Surface detection of alkaline ultramafic rocks in semi-arid and arid terrains using spectral geological techniques

Thesis

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SURFACE DETECTION OF ALKALINE ULTRAMAFIC ROCKS IN SEMI-ARID AND ARID TERRAINS USING SPECTRAL GEOLOGICAL TECHNIQUES

A thesis submitted for the degree of Doctor of Philosophy

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June, 1998

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CHAPTER 9

9 TEST SITE STUDY PINE CREEK, TEROwie DISTRICT, SOUTH AUSTRALIA

9.1 INTRODUCTION

This test site was chosen as an example of an alkaline ultramafic rock, in this case kimberlite, which is not exposed and has been eroded, weathered and covered by residual soil.

The site is located 200km NNE of Adelaide on the flanks of the Flinders Ranges (Figure 9.1). It encompasses a small part of an extensive field of Jurassic aged kimberlite intrusions that extends north and west from this site to Orroroo and Port Augusta (Colchester, 1982). The region can be classed as have semi-arid with slightly higher rainfall between May and October though this is unpredictable by month and year.

Figure 9:1: Location map of the Pine Creek area showing HyMap flight line overlain onto geology map.

The main kimberlite in the study area, designated Pine Creek 01, has a surface area of approximately three hectares. Stockdale Prospecting discovered this pipe in 1970 by collecting concentrates of heavy minerals and analysing them for minerals such as ilmenite, that indicate the presence of kimberlite. It has an associated magnetic anomaly. There are several smaller kimberlites north of the main body. No kimberlites are exposed,
though surface disturbance, from diamond prospecting in the 1970s, has left patches of kimberlitic clay on the surface at the Pine Creek 01 kimberlite.

The vegetation cover in the area is undisturbed and consists of a variety of dry land plant communities comprising open shrub and woodland. Lewis (1996) determined that the various plant communities result in different densities of plant, lichen and litter cover. However, the average amount of bare ground across the entire region is thirteen percent, ranging from four percent to twenty percent and being seventeen percent near the main kimberlite. Lichen covers a further twenty three percent of the soil in the region (eighteen percent over the Pine Creek 01 kimberlite) but as shown below, it does not influence the spectral response obtained. Therefore, spectrally the kimberlite and adjacent areas can be considered as occupying an area of 40 percent bare soil.

I have investigated this site over a number of years with various spectral geological techniques and instruments. Spectra have been recorded along field traverses using the GER IRIS MkIV and PIMA spectrometers. Samples have also been collected from grids covering the main and other kimberlites in the area and these had spectra recorded with a PIMA. Two airborne scanners have also acquired data from this site:

- GEOSCAN MkII – a static test carried out on soil samples collected from a traverse across the area in 1992
- HyMap II – airborne survey in June 1997 with a 5m pixel size.

The results of processing the airborne scanner and latest PIMA data are presented below.

9.2 GEOLOGICAL SETTING.

Kimberlites in the region have been dated at +/- 170Ma (Stracke, 1979) and they intrude folded Neoproterozoic Adelaidian System sediments. The Adelaidian System consists of a monotonous sequence of rocks, which includes sandstones, siltstone and shales. There are horizons of calcareous tillite to the south east of the area investigated (Figure 9.2). Recent studies by Cowley and Priess (1997) have now termed the area the Ucocola Inlier and postulate that the majority of kimberlites in the vicinity are intruded into an inlier of Callana group limestone. They state that these Callana group rocks are more intensely folded than the surrounding Umberatana Group sediments and that it is possible that the inlier is structurally associated with a diapiric intrusion, as occurs elsewhere in the region. The eastern margin of the inlier is defined by a NE trending fault and the western edge is
obscured by alluvium which comprises the majority of the cover material in the west of the area. Calcrete horizons are developed in the quaternary cover sequence which, over the interfluve areas, consists of residual saprolitic soils with rock scree interspersed between outcrop.

Figure 9.2: Geology map of Pine Creek area (after Cowley and Priess, 1997) showing location of kimberlites and Mg-OH anomalies located from airborne scanner data. The white areas are recent colluvium and alluvium.

** Kimberlites **

Petrographic analysis of the kimberlites in the area (Ferguson and Sheraton, 1979), determined that they are highly weathered and consist of olivine phenocrysts converted to pseudomorphs of serpentine, carbonate and chlorite. Phlogopite phenocrysts, up to 2mm, are preserved in the kimberlite matrix and occur in the residual soils. The groundmass consists of serpentinised olivine and phlogopite. These rocks have been classified as diatreme facies micaceous kimberlite (Joyce, 1982).

The soil over the kimberlites varies in depth from 0.5m to 1.5m (determined from auguring). At surface the soil is dominated by red sand but at a depth of 10cm-20cm it grades into a buff coloured sandy-loam with high clay content. XRD analysis of the weathered kimberlite and derived soils, carried out in 1984 (McLaughlin,1984), determined that the clay was tri- and di-octahedral smectite. As noted below spectral analysis has determined that this clay is saponite. Flakes of phlogopite are present in the soils immediately over some of the kimberlites.
The largest kimberlite in the region, Pine Creek 01, is located in a flat area on the southern side of a shallow valley. The ground rises to the south where outcrops of calc-arenites (Callana Group) occur. There are small outcrops of these sediments within the boundary of the kimberlite. These rocks may be xenoliths of country rock in the kimberlite or faulted blocks but insufficient exposure and lack of borehole information exists to verify this.

9.3 FIELD STUDIES

My investigations into the spectral responses in this area have included studies using both the GER IRIS MkIV and PIMA spectrometers. The most recent of these investigations was completed in February 1998 using a PIMA after the area had been surveyed with the HyMap scanner. This study includes not only investigations into the main kimberlite Pine Creek 01 (Figure 9.2) but also a number of Mg-OH anomalies which are now considered to be previously undiscovered kimberlites.

The aims of these spectral investigations have been to:

- Determine the spectral signature of kimberlite in the area.
- Determine the spectral response of the soil derived from the kimberlite.
- Determine the spectral response of lichen encrusted soils.
- Map the extent of the Mg-OH signature in the soils against the background spectral response.

These studies have mainly been carried out over the Pine Creek 01 kimberlite but spectral data were collected from grids covering two other Mg-OH targets derived from the HyMap data (Figure 9.2). These data are discussed in the section on processing of the HyMap data below.

**Spectral Response of the Kimberlite**

There are no outcrops of kimberlite (Figure 3.3) in the area, though occasional pieces of float of weathered kimberlite occur. Past exploration activity in the area has resulted in patches of kimberlite spoil occurring at the surface consisting of a grey clay matrix in which nodules of weathered serpentinised kimberlite and flakes of phlogopite are abundant. Spectra that I have recorded with the PIMA from thirty samples of this weathered kimberlite all produced a spectrum that is typified by that shown in Figure 9.3. This spectrum has a broad diagnostic absorption feature at 2312nm and a secondary feature
at 2386nm; whilst this spectrum lacks other minor features, it can be interpreted as a
generic kimberlite spectrum that results from the mixture of several phyllosilicate minerals
including talc, serpentine, phlogopite and saponite. There is no indication of the presence
of chlorite in any spectra of the kimberlite spoil though it is mentioned in the petrographic
description of the rock (Joyce, 1982). XRD analysis of this material (McLaughlin, 1984)
determined that it comprised mainly of tri-octahedral smectite. Analysis of the spectra
indicates that the smectite is saponite and the deep featureless water absorption features at
1400nm and 1900nm support the identification of smectite by XRD.

Figure 9.3: Average spectra (hull quotient transformed) of Pine Creek 01 kimberlite. Vertical bars at
2312nm and 2386nm for reference.

Spectral Response of Soil derived from Kimberlite

Spectra were recorded at 15cm intervals for soil samples obtained from an augur hole in
the eastern arm of the Pine Creek 01 kimberlite (grid station 1200/1150, Figure 9.4). These
spectra are presented in Figure 9.5, which shows that there is variation in the spectra and,
therefore, mineralogy of the soil derived from the kimberlite. The surface material is red
brown sandy loam that changes to a buff to yellow clay rich soil at a depth of around
20cm.
The spectra of surface material show subdued absorption features at 2208nm, 2310nm and 2386nm with shoulders at 2254nm and 2290nm. These samples can be interpreted as a mixture of Al-OH and Mg-OH clays (illite and saponite respectively; see Chapter 7). At surface the absorption features are shallow (deepest at 2308nm 1.8 percent) and broad due to the admixture of sand (see Chapter 7 on effects of spectral mixtures). However, absorption features increase in depth downwards. At 40cm the soil produces a spectrum that is virtually identical to that obtained from the kimberlite spoil (Figure 9.3) though from 60cm the spectra again show both Al-OH and Mg-OH spectral characteristics.
By ratioing the depths of the 2200nm (Al-OH) and 2312nm (Mg-OH) absorption features (Mg Score ratio) it is possible to determine the percentage of the Al-OH and Mg-OH minerals that have mixed to produce these spectra (see Chapter 6). The proportions derived from the Mg Score ratio values are shown in Table 9.1. XRD analysis of soils from this locality (McLaughlin, 1984) indicates that both tri- and di-octahedral (nontronite) smectites occur with the former (saponite) dominating.

<table>
<thead>
<tr>
<th>SAMPLE NUMBER</th>
<th>DEPTH cm</th>
<th>Mg-OH PERCENT</th>
<th>Al-OH PERCENT</th>
<th>Depth 2312nm Feature</th>
</tr>
</thead>
<tbody>
<tr>
<td>AUGUR_0cm</td>
<td>Surface</td>
<td>73</td>
<td>27</td>
<td>4.6</td>
</tr>
<tr>
<td>AUGUR_20cm</td>
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<td>84</td>
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<td>86</td>
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<td>98</td>
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<td>89</td>
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<tr>
<td>AUGUR_100cm</td>
<td>100</td>
<td>11</td>
<td>89</td>
<td>1.8</td>
</tr>
</tbody>
</table>

Table: 9.1: Pine Creek 01 augur hole spectral analysis.

From a remote sensing point of view, the presence of a relatively deep 2312nm absorption feature (4.6 percent) at the surface is significant. It should be possible to identify this spectrum from image data obtained from scanners with suitable band centres and signal-to-noise ratio (see Chapter 7).
Surface Spectral Mapping

Field work employed a new version of the PIMA, the PIMA RAP spectrometer, to collect spectra which were recorded at regular grid stations by digging down 20cms and placing the instrument on the spoil. These data were processed by focusing on the 2000nm-2500nm wavelength range and after smoothing and applying a hull quotient transform, determining the Mg Score ratio. The Surfer package was used to contour these Mg Score values.

Pine Creek 01 Kimberlite

A 500m by 600m grid covers the Pine Creek 01 kimberlite as well as the majority of an Mg-OH anomaly which is located to the south east and that was detected from the HyMap scanner data.

Contouring of the Mg Score ratio values obtained from the spectra shows a contour pattern that coincides with the kimberlite and the scanner anomaly (Figure 9.4). The higher Mg Score ratio values indicate saponite and the lower values a background derived Al-OH minerals (illite). The Mg Score contour value of .8 marks the boundary between Al-OH and Mg-OH dominant soils.

Figure 9.6: Pine Creek 01 hull quotient transformed Mg-OH (red) and Al-OH (black) soil spectra that are typical of kimberlite and background soils respectively.
Figure 9.7 shows the range of Mg Score ratio values that occur across the kimberlite to background boundary.

![Figure 9.7: Pine Creek 01 soil Mg Score ratio value for grid line 1400(Figure 9.4) plotted as a profile across the kimberlite. The kimberlite is located between grid stations 1175 and 1375.](image)

The contour pattern shown in Figure 9.4 indicates that saponite in the soil extends SE from the kimberlite, up slope, into a region of calc-arenite outcrop that corresponds to a scanner-defined region of anomalous Mg-OH minerals. These outcrops of calc-arenite are characterised by spectra that are typical of carbonate (Figure 9.8). The typical background soil spectra in the area, including areas of calc-arenite, where the Mg-OH spectra are absent, are the Al-OH illite and/or kaolinite type.

![Figure 9.8: Pine Creek region calc-arenite (red) and background (black) soil hull quotient spectra.](image)
Contour plots have been produced of the Mg Score ratio values obtained of samples collected from grids laid over HyMap anomalies Pine Creek 08 (PC8) and Pine Creek (PC9) (Figure 9.9). These plots also show a coincidence of higher Mg Score indicating the presence of Mg-OH minerals (saponite), with the scanner anomalies. There are no known kimberlites at these locations but loam samples collected during field analysis for kimberlite indicator minerals have grain counts that are indicative of kimberlite in the immediate vicinity (Shee, 1998 pers. comm.).

![Contour plots](image)

Figure 9.9: PC8 and PC9 HyMap Mg Score ratio contour maps showing anomalous areas of mineral bearing soil and the outline in black of HyMap scanner derived Mg-OH anomalies derived from spectral image analysis, see below.

The PC8 anomaly is located in a slight depression that is rimmed by outcrops of arenites and shales. The PC9 anomaly is located on a ridge with outcrops of calc-arenites and float of indurated shale.

**Vegetation Cover**

An important factor when considering analysis of scanner imagery is the vegetation cover. The percentage of bare soil and outcrop required before meaningful spectral data obtained from scanner pixels needs to be established.

Of the sites I investigated in this research, the Pine Creek site in the South Australia Park is the least vegetation covered. It is close to the 50 percent phytohydroxeric contour level.
On occasions it receives heavy rainfall that results in rapid ephemeral vegetation growth sustaining a moderate bush cover. To estimate the vegetation cover at this location vertical photographs were taken with a hand held camera over several 5m by 5m areas. These were then mosaiced and areas of bare soil and cover materials were annotated. The interpretation was then digitised and percentages of the area of bare soil calculated (Figure 9.10).

Figure 9.10: Photo interpretation of vegetation cover produced from 5m by 5m photo mosaic. Mauve areas are leaf litter and dry vegetation (30 percent), yellow areas are green vegetation (24 percent), grey areas are soil with lichen cover (4 percent) and white areas are bare soil (42 percent).

At the Pine Creek test site the percentages estimated by this method were as follows:

- bare soil 42 percent
- soil with lichen 4 percent
- vegetation litter 30 percent
- green vegetation 24 percent

One year after this study was carried out Lewis (1996) conducted a vegetation survey of a larger area (Figure 9.11). Whilst her overall assessment suggested that bare soil comprised approximately 11 percent of the total area, in the vicinity where my photographic method was applied, she determined the percentages of materials at surface as:
In this case bare soil and lichen equals 38 percent and Lewis pointed out (Lewis, 1996 pers. comm.) that as the area had not been grazed close to the time of her survey lichen would be preserved. This could account for the difference in bare soil percentages derived from the two methods. Experiments I completed in this area suggest that the lichen does not mask the spectral response of the soil. This study indicates that vegetation surveys should be carried out as close as possible to the time that an airborne scanner survey is completed. Comparing these techniques indicates that the photo technique is a useful method for rapidly obtaining the percentage of soil exposure.

