines the expected position of the pixels in the vector space, the spread of the pixels is determined by the covariance matrix which determines the spread of the pixel around the mean. The covariance matrix is a square symmetric matrix of size [bands x bands] where the diagonal elements are the band variance and off-diagonals represent covariance between bands (Exelis VIS, 2000).

The covariance matrix is defined Richards (2013) as

$$\mathbf{C}_{x} = \varepsilon \{ (\mathbf{x} - \mathbf{m})(\mathbf{x} - \mathbf{m})^{\mathrm{T}} \}$$
 4.7

The unbiased estimate of covariance matrix is given as

$$C_x = \frac{k}{K-1} \sum_{k=1}^{K} (X_k - m) (X_k - m)^T$$
4.8

The correlation matrix whose elements (r_{ij}) are related to elements of covariance matrix (c_{ij}) mathematically by equation 4.8 explains the degree of mathematical correlation between the data dimensions.

$$r_{ij} = C_{ij} / \sqrt{C_{ij} C_{jj}} \tag{4.9}$$

The transformation by PCA thus involved genereation covariance matrix of the data in the coordiantes of the original spectral measurements, followed by finding the eigenvalues and eigenvectors of the covariance matrix,

the eigenvalues are then ranked to identify the principal axes in order of decreasing eigenvalues and finally generation of new brightness values for pixels in each of the principal axes using the matrix of eigenvectors (Richards, 2013). Alternatively principal components can be computed from transformation matrix derived from the eigenvector of the correlation matrix instead of the covariance matrix. This tend to equalize the effect of each band, inflating the influence of bands with relatively small variance and reducing the influence of bands with high variance (Exelis VIS, 2000).

PCA as it implemented in ENVI involves mean correction which involves subtracting the mean of the data before the data is projected to the transformation matrix which is computed from either the eigenvector of covariance matrix or correlation matrix. This mean-correction produces an origin shift in the resulting PCA such that its mean spectrum is zero in every band. Adjusting the origin by mean-correction does not change the properties of the resulting PC image because PCA is a rotation while mean shift is an additional translation which improves the contrast of resulting PC images (Exelis VIS, 2000; Richards, 2013).

ProspecTIR-VS reflectance data of 82 bands was combined with SEBASS emissivity data of 74 bands giving an output data of 156 bands. PCA was applied on combined data using using transformation matrix derived from correlation. Because the data on which PCA is performed is a combiantion of data from two different sensors, also the data are in different using with ProspectTIR-VS image in reflectance and SEBASS data in emissivity, correlation matrix was used because it has been proven to outperform covariance matrix as it is capable of accounting for the large variances in multiscale data (Leis, 2011; Shen et al., 2010).

4.5.2. Wavelength Mapping

Wavelength mapping is a method which identifies minerals in hyperspectral data using the wavelength with minimum reflectance (emissivity minimum in TIR) value within a specified range which can be linked to minerals having absorption in that range. Creation of wavelength maps is a two-step approach. The first step involves determination of the deepest absorption position in the specified wavelength interval. To accentuate spectral absorptions a continuum removal is applied on the wavelength range for which the deepest absorption position is been determined (van Ruitenbeek et al., 2014). Continuum removal is a mathematical function used to isolate a particular absorption feature for analysis of a spectrum. The continuum is removed from the reflectance

spectrum by calculating convex hull which is then used to divide the reflectance spectrum (Clark & Roush, 1984).

$$D_B \equiv \frac{R_C - R_B}{R_C}$$
 4.10

Where D_B is the band depth, R_B is the reflectance at band centre and R_C is the reflectance of the continuum at the band centre.

The application of continuum removal in spectral analysis normalises the spectral and also account for wavelength scattering which imparts the slope of spectral resulting in apparent shift in the band minimum (Clark & Roush, 1984). Continuum removed spectra enable characterization of absorption features associated with certain minerals in terms of their position, depth, width and asymmetry (Clark & Roush, 1984; van der Meer, 2004). The wavelength position of deepest absorption feature is then determined from the continuum removed spectrum through interpolation by fixing second order polynomial to the three consecutive bands where the centre band has the lowest reflectance (van Ruitenbeek et al., 2014). Interpolation is based on simple quadratic method by Rodger et al., (2012) which assumes that the spectrum measured by an instrument of finite sampling interval across a finite spectral region will have its absorption centre located near or at the deepest recorded point after continuum removal and can be sufficiently modelled by fixing second order polynomial across the three data points located in neighbourhood of the maximum absorption of interest (Rodger et al., 2012; van Ruitenbeek et al., 2014). Calculation of interpolated minimum wavelength position and depth from the resulting parabola (fig. 4.4) by van Ruitenbeek et al., (2014) is given as

$$u(x) = ax^2 + bx + c \tag{4.11}$$

where w(x) is the interpolated reflectance value at position x, x is the wavelength position in μ m, while a, b, c are the coefficients of the parabola function.

$$w_{min} = -\frac{b}{2a} \qquad depth = 1 - f(w_{min}) \qquad 4.12$$

where w_{min} is the interpolated wavelength position at the minimum reflectance, a and b are the coefficient of the parabola, and depth is the interpolated depth of the absorption feature.



Figure 4.3: Interpolation method for determining the wavelength position of minimum reflectance of an absorption feature by fitting a parabola through three data points in the immediate vicinity of maximum absorption feature and applying continuum removal. (van Ruitenbeek et al., 2014)

The result of the interpolation is an image that contains interpolated minimum wavelength position of the deepest absorption feature and the depth of this feature relative to continuum as separate bands for each

pixel, the two bands are subsequently fused together to form three band image for visualization where the wavelength position determine the hue and the depth of the feature control the intensity, this is done by transforming RGB colour image of wavelength position into HSV colour space so that Hue (H) is determined by the wavelength position in the image, Saturation (S) is set to 1 for all pixels and Value (V) is obtained from the depth of the absorption feature (van Ruitenbeek et al., 2014).

Wavelength mapping was applied of ProspecTIR-VS using wavelength of minimum reflectance and on SEBASS data using wavelength of emissivity minimum.

4.5.2.1. SWIR Infrared Data Comparison

In order to determine which of the two atmospheric correction methods (ATCOR and VELC) applied on the ProspecTIR-VS data captures the variations between different mineral groups and also gives information comparable to laboratory measurements, it is necessary to adopt an unbiased method. Wavelength mapping provides a way to compare laboratory derived spectral of rocks samples collected from the study area to the spectral of ProspecTIR-VS data corrected using ATCOR and VELC atmospheric corrections. Wavelength maps was created between 2.1 and 2.4µm for the ATCOR and VELC corrected data using the minimum wavelength and wavelength mapping tools in HypPy (Bakker, 2012). Some disparity was observed in the wavelength maps generated from the two dataset, hence it necessary to determine which of the two dataset is more comparable to lab measurements.

To determine this, the spectra of rock samples measured with ASD were used. The laboratory derived spectral is of higher spectral resolution, this implies that direct comparison with image spectral which is of lower resolution will be inappropriate. The interpolated minimum wavelength created for the ATCOR and VELC corrected data through minimum wavelength between 2.1 and 2.4µm was used. The spectral of the sample at each location is compared with that of the two dataset to ensure they are similar, the interpolated minimum wavelength values for the ATCOR and VELC corrected data is extracted, the wavelength position of absorption feature which corresponding to the minimum wavelength in the airborne data is then extracted from the laboratory derived spectral of rock samples collected at each location. For sample location with multiple samples or in which more than one measurement is taken on the sample from the location, the spectral measurement which is most similar to that of the image in that location is used. Comparison was achieved by plotting the values from the ATCOR and VELC data against that of laboratory spectral in a scatterplot.

4.5.2.2. Integration of SWIR and TIR infrared data

An approach to combine the results of wavelength mapping of SWIR and TIR data involve the use of interpolated minimum wavelength position generated during the first step of wavelength mapping. To implement this approach, the method was first applied to spectral derived from SWIR and TIR analysis of rock samples. For each of the rock samples that were analysed, in addition to determining the spectrally detectable minerals, the wavelength position of the deepest absorption feature was determined between 2.1 and 2.4µm for SWIR spectra and between 8 and 12µ for the TIR spectra. The choice to use the wavelength position of the deepest absorption feature was based on the fact that the dominant mineral in each rock sample determines the wavelength of the deepest absorption feature and it allows identification of mineral group in case of noisy spectra (Pontual et al., 1997). The minimum wavelength position determined from SWIR and TIR measurement of samples was plotted against each other in a scatterplot to establish classes of mineral associations. To implement this method on the airborne data, wavelength mapping was applied on the full scene of ProspecTIR-VS and SEBASS airborne data, the result of the first stage of wavelength mapping was then further used to combine the two dataset. The image generated during the first stage of wavelength mapping contains bands with the interpolated minimum wavelength position for each pixel as well as the band for interpolated depth of the absorption feature. By plotting the interpolated minimum wavelength against the interpolated depth for each data, one can have an idea of depth threshold to apply. Depth threshold was applied to eliminate features with shallow depth which are probably not related to mineral absorption.

4.5.2.3. Decision Tree

A decision tree classifier is a multistage classification method which uses a series of binary decisions to place pixels in classes. Each stage of the classification divides the pixel in the image into two classes based on an expression. Decision tree represent Boolean function by combining Boolean yes/no responses into a hierarchical tree-like structure (Aitkenhead, 2008). The basic concept of decision tree is to split complex decision into several simpler decisions which leads to a solution easier to interpret (Safavian & Landgrebe, 1991; Xu et al., 2005). Classification is achieved through repeated use of Boolean yes/no question about specific attributes of the data, attributes may values or properties. Each question or parent node has two daughter nodes which can either be parent node or output nodes for a giving prediction, output predictions are represented as discrete classification (Aitkenhead, 2008). The objective of decision tree is use set of training dataset to build a model of the classes such that it can be used to classify new data whose labels are unknown (Du & Zhan, 2002). Each node of the classes from the remaining classes and this is generally done by moving down the tree until the leaf node is reached (Xu et al., 2005). A number of approach exist for building decision tree, such approach includes bottom-up approach, top-down approach and hybrid approach (Safavian & Landgrebe, 1991).

The Classification And Regression Tree (CART) type of decision tree which is one of the commonest was used because it restrict and simplifies the possible options for how the decision nodes function (Richards, 2013). In this method, only a class is involved in each decision step and a simple threshold is used for making the decision, at each node a decision is used to split the data into two groups, this is done so as to make each subgroup purer than its preceding node. The tree consists of a root node which contains all the data, set of internal nodes (splits) and terminal nodes (leaf), a split is chosen either because the node is purer or can be determined by a single feature. The decision tree algorithm is a supervised classification because it relies on training samples to grow.

In decision tree, a set of independent variables $S_g(x, j)$ is input into a decision tree algorithm where x is an independent variable and j is a dependent variable. The splits are chosen to maximise the reduction of impurity ($\Delta i(t)$) of the parent node t with respect to the impurity of its child node (Safavian & Landgrebe, 1991; Simard et al., 2000) and its given as

$$\Delta i(t) = i(t) - p_l i(t_l) - p_h i(t_h)$$
4.13

Where p_l and p_h are the total proportions of sample in node t that reach into child nodes t_l and t_h . The optimization of impurity is executed by Gini criterion which has been shown to be generally efficient and can also be shown to minimize the resubstitution estimate R(T) which is given below as presented by (Simard et al., 2000).

$$1 - \sum_{i} p^2(j|t)$$

4.14

Decision tree uses decision rule to assign a randomly selected sample x from node t to class j with the probability p(j|t).

Based on the association established using the minimum wavelength position between minerals identified by SWIR and TIR analysis of samples, decision tree was used to combine SWIR and TIR data into mineral assemblages map.

5. RESULTS AND DISCUSSION

5.1. Minerals Identified from SWIR Analysis of Rock Samples

Using the diagnostic absorption features observed in the spectra of rock samples, the SWIR active minerals were identified using both TSG and Spectral Analyst in ENVI. It must however be stated that the reference spectral are collected from relatively pure mineral sample as compared to rock samples measurements that were used in the current study.

Sericite: The sericites identified from sample analysis are illite, muscovite and phengite. The position of the AIOH absorption of Sericites determined from the samples from which only sericite is identified ranges from 2.198-2.220µm (figure 5.1A and 5.1B)

Montmorillonite: The position of AIOH absorption identified lie between 2.206-2.211µm. This fall in the range of AIOH absorption in sericites, differentiation from sericites was based on the secondary doublet features which are present in sericites at 2.35µm and 2.45µm (figure 5.1C).

Alunite: Alunite occurs in samples collected from the Buckskin range. The alunite identified are the sodic variety with the position of AIOH absorption ranging from 2.169-2.188µm (figure 5.1D). Alunite occur typically in regions of argillic alteration and are formed at temperature below 320°c in porphyry epithermal system (Hedenquist & Arribas, 1998).

Kaolinite: The position of AIOH absorption in kaolinites identified range from 2.207-2.208µm. Differentiation between poorly crystallized kaolinites and halloysite was a bit challenging because they have their AIOH absorption in the same wavelength range, the depth of secondary feature was used in differentiating. The depth of the secondary features is more pronounced in kaolinites compared to halloysites.

Tourmaline: Tourmalines are unique with four absorption features associated with AIOH near 2.20 μ m, FeOH near 2.24 μ m and 2.29 μ m and MgOH near 2.36 μ m. The tourmalines identified differ spectrally in the position of their deepest absorption feature which is influence by their chemistry and the other mineral present in the sample. The type of tourmaline identified in most samples is the Fe-Tourmaline which has its deepest absorption at ~2.24 μ m. In samples where the tourmaline occurs with sericites, the near 2.20 μ m becomes the deepest feature as it is influence by the presence of sericite (figure 5.1F). The MgOH absorption was found to be the deepest feature in only one of the tourmaline identified.

Epidote: The prominent absorption in epidote associated with MgOH overlaps with that of chlorite, this can sometimes makes distinction between the two difficult. However, in epidote additional feature usually occur at 1.83µm which is absent in chlorite and also persist in mixed spectral. The position of MgOH in identified epidote ranges from 2.332-2.356µm (figure 5.2 D)

Chlorites: In most of the samples in which chlorites are found, it occurs in mixture with sericite, smectite or epidote. In some samples, chlorite dominates while the spectral feature of the other mineral occurs additionally. For samples in which only chlorites were identified, MgFe-chlorites and Mg-chlorite were identified while in mixtures it is sometimes difficult to determine which type is present.

Hornblende: Hornblende and actinolite belong to the amphibole group of minerals and are quite difficult to distinguish spectrally. While hornblende is a normal rock forming mineral occurring in mafic rocks, it can also be formed in during contact metamorphism. Actinolite is a product of alteration of pyroxene in mafic to intermediate rocks. The main absorption in hornblende and actinolite is driven by MgOH near 2.316µm, and additional features occur at 2.388µm and 2.2520µm. It was found that the 2.316µm absorption feature is deeper in actinolite and in addition a small absorption feature occur at ~2.112µm in actinolite which is relatively absent in hornblende. This ~2.112µm feature in actinolite persist in mixed spectral and helps determine which of the two minerals is present in mixtures (figure 5.2C)

Vesuvianite: Two samples were found to contain vesuvianite of which the two samples were collected from the same sample location. Vesuvianite is a contact metamorphism mineral found in skarn area. The two

samples are collected from clastic and calcareous lithologic unit which is adjacent to Yerington batholith. Most of these calcareous sediments have been altered to skarn and they host some skarn deposits. Initial interpretation of spectral from these samples was carbonate with halloysite, but after TIR analysis in which vesuvianite was uniquely identified, comparison with SWIR spectral of vesuvianite indicates its presence with carbonate (figure 5.2B). In the SWIR vesuvianite has features at 0.935 μ m, a doublet occur at 1.401 μ m and 1.435 μ m related to OH vibrations, H₂O feature occur at 1.983 μ m with a shoulder at 1.918 μ m. Next is a doublet at 2.2150 μ m and 2.355 μ m with a subtle absorption feature occurring between the doublet at 2.2950 μ m.



Figure 5.1: Reflectance spectra of (A) Sericite (Illite) with varying position of AIOH absorption (B) Sericite (Muscovite) (C) Montmorillonite (D) Alunite (E) Kaolinite. (F) Tourmaline. Spectra displayed in continuum removed. Reference spectra in dashed line. 09ch*** - sample number. Spectra displayed in continuum removed.

Mixed spectral: As discussed above, some spectral contain feature from more than one mineral, which is usually the case in most of the analysed sample. Spectral mixtures result in the modification of spectral of the dominant mineral. Generally the feature of one mineral dominates while the features of other minerals occur as additional weak and shallow feature, but it can sometimes be suppressed where more two mineral influences the observed spectral. Although TGS has spectral library of mixtures which were used for some of the interpretations, the library does not capture all the type of mixture found in the sample studied. Interpretations were thus based identification of the position of the deepest feature in the spectrum and followed by identifying mineral(s) with additional feature(s) present. Common mixtures found are sericite+epidote. sericite+chlorite. chlorite+sercite. epidote+sericite. actinolite+sericite. hornblende+sericite. To differentiate a mixture of epidote and sericite from a mixture of chlorite and sericite, the 1.83µm feature in epidote persist in mixed spectral as such it serves as a key to for identification (figure 5.2D), this feature is also useful when interpreting sericite dominated spectral in which epidote occur as additional mineral. In the case of hornblende and actinolite, spectral feature in actinolite is generally deeper than in hornblende, also actinolite has as subtle spectral feature at 2.115 µm which is absent in hornblende (figure 5.2C).



The summary of identified minerals can be found in table A.2 (appendix)

Figure 5.2: Reflectance spectra of (A) Epidote (B) Vesuvianite+Carbonte (Dolomite) (C) I-Horblende+Sericite, II-Actinolite+Sericite (D) I-Chlorite+Sericite, II-Epidote+Sericite. Reference spectra in dashed lines. 09ch*** - sample number. Spectra displayed in continuum removed.

Spectral	Spectral Group	Identified Mineral	Origin	
Range (µm)				
2.160-2.89	Sulphate	Alunite	Hydrothermal origin	
2.190-2.25	Sericite	Illite/Muscovite	Hydrothermal origin	
	Smectite	Montmorillonite	Hydrothermal origin	
	Kaolinite	Kaolinite	Hydrothermal and secondary origin	
		Halloysite	Hydrothermal and secondary origin	
2.226-2.99	Sulphate	Jarosite	Secondary origin	
	Other minerals	Tourmaline	Hydrothermal origin	
		Opal	Hydrothermal and secondary origin	
2.3-235	Amphibole	Hornblende	Igneous process, contact	
			metamorphism	
		Actinolite	Hydrothermal origin	
	Chlorite	Chlorite,	Hydrothermal origin	
		Intermediate chlorite		
	Epidote	Epidote	Hydrothermal origin	
	Others	Vesuvianite	Contact metamorphism	

Table 5.1: Range of position of deepest absorption features (reflectance minimum) of identified minerals between 2.100-2.400µm.

5.2. Comparison of ATCOR and VELC data with Laboratory Spectra

The wavelength minima of obtained from the spectra of ground samples is plotted against interpolated minimum wavelength of VELC and ATCOR data at each sample location. The result shows two spectral groups of minerals, the AIOH group and the MgOH group. For the AIOH mineral group, both the ATCOR and VELC data gives interpolated values which is considerable close to the minimum wavelength of spectral from rock samples. The VELC data however captures variation associated with the AIOH absorption better. In the case of MgOH absorption, the ATCOR data does not sufficiently account for variation within this mineral group, the interpolated minimum wavelength value for MgOH minerals as estimated by the ATCOR data is more or less the same value even when the sample measurements show variation within the MgOH mineral group.



Figure 5.3: (A) Scatterplot of sample minimum wavelength against interpolated minimum wavelength of ATCOR data between 2.150-2.400µm (B) Scatterplot of sample minimum wavelength against interpolated minimum wavelength of VELC data between 2.150-2.400µm.

5.3. Minerals Identified from TIR Analysis of Rock Samples

TIR analysis of rock samples is dominated by silicates minerals that are not OH bearing such as quartz, feldspar, garnet. Few samples in which OH bearing silicates are identified contain mineral such as alunite, kaolinite and illite which are minerals associated with pervasive alteration in which the feldspar in the rock would have been totally destroyed. Mineral identification was done using ENVI spectral analyst using spectral from USGS and JHU as reference spectral. Like in the SWIR, the effect of mixing is also observed in the TIR. The spectral libraries do not contain mixed spectra, interpretation was therefore based on identifying minerals with spectral features at observed wavelength. Usually one mineral dominates while the spectral feature of the other mineral present in the sample occurs as additional weak. Although the 8-12µm range represents the TIR region in which most minerals exhibit diagnostic feature, the range of 2.6-15.5µm which includes the Midwave Infrared (2.5-5.2) region was used in interpretation of laboratory spectral where applicable. In the MWIR, most mineral exhibit a broad spectral feature from 2.5-5.5µm but some few minerals have features in this range.

Quartz: Quartz is one of the dominant minerals present in the samples analysed. The characteristic doublet occurring at ~8.3µm and ~9.2µm with additional doublet occurring at ~12.5µm and 12.7µm which persist in mixed spectral. Based on examination of reference library spectra, the ~9.2 µm is usually the position of emissivity minimal, but occasional, the ~8.3µm might occur as the point of emissivity minimal (figure 5.4A). In mixed spectral, the ~9.2µm in most of the samples is deepest feature, but in four samples in which quartz occur with plagioclase and in a sample in which quartz occur in tourmaline the ~8.3µm was the deepest feature. In samples in which quartz occur with tourmaline, the presence of tourmaline was determined mainly in the MIR with the presence of three spectral features at 3.5µm, 4.0µm and 4.5µm. In figure 5.4B, the lower most spectral in the figure, it could be seen that the ~8.3µm feature is the wavelength of minimum emissivity while in the other two spectral, the ~9.2µm feature is the wavelength of minimum emissivity. In samples where quartz occurs with plagioclase feldspar, the ~9.2µm feature is split into two while additional spectral features of feldspar occur at ~9.6µm and ~9.8µm (figure 5.5A). In mixture of quartz with plagioclase feldspar, the ~8.3µm feature is 5.5B)

Feldspars: Feldspars generally occur with quartz in the interpreted samples, two types of plagioclase feldspar were identified, the intermediate endmember (andesine) and sodic endmember (albite). Although they appear spectrally similar the depth of their features vary but in mixed spectral in which quartz dominates it can be difficult to tell which of the two is present in combination with quartz. In feldspar dominated spectral, the position of emissivity minimal is around ~9.6µm, the influence of quartz is usually manifested by the splitting of ~8.5µm feature in feldspar into two, the splitting occur because the separation between quartz doublet feature occur in this region (figure 5.5B and 5.5C). Potassic feldspar (microcline) was identified only in two samples into samples occurring as additional mineral with quartz which was the main spectrally dominant mineral in the samples.

Garnet: Two types of garnet were identified from sample analysis namely grossular and andradite. The presence of epidote occurring with grossular was detected through the presence of weak spectral features at 3.8μ m, 4.1μ m, 8.9μ m and 9.3μ m (figure 5.5D). Based on reference library, the minimum position in garnets occur between 10-10.5 μ m, however the minimum wavelength position was found to occur beyond 10.5 μ m in samples. In some samples containing andradite the position of minimum emissivity shifts to beyond 11 μ m due to the presence of carbonate (figure 5.5E).