As shown below, the Pine Creek site has a clearly identifiable Mg-OH spectral response associated with ultramafic rocks from airborne scanner data. This is the most densely vegetated site investigated in this study; therefore, it can be asserted that with greater than 37 percent bare soil it is possible to detect Mg-OH spectral signatures in soils using airborne spectrometer data. Further studies are required to determine what is the minimum
soil exposure that precludes useful geological data being acquired from airborne scanner imagery.

Spectral Effects of Lichen

As Lewis (1996) has pointed out lichen can cover up to twenty six percent of the ground in this region. As lichen or algal encrustations are in effect dry vegetation, they have spectra with absorption features near 2300nm which could be a limiting factor in obtaining geologically meaningful information from scanner data in this region. Therefore, spectra were recorded from patches of lichen and adjacent soil (in the field) by placing the PIMA onto the surface and ensuring that it did not disturb the lichen crust. There are two types of lichen seen in the region; a black crust that is ubiquitous and termed by Lewis (1996) “algal crust” rather than lichen senso stricto and true white lichen. The white lichen is far less prevalent and usually occurs close to bushes and shrubs.

Examination of the spectra in Figure 9.12 shows that the soil surface and black lichen are virtually indistinguishable between 2150nm and 2500nm. The lower albedo of the lichen (18 percent at 2100nm compared to 30 percent for soil) would account for the fact that absorption features are shallower for the lichen spectra (0.8 percent at 2200nm) than for the soil (1.7 percent at 2200nm).

Figure 9.12: Pine Creek 01 soil (black) and black lichen (red) spectra (null quotient transformed). The minor differences between these spectra are not significant. The blue spectrum is of white lichen.
This check was carried out on background soils, not over the kimberlite. The soil and lichen spectra both represent poorly ordered kaolinite, with a weak 2168nm shoulder, 2208nm main absorption features and minor absorptions at 2312nm and 2340nm. It confirms my visual inspection in the field, supported by Lewis (1996 pers. comm) that the black lichen-algal crust consists of a matrix of soil bound together by the algae, which explains why the soil dominates its spectra. The white lichen has definite cellulose absorption features in its spectrum (see Chapter 6) with a broad deep absorption (4 percent) at 2100nm and 2300nm. The near 2100nm absorption feature is seen in the black lichen spectra confirming the presence of organic material.

Since the white lichen is not widespread in the area and often occurs in the shadow area of shrubs, it is doubtful that it would cause confusion in interpreting scanner imagery. The widespread black encrustation appears to reduce the soil albedo and, therefore, spectral contrast. However, it does not eliminate diagnostic spectral features. Other vegetation such as trees, shrubs and litter obscure the surface and, therefore, geological signatures, but they can be identified in the imagery.

9.4 GROUND BASED SPECTRAL ANALYSIS OF KIMBERLITE AND BACKGROUND SOILS FROM PINE CREEK USING THE GEOSCAN MK II SCANNER

In 1992 Dr Frank Honey (founder of the GEOSCAN Company) suggested the idea of collecting spectra with the GEOSCAN MkII scanner on the ground. However, he pointed out that there was a problem in extracting a spectral signature from GEOSCAN MkII imagery at the time due to the gain and offsets introduced into the data during data collection. Dr Honey suggested, that dark and light reference plates could be measured together with the sample. With software developed to use the reference readings to correct data collected to reflectance such an experiment would be worthwhile.

An experiment was set-up to determine if data from the GEOSCAN MkII scanner could be used to discriminate between soil derived from kimberlite (Mg-OH mineral rich) and background soils (Al-OH mineral rich). In this experiment only the SWIR2 channels are evaluated (2000nm-2350nm).
Procedures

Twelve surface soil scraps were collected from a traverse across the Pine Creek 01 kimberlite; three were within the kimberlite boundary and the rest from the background.

![Map showing location of GEOSCAN MkII samples](image)

*Figure 9.13: Sketch showing location of GEOSCAN MkII samples relative to the Pine Creek 01 kimberlite location. Note samples M8757 to M8759 and M8765-68 locations are not shown as they were collected to the north and south of the kimberlite respectively. Map is not to scale.*

Dr Honey and I carried out the measurements in February 1992. The GEOSCAN MkII Scanner was removed from the aircraft (Figure 9.14) and set up to record measurements from both the sample and black/white reference targets. As the measurements were made in direct sunlight a shield covered the scanner during the readings to keep it at a constant temperature.

![GEOSCAN MkII Scanner setup](image)

*Figure 9.14: GEOSCAN MkII Scanner set up to measure spectra from soil samples. Below the scanner (on the trestles) is the sample and on each side of it are the black and white reference targets.*
The data were recorded as 768 pixel by 256 line images; the central portion of each image was sample material and about 30 pixels at the end of each line the reference targets.

The electrical engineer responsible for development of this instrument (N. Adronis) provided equations, which allowed the gain and offsets to be removed from the data. These equations were supplied to Dr A Becker who wrote a program (Appendix 4) that was used in conjunction with the average of the dark target reference values to convert the samples to radiance readings in watts per centimetre squared.

Images were then constructed by processing the raw data with this program. These radiance images were then processed using the log residual program to remove the solar background curve and produce pseudo-reflectance images, in effect a hull quotient transform of the data. The log residual transform was carried out using the version developed to run with the i²S S600 system software.

Each sample also had its SWIR spectra measured with the PIMA spectrometer and these were plotted as follows:

- Standard spectra
- Hull quotient spectra.
- Convolved spectra - spectra convolved to GEOSCAN MkII wavelengths.

Analysis

Visual analysis of the various spectra, shown in Figures 9.15 to 9.19 was undertaken and is reported on below.
Figure 9.15: PIMA spectra of the samples measured with GEOSCAN MkII scanner. Only sample M8764 shows a $>2300\text{nm}$ absorption feature. All the other spectra show a feature at 2200nm.

Standard PIMA spectra (Figure 9.15) are typical spectra of soils with Al-OH clays having an absorption feature at 2208nm in all samples except M8764 which shows a $>2310\text{nm}$ (2312nm) feature indicative of Mg-OH clays.

Figure 9.16: Hull quotient PIMA spectra of samples measured with GEOSCAN MkII scanner. In these spectra samples M8762 to M8764 show the $>2300\text{nm}$ absorption feature.

Hull Quotient PIMA spectra (Figure 9.16) indicate that samples M8762 and M873 have the $>2300\text{nm}$ Mg-OH feature as well as the 2200nm Al-OH absorption. Sample M8764 only shows the $>2300\text{nm}$ feature.
The PIMA spectra (Figure 9.17) have been sampled to GEOSCAN MkII bands. These spectra suggest that the 2200nm Al-OH absorption should be visible in all spectra except M8764 and that the Mg-OH feature will only be discernible in samples M8762 and 64.

The un-calibrated spectra obtained from the GEOSCAN MkII data (Figure 9.18) cannot be interpreted in a systematic or meaningful way.

Figure 9.17: PIMA spectra sampled to GEOSCAN MkII scanner bands. The spectra show that the scanner channel 17(2300nm) should show the absorption feature in spectra of samples M8763 and M8764.

Figure 9.18: Un-calibrated spectra obtained from GEOSCAN MkII scanner. These spectra cannot be interpreted in a meaningful way.
Figure 9.19: Calibrated spectra obtained from GEOSCAN MkII. Absorption features are difficult to distinguish in these uniform appearing spectra.

The calibrated GEOSCAN MkII spectra (Figure 9.19) are uniform in appearance. No 2200nm absorption can be distinguished and only in spectrum M8764 is there an indication of an absorption at >2300nm.

Figure 9.20: Calibrated and log residual transformed spectra obtained from GEOSCAN MkII scanner. Spectra of samples M8762 to M8764 all show an absorption at >2300nm. The 2200nm feature is absent from several of these spectra apart from M8760. Vertical line is at 2300nm.

In the Log Residual spectra (Figure 9.20) obtained from the GEOSCAN MKII data the 2200nm Al-OH minimum is not apparent in the spectra M8759, 61, 62, 63, 64, 65 and 67. This is almost certainly due to applying the Log Residual transform to such a spectrally restricted data set. The Log Residual transform removes features that are common to each
pixel, in this case it is removing the ubiquitous 2200nm feature. However, the convolved PIMA spectra (Figure 9.17) indicate that it should be obvious in all of the spectra except M8764. Samples M8762-M8764 all show a minimum at >2300nm that indicates absorption due to the presence of Mg-OH minerals.

Comments and Conclusions

This investigation confirms that the GEOSCAN MkII scanner could, under favourable conditions, with corrections made for atmosphere and gain and offset, detect and differentiate between kimberlite derived soils and those from background Al-OH rich lithologies.

This study was carried out to investigate whether the GEOSCAN MkII had potential to locate Mg-OH bearing rocks and the soils derived from them. In Chapter 11 it is shown that the noise level in GEOSCAN MkII data, when acquired operationally during an airborne survey, can reduce the potential discrimination that this study suggests is possible. As shown in Chapter 7 noise can significantly reduce the discrimination possible with scanner data. Prior to this study, the noise level in operationally acquired GEOSCAN data was estimated to be around 220:1 (Hook, 1990). In the configuration used to acquire these static test data, the signal-to-noise level would have been higher than during airborne operations as induced electronic noise and vibration would have been less (Honey, 1992 pers. comm.).

Dr Honey has recently recommissioned the GEOSCAN MkII scanner. He has modified this scanner to collect data in integer rather than byte format thus eliminating the problems with gain and offset corrections mentioned above. Dr Honey claims (pers. comm) to have improved the SNR by a factor of two or three (400:1?). Therefore, in future this instrument may be able to acquire operationally useful data for the detection of out-cropping and weathered ultramafic rocks.

9.5 IMAGE PROCESSING OF HyMap SCANNER DATA

Conventional Processing

According to the manufacturer (Cocks, 1997 pers. comm.) the signal-to-noise ratio for the HyMap scanner used in this study exceeds 600:1 in the SWIR2 spectral region. It should be possible to use the conventional processing techniques to extract the Mg-OH spectral...
signature as described in Chapter 8. To validate this the following processes have been applied to the data:

- Colour composite images from raw data.
- Colour composites of log residual transformed images.
- Band ratio.
- Crosta principal component transform (Crosta technique).
- Anomaly residual band prediction.

These processes have been applied with consideration to the band centre wavelengths for this imagery shown in Table 9.2.

<table>
<thead>
<tr>
<th>SWIR2 BAND</th>
<th>WAVELENGTH nm</th>
<th>SWIR2 BAND</th>
<th>WAVELENGTH nm</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>2087</td>
<td>17</td>
<td>2267</td>
</tr>
<tr>
<td>2</td>
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<td>18</td>
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<td>7</td>
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<td>23</td>
<td>2328</td>
</tr>
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<td>2225</td>
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<td>2236</td>
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</tr>
<tr>
<td>16</td>
<td>2257</td>
<td>32</td>
<td>2411</td>
</tr>
</tbody>
</table>

Table 9.2: HyMap SWIR2 band centres in nm.

Data used in this study were acquired from the Pine Creek area in February 1998 and Figure 9.1 shows the location of the flight line relative to the known kimberlites. This 18km long north-south flight line has data with a pixel size of ~5m by 6m. In this study a subsection of the imagery 3.65km long, that is 600 lines of data, has been investigated. The swath width is approximately 2.5 km.

In Figure 9.21 the location of the Pine Creek 01 kimberlite and two other Mg-OH spectral anomalies, located in the area, PC 8 and PC9 are shown.
Figure 9.21: HyMap image showing location of Pine Creek 1 kimberlite and Mg-OH anomalies PC8 and PC9. The image is 2.5km from west to east. North is to the top in this and all subsequent images.

Raw Data Colour Composite Image

A three band red, green and blue (RGB) colour composite, derived from the raw data, of the SWIR2 bands 2318nm, 2208nm and 2158nm was produced and is displayed as a negative, Figure 9.22. This is a low colour contrast image due to high correlation of the data between bands that results from the dominance of the solar radiance curve in these data. Examination of this image indicates that further processing is required for geologically useful information to be obtained from these data.

However, this colour composite does show the main topographic features of the area, the vegetation differences and regions of brighter soils associated with the main creek that drains north-east along the western side of the region. Generally the colours are subdued and are pastel in appearance with a dominance of grey tones.
Figure 9.22: HyMap colour composite image of the negative of raw image bands centred at 2318nm, 2208nm and 2158nm displayed in red, green and blue respectively. The image is 2.5km from west to east.

Log Residual Colour Composite

Using the same bands as above, a colour composite (Figure 9.23) was produced from the log residual transformed data which is also displayed as a negative; it shows more diagnostic information than the raw data colour composite (Figure 9.22). In this log residual transformed image, vegetated areas are in red-purple hues. Alluvial soils are green, while other background areas are in green, cyan and blue hues. There is a deeper red region located on the main interfluve ridge that crosses the centre of the region. Localised within this red area are patches of brighter red that correspond to the locations of Pine Creek 1 kimberlite and Mg-OH anomalies PC8, PC9 and PC N.
Figure 9.23: HyMap colour composite of log residual transformed image bands centred at 2318nm, 2208nm and 2158nm displayed in red, green and blue respectively. The image is 2.5km from west to east.

The spectrum in Figure 9.24 is typical of the bright red hued pixels in the log residual transformed colour composite. The strong absorption feature at 2318nm is the source of the red hue in this negative image rendition (Figure 9.23). This spectrum also has a relatively featureless curve of higher reflectance at shorter wavelengths and two subsidiary absorption features near 2380nm and 2410nm (Figure 9.24). This spectrum is diagnostic for the presence of Mg-OH minerals.

Figure 9.24: Spectrum extracted from log residual transformed data at a bright red location in Figure 9.23. It is a typical of spectra obtained from Mg-OH bearing minerals, with a deep absorption feature at >2300nm.

The green areas in Figure 9.23 correspond to the alluvial soils, and spectra extracted from the image in these areas have a distinct spectrum typical of Al-OH clays (Figure 9.25). The
main Al-OH absorption feature is located at >2200nm with subsidiary features near 2390nm and 2410nm. This spectrum can be interpreted as derived from a mixture of Al-OH clays.

![Log Residual - Al-OH](image)

*Figure 9.25: Spectrum extracted from log residual transformed data at a location shown as green (alluvial areas near creeks) in the colour composite, Figure 9.23. It is a typical of spectra obtained from Al-OH bearing minerals with a deep absorption feature >2200nm.*

A spectrum (Figure 9.26) obtained from blue areas in the image (Figure 9.23) is typical of dry vegetation. Significantly, this spectrum also has a deep absorption feature at ~2300nm similar to the Mg-OH spectra, this explains the gradation from blue to mauve to red areas in the image.