Alunite: Alunite identified in mixed spectral occurring mainly with quartz. Alunite has double feature in the TIR, first a narrow feature at 8.5 μ m and a relatively broad feature ~9.0 μ m. The broad feature which is the position of emissivity minimal in alunite overlaps that of quartz in the TIR as it occurs at ~9.0 μ m. The presence of quartz in interpreted spectral is based on identification of doublet feature ~12.5 μ m and 12.7 μ m (figure 5.5F).

Vesuvianite: Vesuvianite has a narrow feature centred at ~9.67µm followed by a set of weak features at ~10.20µm, ~10.89µm and ~11.19µm. Vesuvianite was identified in two samples collected from same location within the clastic and calcareous lithology (figure 5.6A).

Illite and Kaolinite: illite and kaolinite mixture was identified in two samples, which is the same with the SWIR interpretation for these samples, while mixture of illite and guartz was identified in a number of samples. Both kaolinite and illite have their emissivity minimal at ~9.4µm with kaolinite having another feature at 9.9µm which is absent in illite, the depth of features in kaolinite is deeper than in illite. In a mixture of quartz and illite, the position of minimum wavelength is usually centred at ~9.3µm which is between the wavelength positions of minimum emissivity in both minerals. The spectral looks majorly like quartz spectral but the presence of shoulder absorption at ~9.1µm indicates the presence of illite (figure 5.6B). Mixture of quartz and muscovite results in the deeper depth of ~9.2µm relative to the ~8.3µm in quartz.

Range(µm)	Mineral Group	Identified Mineral	origin	
8.2-9.3	Silica	Quartz	Hydrothermal and secondary origin	
		Opal	Secondary origin	
9.31-9.98	Feldspar	Albite	Hydrothermal and igneous origin	
		Andesine	Igneous origin	
		Microcline	Hydrothermal and igneous origin	
	Clay	Kaolinite	Hydrothermal origin	
		Illite	Hydrothermal origin	
	Serpentine	Antigorite	Metamorphism origin of ultramafics	
	Others	Vesuvianite	Contact metamorphism of carbonate rocks	
9.9-11.5	Garnet	Grossular	Contact metamorphism of carbonate rocks (skarn)	
		Andradite	Contact metamorphism of carbonate rocks (skarn)	
	Others	Diopside	Igneous origin and contact metamorphism of carbonate rocks (skarn)	
		Hornblende/Actinolite	Igneous origin and contact metamorphism of carbonate rocks (skarn)	

The summary	of identified	minerals can l	be found in	table A.3 (appendix	X)
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Table 5.2: Range of Position of deepest features (emissivity minimum) of identified minerals between 8.0-11.5µm.



Figure 5.4: Emissivity spectra of (A) Quartz (B) Quartz+Tourmaline. Reference spectra in dashed line. 09ch*** - sample number.



Figure 5.5: Emissivity spectra of (A) Quartz+Albite (B) Quartz+andesine (C) Albite+Quartz (D) Grossular+Epidote (E) Adradite+Carbonate (F) Alunite+Quartz.

Reference spectra in dashed line. 09ch*** - sample number.



Figure 5.6: Emissivity spectra of (A) Vesuvianite (B) Illite+Quartz. Reference spectra in dashed line. 09ch*** - sample number.

5.4. Mineralogical Patterns from PCA and Wavelength Mapping

To test the two methods to be adopted, a test area was selected. The area selected is southern part of Ann Mason block. The area was selected because it is diversified in terms of lithology. The lithologies covered include McLeod Hill quartz monzodiorite, quartzite, clastic and calcareous sediments, tuffaceous sediments, McConnell Volcanics and Gypsum and andydrite. For the test area, subsets of same spatial extent was created from large scene of ProspecTIR-VS and SEBASS data, the subset of the two images was combined and PCA was applied, while wavelength mapping was applied separately on the subset of each image.

PCA was applied on combined data of 156 bands using transformation matrix derived from correlation matric as it is capable of normalizing the variance between the two datasets. The output of PCA was reduced to 10 components, as the first 10 components already accounts for 99% of variance in the data. Beyond the tenth component (figure B.1 in appendix) the subsequent component are dominated by noise and the percentage of variance explained by subsequent components are minimal as the eigenvalues show no significant difference.

By examining the contribution of input bands to output components, it was discovered that the first component is largely driven by variation in albedo within the SWIR data, the second component like the first component is driven by variation in albedo in the TIR. The subsequent components (3-10) contain information related to surface geology. For visualization and interpretation, choice has to be made on the most appropriate components, selection of three appropriate component enables extraction of meaningful information from the scene. Detailed examination shows that components 3,4 and 6 gives the best contrast for visualization. PC 3 and PC 4 are a slightly negatively correlated but largely uncorrelated, PC 3 and PC 6 are uncorrelated, like wise PC 4 and PC 6 (figure B.2A, B.2B and B.2C in appendix). A difficulty with principal components colour display is that there is no longer one-to-one mapping between sensor wavelengths and colours, instead each colour now represents a linear combination of spectral components (Richards, 2013). Also each component receives contribution from several bands making it difficult to assign the result of a component to a specific mineral. Interpretation of the result of PCA was done in combination with the result of wavelength maps from SWIR and TIR images in which the colours is representative of wavelength position related to minerals.

In the figures below, the area in yellow box is a quartzite unit, which is well distinguished by both PCA of combined data (figure 5.7) and wavelength mapping using SWIR (figure 5.8A) and TIR (figure 5.8B) data, in the result of wavelength mapping using SWIR data the area is dominated by sericite which is a common

component of quartzite while in the TIR it is dominated by quartz, few pixels which have blue colour within the quartzite are pixels in which the \sim 8.3µm feature in quartz becomes the deepest feature, but generally the \sim 9.2µm feature is the dominant position of minimum wavelength in quartz as seen in the quartzite lithology.

The region in red box is a body of gypsum along with a linear carbonate feature next to it. Like the guartzite body the gypsum is also well distinguished by PCA of the combined data and wavelength mapping. With wavelength mapping using SWIR the minimum position of the absorption feature in gypsum at ~2.21µm and in TIR the minimum wavelength position is ~8.6µm, but the linear carbonate feature next to it is a suppressed in the PCA result, same applies to carbonate feature in the blue box where it appears different with carbonate area in green box in which two types of carbonates (calcite and dolomite) which is distinguished by wavelength mapping in the SWIR. Calcite minimum wavelength position lies at slightly longer wavelength than dolomite, while in the TIR wavelength mapping does not really differentiate between the two types of carbonates. The region is white box shows the most variation in terms of mineral identified by SWIR and TIR data using wavelength mapping, in the SWIR this area is dominated by epidote and amphibole while in the TIR it is dominated by two types of garnet, grossular and andradite. In PCA result the distinction between the two garnets is not noticeable and also there is no sharp contrast between regions with carbonate and McConnell Volcanics in which sericite and quartz is conspicuously distinguished with wavelength mapping of SWIR and TIR data. In addition to the differences between the result of PCA and wavelength mapping, it is observed that the terrain also has some influences on the result of PCA.

Wavelength mapping was subsequently applied to the full scene of ProspecTIR-VS and SEBASS data.

The uncorrelated principal components have high contrast in regions in which they contain the most information. Combining the components in RGB visualization result in enhancement of the information in each principal component in in the channel in which it is displayed.





Figure 5.7: Colour composite of three principal components with low correlation. R:PC 3, G:PC 4, B:PC 6





linear carbonate feature by its side, green box is contains calcite and dolomite (lighter tone), in white box is an area with epidote and amphibole. Blue box

contains calcite. In figure 5.8B the in the yellow box is the guartzite unit in which guartz is the dominant mineral identified. In red box is gypsum, the linear carbonate feature beside it can also be seen. Green box and blue box contains carbonate in which there is no differentiation in TIR. White box is an area dominated by garnets. COMBINING DOMINANT SPECTRAL FEATURES IN SWIR AND TIR AIRBORNE IMAGERY FOR MINERALOGICAL MAPPING.



Figure 5.10: Wavelength map created from ProspecTIR-VS between 2.1-2.4µm covering the Yerington porphyry-epithermal-skarn system. See figure 5.9A for look-up table for minerals in wavelength map.



Figure 5.11: Wavelength map created from SEBASS between 8.05-11.65µm covering the Yenington Porphyry-Epithermal-Skam System. See figure 5.9B for look-up table for minerals in wavelength map

In the red circle and similar coloured areas is plagioclase feldspar with interpolated minimum wavelength (~9.6µm), the region is white circle and some similar minimum wavelength ~11.2µm surrounded by yellow circle and other similar coloured areas. Between the carbonates and feldspar dominated areas is a garnet coloured is due to spiking at \sim 8.3µm, region within blue circle and similar coloured areas are dominated by quartz (\sim 9.2 µm). Carbonates with interpolated dominated area with interpolated minimum wavelength between 10.2-10.9µm. 39

5.5. Determination of SWIR and TIR Mineral Association

In order to establish the association between minerals identified by SWIR and TIR analysis of samples, the minimum wavelength position was determined between 2.1-2.4µm for SWIR spectra and between 8-12µm for TIR spectra. The minimum position is determined by the dominant spectrally active mineral within a particular wavelength range. The association between SWIR and TIR mineralogy was first established using the rock sample spectra.

Minerals such as alunite, sericite, smectite, kaolinite, actinolite, hornblende, serpentine epidote and chlorite identified as dominant minerals in the SWIR are plotted on the y-axis while minerals such as quartz, plagioclase feldspar, hornblende, diopside and garnet identified dominant mineral in the TIR are plotted on x-axis. The points which plot between 8.3-8.5µm on the x-axis represent samples in which the ~8.3µm feature in quartz becomes the deepest feature. The first step was to group the minerals based on the dominant minerals identified in by both SWIR and TIR (figure 5.12). Based on association observed between minerals identified from both SWIR and TIR, the plot was reconstructed with emphasis on minerals which plot in well-defined clusters (figure 5.13).

In figure 5.13, the points in 1 represents samples in which association is found between guartz and alunite, the point in 2 represents association between normal sericite and guartz, two samples for which kaolinite and guartz association was found also plot together in this box. The points in 3 represent association between sericite and quartz but in this case the sericite are tending towards phengite, thes are samples for which sericite is identified in the SWIR and the position of minimum wavelength is from 2.210µm and above. The point in 4 represent sample for which association is found between sericite and plagioclase mainly albite, two sample for which association between montmorillonite and albite was found also plot within this group. A sample for which illite dominates in SWIR and TIR with quartz occurring as additional mineral also falls in this box, although clay mineral rarely dominates TIR measurements except in the cases where TIR active minerals occur in little amount. The points in 5 represent samples for which association is found between actinolite and quartz including a sample that contained both hornblende and quartz. The points which plot in 6 represent samples in which relationship is found between actinolite and plagioclase dominantly albite and a sample with andesine. The points in 7 represent samples for which association is found between majorly epidote and quartz and a sample with chlorite and quartz. However 8 represent samples which chlorite and plagioclase as well as epidote and plagioclase are identified in the SWIR and TIR. The samples in 9 are samples for which association between garnets, epidote and actinolite are found as well association between hornblende and diopside. Garnets usually have their deepest feature between 10-10.5µm associated with a broad feature but the effect of mixture sometimes result in the position shifting to longer wavelength. For samples for which the minimum wavelength shifts above 11µm, such samples were excluded as the position is now influenced by carbonate which is not the dominant mineral. This occurs because garnet has a feature in this region which is not the deepest feature but combination with carbonate increases the depth of the feature (5.5E).

Based on the association found between minerals identified from SWIR and TIR analysis of the rock samples, the decision tree algorithm was used to implement the established association on interpolated minimum wavelength images generated from application of wavelength mapping on ProspecTIR-VS and SEBASS data.



Wavelength position of minimum emissivity (µm)

Figure 5.12: Scatterplot of minimum wavelength position between 2.1-2.4µm against minimum wavelength position between 8-12µm obtained from rock sample spectra.