![Log Residual - Dry Vegetation](image)

*Figure 9.26: Spectrum extracted from log residual transformed data at a location shown as blue (vegetated areas) in Figure 9.23. It is a typical of spectra obtained from dry vegetation, deep asymmetric absorption feature at ~2300nm and broad absorption at 2150nm. The image is 2.5km from west to east.*

However, there are features that distinguish it from a Mg-OH spectrum (Figure 9.24):

- A distinct broad absorption feature at 2150nm results in a spectral peak near 2215nm, not seen in Mg-OH spectra.
- The ~2300nm feature is asymmetric.
- On the >2300nm slope minor absorption features are developed.
However, in the colour composite this spectral type results in confusion between Mg-OH minerals and dry vegetation (mauve-red hues).

*Mg Score Ratio*

The confusion between Mg-OH bearing minerals and dry vegetation is due to the coincidence of the 2300nm feature in their spectra as illustrated by the Mg Score ratio image (Figure 9.27). This image is produced by dividing the 2203nm band by the 2318nm band. Both Mg-OH minerals and dry vegetation are highlighted in brighter tones in the resultant image. This image was produced from the log residual transformed data.

![Figure 9.27: HyMap Mg Score ratio image of log residual transformed image band 2203nm divided by 2318nm. Bright areas have an absorption feature at 2306nm. The image is 2.5km from west to east.](image)

*Crosta Principal Component Transform*

Applying the Crosta principal component transform (Crosta technique) produces images that lessen this mixed spectral response though do not eliminate it. Bands centred at 2158nm, 2203nm, 2257nm and 2318nm were used for the transform. The eigen matrix resulting from this transform is:
<table>
<thead>
<tr>
<th>BAND</th>
<th>2158nm</th>
<th>2203nm</th>
<th>2257nm</th>
<th>2306nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC1</td>
<td>0.081</td>
<td>-0.280</td>
<td>-0.600</td>
<td>0.745</td>
</tr>
<tr>
<td>PC2</td>
<td>-0.381</td>
<td>-0.433</td>
<td>-0.573</td>
<td>-0.583</td>
</tr>
<tr>
<td>PC3</td>
<td>0.590</td>
<td>-0.548</td>
<td>0.532</td>
<td>0.279</td>
</tr>
<tr>
<td>PC4</td>
<td>0.707</td>
<td>0.659</td>
<td>0.197</td>
<td>-0.166</td>
</tr>
</tbody>
</table>

An index image was produced whereby density slicing out the values over the mean plus twice the standard deviation from Crosta PC4 are overlain onto a black and white background image in red (Figure 9.28). This image shows that there is a broad spread of this spectral signature throughout the core of the region, though the Pine Creek 01 kimberlite and Mg-OH mineral anomalies PC8 and PC9 show as distinct anomalous clusters of red pixels.

Figure 9.28: HyMap Crosta principal component transform index image from log residual transformed image. Red areas are from density slice of Crosta PC Band 4 that shows the pixels that have Mg-OH absorption feature in 2306nm band. The image is 2.5 km from west to east.

**Anomaly Residual Band Prediction**

The anomaly residual band prediction transform (Pendock and Lamb, 1989) was used to predict the 2306nm band from the linear combination of the other bands. In the index image produced, using the mean plus twice standard deviation criteria to density slice the data, the brightest pixels are coloured red and they highlight the areas that have the strongest 2306nm absorption features in their spectra (Figure 9.29). This image indicates a spread of materials and minerals with the 2306nm absorption extending beyond the Pine 9-27
Creek 01 kimberlite and other Mg-OH anomalies in the area; though in a more diffuse manner than is the case with the Crosta principal component transform.

![Figure 9.29: HyMap Anomaly Prediction Index image of 2306nm band predicted from other log residual transformed SWIR2 bands. The red areas highlight the pixels with 2306nm absorption features indicating the presence of Mg-OH bearing minerals. The image is 2.5km from west to east.](image)

### Spectral Processing

The spectral unmixing techniques discussed in Chapter 3 were applied to the log residual transformed data. A number of end member spectra that represent different minerals and materials were obtained from processing of the imagery. One of these end-member spectra (Figure 9.30) has an absorption feature the 2306nm and is very similar in appearance to that recorded with the PIMA from the kimberlite spoil (Figure 9.3).

![Figure 9.30: HyMap Mg-OH mineral end-member spectrum obtained from log residual transformed data. It represents a distinct class of spectra within the image having a 2306nm absorption feature.](image)
Figure 9.31: HyMap un-mixed index image for Mg-OH end-member spectra shown in Figure 9.28. The red areas show pixels that contain a proportion of the end-member above the mean image pixel value plus twice the standard deviation. The image is 2.5 km from west to east.

Un-mixing of the log residual transformed data produces images that map the distribution of the various end-member spectra within the image. Density slicing these images, using the mean plus twice standard deviation technique, produces index images such as that for the Mg-OH end-member spectra (Figure 9.31). This Mg-OH un-mixed index image highlights the Pine Creek 01, PC8, PC9 and PC N kimberlite/Mg-OH soil anomalies as red pixels but this image (Figure 9.31) also shows a spread of the signature beyond the anomalies and kimberlite. However, it is reduced in extent when compared to the images produced from the classical data transforms that have been discussed.

Comparing the images produced by conventional processing techniques, such as the Crosta technique, and the Mg-OH un-mixed image it is apparent that the results are similar. However, the overall distribution of Mg-OH regions is more confined in the un-mixed image highlighting the Pine Creek 01 and other kimberlites more distinctly. This is illustrated in Figure 9.32, where the Crosta principal component and un-mixed Mg-OH images are overlain onto the same image base. Note that using ENVI the green un-mixed result is covering pixels that are in fact also highlighted (red) in the Crosta principal component image (see Figure 9.28). The spread of the highlighted pixels does show that some mis-identification is occurring in the un-mixed image.
Figure 9.32: Results of end-member un-mixing to determine the distribution of pixels with Mg-OH spectra shown green and Crosta principal component result in red. Note that the Crosta result indicates a wider spread of Mg-OH positive pixels than the un-mixing process. The image is 2.5km from west to east.

Another end-member with a $>2300\text{nm}$ absorption feature can be isolated from the log residual transformed data. This spectral end-member is characterised by a broad asymmetric feature typical of dolomite (Figure 9.33).

Figure 9.33: HyMap dolomite end-member spectrum. This spectrum has the asymmetry typical of dolomite spectra with a broad $>2300\text{nm}$ absorption feature.
A colour composite has been produced by combining the two un-mixed image \( \sim 2300\text{nm} \) end-member bands with the end-member band for Al-OH (spectra Figure 9.34). When contrast stretched between the mean and maximum values this image shows the extent of Mg-OH signature almost exclusively confined to the Mg-OH anomalies/kimberlites, PC1, PC8, PC9 and PC N (Figure 9.35). In this image an area west of PC8 and north of PC1 remains highlighted and would be worthwhile investigating as a potential kimberlite.

![End Member Spectra (Al-OH)](image)

*Figure 9.34: HyMap Al-OH end-member spectrum.*

![Mg-OH/Al-OH mineral end-members un-mixed colour composite image](image)

*Figure 9.35: HyMap Mg-OH/Al-OH mineral end-members un-mixed colour composite image. Areas highlighted red are Mg-OH, green dolomite and blue Al-OH bearing pixels. Note that the red areas are confined to the main Mg-OH anomalies / kimberlite, except for area west of PC8 to north of PC1. Yellow areas show where dolomite and Mg-OH minerals are intermixed. The image is 2.5km from west to east. Top is to north.*
Comments

Of the conventional processing techniques investigated, the Crosta and anomaly prediction technique index images provide the most interpretable results for discriminating the Mg-OH regions of interest. These techniques are simple to apply using the ENVI software, though the Crosta technique does require several iterations to determine the best combination of three bands to input with the band of interest (2306nm).

The end-member un-mixing technique is interactive and time consuming, though this is being addressed with improved software that should automate the end-member spectra selection. The need for such automated processing will increase when satellite systems such as ARIES produce vast amounts of data routinely (Huntington, 1997 pers. comm.). This technique provides specific and consistent results with the advantage of selecting the end-member of interest based on spectra that show only the Mg-OH characteristics.

This study shows that the Crosta principal component, Anomaly Residual Prediction and end member un-mixing index techniques produce images that separate the dry vegetation from Mg-OH spectral signatures. This is not achieved using the other conventional processing techniques such as the Mg Score Band ratio and negative colour compositing of Log Residual transformed bands.

The combined end-member colour composite image separates the dolomite from Mg-OH mineral regions. This separation better highlights the Pine Creek 01 Kimberlite and identifies other anomalies including PC8, PC9 and PC N which heavy mineral indicator grain studies indicate are probable Kimberlites (Shee, 1998 pers. comm.).

Discussion

The 1998 and previous field studies in the Pine Creek area confirm that saponite is associated with the Pine Creek 01 Kimberlite and other regions defined from the Mg-OH end-member un-mixed image. These field studies have also confirmed the presence of saponite in soils associated with the calcareous Callana formation rocks. The intermixing of the dolomite and Mg-OH spectral end-members (yellow areas from red Mg-OH and green dolomite) seen in the un-mixing colour composite image (Figure 9.35) supports the observed association between saponite and calcareous sediments.
Graham (1967) postulates that weathering of dolomite with kaolinite present can produce saponite; this reaction is enhanced by elevated temperatures and hydration (Post, 1984 and Fulignati et al., 1997) associated with hydrothermal activity. Cowley and Priess (1997) have stated that the Callana formation is an inlier of carbonate rich rocks. My field observations suggest that the Callana formation can be classed as a dolomitic calc-arenite, as these rocks contain a high proportion of quartz grains. Therefore, the intrusive event associated with the emplacement of the kimberlite may have catalysed the formation of saponite from the Callana formation sediments. This would have extended the area of saponite beyond the limits of the kimberlite in this instance. Further studies into the genesis of saponite in the soils would be worthwhile.

9.6 CONCLUSIONS FROM PINE CREEK SPECTRAL STUDIES

This investigation has shown that spectral studies in this region can locate kimberlites from their Mg-OH spectral signature. It also reveals useful information on the mineralogy of the regolith and soils in this area.

The study shows that HyMap scanner data, when appropriately processed (most reliably by end-member un-mixing), can locate the areas of saponite associated with the kimberlites. The static test with the GEOSCAN MkII scanner shows that data acquired from this scanner have the potential to locate the saponite spectral signature associated with the Pine Creek 01 kimberlite. Whether such data could be processed using Log Residual transforms and end-member un-mixing to discriminate the 2306nm spectral signature (saponite) as was achieved with the HyMap data, is not proven by this study.

The occurrence of saponite in this area, and its apparent association with both kimberlite and Callana formation dolomitic rocks, requires further study. Unless there is a much wider occurrence of kimberlite within the Callana formation, perhaps as widespread veins, then the spread of saponite indicated by this study may be due to either:

- Weathering of the dolomitic rocks of the Callana formation which is producing the saponite, in which case the identification of saponite from remotely sensed data may result in misleading results when seeking kimberlites and other ultramafic rocks in dolomitic areas; or

- The thermal event associated with the kimberlite emplacement also produced saponite from the calc-arenites, which would be a rarer occurrence than if the saponite were produced by the weathering of dolomites alone.
Studies into the formation temperature of the saponite in this area would be required to determine which of these possible explanations is correct. This might be achieved by using oxygen isotope studies. In another area studied by the author, this technique confirmed that a totally kaolinised kimberlite was the result of weathering, not hydrothermal alteration as had been suspected (Pontual, 1995).
CHAPTER 10

10 TEST SITE STUDY - JUBILEE, KURNALPI AREA, WESTERN AUSTRALIA

10.1 INTRODUCTION

The Jubilee site is situated 60km northeast of Kalgoorlie in the Yilgarn region of Western Australia (Figure 10.1) and was selected as an example of an exposed ultramafic rock, serpentinite. The area is a partially stripped landscape with prominent ridges of fresh greenstones of low to moderate relief. Soil types range from shallow residual material developed on the ridges and outcrops to more deeply weathered and transported soils on the slopes. There are extensive areas of colluvium on the lower lying areas. These flats form the loci for the drainages that flow south into Lake Yindarlgooda.

Figure 10.1: Location Map Jubilee Area, Western Australia showing line of the HyMap, GER IS and GEOSCAN MkII scanner flights.
The intrusive body investigated in this study is nearly rectangular and it is orientated northwest southeast. This intrusive has a surface area of 150 hectares and intrudes into the clastic sediments of the Mulgabbie formation. The petrographic report on this rock (McMaster and Marx, 1984) states that it is a serpentinised peridotite/dunite. The geology map of the area (Williams, 1973) identifies this intrusive as belonging to the Kalpini formation ultramafic sequence that is identified as the youngest of the Archaean rocks in the area. The margins of the body, particularly on the northern and southern sides, are probably fault controlled. These shear zones have been investigated for gold and nickel mineralisation and trenches have been dug across them. On the western side of the intrusive, a northeast to southwest trending fault offsets it dextrally. Where this fault extends northwards from the intrusive, trenches have been dug across it by mineral exploration companies in previous years. This fault and the trenched area are clearly seen in several of the HyMap processed images (Figure 10.25 to 10.27).

To the west, the margin of the intrusive is obscured by sand plain and lateritic duricrust and in the east by colluvium. On the south and north, the contact with the clastic rocks is exposed. A typical lateritic weathering profile is developed on the clastic sediments to the south of the intrusive. Two kilometres north of the intrusive, there is an outcrop of east-west trending greenstones of the Mulgabbie formation. These rocks are described as greenschist facies, basic to intermediate intrusives in the legend of the geology map (Williams, 1973).

As Figure 3.1 shows, the area is sparsely vegetated with exposed soil and outcrop comprising up to 70 percent of the region. There is no significant lichen development in this area. However, on the southeastern side of the ultramafic, there are dense areas of spinifex.
Figure 10.2: Geological sketch map of Jubilee ultramafic outcrop with the location of grid sampled for PIMA spectral investigations; the contours for the Mg Score ratio values are shown. This map covers only the western edge of the main ultramafic intrusive that appears in the images below.

Figure 10.2 is the geological sketch map that I drafted from aerial photograph interpretation and fieldwork, it covers the western end of the intrusive. This map shows the location of the grid from which I collected soil samples for spectral analysis. This 400m by 400m grid had samples collected at 40m intervals along lines 40m apart. Spectra were recorded from each sample using the PIMA spectrometer. The Mg Score ratio was calculated (described in Chapter 8) for each spectrum and these values contoured. In Figure 10.2 the Mg Score contours show a marked increase in the southeastern section of the grid, coincident with the ultramafic outcrop. The spectra in Figure 10.3 show the Al-OH and two Mg-OH spectral types that occur in the grid area. These spectra can be identified as representing poorly ordered kaolinite, saponite and serpentinite.
Figure 10.3: Field spectra from Jubilee grid spectral hull quotient transformed. Red spectrum is background Al-OH poorly ordered kaolinite. Black spectrum is saponite and blue spectrum is serpentine, these spectra are from samples taken on ultramafic.

10.3 IMAGE PROCESSING – DATA SETS

Three airborne scanner data sets were acquired of the area centred on the flight line shown in Figure 10.1. The pixel sizes and swath widths for the various images are:

- GER IS (1987)  16 m pixels   4.9 km swath
- GEOSCAN MkII (1988)  7 m pixels   5.3 km swath
- HyMap (1996)  5 m pixels   2.56 km swath

No attempt has been made to remove noise from these images, though Huntington (1994) proved that it is possible to reduce the impact of noise in GEOSCAN MkII data, and by analogy in data from other scanners. This is a highly interactive and time consuming process which involve combining the Maximum Noise Fraction (MNF) and FFT transforms to reduce speckle noise and banding. Operationally it is not practical to carry out this amount of processing on large data sets. Hence, the variation in signal-to-noise ratio between these different data sets should be considered when analysing the images produced. It has been ascertained from the various scanner manufacturers, or other sources, that the signal-to-noise ratios of the instruments at the time these data were acquired are as follows:

- GER IS   -   50:1 at 2200nm
- GEOSCAN MkII -   200:1 at 2200nm (Hook et al., 1990)
- HyMap   -   500:1 at 2200nm
10.4 GEOSCAN MkII DATA

The band centres for the GEOSCAN MkII SWIR data at the time of data acquisition are shown in Table 10.1.

<table>
<thead>
<tr>
<th>Band</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
<th>18</th>
</tr>
</thead>
<tbody>
<tr>
<td>nm</td>
<td>2038</td>
<td>2085</td>
<td>2126</td>
<td>2173</td>
<td>2218</td>
<td>2261</td>
<td>2301</td>
<td>2345</td>
</tr>
</tbody>
</table>

*Table 10.1: GEOSCAN MkII SWIR2 band centres for data discussed in this chapter.*

Conventional Image Processing

These data have had conventional and spectral processing applied to them. Processing included removal of system offsets by dark pixel subtraction which was carried out as a pre-processing stage using an I2S S600 software function. The log residual transform was also applied and the following image products were produced using the ENVI 2.7 software:

- Raw data colour composite
- Log residual colour composite
- Mg score ratio
- Crosta principal component transform

*Raw Data Colour Composite*

The red, green and blue display of bands 2301nm, 2218nm and 2173nm has been produced and is shown as a negative image in Figure 10.4. In this colour composite image, the ultramafic can clearly be distinguished as a beige-brown area in the centre of the scene. Overall this image shows poor contrast due to the highly correlated nature of the data. Vegetated areas are white and outcrops of other rock types and the sand plain are shown in various pale toned colours and greys.
Figure 10.4: Jubilee GEOSCAN MkII negative colour composite of raw data bands at 2301nm, 2218nm and 2173nm in red, green and blue. The image is 5.3km east to west. North is towards top in this and all other images in this chapter.

Log Residual Transformed Colour Composite

The negative of the colour composite derived from the log residual transform data was produced (Figure 10.5) using the same band combination used for the raw data colour composite. This image highlights the intrusive in red and orange hues, other patches of red indicate the presence of minerals and materials with the near 2300nm absorption feature to the north and west of the intrusive. Red areas to the north correspond to the outcrop of greenstones. The geological map (Figure 10.1), and fieldwork by the author, indicate only a sand plain to the west. However, further west greenstones are mapped, therefore, this area of red in the image probably indicates residual soils developed over un-exposed greenstones. The remainder of the image shows regions of green and cyan hues indicating soils and vegetation with absorption features centred at 2173nm and 2218 nm.
Figure 10.5: Jubilee GEOSCAN MkII negative colour composite of log residual transformed data of 2301nm, 2218nm and 2173nm bands in red, green and blue. The image is 5.3 km east to west.

![Image of Figure 10.5]

Figure 10.6: GEOSCAN MkII average Mg-OH spectrum derived from log residual transformed image data, red area in Figure 10.5. Note band numbers not wavelength on X axis, see table 10.1 for wavelengths.

The spectrum shown in Figure 10.6 is taken from an average of pixels located on the serpentinite intrusive (the red area on the log residual colour composite) and shows a strong absorption minimum centred at band 17 (7 in Figure 10.6 centred near 2300nm) which was predicted (Chapter 5) to contain the spectral response of an ultramafic rock in GEOSCAN MkII data. This agreement, with the theoretically predicted spectra, indicates that the noise level is not significantly degrading the data and indicates that the signal-to-noise ratio established by Hook et al, (1990) for this instrument may be correct.
Figure 10.7: is a spectrum obtained from an area of outcrop of clastic sediments situated to the south of the ultramafic outcrop; green on the log residual transform colour composite. This spectrum is that expected for Al-OH clay, probably kaolinite and/or illite. Note band numbers (1-8=11-18) not wavelength on X axis, see Table 10.1 for wavelengths.

The green-cyan areas shown in Figure 10.5 show the distribution of Al-OH bearing materials of which the spectrum shown in Figure 10.7 is typical. The near 2200nm absorption feature, typical of Al-OH clays such as illite and kaolinite, occurring in band 15 (5 in Figure 10.7).

Mg Score Ratio

In this case, the Mg Score was derived by dividing band 2301nm (17) by 2218nm (15), using the log residual transform data. The image produced (Figure 10.8) shows the Mg-OH containing pixels in darker tones which are highlighted red in the index presentation. The red pixels in this image highlight the serpentinised intrusive and also areas to the north and northwest which, as mentioned above, are considered to be areas of thin residual soil developed over greenstones.
Figure 10.8: Jubilee GEOSCAN MkII Mg Score index image produced from log residual transformed data by dividing band 17 by band 15. Index image produced by density slicing using image mean plus twice standard deviation value to clip data. Red pixels highlight areas of Mg-OH minerals including serpentinised ultramafic. The image is 5.3km east to west.

**Crosta Principal Component Transform**

The Crosta technique was applied using bands 12(2085nm), 14(2173nm), 15(2218nm) and 17(2301nm) to derive the eigen matrix:

<table>
<thead>
<tr>
<th>Band</th>
<th>12</th>
<th>14</th>
<th>15</th>
<th>17</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC1</td>
<td>0.512</td>
<td>0.494</td>
<td>0.697</td>
<td>0.095</td>
</tr>
<tr>
<td>PC2</td>
<td>0.457</td>
<td>0.230</td>
<td><strong>0.395</strong></td>
<td><strong>-0.763</strong></td>
</tr>
<tr>
<td>PC3</td>
<td>0.498</td>
<td>0.158</td>
<td><strong>-0.565</strong></td>
<td><strong>0.638</strong></td>
</tr>
<tr>
<td>PC4</td>
<td>0.530</td>
<td>-0.824</td>
<td>0.199</td>
<td>-0.034</td>
</tr>
</tbody>
</table>

The eigen matrix shows that eigen vector PC2 will provide the best discrimination between band 17 (2301nm Mg-OH absorption) and the other bands. In eigen vector PC3 the most difference is between band 15, (2218nm, Al-OH absorption) and the other bands.

The Crosta technique colour composite image produced (Figure 10.9) with PC2, PC3 and PC1 in red, green and blue respectively has a colour distribution that resembles the log residual colour composite (Figure 10.5) but it has more contrast and appears to be less affected by noise. In this image:
• the ultramafic is highlighted by red hues
• interpretation of areas of potentially sub-cropping greenstones west of the ultramafic, are reinforced by the distribution of the red colour
• green areas map the distribution of Al-OH (band 15 –2218nm absorption) minerals
• a distinct green area on the western margin of the image is due to a cloud and is clearly seen in both of the colour composite images.

Figure 10.9: Jubilee GEOSCAN MkII Crosta technique colour composite image produced from log residual transformed data. Red pixels highlight areas of Mg-OH minerals including serpentinised ultramafic. Green colour shows areas of Al-OH minerals as it represents eigen vector PC3 transformed image in which band 15 weighted strongly against other bands. The image is 5.3km east to west.

Spectral Processing

The end member spectrum (Figure 10.10) derived from these data represents the Mg-OH bearing pixels. It is an excellent example of a GEOSCAN MkII Mg-OH spectrum as it should appear when the signal-to-noise ratio is sufficient.
Figure 10.10: Jubilee GEOSCAN MkII end-member Mg-OH spectrum derived from log residual transformed image data. Note band numbers (1-8=11-18) not wavelength on X axis, see table 10.1 for wavelengths.

Figure 10.11: Jubilee GEOSCAN MkII Mg-OH end-member un-mixed index image. Index image produced by density slicing using image mean plus twice standard deviation value to clip data. Red pixels overlain on the un-mixed grey tone image to highlight the Mg-OH mineral distribution. The image is 5.3km east to west.

Figure 10.11 is the un-mixed index image of the Mg-OH end-member spectrum, which shows pixels containing a high proportion of this spectral end-member, highlighted in red. This image defines the areas of Mg-OH minerals including the serpentinised ultramafic, but shows no significant differences to the mineral mapping obtained by the classical processing techniques.
10.5 GER IS DATA

I have examined these data using the same processing techniques that were applied to the GEOSCAN MkII data. These data have a much lower signal-to-noise ratio and this is shown by the striping and speckle apparent in the image products. No signal-to-noise figures for these data were supplied by GER at the time this survey was conducted.

The wavelengths supplied by the manufacturer at the time of this survey are shown in Table 10.2.

<table>
<thead>
<tr>
<th>Band</th>
<th>Wavelength nm</th>
<th>Band</th>
<th>Wavelength nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2005</td>
<td>15</td>
<td>2232</td>
</tr>
<tr>
<td>2</td>
<td>2022</td>
<td>16</td>
<td>2249</td>
</tr>
<tr>
<td>3</td>
<td>2038</td>
<td>17</td>
<td>2265</td>
</tr>
<tr>
<td>4</td>
<td>2054</td>
<td>18</td>
<td>2281</td>
</tr>
<tr>
<td>5</td>
<td>2070</td>
<td>19</td>
<td>2297</td>
</tr>
<tr>
<td>6</td>
<td>2087</td>
<td>20</td>
<td>2314</td>
</tr>
<tr>
<td>7</td>
<td>2103</td>
<td>21</td>
<td>2330</td>
</tr>
<tr>
<td>8</td>
<td>2119</td>
<td>22</td>
<td>2346</td>
</tr>
<tr>
<td>9</td>
<td>2135</td>
<td>23</td>
<td>2362</td>
</tr>
<tr>
<td>10</td>
<td>2151</td>
<td>24</td>
<td>2378</td>
</tr>
<tr>
<td>11</td>
<td>2168</td>
<td>25</td>
<td>2395</td>
</tr>
<tr>
<td>12</td>
<td>2184</td>
<td>26</td>
<td>2411</td>
</tr>
<tr>
<td>13</td>
<td>2200</td>
<td>27</td>
<td>2427</td>
</tr>
<tr>
<td>14</td>
<td>2216</td>
<td>28</td>
<td>2443</td>
</tr>
</tbody>
</table>

Table 10.2: GER IS SWIR2 wavelengths supplied by manufacturer at time of the survey.

Conventional Processing

Log Residual Colour Composite

This colour composite image (Figure 10.12) was produced by displaying the negative of the 2330nm, 2200nm and 2314nm log residual transformed bands in red, green and blue respectively. This image maps the Mg-OH and Al-OH mineral areas into red and green regions; vegetated and general background areas are blue. This is the same colour distribution as seen in the equivalent GEOSCAN MkII image (Figure 10.5). The spectra shown in Figures 10.13 and 10.14 were taken from the red Mg-OH (serpentinite) and Al-OH areas and are representative spectrum of these mineral groups. These spectra are quite jagged in appearance, resulting from the low SNR inherent in these data.
Figure 10.12: Jubilee GER IS negative colour composite of log residual transformed data of bands 2330nm, 2200nm and 2134nm in red, green and blue. The image is 4.9 km east to west.

Figure 10.13: Jubilee GER IS average Mg-OH spectrum derived from log residual transformed image data, red area in Figure 10.12. Vertical red line 2314nm.

Figure 10.14: Jubilee GER IS average Al-OH spectrum derived from log residual transformed image data, green area in Figure 10.12. Vertical red line 2200nm.
**Mg Score Ratio**

In this case the Mg Score ratio image (Figure 10.15) was derived from the log residual data by dividing the 2200nm band by the 2300nm band. The output image derived from this process maps the area of the ultramafic clearly as lighter pixels strongly contrasted with the dark background. It also highlights the areas of Mg-OH spectral signature to the north and west mentioned previously.

![Image of Mg Score Ratio](image)

*Figure 10.15: Jubilee GER IS Mg Score ratio produced by dividing band 2200nm by band 2330nm. The ultramafic is bright compared to the dark background. The image is 4.9 km east to west.*

**Crosta Principal Component Processing**

By choosing 2103nm, 2151nm, 2265nm and 2330nm to derive the eigen matrix, it was expected that one of the eigen vectors would weight band 2330nm for Mg-OH against the rest. In the eigen matrix this weighting is seen in eigen vector PC3:

<table>
<thead>
<tr>
<th>BAND</th>
<th>2103</th>
<th>2151</th>
<th>2265</th>
<th>2330</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC1</td>
<td>0.567</td>
<td>-0.365</td>
<td>-0.504</td>
<td>0.539</td>
</tr>
<tr>
<td>PC2</td>
<td>0.492</td>
<td>0.867</td>
<td>-0.077</td>
<td>-0.003</td>
</tr>
<tr>
<td>PC3</td>
<td>0.492</td>
<td>0.291</td>
<td>-0.107</td>
<td>-0.814</td>
</tr>
<tr>
<td>PC4</td>
<td>0.441</td>
<td>-0.174</td>
<td>0.854</td>
<td>0.216</td>
</tr>
</tbody>
</table>
The index image produced using eigen vector PC3, so that red areas are the clipped values above the image mean plus twice the standard deviation, highlights the ultramafic in red. (Figure 10.16).

Figure 10.16: Jubilee GER IS Crosta index image produced from the PC3 eigen vector. The ultramafic intrusive is highlighted in red. The image is 4.9 km east to west.

Spectral Processing

Two end-member spectra have been extracted from the log residual transformed data. The end-member spectrum shown in Figure 10.17 is representative of Mg-OH minerals and Figure 10.18 shows the spectrum of the Al-OH end-member.