Wavelength position of minimum emissivity (µm) (TIR)

Figure 5.13: Scatterplot of minimum wavelength position between 2.1-2.4µm against minimum wavelength position between 8-12µm with emphasis on mineral assemblage which was implemented on airborne data.

Box	Mineral Assemblage	Number of samples	Associated alteration type
1	Alunite+Quartz	4	Advance argillic in epithermal regime
2	Sericite+Quartz	18	Advance argillic in epithermal regime
	Kaolinite/Halloysite+Quartz	3	and sericitic alteration in transition
			zone between porphyry and
			epithermal regime.
3	Sericite(->Phengite)+Quartz	5	Similar to 2, Advanced argillic and
			sericitic alteration.
4	Sericite + Plagioclase (albite)	10	Sericitic and sodic alteration in
	Smectite+Plagiocase(albite)	2	transition zone between porphyry and
	Halloysite+Plagiocase(albite)	2	slightly in epithermal regime.
5	Actinolite+Quartz	3	Sodic-calcic alteration and propylitic
	Hornblende+Quartz	1	alteration in porphyry regime.
6	Actinolite+Plagioclase(albite)	5	Sodic-calcic alteration in porphyry
	Actinolite + Plagioclase(andesine)	1	regime.
7	Epidote+Quartz	7	Propylitic and partly in chloritic in
	Chlorite+Quartz	1	porphyry regime.
8	Epidote+Plagioclase(albite)	4	Chloritic alteration in porphyry
	Chlorite+Plagioclase(albite)	7	regime.
9	Garnet(grossular)+Epidote	1	Skarn regime.
	Garnet(andradite)+Actinolite	1	
	Garnet(andradite) + Tourmaline	1	
	Hornblende+Diopside	2	7

Table 5.3: Association established between minerals identified from SWIR and TIR analysis of minerals.

5.6. Classification of Airborne Data Based on Established Association

The classification of mineral assemblages identified from SWIR and TIR analysis of rock samples was achieved using decision tree algorithm. Decision tree was implemented via Exelis VIS ENVI software (Exelis VIS, 2015) using the top down approach which involves moving down the tree until the leaf node is reached (figure B.7). The interpolated minimum wavelength images from PropecTIR-VS and SEBASS was combined together into a two band image data after depth threshold has been applied. By plotting interpolated minimum wavelength against interpolated depth, this provide an insight of depth threshold to apply, for ProspecTIR-VS data, several depth thresholds were evaluated after which a threshold of 0.08 was adopted for absorption features that are most related to mineralogy, hence interpolated minimum wavelength with interpolated depth less than 0.08 were masked out (figure B.3A and figure B.3B in appendix). For SEBASS data, similar approach was adopted. A depth threshold of 0.01 was adopted as the depth threshold of interpolated minimum wavelength for absorption features (figure B.4A and fig B.4B in appendix). After application of depth threshold, decision tree was then used to classify the combined interpolated minimum wavelength data into mineral distribution map using a set of decision rules based on association established between minerals identified from SWIR and TIR analysis.

However, because the samples available cannot account for all the minerals identified from the airborne data and also not all minerals identified from sample analysis can be detected by airborne data, the decision rule was modified to incorporate minerals which are present in the image but with no representative rock sample. Carbonate and gypsum are detected from image analysis but with no representative sample, as such the classification using decision tree was designed incorporating gypsum and carbonate (see spectra for gypsum and carbonate from SEBASS data in appendix (figure B.5-A and figure B.5-B). Also pyrophyllite was found to occur with alunite in some areas for which there is also no representative rock sample. The combination of sericite and quartz with the deepest feature of ~8.3µm was due to quartz was not integrated into the decision tree because of spiking due to residual atmospheric effect in some pixels around this wavelength range (figure B.6-A).





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5.7. Evaluation of Patterns in Relation to Lithology and Existing Alteration Maps

The current exposure of the Yerington hydrothermal system is a result of basin and range extension during the Miocene, result in approximately 90° tilt westward. For this reason figure 5.14B is tilted to facilitate interpretation In figure 5.14A above, the red line indicates the cupola of Luhr Hill granite at about 4km paleodepth which is in contact with McLeod Hill unit. The dashed lines are major faults running through the area. Based on the current orientation of the system, the part of McLeod Hill unit hosting the porphyry stock in Ann Mason area is covered by Quaternary sediments. The presumed contact between Luhr Hill granite and McLeod Hill unit currently exposed to the surface is also marked with red line in figure 5.14B. Above this contact in figure 5.14B which correspond to region marked A in figure 5.14A is an assemblage of plagioclase-actinolite which is associated with sodic-calcic alteration. This corresponds to actinolite-plagioclase (6) assemblage determined from airborne data. Gradual overprint of plagioclase-albite assemblage can be seen with complete transition into assemblage of albite-chlorite-sericite-tourmaline-pyrite at about 3km and inclusion of quartz-sericite-pyrite assemblage at about 2km paleodepth in figure 5.14B. This can be related to region B and C in figure 5.14A. Region marked B is characterized chlorite-epidote-plagioclase assemblage (8) with minor actinolite-plagioclase (6) while the region marked C is characterized by assemblage of sericite-plagioclase (4) and sericite-quartz (2 and 3) with minor chlorite-epidote-plagioclase assemblage (8). This reflects increasing alteration intensity towards the top of McLeod unit. The region marked G and H has similar assemblage as regions A and B, the presence of few pixels wrongly classified as garnet-epidote-amphibole (9) is due to actinolite becoming the dominant TIR while epidote/chlorite occur as dominant mineral in SWIR in this region. The minimum wavelength position of actinolite overlaps with that of garnets in TIR. Hydrothermal alteration in the regions G and H is probably not be produce by same set of porphyry dikes as regions A and B because the intrusion of porphyry dikes which produces the alteration was episodic. Also very few porphyry dikes cut across region H as compared to region B. The region marked J which is characterize sericite-quartz (2) is a quartzite unit composed of quartz and sericite. The regions marked as D and E in figure 5.14A with garnet-epidote-amphibole assemblage (9) corresponds with the garnet skarn and garnet pyroxene skarn in figure 5.14B. These skarns are produced by contact metamorphism of clastic and calcareous sediments and tuff breccia during the intrusion of McLeod Hill and Bear intrusions. The While region marked E is not present in the hydrothermal model, it represents skarns which lie most distant to the Yerington Batholith occurring with massive limestone (Einaudi, 2000). While more carbonate occur with garnets within region marked E, its presence in region marked D is minute but occur father from the contact with the batholith (I). This can be explained to be the result of reduced heat reaching the distal sediments. In F two linear feature with sericite(->phengitic)-quartz (3) assemblage can be seen. These linear features occur within McConnell Volcanics which is one of the pre-existing unit before the intrusion of Yerington batholith, one of the linear features is found to be associated to be as associated with the intrusion of porphyry dikes and smaller late intrusion of similar age with Luhr hill granite, no information in the geologic map can be linked with the second one. It may probably be related to similar dike which is not mapped.

The contact between Luhr Hill granite and overlying Bear and McLeod units is not exposed at Blue Hill and MacArthur Area. Both Blue Hill and Mac Arthur are bounded by major fault as such relationship of current rock exposure to the model involves some uncertainty. This is because the Blue Hill and MacArthur block might have been rotated by this fault in addition to Cenozoic tilting. Moreover an attempt will be made.

The regions marked P in Blue Hill, M and N in MacArthur can be considered to be at relatively the same depth (2km) as region B Ann Mason, while region marked Q, R in Blue Hill and L at MacArthur can be considered to be at relatively same depth as region C before tilting and faulting. The assemblages at Blue Hill at this depth up to about 1km are actinolite-plagioclase, albite-chlorite-tourmaline-sericite-pyrite assemblage and quartz-sericite-pyrite (figure 5.14B). Relating this to region marked P, the dominant assemblage is chlorite-epidote-plagioclase (8) with minor actinolite-plagioclase (6) which graduates into epidote-quartz±chlorite assemblage. The zone of epidote-quartz±chlorite (7) in P graduates into sericite (->phengitic)-quartz (3) assemblage in region Q. Region marked R is characterized by sericite-plagioclase-assemblage, chlorite-epidote-plagioclase (8) and minor sericite

quartz (2) assemblages also graduates into region Q which is similar to increasing alteration intensity with decreasing depth observed in regions B and C in Ann Mason. Increase in alteration intensity is reflected in this region, first by destruction of feldspars and subsequently destruction of mafic minerals. Unlike Ann Mason, the presence large zone with actinolite-plagioclase underlying chlorite-epidote-plagioclase was not observed in Blue Hill. The region marked S is characterized by sericite-quartz (2), sericite-plagioclase (4) and minor alunite-quartz (1) assemblages. This assemblage can be considered argillic alteration, a transition towards advanced argillic alteration. Regions can be considered to be at less than 1km depth.

The region marked K with sericite-quartz (2) and region marked T with sericite-plagioclase (4) and sericite-quartz (2) assemblages are younger units of Singatse Volcanics. The presence of sericite assemblages in these rocks in not related to hydrothermal alteration associated with Yerington intrusions as they were emplaced at later periods.

Similar to Blue Hill, at MacArthur the presence of actinolite-plagioclase underlying chlorite-epidoteplagioclase was not observed from the result airborne data, however, the presence of actinolite-quartz (5) occurring with chlorite-epidote-plagioclase (8) and epidote-quartz±chlorite was observed. Above this zone is a region marked M with chlorite-epidote-plagioclase (8), sericite-plagioclase (4) and minor sericite-quartz (2). The region marked L in figure 5.14A characterized by sericite-quartz (2) and sericite-plagioclase (4) assemblage can be linked with quartz-sericite-pyrite occurring at around 1km paleodepth in figure 5.14B. The region marked O with garnet-epidote-amphibole and minor epidote-quartz±chlroite can be linked with skarns and hornfels occurring slightly below 1km paleodepth at MacArthur.

The assemblage at Buckskin range which represents the top of the system which was separated by basin and range extension is majorly sericite-quartz and quartz-pyrophyllite assemblage (advanced argillic alteration) (figure 5.14B). This can be linked with sericite-quartz (2), sericite(->phengitic)-quartz (3) and alunitequartz±pyrophyllite assemblage identified in regions W, V and Y in Buckskin range from airborne analysis. Where pyrophyllite occurs, it occurs with alunite and quartz which then surrounded by alunite and quartz with no pyrophyllite (Lipske & Dilles, 2000). Most of the alunite-quartz±pyrophyllite occur within the Artesia Lake Volcanics but its occurrence within Churchill Canyon Sequence which is part of the Fulstone Spring Volcanics was identified in region W which is contrary to previous report (Lipske & Dilles, 2000). Region marked X dominated sericite-quartz assemblage (2) and minor actinolite-plagioclase and alunite-quartz±pyrophyllite is a McLeod unit. The presence of sericite-plagioclase (4) was also observed within Artesia Lake Volcanics and Metavolcanics of Buckskin range (region marked X). The sericite tending towards phengite or of phengitic (3) composition was most observed in Buckskin Range where it mostly surrounds sericite-quartz (2) alteration with normal potassic sericite.

Relating alteration assemblages determined from airborne data to alteration maps.

In the alteration maps used for comparison, the regions not symbolized are not mapped, as such strict comparison can only be limited to mapped areas

The region marked A in figure 5.15A with actinolite-plagioclase (6) which is characteristic of sodic-calcic alteration correspond with the regions mapped as sodic-calcic alteration (S5, S2 and SW) in alteration map (figure 5.15B). The difference between these alteration zones is related to the presence of minor garnet-epidote-amphibole (9) assemblage with actinolite-plagioclase (6) in S5 and S2. This is also captured in the assemblage determined from airborne data as zones of mapped S5 and S2 occurring close to the skarn area are found to contain garnet assemblage. The skarn cutting through the cupola of Luhr Hill granite (red line) in figure 5.15B can also be identified from airborne data.