Figure 10.17: Jubilee GER IS end-member spectrum typical of Mg-OH minerals, derived from log residual transformed image data.
A colour composite image has been produced from three bands of the un-mixed spectral end-members: Mg-OH, Al-OH and dry vegetation. The image was produced by linear contrast stretching these un-mixed image bands between the mean and maximum. In this image the red pixels highlight the ultramafic intrusive, green areas are Al-OH mineral rich and blue areas dense dry vegetation. Note the faint yellow zone crossing the ultramafic from northwest to southeast, this is a drainage channel in which both Al-OH and Mg-OH clays occur. It is not apparent in the any of the GEOSCAN MKII, nor the conventionally processed GER, images.
10.6 HyMap DATA

These data have been processed with the same techniques applied to other scanner imagery in this study. As the HyMap has a smaller pixel size than the other data sets its images only represent a subsection of the area seen in the GEOSCAN MkII and GER IS images. The effect of this reduced pixel size on the spatial resolution of the data is immediately apparent; minor creeks and individual trees are clearly discernible in the HyMap images. Such detail is not seen in the other scanner data sets.

Conventional Processing

Raw Data Colour Composite

The negative colour composite derived from the raw data is shown in Figure 10.20 and has bands 2318nm, 2203nm and 2150nm displayed in red, green and blue respectively. This image is similar in appearance to the GEOSCAN MKII colour composite (Figure 10.4) of this area. In this HyMap colour composite the serpentinite is highlighted in red-purple hues while the remainder of the image has pastel shades of grey, cyan and green. Vegetation, trees and clumps of bushes are white in this image rendition. This image also indicates that there are some dense patches of vegetation developed on the southeastern side of the serpentinite. Field visits have shown that this is spinifex. The letters S, V and BG annotated on the image indicate where spectra have been extracted from the log residual transform of these data.
Figure 10.20: Jubilee HyMap negative colour composite of raw data bands 2318nm, 2203nm and 2150nm in red, green and blue. The image is 2.5 km east to west.

Log Residual Transform Colour Composite

Figure 10.21: Jubilee HyMap negative colour composite of log residual transform of bands 2318nm, 2203nm and 2150nm in red, green and blue. The image is 2.5 km east to west.

In the negative log residual transform colour composite (Figure 10.21) the ultramafic is highlighted in red, the background rocks are green and the sand plain and cover rocks show as blue. Vegetation situated in the drainage channel to the west of the ultramafic shows as blue and mauve.
Spectra were extracted from the log residual data at sites, marked on Figure 10.20, representing the ultramafic, background and vegetation spectral classes. These spectra are presented in Figures 10.22 and 10.23.

Two different spectra were obtained from within the area of the ultramafic and these are shown in Figure 10.22, they are typical of spectra obtained from Mg-OH minerals. In this example, the width of the 2318nm absorption feature (2305nm-2320nm) suggests that one of the spectra results from serpentine (possibly mixed with saponite - as discussed in Chapter 5).

Figure 10.22 Jubilee HyMap log residual spectra extracted from the area of the ultramafic. Spectra are typical of Mg-OH minerals; they have a main absorption feature at >2300nm and a minor feature at >2380 nm. The left spectrum is interpreted as serpentine, broader >2300nm feature than in the right spectrum which is saponite. Note wavelengths in diagrams label not values are microns(multiply by 1000 to convert).

Figure 10.23: Jubilee HyMap log residual spectrum extracted from the background area. Spectrum is typical of Al-OH minerals; it has a main absorption feature at 2203nm and minor feature at 2250nm and 2300nm. Note wavelengths in diagrams label not values are microns(multiply by 1000 to convert).

The spectrum shown in Figure 10.23 can be classed as that derived from a mixture of the Al-OH minerals illite and kaolinite (Chapter 6). The spectrum has the main absorption feature at 2210nm and subordinate features at 2300 nm and 2350 nm. It also displays
distinct shoulders at 2155nm and 2250nm that may indicate traces of Fe-OH bearing minerals mixed with the Al-OH clays.

![Dry_Veg Spectra](image)

**Figure 10.24:** Jubilee HyMap log residual spectrum extracted from vegetated area. Spectrum is typical of dry vegetation; it has an asymmetric absorption feature at >2300nm and broad feature at >2100nm resulting in a peak at 2200nm.

As noted in Chapter 6, the spectrum of dry vegetation has a major absorption feature near 2300nm and can be confused with spectra derived from Mg-OH bearing minerals. This confusion is particularly troublesome when using conventional processing techniques to identify potential areas of ultramafic rock based on highlighting the distribution of the 2300nm absorption features. The spectrum shown in Figure 10.24 has a distinct 2300nm absorption feature. However, this spectra also has a broad minima at >2100nm, a distinct peak at 2200nm and a shallow upward gradient toward longer wavelengths, past 2300nm, all diagnostic of vegetation spectra.

**Mg Score Ratio**

The Mg Score ratio image (Figure 10.25) was derived from the log residual data by dividing the 2318nm band by the 2200nm band. The index image produced from this image ratio with pixel values above the image mean plus twice the standard deviation shown in red, highlights the serpentinite intrusive. This image also highlights an area of vegetation (see discussion of vegetation's spectral response in previous section) to the west and the trenches and pits to the north of the ultramafic. The pits and trenches mark the line of the fault mentioned previously.
Figure 10.25: Jubilee HyMap Mg Score index image, produced by dividing band 2318nm by 2210nm and density slicing the image. The ultramafic is highlighted in red. The image is 2.5 km east to west. Note the NE trending line of pits some with the red Mg-OH signature, that are aligned with a dextral offset in the northern edge of the ultramafic, this marks the fault.

**Crosta Principal Component Transform Processing**

The Crosta principal component transform of the data using bands 2125nm, 2214mm, 2266nm and 2318nm results in an eigen matrix in which eigen vector PC2 has the 2318nm band weighted against the other bands:

<table>
<thead>
<tr>
<th>Band</th>
<th>2125nm</th>
<th>2214nm</th>
<th>2266nm</th>
<th>2318nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC1</td>
<td>0.532</td>
<td>0.248</td>
<td>-0.748</td>
<td>-0.277</td>
</tr>
<tr>
<td>PC2</td>
<td>0.478</td>
<td>0.514</td>
<td>0.646</td>
<td>-0.3</td>
</tr>
<tr>
<td>PC3</td>
<td>0.482</td>
<td>0.027</td>
<td>0.290</td>
<td>0.875</td>
</tr>
<tr>
<td>PC4</td>
<td>0.507</td>
<td>-0.809</td>
<td>0.149</td>
<td>-0.259</td>
</tr>
</tbody>
</table>

The PC2 eigen vector image shown in Figure 10.26, has been density sliced to highlight (as red) the responses above the mean plus twice the standard deviation threshold. These red pixels map the ultramafic but not the areas of dry vegetation in the drainage to the west.
Figure 10.26: Jubilee HyMap Crosta transform image for eigen vector PC2. This index image has been thresholded so that the red pixels have values above the mean plus twice standard deviation and these pixels highlight the ultramafic. Note the NE trending line pits, all showing the red Mg-OH signature in this image, that are aligned with a dextral offset in the northern edge of the ultramafic, this marks the fault. The image is 2.5 km east to west.

The colour composite of the Crosta technique transform with bands PC2, PC3 (negative) and PC1 (negative) displayed in red, green and blue respectively were linearly contrast stretched between the mean and the maximum value. This image highlights the serpentinised ultramafic intrusive in red (Figure 10.27). Trenches situated on the NE trending fault north of the ultramafic and a number of areas to the southeast, which may be outcrops of ultramafic rock, are also red in this image. Green areas in this image are mapping the distribution of the Al-OH minerals (eigen vector PC3 weighting of 2214nm). A zone of yellow crossing the intrusive indicates mixed pixels where both Mg-OH and Al-OH minerals are combined equally within a pixel area. This was also noted in the end-member un-mixed GER image. The negative of PC1 is mapping areas of dry vegetation; this can be explained by the largest eigen vector in PC1 being from the 2125nm band which is in the dry vegetation absorption feature.
Figure 10.27: Jubilee HyMap Crosta transform colour composite image for eigen vectors PC2, PC3(-ve) and PC1(-ve) in red, green and blue. Bands 2125nm, 2214nm, 2260nm and 2318nm were used to derive the eigen matrix. The ultramafic is highlighted by the red pixels, green areas represent Al-OH minerals and blue is vegetation. The image is 2.5 km east to west.

Spectral Processing

In Figure 10.28, two distinct end-member spectra of the Mg-OH type are shown. The left spectrum has the main absorption developed at 2307nm while the right spectrum shows this feature shifted to 2318nm; both of these spectra have a 2380nm feature. Pixels with these spectra are highlighted in red (2307nm) and yellow (2318nm) in the end-member unmixed index image (Figure 10.29).

This index image was produced by clipping the two spectral end-member unmixed images so that pixels above the mean plus twice standard deviation were thresholded to red and yellow hues using the ENVI region of interest function. The regions of interest were overlain onto the Al-OH end-member unmixed band and the Al-OH mineral index was added to this image as green. It is clear that the Mg-OH spectral end-members are mapping different zones within the serpentinite ultramafic outcrop. The yellow region (2318nm) maps the trenches while the red region (2307nm) is only apparent in the core area and some of the trenches. Areas to the southeast, highlighted in the Crosta technique as Mg-OH rich, are not highlighted by either region of interest in this end-member spectra unmixed image.
Figure 10.28: Jubilee HyMap end-member spectra from log residual data. Spectra are typical of Mg-OH minerals; main absorption feature >2305nm. In the left spectra the >2300nm feature is at 2307nm and indicates saponite in the right spectra this feature has shifted to 2318nm diagnostic of serpentine.

When comparing these end-member spectra with the PIMA spectra measured from the grid samples (Figure 10.3) this confirms the interpretation that the spectrum with the longer wavelength feature (2318nm) is serpentine and the shorter is saponite (2307nm).

Figure 10.29: Jubilee HyMap un-mixed index image for two Mg-OH spectral end-members and the Al-OH end-member. The yellow regions of interest map the pixels dominated by spectra with the 2318nm absorption feature and the red pixels the 2307nm absorption feature. Green areas show the distribution of the Al-OH end-member. The image is 2.5 km east to west, north is to the top.

The Al-OH end-member is distributed along the break-away south of the ultramafic and suggests the presence of kaolinite. Kaolinite is ubiquitous in the lateritic profile and frequently exposed in break-aways. Examination of the spectra of this end-member, Figure 10.30, confirms a kaolinite spectrum.
These results indicate that these techniques work exceptionally well on small pixel (5m) data with a high SNR in an area of minimal vegetation cover. They detect spectral differences that were noted in spectra collected in the field. These spectral variations are probably related to the degree of weathering of the ultramafic indicated by the concentration of saponite on the southern side of the intrusive. This is reinforced where the serpentinite has been exposed by trenching to the north of the ultramafic; there the end-member spectra are serpentine rather than saponite.

10.7 CONCLUSIONS

This study shows that in this area of low vegetation cover and strong spectral contrast between the ultramafic rocks and background, it is possible to discriminate between them even in data with a low SNR. In this case conventional image processing techniques, such as band ratios and Crosta principal component transforms, work. However, with better quality data, smaller pixel size (HyMap scanner) and the use of spectral geological techniques it is possible to detect changes of surface mineralogy within the ultramafic. These subtle changes are not revealed by processing the GEOSCAN MkII and GER IS data, nor when using conventional processing techniques with the HyMap data.

The detection of other areas of Mg-OH signature in the area, particularly to the west in the sand plain is also significant. It indicates that in some areas of the Yilgarn it will be possible to detect areas of unexposed ultramafic rocks. This would be an important application of airborne scanner surveys for mineral exploration (Au and Ni deposits) in this
region. Such results, if combined with the investigation of aeromagnetic data (Arvind, 1990) which can also indicate the occurrence of unexposed ultramafic rocks, could improve targeting areas with potential for mineralisation. This study suggests that data of the HyMap quality, if processed spectrally, would certainly benefit such investigations.
CHAPTER 11

11 TEST SITE STUDY 81MILE VENT, ELLENDALE AREA, KIMBERLEY REGION, WESTERN AUSTRALIA

11.1 INTRODUCTION

The 81-Mile Vent lamproite is located 150 km south east of Derby in the southern part of the Kimberley region of Western Australia (Figure 11.1) This test site was chosen as an example of an ultramafic rock (lamproite) that outcrops.

Figure 11.1: 81-Mile Vent location map and flight line flown with scanners.

81-Mile Vent is one of more than forty five lamproites that occur in this region. It lies on the southeastern edge of a field of similar intrusives and has the typical lamproite expression in the area of a low circular mesa 200m in diameter (three hectares). The pipe extends beyond the fringes of the mesa below the soil cover and its contact with the wall rock is not exposed. This lamproite is adjacent to the access road that was constructed through the area during a diamond exploration program carried out during the 1970s. This lamproite pipe is situated in a black soil plain that is covered by a veneer of aeolian sand. This and the other lamproites were intruded during the early Miocene (Jaques et al., 1986) and are intruded into the Grant formation Permian sandstone. Five kilometres to the south of 81-Mile Vent, the Oscar Ranges rise from the plain as hills comprised of Devonian reef
limestone displaying karstic features.

The area is situated in a monsoon rainfall zone that has variable rainfall from season to season but is virtually rain-free and therefore arid in the dry season which commences in April and lasts until November. Vegetation is typical savannah grassland with scattered trees. A uniform cover of cane grass obscures much of the soil during and shortly after the wet season. This grass cover dries back during the dry season, progressively exposing the soil. The 81-Mile Vent pipe is classified as a leucite lamproite with a magnesium content ranging from 6 percent to 11 percent (Jaques et al., 1986). This is a lower magnesium content than the other alkaline rocks considered in this study. However, the other olivine lamproites in the area have magnesium contents from 23 percent to 26 percent (Jaques et al., 1986). The petrographic description of 81-Mile Vent (Jaques et al., 1986) states that it has abundant phlogopite in the ground mass and as phenocrysts. During the fieldwork I conducted for this study, phlogopite was seen to be distinct in the outcrop, the residual soil cover and in the sands surrounding the mesa where grass cover is minimal (Figure 11.2).

Figure 11.2: 81-Mile Vent lamproite mesa, aerial view from northwest, source Jaques et al. (1986).

11.2 FIELD STUDIES

Figure 11.3 shows the location of a grid covering the northeastern corner of this lamproite pipe and the adjacent background that was sampled in 1993. This square grid is 250m on each side and samples were collected at 25m intervals on lines 25m apart. Spectra were
obtained from these samples, with the PIMA spectrometer and the Mg Score ratio values were calculated from these data. These contours were plotted over the geology map obtained from Jaques et. al. (1986) which indicates the association of the lamproite with the elevated Mg Score value (Figure 11.3).

![Figure 11.3: 81-Mile Vent geology map after Jaques et al. (1986) with outline of grid sampled for spectral analysis and with Mg Score values contour plot overlain.](image)

Spectra obtained from the lamproite residual and background soils are typical of Mg-OH and Al-OH minerals (Figure 11.4). The Al-OH spectrum can be interpreted as illite having a 2210nm main absorption feature and a broad 2350nm feature. Absorption features at 2312nm and 2385nm suggest that the Mg-OH spectrum is that of saponite.
Figure 11.4: 81-Mile Vent spectra obtained from grid samples situated on the background soil, red spectrum Al-OH, and lamproite residual soil, black spectrum Mg-OH.