The region marked B in figure 5.15A characterized by actinolite-plagioclase (6) grading into chloriteepidote-plagioclase (8) assemblage correlates with the presence of weak sodic-calcic (WS) alteration grading into chloritic-propylitic (PC) alteration and sodic alteration in the alteration map (figure 5.15B). Chloriteepidote-plagioclase assemblage is characteristic of chloritic-propylitic alteration. Similar alteration of chlorite-epidote-plagioclase can also be found within region marked H in 5.15A, but the zone of actinoliteplagioclase (6) assemblage adjacent to H which is marked G in is not mapped.

The region marked D in figure 5.15A classified as garnet-epidote-amphibole (9) assemblage which is the assemblage associated with skarns corresponds with mapped as endoskarn and garnet skarn in alteration map figure (5.15B). This region is also mapped as garnet bearing region by Cudahy et al., (2001a). The contact of region D and A is characterized by actinolite-quartz assemblage due to reduction in plagioclase content towards the skarn (Cudahy et al., 2001a; Hecker, 2012a)

At the top of Ann Mason marked C in figure 5.15A is the assemblage of sericite-plagioclase (4), sericitequartz (2 and 3) and minor chlorite-epidote-plagioclase (8). The region is mapped as sericitic alteration (SQ and TBx), sodic alteration (A-2 and ATm) and minor chloritic-propylitic alteration (CB) (figure 5.15B). While the zones mapped as sericitic alteration are consistent with the alteration map, the region mapped as sodic are dominated by sericite bearing assemblage with very little chlorite assemblage. Rock samples from this region have sericite as dominant mineral. Previous studies in this area using remote sensing also indicate the dominance of sericite in this region (Cudahy et al., 2001a). The dominance of sericite in this region can be attributed to the fact that sericite occur as a major alteration mineral in both sericitic and sodic alteration.

The assemblages determined from airborne data vary from assemblage expected in alteration zones in existing alteration map in parts of Blue Hill. The regions of sodic-calcic alteration in existing alteration map have (5.16B) show no actinolite composition in airborne data. This region mostly fall in region marked P in figure 5.16A which is rather dominated chlorite-epidote-plagioclase composition that changes into epidotequartz assemblage. Similarly the region mapped as chloritic alteration surrounding sericitic-alteration in the alteration map is dominated by sericite-quartz assemblage (region marked Q in figure 5.16A). This region show prominent presence of sericite in the SWIR data (figure 5.10). Within the region marked R (figure 5.16A), the assemblage of sericite-plagioclase (4) dominates along with the presence of chlorite-epidoteplagioclase (8), sericite-guartz (2 and 3) and minor actinolite-plagioclase. In the alteration map, part of region R which mapped includes sodic alteration (A-2 and A-1) and weak sericitic alteration (WS). Based on the mineral assemblage presented in the alteration map in the two alteration zones clear separation can be not be achieved remote sensing using the approach adopted. The region marked S is largely unmapped, the occurrence of alunite with sericite quartz identified in three locations marked with yellow, blue and red box in figure 5.16A. The blue box is mapped as alunite bearing assemblage in the alteration map, the region is yellow box is mapped as weak sericitic in the alteration map, while the region in the red box is not mapped. At MacArthur area the region marked N in figure 5.17A is characterized by epidote-quartz±chlorite (7), chlorite-epidote-plagioclase (8), actinolite-quartz (5) and minor sericite quartz. This region mapped as propylitic-actinolite and sodic-calcic alteration (figure 5.17B). The assemblage identified from airborne data fits the assemblage of propylitic-actinolite alteration (PA) which is characterized by dominance of epidote and presence of actinolite. The assemblage of actinolite-plagioclase diagnostic of sodic-calcic was not found in regions mapped as sodic-calcic. Mining and excavation in the region mapped as potassic alteration (figure 5.17B) has probably resulted in weathering, producing clays and silica observed in this region. The area marked M in figure 5.17A, chlorite-epidote-plagioclase (8) occur with minor actinolite-quartz (5) and actinolite-plagioclase (6) in at the lower part which changes into assemblage of sericite-plagioclase (4) and sericite-quartz towards the centre of the area. The region mapped as chloritic-propylitic alteration in the alteration map (figure 5.17B) has assemblages which is similar to regions classified as chloritic-propylitic in Ann Mason. Correspondence is also found in parts mapped as sericitic alteration within region marked M in figure 5.17A as it is dominated by sericite-quartz and sericite-plagioclase, however the upper part which is mapped propylitic (figure 5.17B) do not show dominance of epidote bearing assemblage like region N. Region L in figure 5.17A correspond with region mapped as sericitic alteration in the alteration map. The assemblage identified in L conforms with expected assemblage. Variation in alteration intensity of the types of sericitic alteration is also reflected in airborne assemblage. Region marked O with assemblage of garnetepidote-amphibole correspond to the skarn and endoskarn in the alteration map.



Figure 5.15: (A) Distribution of alteration assemblages in Ann Mason (B) Map of alteration zones in Ann Mason after Dilles and Einaudi (1992).

The boundaries of alteration patterns determined from airborne data 5.15A are introduced into figure 5.15B to facilitate comparison.



Figure 5.16: (A) Distribution of alteration assemblages in Blue Hill area (B) Map of alteration zones in Blue Hill area (unpublished). Modified after Dilles (2001)

The boundaries of alteration patterns determined from airborne data in figure 5.16A are introduced into figure 5.16B to facilitate comparison



Figure 5.17: (A) Distribution of alteration assemblages in MacArthur area (B) Map of alteration zones in MacArthur area (unpublished). Modified after Dilles (1995)

The boundaries of alteration patterns determined from airborne data in figure 5.17A are introduced into figure 5.17B to facilitate comparison



Figure 5.18: Distribution of alteration assemblages in Buckskin Range

5.8. Comparison of Laboratory Assemblages to Airborne Alteration Assemblages

Comparison of airborne assemblage with laboratory determined assemblage was done to validate the result of decision tree classification. The mineral assemblage determined for every sample location is plotted on the airborne assemblage. Generally consistency was found between airborne assemblage and laboratory assemblage. At Ann Mason area, the assemblage of garnet-epidote-amphibole (9) falls in zones classified as (9) (figure B.7). At the top of Ann Mason, in regions marked as B, C, the assemblage of sericite-quartz (2) from samples also falls on zones classified as the same assemblage. Likewise the assemblage of sericite-plagioclase (4) also shows consistency between airborne and laboratory determined assemblage. The assemblage of actinolite-plagioclase (6) in this area falls on unclassified area close to zones classified as actinolite-plagioclase assemblage (region marked A) (figure B.8A). In Buckskin range, agreement was found between the assemblage of alunite-quartz (1) and sericite-quartz (2) determined from airborne data and laboratory analysis (figure B.8B). In MacArthur consistency was found between airborne and laboratory assemblage for sericite-plagioclase (4), sericite-quartz (2) and considerably for assemblage of chlorite-epidote-plagioclase (8). However epidote-quartz±chlorite (7) assemblage falls on pixel classified as sericite quartz (figure B.8C). In Blue hill area, while consistency was found between sericitequartz (2 and 3) and sericite-plagioclase (4) assemblages of rock samples and airborne data to a large extent, however most of the rock samples in which chlorite-epidote-plagioclase (8), epidotequartz±chlorite (7) and actinolite-quartz (5) assemblages were established fall on pixels which are classified as sericite-quartz or sericite-plagioclase (figure B.8D).

5.9. Discussion

5.9.1. Synopsis

The currently adopted atmospheric correction (ISAC) used for SEBASS does fully account for all atmospheric effect particularly down-welling radiance, thus produces data with very little spectral contrast. This explains why the interpolated depth of SEBASS is shallow compared to that of ProspecTIR-VS. Also spiking occurs in some bands which contain residual atmospheric effects especially at longer wavelength, the problem was reduced by removing these bands before emissivity calculation. The removal of these bands does not affect integrity of the resulting data, but rather it improves emissivity calculation from the data. The spectral region for which residual spiking remain were excluded from decision tree analysis to avoid misclassification.

Due to combination of several flightlines for both airborne dataset, variation across flightline can be seen in some parts, this particularly noticeable in the wavelength maps. By application of depth threshold to the interpolated minimum wavelength data before using it in decision tree classification, the variation across flight was largely reduced.

In order to determine mineral distributions and patterns, two methods approaches were evaluated;

The first involves combining the data and application of PCA on the on the combined data, it was discovered that the application of PCA supresses some information related to mineralogy and again interpretation was difficult because each PC receives contribution from numerous wavelength bands making it impossible to directly relate to each PC to a particular mineral group.

The application of minimum wavelength on SWIR and TIR data gives a good overview of dominant minerals in each airborne data. This method offers a good way to determine mineralogical pattern associated with different mineral groups but it has the drawback of using only the minimum wavelength position and not the entire spectral information. This can be of advantage in situations where subtle variation in minimum wavelength position which is related to variation in chemistry is of interest, but the disadvantage is it is sensitive to slight variation across fightlines. With the use minimum wavelength position only the dominant mineral in each pixel can be identified.

Integration of minimum wavelength position information from SWIR and TIR airborne data was achieved through decision tree. This was accomplished using trained result derived from laboratory analysis of samples and also be interpretation of wavelength maps. The methods works considerably well resulting in hard classification in which for each pixel at least one SWIR active mineral or group is present along with one TIR active mineral or group. To avoid false classification of noisy pixels, depth threshold is needed to eliminate features with shallow absorption depth which are probably not related to mineralogy. Misclassification of few pixels was observed due to overlapping of minimum wavelength position of minerals involved. Few pixels where actinolite occur as dominated spectrally active mineral in TIR and epidote or chlorite occur as dominant mineral in SWIR, resulted in misclassification of these pixels as garnet-epidote assemblage because of the minimum wavelength position of actinolite in TIR overlaps with that of garnets, although this problem can be solved by using a classification methods which uses of entire spectral information. Differentiation between zones classified as weak sericitic and sodic alteration in existing alteration maps was not achievable from airborne data in places where the two alteration types occur together in based on alteration map. The assemblage of weak sericitic alteration is sericite-plagioclase or sericite-quartz±chlorite, while the assemblage in sodic alteration is plagioclasesericite-chlorite. While plagioclase is the mineral identified in TIR for both zones, sericite is more likely to dominate spectral information in SWIR because it reflects more compare to chlorite with darker tone.

Although no samples was available to establish assemblage for potassic alteration, evaluation of airborne data show that it is dominated by feldspar in TIR and mafic minerals with very shallow depth in SWIR, thus they have no expression in wavelength map. Application of threshold also eliminates such information.

The novelty of this research lies in developing a method which integrates SWIR and TIR airborne imagery without fitting the data to match existing alteration zones, integration was based on association established from rock sample analysis from the study area. Therefore it can be adopted in areas in which no alteration maps exist using rock samples from the area to determine assemblages. Based on the method developed, similarity can be seen between of existing alteration zones and assemblage determine from airborne data. In places where there are disparity, it can be considered that this disparity cannot be solved with remote sensing, at least with the method adopted because of the tendency of some minerals to dominate mixed spectral in airborne data. The method can also be improved by purpose sampling based on current assemblage determined from airborne data.

5.9.2. Problematic Mixtures

Actinolite-diopside and hornblende-diopside. The mixture of diopside with actinolite or with hornblende usually results in a spectral which is difficult to determine which of the three minerals is present in the SWIR because the main absorption features in these minerals occur relatively in the same wavelength. The resulting spectral can be wrongly interpreted as any of the three minerals. In the TIR the resulting spectral indicates the presence of an amphibole but difficult to tell which of the amphibole is present. Also the presence of diopside is also manifested in the spectral however the features resulting from the presence of diopside can be misinterpreted for presence of epidote as this feature are also present in epidote. The problematic mixture was solved with XRD analysis in during this research.