11.3 IMAGE PROCESSING

Two scanner data sets were acquired from this area: GEOSCAN MkII in 1989 and HyMap in 1996. These data were acquired from flight lines that follow the road shown on Figure 11.1. In this case the pixel sizes and swaths for these data were:

- GEOSCAN MkII 10m pixels - 7.68km
- HyMap 5m pixels - 2.5km

No attempt has been made to reduce the noise in these data. The GEOSCAN MkII data were offset corrected by dark pixel subtraction (see Chapter 8).

Since the GEOSCAN MkII data was acquired in October at the end of the dry season these data should show a greater proportion of the area as exposed soil than the HyMap data. The HyMap data was acquired during June earlier in the dry season, when the grass cover is usually thicker. However, due to smoke haze any advantages in reduced vegetation cover in the GEOSCAN MkII data are more than offset by the considerably reduced SNR that results from the smoke and haze attenuation of the radiation (signal).
11.4 GEOSCAN MkII DATA

Conventional Processing

The following processes have been applied to these data: raw data colour composite production, log residual colour composite, Mg Score ratio and Crosta principal components transform. The images resulting from these processes are displayed in Figures 11.5 to 11.8. None of these images show the 81-Mile Vent lamproite, located in the east of the area adjacent to the road (Figure 11.5), as distinct from the background.

Figure 11.5: 81-Mile Vent GEOSCAN MkII raw data negative colour composite of bands 17,15,14 shown in red, green and blue. The position of the 81-Mile Vent lamproite is labelled 81 Mile Vent. The image is 7.68km from west to east. North is to the top right in this and all subsequent images.
Figure 11.6: 81-Mile Vent GEOSCAN MkII log residual transformed data negative colour composite of bands 17, 15, 14 shown in red, green and blue. Label E6 locates Ellendale 6 lamproite, note the green colour of this outcrop rim indicates an absorption in band 15 (Al-OH). The image is 7.68km from west to east.

Figure 11.7: 81-Mile Vent GEOSCAN MkII Mg Score index image produced from ratio of log residual transformed bands 15 divided by 17. The image is 7.68km from west to east.
All the enhancement techniques applied produce images that are dominated by noise and this is particularly apparent in both the Crosta principal component and Mg Score ratio images.

To the west of the 81-Mile Vent lamproite there is a near-circular outcrop of indurated sandstone (Jaques et al., 1986) that flanks the lamproite pipe known as Ellendale 6. In the log residual transform colour composite image, this outcrop area shows green (Figure 11.6) indicating absorption at 2200 nm (GEOSCAN MKII band 15) diagnostic of an Al-OH spectral signature (Figure 11.9). The green areas seen in the log residual colour composite extend throughout the image and are not unique to the location of Ellendale 6 lamproite. The Al-OH spectral signature obtained from the log residual transformed data on an area of sandstone outcrop indicates that some meaningful spectral information can be derived from these noisy data.

Figure 11.8: 81-Mile Vent GEOSCAN MKII Crosta principal component transformed index image of eigen vector PC2. The image is 7.68 km from west to east.
Figure 11.9: 81-Mile Vent GEOSCAN MkII log residual transform spectrum from pixel on rim of outcrop flanking Ellendale 6. Spectrum shows absorption at band 15 (2200nm) and indicates Al-OH mineral(s).

Spectral Processing

No Mg-OH end-member spectra could be extracted from these data. However, an end-member of Al-OH spectral type (Figure 11.10) was obtained from the log residual transformed data. The un-mixed image for this end-member spectrum (Figure 11.11) highlights the indurated sandstone outcrop that rims the Ellendale 6 lamproite and is very similar in appearance to the Crosta PC2 image in Figure 11.8. This contrast stretched image also highlights portions of the road and some drainage channels where areas of bare soil are exposed.

Figure 11.10: 81-Mile Vent GEOSCAN MkII log residual transform end-member spectrum that shows an absorption at band 15 (2200nm) and indicates Al-OH mineral(s).

This result also indicates that there is spectrally useful information in these noisy data but not at the wavelengths (bands) where diagnostic information on Mg-OH minerals can be obtained, rendering it unsuitable for locating ultramafic rocks. This may well be because as the signal level attenuates at longer wavelengths, due to the decrease in solar radiance
(Chapter 8), the signal-to-noise ratio falls below what is required to produce spectrally meaningful data in this smoke affected imagery.

Figure 11.11: 81-Mile Vent GEOSCAN MkII un-mixed log residual transform image for end-member spectrum that shows absorption at 2200nm (GEOSCAN MKII Band 15) and indicates Al-OH mineral(s). This image is very similar in appearance to the Crosta PC 2 image, Figure 11.8. The image is 7.68km from west to east and has been contrast stretched.

There is a very strong correspondence between the Al-OH end member un-mixed image (Figure 11.11) and the Crosta PC2 image (Figure 11.8). This indicates that the Crosta technique is as effective as un-mixing in this noisy data.

11.5 HyMap DATA

These data were acquired with the HyMap scanner with the same wavelength configuration used to collect the data at the Pine Creek and Jubilee sites.

Conventional Processing

Raw Data Colour Composite

The colour composite image of the raw HyMap data (Figure 11.12) has the same general appearance as the GEOSCAN MkII raw data colour composite shown in Figure 11.3.
Figure 11.12: 81-Mile Vent HyMap raw data negative colour composite of bands 2318nm, 2203nm and 2150nm shown in red, green and blue. The image is 2.5km from west to east.

Log Residual Transform Colour Composite

Figure 11.13: 81-Mile Vent HyMap log residual transformed data negative colour composite of bands 2318nm, 2203nm and 2150nm shown in red, green and blue respectively. The location of the 81-Mile Vent lamproite is shown. The image is 2.5km from west to east.

The log residual transform colour composite of bands at 2318nm, 2203nm and 2150nm in red, green and blue respectively reveals the 81-Mile Vent lamproite as a bright red feature in Figure 11.13. However, this colour signature is also seen extensively in the image being particularly well developed over areas of limestone outcrop that occur on the southern
margin of the scene (marked Limestone in Figure 11.13). East of the road there are extensive areas of green signature that result from the presence of Al-OH minerals in the soil. In the north east of the area and along the drainage channel east of the road there are areas of cyan colour (blue plus green) which can be interpreted as resulting from the mixed spectral response of Al-OH clays and dry vegetation. Similarly, mauve (red plus blue) areas can be interpreted either as dry vegetation alone or dry vegetation combined with Mg-OH or carbonate bearing areas. These ambiguities require the application of more diagnostic processes.

The main types of spectra extracted from the log residual data are presented in Figures 11.14 to 11.16 and examining them explains the colour distribution in Figure 11.13 discussed above.

Figure 11.14 shows a spectrum (green) taken from pixels located on the northern flank of the 81-Mile Vent mesa. It is a distinct Mg-OH type spectrum with a deep (10 percent) feature at 2305nm and a deep (6 percent) 2386nm feature. This is a diagnostic spectrum for phlogopite. Also shown in, Figure 11.14, is a spectrum (red) obtained from the area indicated as limestone in Figure 11.13. This spectra has a broader >2300nm absorption than the Mg-OH spectra.

![Mg-OH/CO3 Log Residual Spectra](image)

**Figure 11.14**: 81-Mile Vent lamproite HyMap log residual transform spectra with >2300nm absorption features. The green spectrum shows deep absorption features at 2306nm and 2385nm; this can be interpreted as a spectrum of phlogopite and was obtained from a pixel located on northern flank of the 81-Mile Vent lamproite. The red spectrum was extracted from the area marked limestone in Figure 11.13. Spectra have been hull quotient transformed to facilitate comparison.

The spectrum shown in Figure 11.15 was obtained from a breakaway area where soil is exposed to the east of the road. This spectrum shows Al-OH characteristics, possibly due to illite.
Figure 11.15: 81-Mile Vent lamproite HyMap log residual transform spectrum that shows an absorption feature at 2200nm; it can be interpreted as an Al-OH (illite) spectrum. Spectrum obtained from pixel located in a breakaway area east of the road.

The dry grass/vegetation spectrum (Figure 11.16) obtained from pixels west of the road, show the typical >2100nm and >2300nm dry vegetation absorption features.

Figure 11.16: 81-Mile Vent lamproite HyMap log residual transform spectrum with absorption features at >2120nm and >2300nm that are indicative of dry vegetation. Note the distinct pointed maxima at >2200nm.

**Mg Score Ratio**

Areas highlighted red in the Mg Score ratio image (Figure 11.18) are those that have values of the mean plus twice the standard deviation. These areas highlight the 81-Mile Vent lamproite as well as limestone and dry grass. In fact dry vegetation has the strongest response. In Figure 11.17 the 2305nm band is relatively deeper in the dry vegetation spectrum than in the Mg-OH spectrum. By dividing the >2200nm band by the >2300nm the highest values characterise dry vegetation (grass).
Figure 11.17: Hull Quotient transform of Log Residual spectra. Red - dry vegetation Black - Mg-OH mineral. Note >2300nm feature is deeper in dry vegetation spectrum.

Figure 11.18: 81-Mile Vent HyMap log residual transformed Mg Score image, produced by dividing the 2318nm band by the 2200nm band. The image is 2.5km from west to east.

**Crosta Principal Component Transform**

The Crosta eigen vector PC4 index image, derived from bands 2214nm, 2249nm, 2318nm and 2401nm highlights both the 81-Mile Vent lamproite and limestone outcrops as pixels coloured in red (Figure 11.19).
Figure 11.19: 81-Mile Vent HyMap log residual transformed Crosta eigen vector PC4 index image. 81-Mile Vent lamproite and limestone highlighted in red. The image is 2.5km from west to east.

Anomaly Residual Band Prediction

The anomaly band prediction transform was used to predict the residual values for band 2318nm from the other bands. This residual image (Figure 11.20) highlights the 81-Mile Vent lamproite but not the areas of limestone outcrop or dry vegetation. This result shows that there are sufficient differences in the spectra of Mg-OH minerals and carbonates for spectral segregation to be achieved. However, in the south east corner of the image is an area of pixels highlighted by this technique. This area is not highlighted by the other processing techniques. Examination of spectra, Figure 11.21, obtained from this area suggests that the area is characterised by exposed soil in which Al-OH and carbonate minerals are equally mixed.
Spectral Processing

The red end-member spectrum shown in Figure 11.22 shows the >2300nm and >2380nm absorption features observed in the spectrum obtained in the field at the 81-Mile Vent lamproite (Figure 11.4). The blue end-member spectrum has the broad >2300nm feature centred at longer wavelengths than Mg-OH minerals and is typical of carbonate.

The un-mixing index image (Figure 11.23), derived from the log-residual transformed data, shows the spatial distribution of the end-member spectra depicted in Figure 11.22. Those
areas with the Mg-OH end-member spectrum are flagged as red pixels, and those with the carbonate are shown in blue. In this image, the 81-Mile Vent lamproite and sections of the road are highlighted. During fieldwork I noted that the stretches of the road are paved with lamproite tailings from diamond evaluation work. The exposed limestone is highlighted but not the mixed Al-OH – carbonate areas shown in Figure 11.20. In this case, end-member un-mixing is in fact discriminating between those regions which have spectra with >2300nm spectra, that is, lamproite, outcropping carbonate (limestone), dry vegetation (mapped as a different end-member un-mixed band but not shown), and the area interpreted to be of mixed Al-OH / carbonate soil.

Figure 11.22: 81-Mile Vent lamproite CO3 HyMap end-member spectra. The red spectrum has absorption features at 2318nm and 2386nm that are indicative of Mg-OH minerals possibly phlogopite. The blue spectrum has a broad >2300nm feature at longer wavelengths and is interpreted to be a carbonate spectrum (limestone).

Figure 11.23: 81-Mile Vent HyMap end-member un-mixed index image. The 81-Mile Vent lamproite is highlighted red. The limestone outcrop areas are highlighted in blue. The image is 2.5km from west to east.
11.6 CONCLUSIONS

The combination of larger pixels, lower spectral resolution and low signal-to-noise ratio (due to smoke haze) have the effect of severely reducing the effectiveness of GEOSCAN MkII data for detecting the ultramafic rocks in this area. This may not have been the case if the data had been acquired at a more optimal time of the year (less smoke) and with smaller pixels. As is shown in Chapter 10 it should be possible to map the distribution of materials with >2300nm absorption features with GEOSCAN MKII data. That this could not be achieved in this case is therefore a reflection on data quality rather than the system.

As noted in Chapter 10, the Crosta principal component and end-member un-mixing processes gave virtually identical images for the selected spectral class, Al-OH in this Chapter and Mg-OH in Chapter10. This suggests that the lower spectral resolution of the GEOSCAN MKII data is limiting the amount of unique spectral information to such an extent that any process that enhances the spectral content will produce the same result. This is not the case with data having higher spectral resolution such as HyMap. Therefore, with GEOSCAN MKII and other systems with low spectral resolution, eight or fewer bands, it is not worthwhile using the more time consuming end-member un-mixing when the simpler Crosta principal component transform can be applied. However, as the number of bands increases the problem of which band to select for generating the eigen matrix becomes more complex. For such data end-member un-mixing will be the preferred technique to map the location of a particular spectral class.

When the HyMap data is processed using spectral techniques it is possible to differentiate between spectrally similar minerals, in this case Mg-OH clays, carbonate rocks (limestone) and dry vegetation, as observed in the Pine Creek investigation (Chapter 9). This differentiation cannot be achieved with any of the conventional processing techniques except with the anomaly band prediction process. The spectral processing technique was the only method tested which unambiguously highlighted the lamproite.
CHAPTER 12

12 CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER STUDIES

12.1 CONCLUSIONS

The primary objective of this thesis is to demonstrate how spectral geological techniques can be applied to locate and delineate alkaline ultramafic rocks. Using results obtained from field spectral studies, with spectrometers and airborne scanner data, I demonstrate that alkaline and other ultramafic rocks have a diagnostic spectral signature. This signature can be detected using data obtained from spectrometers, when these rocks are exposed and weathered into residual soils.

To achieve the detection of ultramafic rocks and probably other rock types consistently, when exposed and by inference from soils, consistently requires instruments that have sufficient spectral resolution and a high enough signal-to-noise ratio. It is only within the last 5 to 7 years that such hyperspectral instruments (field and airborne) have become available operationally. From this study it is possible to derive a set of specifications that should be met by an airborne hyperspectral instrument, if it is to be considered for operational spectral geological investigations.

Airborne scanners such as the HyMap and AVIRIS can and do meet these specifications. Therefore, it is reasonable for a user to insist that data acquired commercially meets these specifications, if not the survey should be re-flown or the acquisition cost adjusted accordingly.

Currently there are no operational hyperspectral spaceborne systems. However, when considering using data from future systems these specifications can be used as a benchmark by which to judge the likely utility of data from these systems, for spectral geological applications.

Non-hyperspectral scanners provide useful spectral data that can be used to discriminate ultramafic and other rocks but the results are likely to be less definitive and more ambiguous than that obtained with hyperspectral data. Data from systems such as Landsat TM, that have broad bands with restricted wavelength coverage, cannot be used to map
ultramafic rocks consistently. The processing techniques applied to these data, particularly when utilising the iron oxide information, do not produce consistent results in different areas. Some idea of a system's potential for discrimination of alkaline (and other) ultramafic rocks can be determined by comparing its specifications to those listed for hyperspectral system's below and by referring to Chapter 6.

It can be concluded that to locate alkaline and other ultramafic rocks in an area where they have not been detected previously requires detecting the \( \text{Mg-OH} \) spectral signature. This can only be achieved reliably with data from hyperspectral scanners that meet the specifications detailed below.

**Diagnostic Spectral Signature of Alkaline ultramafic rocks**

In this thesis it is established that alkaline and other ultramafic rocks, have a spectral signature that is derived from minerals that contain \( \text{Mg-OH} \). These minerals produce spectra that have distinct absorption features between 2305nm and 2318nm and near 2385nm in the SWIR2 spectral region. Minerals that have this spectral signature include serpentine, talc and phlogopite and their weathering product saponite. In this study the alkaline ultramafic rocks investigated spectrally are kimberlite and lamproite, as well as other ultramafic rocks, dunite, peridotite and serpentinite and all show the same basic spectral signature in the SWIR2.

**Spectral signature of the weathering products of ultramafic rocks**

Ultramafic rocks are altered by hydrolysis and weathering, breaking down into serpentine, and subsequently \( \text{Mg-OH} \) bearing smectite clays (saponite). Saponite has a SWIR2 spectrum that is very similar to the primary \( \text{Mg-OH} \) bearing minerals, therefore, the diagnostic spectral signature of ultramafic rocks is preserved when these rocks weather into residual soils. Weathering eventually breaks down saponite into kaolinite, this means that the residual soils also contain a proportion of \( \text{Al-OH} \) bearing minerals, as well as quartz and other minerals introduced into the soil by the erosion of surrounding rocks.

**Non Ultramafic Rock Signatures**

The diagnostic absorption feature associated with alkaline and other ultramafic rocks near 2300nm can also occur in a variety of other rocks. Either, because they contain minerals that also have spectral absorption features near 2300nm (such as calcite, dolomite, chlorite
and certain amphiboles) or the mixture of minerals in the rock can emulate an individual mineral with a 2300nm feature.

In weathered terrains the presence of several clay minerals such as vermiculite, glauconite and even kaolinite may produce targets, in the processed image data, due to their spectra containing a near 2300nm absorption feature.

Applying knowledge of the precise spectra of these confusers to direct the processing strategy should eliminate most false targets caused by spectral similarities. For example, using the Mg Score ratio to distinguish areas of kaolinite from saponite. In other cases the context may permit interpretive grading of anomalies and this may be assisted with information from other spectral regions. However, there will be cases where targets selected from imagery will not be spectrally distinguishable from ultramafic rocks even with field spectra. In such cases only field work will provide a definitive identification. As experience builds with this technology it is probable that skilled spectral geologists and a data base of case histories will assist in the correct assignment of spectral anomalies to a specific rock type or group.

Spectra of Mineral Mixtures

This study has indicated that dilution reduces the intensity of the diagnostic absorption features proportionally to the amount of Mg-OH clay (saponite) remaining. Experiments conducted in this study determined that, for binary mixtures, dilution of saponite to 30 percent with minerals and dry vegetation, typically found in soils, still produces a diagnostic spectrum. The fact that the presence of ultramafic rocks can be detected from residual soils containing saponite using data collected with field and airborne spectrometers substantiates the experimental results.

Therefore, such mixing experiments can be used to determine when a mineral being sought by spectral means will be rendered undetectable due to dilution and/or the masking effects of other mineral spectra.

Line Scanning Systems Specifications

There are four factors whose specifications determine a scanner's ability to deliver effective data for use in spectral geological applications:
- Signal-to-Noise Ratio
- Spectral Resolution
- Pixel Size (or instantaneous field of view)
- Pixels per Scan Line (swath width)

Of these the SNR ratio is critical; any modification to the other specifications directly effects the signal-to-noise ratio. Increasing pixel size will generally improve the signal-to-noise ratio while increasing spectral resolution will decrease it.

Two other features need to be implemented in a scanning system; the dark current should be measured for each scan line and the digital data capture should be at least 12 bit.

Other issues that can effect the performance of a scanner system are F number defined by the optical design, primary mirror design, detector material, detector cooling system and electronics configuration. These are specialist engineering and optical design areas that have to be optimised so that the system meets the desired performance specifications.

**Signal to Noise Ratio**

Investigations carried out into the signal-to-noise ratio of various scanners suggest to me that an acceptable value is 600:1 at 2200nm from a 50% reflecting surface, for data delivered from a survey. Which is how the value should be quoted by the systems manufacturer and/or survey contractor.

A higher noise level can produce spurious absorption features that can result in mis-identification of the spectral signatures. Noisy image data also result in the targets sought being obliterated by speckle. The signal-to-noise level decreases with increasing wavelength due to the marked drop in solar irradiance towards longer wavelengths. This drop in signal-to-noise ratio is critical when using scanner data to detect ultramafic rocks because the diagnostic 2300nm absorption feature is located in the longer SWIR2 wavelength spectral region. The Ellendale GEOSCAN MkII data demonstrated this effect. Smoke and haze, encountered during the airborne survey reduced the signal. The resultant reduction in signal-to-noise ratio meant that only the near 2200nm absorption features were detectable. Consequently only the distribution of Al-OH minerals could be ascertained with any certainty from these data. The ultramafic target was not detectable in the GEOSCAN MkII data but it was with the HyMap data, which has a substantially higher signal-to-noise ratio and spectral resolution. GEOSCAN MkII scanner data from the
Jubilee site has a higher signal-to-noise ratio than at 81-Mile Vent and it could be used to located ultramafic rocks at this site. These results reinforce the importance of noise levels when evaluating scanner data.

There are ways of reducing noise in the data. The limited study into the effects of noise showed that with limited spectral resolution systems such as the GEOSCAN MkII, applying filters to reduce noise smooths the spectra and shifts the position of absorption features. Applying these filters can also change overall spectral shapes. This increases the difficulties of accurately identifying the spectra. With a sufficiently high signal-to-noise ratio the need for filtering of the data is removed, which is of critical importance when using these systems operationally. Noise reduction filtering is time consuming and will adversely effect processing and interpretation times when dealing with the large volumes of data, typically tens of gigabytes, that these systems produce from large scale surveys (thousands of square kilometres).

Spectral Resolution

From these studies I conclude that to produce data that can unambiguously identify areas of ultramafic rocks when exposed and weathered requires a hyperspectral scanner. Such instruments require SWIR2 bands that of ~15nm in width (32 bands covering the spectral region 2000nm to 2500nm). Typically such an instrument would have between 64 and 96 channels if it recorded data from the VNIR and SWIR1 as well.

Narrower bands would probably provide more mineral discrimination but there is an optical and electronic system trade off between signal-to-noise ratio and spectral bandwidth (T. Cocks, 1997 pers. comm.). This is an engineering issue. This study showed that lower signal-to-noise ratio and broader band systems (GEOSCAN MkII and GER IS) can produce data from which ultramafic rocks can be delineated, as the Jubilee results indicate. However, any deterioration in system performance or survey conditions will render data from such systems useless for this application, as is the case with the Ellendale GEOSCAN MkII data.

Pixel Size

This issue has not been investigated in this study. A reasonable assumption might be that the smaller the pixel size the less mixing of the minerals and materials there will be and,
therefore, the more reliable will be the spectral information derived from the data. In this study all of the HyMap data was obtained with a 5m pixel. Since these data produced results consistent with field studies at each test site it can be assumed that 5m is a satisfactory pixel size.

At the Jubilee site the HyMap scanner produced the most definitive data and also had the smallest pixel size, 5m compared to the 10m and 15m for the GEOSCAN MkII and GER scanners respectively. However, since these instruments all have different signal-to-noise and spectral resolutions these data cannot be used for a meaningful comparison of the spectral effects of pixel size.

**Pixels Per Scan Line**

This is an operational consideration. The less pixels per scan line the smaller the swath width and the greater the number of flight lines and, therefore, the costs of surveying a given area. Most airborne line scanning systems scan 512 pixels per line, which with 5m pixels cover an area of 2.5 sq km per line km.

Systems (apart from single pixel airborne profiling systems which are not intended for regional surveys) with less than 512 pixels would probably not now be considered worth building. Since, survey costs are reduced if the swath width is increased for a given pixel size, any increase in this specification will be desirable so long as the signal-to-noise ratio is not compromised.

**Dark Current and Digital Quantisation**

Scanners such as the GEOSCAN MkII did not measure the dark current during scanning which makes this fluctuating system offset difficult to remove. This scanner also captured data with a 7 bit quantisation giving a dynamic range of only 0 to 256. This meant that offset and gain adjustments were carried out manually during surveys to prevent light and dark signal saturation. Both of these adjustments need to be removed during data processing to produce meaningful spectra and this is not always possible.

If the dark current is measured and recorded during the scan cycle its removal becomes a simple value subtraction from each data value. Increasing the quantisation to 12 bit
produces a dynamic range of 0 to 4096 which is sufficient to permit scanning of very bright and dark targets without the need to apply offsets and adjust the gain of the system.

**Summary**

A base line scanning system that can reliably detect ultramafic rocks in arid environments would scan 512 pixels with minimum pixel size of 5m. It would have at least 64 channels of which 32 would be in the SWIR2. The spectral resolution in the SWIR2 being 15nm per detector covering the range \(-2000\text{nm}\) to \(-2500\text{nm}\). Other spectrometers would cover the VNIR and SWIR1. The generally broader width of diagnostic absorption features, such as those related to iron oxides in the NIR, mean that the VNIR and SWIR1 spectrometers could have only sixteen 30nm detectors. The system should be quantised at least 12 bits and the dark current should be measured during the scan cycle.

The HyMap scanners meet these specifications and this study has demonstrated their ability to detect alkaline and other ultramafic rocks when exposed and covered by residual soils in arid areas.

**Data Processing Techniques**

Once data of sufficient quality have been obtained, it must be processed to extract the information diagnostic of ultramafic rocks. For spectra obtained from samples collected in the field, this is straightforward. The Mg Score ratio can be used to determine values from spectra that can be contoured or profiled to discriminate between regions of Mg-OH and Al-OH minerals. When non Al-OH bearing minerals, for example dolomite, are mixed with Mg-OH minerals other parameters such as the shifts in position of the near 2300nm absorption feature can be extracted and analysed.

For image data that are not collected as reflectance, processing must commence with the removal of data offsets, atmospheric effects, the solar irradiance curve and topographic/albedo variations so that absorption features can be recognised. Correcting the data for these effects not only assists with visual interpretation of the spectra but also enhances spectral variations, enabling meaningful values to be extracted from the data. In this study the log residual transform or variations on it such as the ENVI IARR function have been used to transform scanner data to pseudo reflectance. I was able to demonstrate that this technique is reliable with the data that have been studied. Log residual image
spectra taken from uniform and homogeneous materials were shown to match the equivalent spectra collected in the field using the PIMA spectrometer. This similarity is emphasised when the PIMA spectra are hull quotient transformed.

Of the conventional image processing techniques applied to detect the location of ultramafic rocks from scanner imagery the Crosta principle component transform and the anomaly residual technique provided the most unambiguous results. This was emphasised when output images from these transforms were clipped to produce index images.

Overall, however, the end-member selection and un-mixing techniques produce the most consistent results and in two instances, 81 Mile Vent and Pine Creek, were able to distinguish between different Mg-OH and other minerals showing near 2300nm absorption features.

Simulated Data

By producing image data simulated from spectra, that is, data cubes it is possible to test the various processing techniques. Applying conventional processing techniques to modelled data in this study produced results that do not show the ambiguities produced when real data is processed. This permitted, for example, the effects of noise on data to be more easily assessed and how noise effects the different processing techniques abilities to produce spectrally meaningful images, that is, those in which the targets are highlighted.

Such modelling studies are recommended whenever new processing techniques are being tested, as it will permit them to be reliably rated against existing techniques. Similarly variations in spectral resolution and band centres can be tested on simulated data to determine optimum scanning system parameters.

Simulated mixtures can also be used to determine to what extent minerals can remain uniquely identifiable spectrally both from field/laboratory spectra and image data. Spectra of mixed minerals can also be incorporated into image data cubes to test which processing technique is the most effective at identifying the target mineral.
Test Site Studies

At the test sites investigated, Mg-OH spectral anomalies are identified by analysis of samples collected from grids or traverse lines in the field. These anomalies are also detectable in scanner imaged data collected at these sites. Scanners can record spectra from a large area within minutes as opposed to days using field spectrometers. Therefore, in arid to semi-arid areas (where 40 percent of the ground is exposed) scanners are more effective for conducting regional investigations than are field studies for locating ultramafic, and by analogy, other rocks.

Pine Creek

At the Pine Creek test site the surface soil over the ultramafic rock contains between 60% and 90% saponite. This value has been obtained by applying the method suggested in Chapter 7 for estimating the Mg-OH content of mineral mixtures from the Mg Score ratio value. At this location it is possible to spectrally distinguish soils derived from the ultramafic rock from the background soils that contain kaolinite and illite.

The results in this study indicate that, even when the minerals of interest are present and can be identified spectrally, ultramafic rocks may still be confused with other materials in some circumstances. At Pine Creek in South Australia there appear to be areas of saponite developed in the soil that may result from the weathering of dolomite (calc-arenite) as well as that derived from the ultramafic rocks. This indicates that there are limits to using these methods to locate previously unknown and blind ultramafic rocks.

Jubilee

Data obtained from three scanners (GEOSCAN MkII, GER IS and HyMap) provided spectral information that mapped the extent of the ultramafic rock at the Jubilee test site. These data also indicated that unexposed Mg-OH bearing rocks occur to the west of the main area of ultramafic rock. Spectra recorded in the field mapped mineral variations within the area of Jubilee ultramafic rock; this difference may be caused by weathering as the spectra obtained were of serpentine and saponite. This spectral discrimination was only observed in the HyMap scanner data, which has four times as many SWIR2 bands as the GEOSCAN MkII and a signal-to-noise ratio that is an order of magnitude better than the GER IS scanner. Data from these latter two instruments were unable to detect the
variation in the mineralogy within the Jubilee ultramafic. The smaller pixel size of the HyMap data may have contributed to the additional discrimination achieved but this aspect of these data sets was not investigated in this study.