Garnet-carbonate: Garnets have their most intense feature in the TIR between 10-11µm, this feature is a broad feature in which the minimum wavelength position is usually between 10-10.7µm. Carbonates contain the most intense feature between 11-11.3µm. The carbonate feature is a narrow feature which overlaps with the garnet feature. The occurrence of carbonate with garnet in a rock sample results in shifts in the position of the minimum wavelength of garnet spectral towards longer wavelength even though no prominent spectral feature is indicates the presence of carbonate.

Quartz-andesine: The minimum wavelength position in quartz is usually the \sim 9.2µm feature but the \sim 8.3µm feature can occasionally become the deepest feature. In the mixture of quartz with andesine, the fluctuation in the minimum wavelength position was observed the most frequently. It is unknown if the percentage of quartz present in in a rock sample with andesine influence which wavelength position of the quartz feature becomes the most intense.

Epidote-hornblende and epidote-actinolite: In spectral where epidote occur as dominant mineral and hornblende or actinolite occur as additional mineral, it is difficult to determine which of the two amphibole is present because the spectral features which can be used to differentiate between the two amphibole is absent or relatively suppressed. Similar problem is also encountered when chlorite occur as dominant mineral with any of the two amphibole.

5.9.3. Mappable Alteration Zones

The following alteration zones can be mapped by the method adopted for combining SWIR and TIR data *Advance argillic zone:* The assemblage of alunite-quartz±pyrophyllite can be readily mapped by the method adopted. Zones of advanced argillic alteration occur mainly in the Buckskin range and are characterized by lack of feldspar and presence of minor sericite.

Argillic zone: The intermediate argillic is characterized by sericite-quartz, sericite-plagioclase and alunitequartz assemblage, this can be identified in the western part of Blue Hill area where minor alunite-quartz assemblage occurs within dominantly sericite quartz assemblage. In these zones residual feldspars are also present as sericite-plagioclase occurs in traces in this region.

Sericitic Alteration: sericitic alteration with assemblage of sericite-quartz can be easily characterized by the method adopted. Sericite-quartz assemblage occurs in most part of the system, starting from the top Yerington batholith in Ann Mason area. In this region it occurs mainly within the Bear unit. This

assemblage is also found in Blue Hill, MacArthur and Buckskin Range. In the Buckskin range, the sericitequartz alteration surrounds the advanced argillic alteration.

Sodic-calcic: combination of the two datasets enables characterization of sodic-calcic alteration which is characterized by assemblage of plagioclase-actinolite and actinolite quartz. This assemblage was identified in the lower part of the system in Ann Mason which it occurs within the McLeod Hill unit. This assemblage was also identified in McArthur and Blue Hill area, although in Blue Hill area parts of the region mapped as sodic-calcic did not show the presence of actinolite in airborne assemblage.

Chloritic (propylitic): This alteration types characterized by chlorite-epidote-plagioclase with minor actinolite assemblage is sufficiently characterized in Ann Mason and MacArthur area. This alteration occurs above sodic-calcic alteration and above the quartzite unit in Ann Mason area. In MacArthur the assemblage was identified next to sericite-quartz alteration.

Propylitic Alteration: This alteration characterize by the dominance if epidote with minor chlorite and actinolite. This assemblage with epidote-quartz±chlorite identified mainly in MacAthur Area in the bear unit. Other zones with epidote-quartz±chlotite with sericite-quartz occur in Blue Hill area, which are classified as sodic-calcic alteration in the alteration map.

Skar*n:* The assemblage of garnet-epidote-amphibole was identified majorly in Ann Mason. The TIR data provides information about the garnets while information about epidote and amphibole is derived from the SWIR data. Mapping of skarn areas can be done using the TIR alone but combination of both wavelength ranges can be used to characterize the skarn further in terms minerals occurring with each type of garnet.

6. CONCLUSION

6.1. Conclusion

Analysis of rock samples from Yerington area with SWIR and TIR spectroscopy show that each wavelength range is more suitable for identification of certain group of minerals. The SWIR region is most suitable for identification of OH and H₂O bearing minerals such as alunite, sericite, smectite, kaolinite, hornblende, actinolite, jarosite, chlorite, epidote, vesuvianite, tourmaline and opal while Thermal Infrared region is most suitable for identification non OH bearing silicates such as quartz, feldspar, garnets and pyroxenes. Alunite, vesuvianite, opal and serpentine can be identified from rock samples using either of the wavelength regions. In the Midwave Infrared, epidote, diopside, tourmaline has features which can be used to identify their presence in a sample.

Wavelength mapping is a good tool which gives overview of mineralogical patterns from airborne data based on dominant mineral in each pixel. The method provides a means to determine systematic variation in mineralogy related to minimum wavelength position in mineral spectra. With application of wavelength mapping, SWIR airborne data was able to identify carbonates (dolomite and calcite), gypsum, sericite, alunite, epidote, chlorite and actinolite while in the TIR quartz, alunite, plagioclase, carbonate, garnet, actinolite and gypsum were identified.

The combination of information derived from application of wavelength mapping on SWIR and TIR airborne data through decision tree enable identification of advance argillic, argillic, sericitic, sodic-calcic, propylitic, chloritic and skarn alterations as consistency in found in most part between assemblages in existing alteration maps and assemblage determined from airborne data, while separation between week sericitic and sodic alteration remains a challenge.

The synergistic use of both wavelength ranges offers additional information in terms of minerals identifiable and also separability. Carbonates whose features overlap with chlorite, epidote and amphibole in the SWIR have distinct spectral feature in the TIR which enables easy separation. While differentiation between carbonates is difficult in TIR, combination of both wavelength ranges enables differentiation between carbonates and also differentiation of carbonates from other minerals. The feature of gypsum can sometimes overlap with sericite in the SWIR but it has a distinctive feature in the TIR and can be better differentiated.

Generally increasing alteration intensity with decreasing depth was observed in the system. The less pervasive alterations occur at deeper depth while more pervasive feldspar destructive alteration occurs at shallow depth. Variations in sericite are also observed within the system, with sericite of longer wavelengths occurring more in the epithermal regime.

6.2. Recommendation

- Based on the result of this research, the following recommendations are put forward
- TIR has proven to be an additional tool which is complimentary for SWIR for mineralogical mapping, but for its potential to be fully explored in geological remote sensing there is need for improved atmospheric correction method. The current atmospheric method been adopted does not fully eliminate atmospheric effects.
- The method applied for combining SWIR and TIR data in this research was developed using laboratory spectral to determine association between SWIR and TIR active minerals using the minimum wavelength position in each wavelength region which is influenced by the dominant spectrally active mineral. Application of the method in airborne data indicate the presence of dominant SWIR and TIR mineral per pixel and also differentiation between endmembers of some mineral specie is not fully achievable. Further methods which consider proportion of minerals in each pixel such as abundance method can be consider for integration of the wavelength ranges. Other

methods which use the entire spectral information would increase the amount of information derivable from combination of SWIR and TIR data.

- The Tertiary volcanics of Singatse Tuff and Mickey Pass tuff appear to be altered in some places (region marked T and K), as it show sericite-quartz composition which is absent in other regions in which the lithology occurs. This requires validation through ground sampling in regions in which they appear altered in airborne data.
- Validation of mineral distributions produced by this research is also essential particular in the Blue Hill area which most disparity between airborne assemblage and alteration maps exists.
- In other to be able to optimally combine the two dataset, there is also need for detailed and purposive sampling within each alteration type already determined by existing work. This enables sufficient comparison of assemblage determined from spectroscopy to those determined from other methods.
- Detailed study of variation in garnet chemistry is another promising area for future studies.

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COMBINING DOMINANT SPECTRAL FEATURES IN SWIR AND TIR AIRBORNE IMAGERY FOR MINERALOGICAL MAPPING.

Mineral identification and minimum wavelength position used to establish association APPENDIX Å.

Station X		>	SWIR Spectral Name	SWIR Interpretation	Position of Minimum Wavelength	Position of Minimum wavelength	TIR Interpretation	TIR Spectral Name	Group
09ch001			09ch001a_iii	Hornblende + Epidote	2.335	9.553	K-feldspar(Mcr)+Quartz.	09CH001	Hbl+kfds
			09ch001b_i	Hornblende + Illite(\pm Epidote)	2.322	9.206	Ouartz + Plagioclase (And)	09CH001b	Hbl+Qtz
09ch002 306	6575.2	4314896.08	09ch002_i	MgChlorite	2.248	9.628	Plagioclase(Alb) + Quartz	09CH002	Chl+Plag
09ch003 306	5574.1	4315140.36	09ch003_ii	Hornblende + Epidote	2.332	10.133	Hornblemde+Epidote.	09CH0003	Hbl
09ch004 306	6549.7	4315271.62	09ch004_i	illite+chlorite	2.206	9.338	Quartz + Plagioclase(And)	09CH004	Ser+Qtz
09ch005 306	6953.9	4317268.108	09ch005a_i	Muscovite	2.212	8.97	Quartz + Muscovite	09CH005	Ser(-
									>Pheng)+Qtz
09ch005b 306	5962.6	4317248.221	09ch005b_i	IntChlorite + Epidote	2.34	9.602	Plagioclase(Alb)	09CH005b	Ch1+Plag
09ch006 306	5332.5	4316824.179	09ch006	illite + FeChlorite	2.216	9.554	Serpentine(Antigorite) + Quartz.	09CH006	Ser+Spt
09ch007 305	5919.6	4316664.183	09ch007a_ii	Actinolite + illite	2.317	9.649	Plagioclase(Alb) + Epidote	09CH007	Act+Plag
09ch008 304	4423.3	4317367.218	09ch008_ii	Muscovite	2.208	9.616	Plagioclase(Alb) + Illite + Quartz.	09CH008	Ser+Plag
09ch009 307	7628	4324723.607	09ch009_ii	Actinolite + illite	2.319	9.644	Plagioclase (Alb) + Quartz.	09CH009	Act+Plag
09ch010 305	5892.1	4324486.803	09ch0010_ii	IntChlorite	2.339	9.64	Plagioclase (Alb) + Quartz.	09CH010	ChI+Plag
09ch011 305	5885.7	4324479.696	09ch011a_iii	Muscovite + Chlorite	2.207	8.407	Quartz + Plagioclase (And)	09CH011a	Ser+Otz
			09ch0011b_ii	Chlorite+Carbonate (+Smectite)	2.339	9.636	Plagioclase(Alb) + Quartz	09CH011b	ChI+Plag
09ch012 305	5896.6	4324501.963	09ch012	Chlorite+illite	2.342	9.631	Plagioclase(Alb) + Illite + Ouartz.	09CH012	Ch1+Plag
09ch013 305	5872.3	4324450.227	09ch013_ii	Montmorillonite	2.208	9.525	Plagioclase(Alb) + Quartz	09CH013	Smt+Plag
09ch014 302	2871.7	4317798.496	09ch014_ii	Halloysite + Tourmaline	2.209	9.632	Plagioclase(Alb) + Quartz	09CH014	Hal+Plag
09ch015 302	2827.1	4317847.348	09ch0015a1_i	illite	2.205	9.04	Quartz + illite	09ch015ai	Ser+Otz
15aii 302	2807.7	4317849.662	09ch015a2_ii	Illite	2.202	9.337	Illite.	09ch015aii	Ser+Otz
			09ch015b_i	illite	2.198	9.206	Quartz + illite	09CH015b	Ser+Qtz

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Ser+Otz	Act+Plag	Act+Otz	Ser+Otz	Epi+Smt	Epi+Otz	Tour+Qtz	Tour+Otz	Ser + Plag	Alu+Qtz	Alu+Qtz	Ser(-	>Pheng)+Otz	Ser(-	>Pheng)+Otz	Alu+Qtz	Ser+Qtz	Alu+Qtz	Ser(-	>Pheng)+Plag	Spt	Spt	Jar	Hal+Plag	Ser+Plag	Smt+Plag	Ves	Epi+Gar	Ves	Gar + Tml
09CH015c	09CH016a	09ch016b	09ch016c	09CH017a	09CH017b	09CH018a	09CH018b	09CH019	09ch020a	09ch020b	09ch020c		09ch020d		09CH021a	09CH021b	09CH021c	09CH022		09CH023a	09CH023b	09CH025	09CH026	09CH027	09CH028	09CH030a	09CH030b	09CH030c	09CH031
Quartz + Muscovite.	Plagioclase(Alb) + Quartz.	Quartz + Plagioclase (And)	Quartz + Plagioclase (And)	Montmorillonite + Hornblende	Quartz + Montmorillonite.	Quartz + Tourmaline	Quartz + Tourmaline	Plagioclase(Alb)+Quartz	Alunite + Quartz.	Alunite + Quartz.	Quartz + Muscovite (+ Plag)		Quartz +Muscovite (+Plag)		Alunite + Quartz.	Quartz + Muscovite(+ Alunite).	Alunite + Quartz (+Muscovite)	Plagioclase(Alb) + Quartz.		Serpentine (Antigorite)	Serpentine (Antigorite)?	Jarosite+illite	Plagioclase(Alb)	Plagioclase(Alb)+Quartz	Plagioclase(Alb)	Vesuvianite.	Garnet (Grossular) (+epidote).	Vesuvianite.	Garnet(Andradite) + Epidote
9.207	9.633	8.879	9.129	9.342	9.025	8.278	9.092	9.617	9.12	8.984	9.086		9.087		8.916	9.105	9.103	9.623		9.547	9.652	9.029	9.645	9.631	9.631	9.753	10.481	9.665	10.974
2.198	2.319	2.323	2.202	2.336	2.337	2.246	2.247	2.209	2.188	2.169	2.211		2.211		2.169	2.203	2.176	2.22		2.323	2.297	2.264	2.207	2.209	2.211	2.35	2.356	2.216	2.38
Illite	Actinolite + illite + Epidote	Actinolite+illite	Illite	Epidote	Epidote	FeTourmaline	FeTourmaline	Illite	Na_Alunite	Na_Alunite	Muscovite		Muscovite		Na_Alunite	Muscovite	Na_Alunite	Phengite + Chlorite		Serpentine	Opal?	Jarosite	Halloysite	Illite + Kaolinite	Montmorillonite.	Vesuvianite+carbonate	Epidote	Vesuvianite+carbonate	FeTourmaline?
09ch015c_i	09ch016a_i	09ch016b_ii	09ch016c_i	09ch017a_i	09ch017b_i	09ch018a_ii	09ch018b_i	09ch019_i	09ch020_i	09ch020b_ii	09ch020c_i		09ch020d		09ch021a_i	09ch021b_ii	09ch021c_i	09ch022_i		09ch023_i	09ch023b	09ch025_iii	09ch026	09ch027_i	09ch028_i	09ch030a_ii	09ch030b_ii	09ch030c_ii	09ch031_ii
	4320673.244			4322328.332				4321127.015	4321421.662		4321421.075				4322118.09	4322021.66		4322093.662		4327103.129		4320921.662	4320970.016	4319597.894	4314505.198	4314373.506			4314251.855
	302872.3			301620.7				301494	301211.7		301194.7				295768.7	295675.7		295559.7		297943.7		300923.7	300866.1	301393	303030.8	303563.1			303511.9
	09ch016			09ch017		09ch018		09ch019	09ch020						09ch021			09ch022		09ch023		09ch025	09ch026	09ch027	09ch028	09ch030			09ch031

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Opal	Epi+Plag	Act+Plag	Epi+Gar	Act+Gar	Act+Gar	Hbl+Dio	Hbl+Dio	Ser(-	>Pheng)+Otz	i Kao+Otz	Ser+Plag	Ser+Plag	Epi+Otz	Epi+Otz	Epi+Otz	Ser+Plag	Ser+Otz	Epi+Plag	Epi+Otz	Epi+Otz	Ser+Otz	Ser+Otz	Ser+Otz	Ser+Otz	Act+Otz	Ser+Otz	Qtz+Tml	Act+Otz	
09CH032	09CH033a	09CH033b	09CH034a	09CH034b	09CH035a	09CH035b	09ch035c	09CH036a		09CH036ai	09CH036b	09CH037	09CH038a	09CH038b	09CH039	09CH040	09CH041	09CH042	09CH043a	09ch043b	09CH044a	09CH044b	09CH045	09CH046	09CH047	09CH048	09ch049a	09ch049b	
Opal+Carbonate	Plagioclase (Alb)+Quartz.	Plagioclase (Alb) + Quartz.	Garnet (Andradite)	Garnet (Andradite) + Epidote	Actinolite + Diopside + Adradite	Hornblende + Diopside	Hornblende + Diopside	Ouartz + Plagioclase(And)		Kaolinite+Quartz.	Plagioclase(Alb) + Quartz	Plagioclase(Alb) + Ouartz	Quartz + Plagioclase (And)	Quartz + Plagioclase (And)	Quartz + Plagioclase (And)	Plagioclase (Alb) + Quartz.	Quartz + Muscovite	Plagioclase (Alb)+Quartz.	Quartz + Plagioclase (And)	Quartz + Plagioclase (And)	Quartz+Muscovite	Quartz + Tourmaline	Quartz + Plagioclase (And)	Quartz+Microcline	Quartz + Plagioclase (And)	Quartz.	Quartz + Tourmaline	Quartz + Actinolite	
8.962	9.648	9.638	11.121	11.29	10.409	10.497	10.422	8.523		9.355	9.647	9.627	9.276	9.21	9.262	9.63	9.037	9.624	8.785	8.858	9.095	9.244	8.34	9.314	8.792	8.262	9.098	9.092	
2.218	2.351	2.32	2.34	2.303	2.308	2.321	2.323	2.213		2.207	2.208	2.208	2.342	2.341	2.342	2.207	2.202	2.351	2.346	2.343	2.202	2.207	2.2	2.207	2.318	2.206	2.245	2.32	
Opal + Carbonate	Epidote	Actinolite + illite + Epidote	Epidote	Actinolite	Actinolite + Diopside	Hornblende + Diopside	Hornblende + Diopside	Muscovite		Halloysite	illite	illite 1 & illite 2 (+minor kaolinte)	Epidote+Muscovite	Epidote+Halloysite	Epidote+Montmorillonite	illite 1 & illite 2 (+minor kaolinte)	Muscovite	Epidote+Halloysite	Epidote+Muscovite	Epidote+Muscovite	Illite	illite + Fe Tourmaline	illite	illite + Epidote	Actinolite + Epidote + illite	Illite + Epidote	FeTourmaline	Actinolite + Halloysite	
09ch032_i	09ch033a_iii	09ch033b_i	09ch034a_iii	09ch034b_ii	09ch035a_i	09ch035b_i	09ch035c_ii	09ch036a1_iii		09ch036a2_i	09ch036b_i	09ch037_ii	09ch038a_iii	09ch038b_ii	09ch039_i	09ch040_iii	09ch041_ii	09ch042_iii	09ch043a_i	09ch043b_i	09ch044a_i	09ch044b_i	09ch045_ii	09ch046_ii	09ch047_i	09ch048_i	09ch049a_i	09ch049b_i	
4314187.552	4314383.086				4313286.109			4319719.776				4319795.234	4319819.696		4319932.6	4319966.761	4320036.656	4320183.898	4320185.052		4320256.033		4320304.077	4320378.926	4320498.937	4320731.225	4320679.582		
303706	304092.6				303010.3			301706.1				301673.3	301679.5		301724.9	301746.1	301793.3	301904.2	301980.7		301950.7		301933.1	301941.2	301961.6	301935.6	301925.8		
09ch032	09ch033		09ch034		09ch035			09ch036			36b	09ch037	09ch038		09ch039	09ch040	09ch041	09ch042	09ch043	43b	09ch044		09ch045	09ch046	09ch047	09ch048	09ch049		

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09ch050	302087.7	4320565.662	09ch050a_i	Epidote	2.326	10.137	Hornblende+Quartz	09CH050a	Epi+Hbl
			09ch050b_i	Actinolite	2.317	9.536	Serpentine(Antigorite)+Calcite.	09CH050b	Spt
09ch051	302196.4	4320324.924	09ch051_ii	illite	2.21	9.023	Ouartz+Plagioclase(And)	09CH051	Ser(-
									>Pheng)+Qtz
09ch052	302251.6	4320236.042	09ch052_ii	Actinolite + illite	2.319	9.621	Plagioclase(Alb)+Ouartz	09CH052	Act+Plag
09ch053	302237.9	4320002.66	09ch053a_i	Chlorite+IIIite	2.351	8.328	Quartz + Plagioclase (And)	09CH053a	ChI+Qtz
			09ch053b_i	illite+MgChlorite+Actinolite?	2.204	9.269	Ouartz+Plagioclase(Alb)	09CH053b	Ser+Qtz
09ch054	302267.7	4319873.662	09ch054_i	Mgchlorite+illite	2.35	8.779	Ouartz+Plagioclase(And)	09CH054	Chl+Qtz
09ch055	302175.6	4319536.812	09ch055_i	Chlorite+Carbonate (+Smectite)	2.339	9.635	Plagioclase(Alb)+Ouartz	09CH055	ChI+Plag
09ch056	302190.9	4319516.493	09ch056_i	Opal	2.253	9.34	Quartz+Montmorillonite+Plagioclase	09CH056	Opal
09ch057	302299.6	4319545.811	09ch057_iii	Muscovite	2.207	8.38	Quartz + Plagioclase (And) + Muscovite	09CH057	Ser+Qtz
09ch058	305024.6	4325597.129	09ch058_i	Epidote+Muscovite	2.341	9.613	Plagioclase(Alb)+Ouartz	09CH058	Epi+Plag
09ch059	304892	4325473.5	09ch059_i	Epidote+Muscovite	2.342	9.242	Ouartz+Plagioclase (And)	09CH059	Epi+Otz
09ch060	304840.2	4325342.005	09ch060_i	illite+Carbonate+chlorite+Kaolinite	2.206	9.627	Plagioclase(Alb)+Ouartz	09CH060	Ser+Plag
09ch061	304831.7	4325293.662	09ch061_i	FeTourmaline	2.246	9.127	Quartz + Tourmaline	09CH061	Otz+Tml
09ch062	304835.7	4325249.662	09ch062_ii	Chlorite+IIIite	2.339	9.641	Plagioclase(Alb)+Ouartz	09CH062	ChI+Plag
09ch063	304814.2	4325142.586	09ch063_i	Illite + Kaolinite	2.209	9.536	Plagioclase(Alb) + Illite + Ouartz.	09CH063	Ser+Plag
09ch064	304786	4325004.987	09ch064_i	Illite + Kaolinite	2.21	9.629	Plagioclase(Alb) + Illite + Quartz.	09CH064	Ser(-
									>Pheng)+Qtz
09ch065	304742	4324934.774	09ch065_i	Kaolinite	2.208	9.253	Quartz + Plagioclase (Alb)	09CH065	Kao+Otz
09ch066	304716.4	4324739.464	09ch066a_ii	Muscovite + Jarosite	2.21	9.036	Quartz+Muscovite.	09ch066a	Ser(-
									>Pheng)+Otz
			09ch066b_iii	Muscovite	2.201	9.214	Quartz.	09CH066b	Ser+Otz
09ch067	304604.2	4324603.496	09ch067a_i	Chlorite+Carbonate (+Smectite)	2.341	9.615	Plagioclase(Alb)+Ouartz	09ch067a	ChI+Plag
			09ch067b_i	illite	2.206	9.517	Illite+Quartz.	09ch067b	Ser+Otz
			09ch067c_i	illite	2.2	9.34	Illite+Quartz.	09ch067c	Ser+Otz
09ch068	302011.4	4319425.649	09ch068_i	Epidote+Muscovite	2.34	9.614	Plagioclase(Alb)+Quartz	09CH068	Epi+Plag
09ch069	301959.8	4319495.736	09ch069_ii	Kaolinite	2.207	8.942	Quartz + Plagioclase (And)	09CH069	Kao+Otz
Table A.1	: Minimum	wavelength po	osition of SWIF	and TIR spectra of rocks samples u	used to estab	ish mineral asso	ciation.		

A.1 Summary of minerals dentified from analysis rock sample

Minerals identified from SWIR analysis of rock samples

SWIR Mineralogy	Number of sample
Alunite	4
Illite	12
Illite+chlorite	2
Illite+kaolinite	5
Illite+epidote	2
Illite+FeToutmaline	1
Illite+MgChlorite+actinolite	1
Illite+carbonate+chlorite+kaolinite	1
Muscovite	9
Muscovite+chlorite	1
Muscovite+jarosite	1
Phengite+chlorite	1
Montmorillonite	2
Kaolinite	2
Halloysite	2
Halloysite+FeTourmaline	1
FeTourmaline	4
Tourmaline	1
Epidote	6
Epidote+muscovite	6
Epidote+halloysite	2
Epidote+Montmorillonite	1
Hornblende+epidote	2
Hornblende+illte+epidote	1
Hornblende+diopside	2
Actinolite	2
Actinolite+diopside	1
Actinolite+illite	4
Actinolite+illite+epidote	3
Actinolite+halloysite	1
Actinolite+epidote+halloysite	1
Chlorite+illite	3
MgChlorite	1
MgChlorite+illite	1
Intermediate Chlorite	1
Intermediate Chlorite+Epidote	1
Chlorite+carbonate+smectite	3
Opal	2
Opal+carbonate	1
Serpentine	1

Jarosite	1
Vesuvianite+carbonate	2
Total	101

Table A.2: Summary of minerals identified from SWIR analysis of rock samples

Minerals identified from TIR analysis of rock samples

TIR Mineralogy	Number of sample
Quartz	2
Quartz + andesine	18
Quartz+albite	2
Quartz+andesine+musocvite	1
Quartz+microcline	1
Quartz+muscovite	5
Quartz+muscovite+plagioclase	2
Quartz+illite	2
Quartz+montmorillonite	2
Quartz+tourmaline	5
Quartz+muscovite+alunite	1
Quartz+actinolite	1
Albite	3
Albite+quartz	23
Albite+illite+quartz	4
Albite+epidote	1
Andesine+Quartz	1
Microcline+quartz	1
Alunite+quartz	3
Alunite+quartz+muscovite	1
Illite	1
Illite+quartz	2
kaolinite+quartz	1
Montmorillonite+Hornblende	1
Andradite	1
Andradite+epidote	2
Grossular+epidote	1
Hornblende+epidote	1
Hornblende+quartz	1
Hornblende+diopside	2
Actinolite+diopside	1
Serpentine	2
Serpentine+calcite	1
serpentine+quartz	1
Opal+carbonate	1
Jarosite+Illite	1

Vesuvianite	2
Total	101

Table A.3: Summary of minerals identified from TIR analysis of rock samples

B. ADDITIONAL INFORMATION FROM IMAGE ANALYSIS



Figure B.1: Plot Eigenvalue against Eigenvalue number, where each Eigen number represent a band in the original image.



Figure B.2: (A) Scatterplot of PC 3 against PC 4 (B) Scatterplot of PC 3 against PC 6 (C) Scatterplot of PC 4 against PC 6.



Figure B.3: (A) Scatterplot of interpolated minimum wavelength against interpolated depth from application of wavelength mapping on ProspecTIR-VS before application of depth threshold. (B) Scatterplot after application of 0.08 depth threshold



Figure B.4: (A) Scatterplot of interpolated minimum wavelength against interpolated depth from application of wavelength mapping on SEBASS before application of depth threshold. (B) Scatterplot after application of 0.01 depth threshold.



Figure B.5: (A) Gypsum spectra from SEBASS compared with reference spectra in dashed lines. (B): Carbonate spectra from SEBASS compared with reference spectra in dashed line.



Figure B.6: Spiking due to residual atmospheric to effect





Number on legend for each assemblage is related to figure 5.13 and table 5.3





C. Decision tree details



Figure C.1: Decision tree used for classification of airborne data

Binary decisions used for classification in ENVI Decision Tree

ENVI Decision Tree Text File (version=1.0)

```
begin node
name = "Calcite"
type = Decision
location = 1,1
expression = "(B1 GT 2.329) AND (B2 GT 11)"
end node
begin node
```

```
name = "Class 1"
```

type = Result location = 2,2parent name = "Calcite" parent decision = Yes class value = 1 class rgb = 0,139,139end node begin node name = "Dolomite" type = Decision location = 2,1parent name = "Calcite" parent decision = No expression = "(B1 GT 2.29) AND (B2 GT 11)" end node begin node name = "Class 3" type = Result location = 3,2parent name = "Dolomite" parent decision = Yes class value = 3 class rgb = 0,255,255end node begin node name = "Gar+Epi+Amp" type = Decision location = 3,1parent name = "Dolomite" parent decision = No expression = "(B1 GT 2.28) AND (B2 GT 9.9)" end node begin node name = "Class 4" type = Result location = 4,2parent name = "Gar+Epi+Amp" parent decision = Yes class value = 4 class rgb = 239,51,56end node begin node name = "Chl+Epi+Plag"

```
type = Decision
 location = 4,1
 parent name = "Gar+Epi+Amp"
 parent decision = No
 expression = "(B1 GT 2.330) AND (B2 GT 9.4)"
end node
begin node
 name = "Class 5"
 type = Result
 location = 5,2
 parent name = "Chl+Epi+Plag"
 parent decision = Yes
 class value = 5
 class rgb = 204,0,204
end node
begin node
 name = "Act+Plag"
 type = Decision
 location = 5,1
 parent name = "ChI+Epi+Plag"
 parent decision = No
 expression = "(B1 GT 2.309) AND (B2 GT 9.4)"
end node
begin node
 name = "Class 6"
 type = Result
 location = 6,2
 parent name = "Act+Plag"
 parent decision = Yes
 class value = 6
 class rgb = 185,220,25
end node
begin node
 name = "Epi+Qtz±Chl"
 type = Decision
 location = 6,1
 parent name = "Act+Plag"
 parent decision = No
 expression = "(B1 GT 2.330) AND (B2 LT 9.3)"
end node
begin node
 name = "Class 7"
 type = Result
```

```
location = 7,2
 parent name = "Epi+Qtz±Chl"
 parent decision = Yes
 class value = 7
 class rgb = 40,42,152
end node
begin node
 name = "Act+Qtz"
 type = Decision
 location = 7,1
 parent name = "Epi+Qtz±Chl"
 parent decision = No
 expression = "(B1 GT 2.310) AND (B2 LT 9.3)"
end node
begin node
 name = "Class 8"
 type = Result
 location = 8,2
 parent name = "Act+Qtz"
 parent decision = Yes
 class value = 8
 class rgb = 255,255,25
end node
begin node
 name = "Alu+Qtz±Pyl"
 type = Decision
 location = 8,1
 parent name = "Act+Qtz±Pyl "
 parent decision = No
 expression = "(B1 LT 2.189) AND (B2 GT 8.8)"
end node
begin node
 name = "Class 9"
 type = Result
 location = 9,2
 parent name = "Alu+Qtz"
 parent decision = Yes
 class value = 9
 class rgb = 238,121,66
end node
begin node
 name = "Gypsum"
 type = Decision
```

```
location = 9,1
 parent name = "Alu+Qtz±Pyl "
 parent decision = No
 expression = "(B1 GT 2.216) AND (B2 LT 8.8)"
end node
begin node
 name = "Class 10"
 type = Result
 location = 10,2
 parent name = "Gypsum"
 parent decision = Yes
 class value = 10
 class rgb = 139,0,0
end node
begin node
 name = "Ser+Plag"
 type = Decision
 location = 10,1
 parent name = "Gypsum"
 parent decision = No
 expression = "(B1 GT 2.195) AND (B2 GT 9.4)"
end node
begin node
 name = "Class 11"
 type = Result
 location = 11,2
 parent name = "Ser+Plag"
 parent decision = Yes
 class value = 11
 class rgb = 170, 100, 96
end node
begin node
 name = "Ser (->Pheng)+Qtz"
 type = Decision
 location = 11,1
 parent name = "Ser+Plag"
 parent decision = No
 expression = "(B1 GT 2.209) AND (B2 LT 9.3)"
end node
begin node
 name = "Class 12"
 type = Result
 location = 12,2
```

```
parent name = "Ser (->Pheng)+Qtz"
 parent decision = Yes
 class value = 12
 class rgb = 51,255,51
end node
begin node
 name = "Ser+Qtz"
 type = Decision
 location = 12,1
 parent name = "Ser (->Pheng)+Qtz"
 parent decision = No
 expression = "(B1 GT 2.190) AND (B2 LT 9.3)"
end node
begin node
 name = "Class 13"
 type = Result
 location = 13,2
 parent name = "Ser+Qtz"
 parent decision = Yes
 class value = 13
 class rgb = 10,86,44
end node
begin node
 name = "Class 2"
 type = Result
 location = 13,1
 parent name = "Ser+Qtz"
 parent decision = No
 class value = 2
 class rgb = 255,255,255
end node
begin variable
 variable name = "B1"
 file name = " file_directory\file_name "
 file pos = 1
end variable
begin variable
 variable name = "B2"
 file name = " file_directory\file_name "
 file pos = 3
end variable
```

D. AIRBORNE DATA INFORMATION

List of SEBASS flight scenes used

006_080617_160847_YTN_nw_1_I_L2S 006_080617_162202_YTN_nw_2_I_L2S 006_080618_134302_YTN_nw_3_I_L2S 006_080618_135510_YTN_nw_4_I_L2S 006_080618_140850_YTN_nw_5_I_L2S 006_080618_142215_YTN_nw_6_I_L2S 006_080618_143545_YTN_nw_7_I_L2S 006_080618_144928_YTN_nw_8_I_L2S 006_080618_150326_YTN_nw_9_I_L2S 006_080618_151719_YTN_nw_10_L_L2S 006_080618_153058_YTN_nw_11_LL2S 006_080618_154425_YTN_nw_12_I_L2S 006_080618_155818_YTN_nw_13_I_L2S 006_080618_161114_YTN_nw_14_L_L2S 006_080621_141921_YTN_nw_15_I_L2S 006_080623_142405_YTN_nw_16_I_L2S 006 080623 143754 YTN nw 17 I L2S 006_080617_155559_YTN_nw_19_I_L2S 006 080617 154233 YTN nw 20 I L2S 006_080617_152936_YTN_nw_21_I_L2S 006_080617_151628_YTN_nw_22_I_L2S 006_080617_150403_YTN_nw_23_I_L2S 006_080617_145056_YTN_nw_24_I_L2S 006 080617 143655 YTN nw 25 I L2S 006_080617_142321_YTN_nw_26_I_L2S 006_080617_141003_YTN_nw_27_I_L2S 006_080617_135627_YTN_nw_28_I_L2S 006_080617_134311_YTN_nw_29_I_L2S 006_080617_132949_YTN_nw_30_I_L2S 006_080617_131658_YTN_nw_31_L_2S 006_080617_130307_YTN_nw_32_I_L2S 006_080617_124959_YTN_nw_33_I_L2S 006_080617_123509_YTN_nw_34_I_L2S

List of ProspecTIR-VS flight scenes used

0617-0937_rad_VELC 0617-1005_rad_VELC 0617-1045_rad_VELC 0617-1125_rad_VELC 0617-1206_rad_VELC 0617-1245_rad_VELC 0618-1031_rad_VELC 0618-1111_rad_VELC 0618-1152_rad_VELC 0618-1233_rad_VELC 0618-1314_rad_VELC





For SEBASS, 33 flight scenes were used

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