It was only at the Jubilee site that spectral differentiation within exposed ultramafic rocks was observed. In fact SWIR2 spectra of the various ultramafic rocks are so similar I consider it unlikely that data from this spectral region alone will be useful in mapping differences between ultramafic rocks. The studies reviewed in Chapter 2 indicate that it is possible, using TM data in arid areas, to distinguish differences between ultramafic rocks spectrally. Most of the spectral variation noted in these studies was attributed to the iron oxide content of these rocks. I have noted in this study that there are differences in the VNIR spectral region between alkaline (kimberlite) and other ultramafic rocks but these differences have not been investigated in detail.

Ellendale

At this site it was confirmed that using end-member un-mixing it is possible to distinguish exposed alkaline ultramafic rocks from spectrally similar limestone using HyMap data.

The limitations of the GEOSCAN MkII imaging spectrometer were apparent in data from this site. Smoke haze had reduced the signal level in the SWIR2 to such an extent that little meaningful spectral discrimination was possible with these data.
12.2 RECOMMENDATIONS FOR FURTHER INVESTIGATIONS

Every study has limits to what can be investigated and ideas for further research are developed. From the studies completed in this thesis I recommend that the following topics warrant further research.

- Discriminating between alkaline ultramafic and other ultramafic rocks is economically significant (as kimberlites/lamproites can have a significant diamond content). The use of spectral geological techniques for this purpose requires further investigation. This, and other studies, have indicated that the VNIR spectral region may contain spectral information that can be used for this discrimination once the ultramafic rock has been located from the SWIR2 spectral signature. Further research on this topic requires spectral data from areas where these rock types are in juxtaposition.

- In arid areas that have been subjected to a previous phase of intense lateritic weathering the typical clay mineral weathering products of serpentinised ultramafic rocks may have been replaced by ferruginous silicified saprolite (silcrete). This material has a diagnostic SWIR2 spectra with a broad shallow absorption feature near 2240nm. Therefore, a study (using the methods detailed in this thesis) to determine if this spectral signature can be used to locate ultramafic rocks is warranted.

- The end-member un-mixing routines in ENVI work but they require streamlining and developing into an automated package for routine processing of operationally acquired data.

- The effect of noise filtering on hyperspectral data requires further study. Distortion of the spectral form can result from filtering. Therefore, there is a trade-off between noise reduction and maintaining spectral resolution. Hence the type and optimum level of filtering that successfully removes noise but does not degrade the diagnostic spectral information needs to be established. This requires developing a program or programs that can accurately estimate the signal-to-noise level from the data directly.

- Atmospheric corrections based on ATREM and other atmospheric models (Clarke et al., 1994) are becoming more accessible but they rely on input of generalised atmospheric parameters that may be different to the model on the survey day. These techniques are particularly important when working with the VNIR where atmospheric offsets are more severe than in the SWIR2. The log residual transform was used to convert radiance data to pseudo reflectance in this study but it does not produce reliable results when applied to VNIR data. Furthermore, if the scene contains significant amounts of the material of interest the log residual transform can produce spurious results. Therefore, experiments to determine the level at which the percent of ultramafic rock in a scene will cause this problem are required. Techniques should be developed which correct the scanner data from the spectral variations within it, without the need to develop atmospheric models.
This research suggested that variations in image pixel size could affect the results obtained. At the Jubilee site where variations in pixel size occurred they resulted from different instruments and so this aspect of system characteristics could not be adequately investigated. This study should be conducted using real data rather than simulated data from mathematical models. It is suggested that the Jubilee and/or Pine Creek sites be resurveyed with the HyMap scanner to obtain a range of pixel sizes from 3m to 20m. From such data sets it would be possible to determine how pixel size actually affects the ability of these data to spectrally discriminate ultramafic rocks. This would also have generic implications for all remote sensing systems.

This research has demonstrated that it is possible to locate alkaline and other ultramafic rocks. However, the possibility that saponite, an important mineral in achieving this in soil covered areas, can also be produced by the weathering of dolomite requires investigation. It needs to be determined whether such saponite formation results from hydrothermal alteration or from a weathering phenomenon. The Pine Creek area of South Australia would be an ideal site to commence such a study.
GLOSSARY OF TERMS AND ACRONYMS

Arid  A climate characterised by dryness variously defined as rainfall insufficient for plant life or crops without irrigation; less than 25cms of annual rainfall or higher evaporation rate than precipitation rate.

ATREM  Atmosphere Removal Program - program developed at University of Colorado that converts airborne scanner radiance values to reflectance percent.

AVIRIS  Airborne Visible/Infrared Imaging Spectrometer.

Bands (Channels)  The interval over which a spectrometer samples the spectrum. The larger the number over a defined range the greater the spectral resolution of the instrument.

Crosta technique  A method of applying principal component transforms to image data so that regions which contain a diagnostic absorption feature are highlighted. Four bands are input to the transform, one in which the absorption feature of interest is located and three reference bands. Examination of the Eigen matrix for these bands shows which Eigen vector has the weights which will result in a transformed image that highlights the absorption feature of interest.

End-member  A spectrum in a series of spectra collected from the field samples or image pixels that are unique and represent one pure mineral type.

GER  Geophysical Environmental Research Company.

Hull Difference  Value obtained by subtracting the Y-axis values of a spectrum from the Y-axis values of a line constructed as a hull across the apex of all peaks along the spectrum. It is expressed as a percentage and permits detection of the relative depths of the absorption features that is emphasised.

Hull Quotient  Value obtained by dividing the Y-axis values of a spectrum into the Y-axis of a line constructed as a hull across the apex of all peaks along the spectrum. It is expressed as a percentage and removes the background spectral curve so emphasising absorption features.

HyMap  Trade mark for a range of hyperspectral scanners produced by Integrated Spectronics.

Hyperspectral Scanner Imaging Spectrometer  A scanner that has more than 24 bands that are contiguous within wavelength regions VNIR, SWIR1 and SWIR.2 Usually taken as synonymous with hyperspectral scanner, in this study defined as scanners that have between 8 and 24 bands that are contiguous within wavelength regions.

Mg Score ratio  The value obtained from dividing the Y-axis value of a spectrum at 2300nm by the value at 2200nm. When obtained from field spectra this ratio value can be plotted to delineate the extent of Mg-OH compared to Al-OH minerals. The ratio is usually calculated from hull quotient transformed spectra. This term can also be used to specify the image ratio obtained by dividing the scanner image bands at these wavelengths data.

Multispectral Scanner (MSS)  An imaging scanner that has limited bands. In this study less than eight that are not contiguous. These instruments under sample the spectrum.
PIMA  Portable Infrared Mineral Analyser. SWIR field spectrometer produced by Integrated Spectronics.

Semi Arid  Type of climate in which there is slightly more precipitation 25-50cms than in arid climate and in which sparse grasses are the characteristic vegetation.

SWIR1  Short Wave Infra red spectral region from 1200nm-2000nm

SWIR2  Short Wave Infra red spectral region from 2000nm-2500nm

Un-mixing  Techniques used to calculate the proportions of end-member spectrum that are combined in the spectra of a mineral mixture. These techniques can be applied to image data to map the spatial distribution of various minerals and materials from their spectral signatures.

VNIR  Visible to Near Infra red spectral region from 400nm-1200nm
List of References

There are several instances of personal communication referred to in this thesis most significantly by:

- Dr J.F. Huntington, Chief Research Scientist of the Mineral Mapping Technology Group, Division of Exploration and Mining, CSIRO, an internationally recognised authority on Remote Sensing.

- Dr T Cocks, Managing Director of Integrated Spectronics and previously a CSIRO physicist, the designer and developer of the PIMA spectrometer and HyMap airborne scanners.

The AMIRA/CSIRO Reports referred to in this thesis were first distributed as restricted circulation documents to project sponsors and remain confidential for a period of five years. Reports more than five years old may be obtained, subject to sponsor approval, by contacting AMIRA, 9th Floor, 128 Exhibition Street, Melbourne, 3000, Australia.

Company reports referred to remain confidential. However, they may be requested from the author, subject to approval from De Beers, re-prints of relevant sections can be provided. The same applies to data used in this study. Stockdale Prospecting Limited, 60 Wilson Street, South Yarra, Victoria, 3141, Australia.


Agar, R. A. (1994). Geoscan airborne multispectral scanners as exploration tools for Western Australia diamond and gold deposits. Geology and geophysics department and UWA extension, University of Western Australia Publication No 26, pp435-447.


Bouchet, P., Cervelle, B. and Chorowicz (1984). Contribution to spectral signature research on ore bodies found in south Morocco, at three levels of investigation: satellite, ground and laboratory. Presented at remote sensing for geological mapping: proc. seminar BRGM number 82, pp 251-265.


List of References


Crippen, R.E., Estes, J. E., and Hajic, E. J. (1987). Band and band ratio selection to maximise spectral information in colour composite displays. Presented a GSA, cordilleran section, 83rd annual meeting. GSA, v19-6, p368


Ross, J. (1986). Kimberlites and related rocks. 1986, GSA special publication no. 14, v1


## APPENDIX 1

### SPECIFICATIONS OF FIELD SPECTROMETERS

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<th>Model</th>
<th>Light Source</th>
<th>VNIR</th>
<th>SWIR1</th>
<th>SWIR2</th>
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<th>Dimensions/Weight</th>
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APPENDIX 2

BAND CENTRES USED TO SAMPLE SPECTRA IN CHAPTER 8.

JERS OPS

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GEOSCAN MkII

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| 6 740           | 6 2264           | 6 2264           |
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ARIES (Suggested SWIR1 and SWIR2 Bands)

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APPENDIX 3
MODELLING SOFTWARE

A) MICROSOFT EXCEL SPREAD SHEET TO ADD NOISE TO SPECTRA

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>D</th>
<th>F</th>
<th>G</th>
<th>I</th>
<th>J</th>
<th>K</th>
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<tr>
<td>1</td>
<td>1000:1</td>
<td>500:1</td>
<td>300:1</td>
<td>100:1</td>
<td>50:1</td>
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<tr>
<td>2</td>
<td>73.83</td>
<td>73.52413</td>
<td>74.56299</td>
<td>74.12519</td>
<td>71.10268</td>
<td>78.6691</td>
<td>C2=0.0005<em>B2</em>(2*(RAND()-1)+B2</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>73.81</td>
<td>73.21181</td>
<td>73.23382</td>
<td>71.95498</td>
<td>75.83708</td>
<td>86.88037</td>
<td>D2=0.001<em>B2</em>(2*(RAND()-1)+B2</td>
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<tr>
<td>4</td>
<td>73.9</td>
<td>74.36587</td>
<td>74.24677</td>
<td>73.26663</td>
<td>67.70553</td>
<td>70.26935</td>
<td>G2=0.033<em>B2</em>(2*(RAND()-1)+B2</td>
<td></td>
</tr>
</tbody>
</table>

This is a section of the spreadsheet used to add noise to spectra. The values in column B are the reflectance percent values from a PIMA spectrum, row 1 shows the signal-to-noise ratios and column K the formulae used.

To determine the SNR of 300:1 for the reflectance value B2 the formula K4 is applied: the signal-to-noise weighting (.033 for 300:1) is multiplied by the value of B2, then multiplied by the random function and added back to B2. The formulae are applied across the spreadsheet as shown.
B) C PROGRAM TO PRODUCE IMAGE DATA CUBES FROM SPECTRA

#include <stdio.h>
#include <stdlib.h>
#include "define.h"
#include "specmodel.h"

void main(int argc, char *argv[])
{
    char error_flag = ERROR;
    if (init(argc, argv) == OK)
        if (input() == OK)
            if (readspec() == OK)
                if (writeimage() == OK)
                    error_flag = !ERROR;
    terminate(error_flag);
    exit(0);
}

#include <stdio.h>
#include <string.h>
#include "define.h"
#include "specmodel.h"

init(argc, argv)
int argc;
char *argv[];
{
    /* Command line */
    if (argc != NO_ARGUMENTS)
    {
        strcpy(message, "Usage: specmodel input_parameter_file output_image_file\n");
        return(ERROR);
    }
    strcpy(infile, argv[1]);
    strcpy(outfile, argv[2]);
    /* open input parameter file */
    if (! (infp = fopen(infile, "r")))
    {
sprintf(message, "Error in init: can't open %s", infile);
return(ERROR);
}

/* open output image file */
if (!((outfp = fopen(outfile, "w")))
{
    sprintf(message, "Error in init: can't open %s", outfile);
    return(ERROR);
}

return(OK);
}
# Include <stdio.h>
#include <string.h>
#include <stdlib.h>
#include "define.h"
#include "specmodel.h"

input()
{
    char text[80];
    int i, bnd;

do {
    if (getline(infp, text, 3*BUFFERSIZE) <= 0)
        {
        strcpy(message, "Error reading parameter file: noise percentage");
        return(ERROR);
        }
    while (text[0] == '#');

    sscanf(text, "%f", &noise);
    if ( noise < 0 || noise > 100 )
        {
        sprintf(message, "Invalid noise percentage: %f", noise);
        return(ERROR);
        }

    do {
    if (getline(infp, text, 3*BUFFERSIZE) <= 0)
        {
        strcpy(message, "Error reading parameter file: topographic range");
        return(ERROR);
        }
    while (text[0] == '#');

    sscanf(text, "%f", &topo);

do {
    if (getline(infp, text, 3*BUFFERSIZE) <= 0)
        {
        strcpy(message, "Error reading parameter file: x spectra");
        return(ERROR);
        }
    while (text[0] == '#');

    sscanf(text, "%d", &xblocks);
    if ( xblocks < 0 || xblocks > MAX_X )
        {
        sprintf(message, "Invalid no. x blocks: %d", xblocks);
        return(ERROR);
        }

}
do
    if (getline(infp, text, 3*BUFFERSIZE) <= 0)
    {
        strcpy(message, "Error reading parameter file: y spectra");
        return(ERROR);
    }
while (text[0] == '#');
sscanf(text, "%d", &yblocks);
if ( yblocks < 0 || yblocks > MAX_Y )
{
    sprintf(message, "Invalid no. y blocks: %d", yblocks);
    return(ERROR);
}
do
    if (getline(infp, text, 3*BUFFERSIZE) <= 0)
    {
        strcpy(message, "Error reading parameter file: no. pixels per block");
        return(ERROR);
    }
while (text[0] == '#');
sscanf(text, "%d", &numpix);
do
    if (getline(infp, text, 3*BUFFERSIZE) <= 0)
    {
        strcpy(message, "Error reading parameter file: bands");
        return(ERROR);
    }
while (text[0] == '#');
sscanf(text, "%d", &bands);
if ( bands < 0 || bands > MAX_BANDS )
{
    sprintf(message, "Invalid no. bands: %d", bands);
    return(ERROR);
}
for (i=0; i < bands; i++)
{
    do
    {
        if (getline(infp, text, 3*BUFFERSIZE) <= 0)
        {
            strcpy(message, "Error reading parameter file: wavelengths");
            return(ERROR);
        }
    }
while (text[0] == '#');
sscanf(text, "%d%f", &bnd, &wav[i]);
if (bnd < 0 || bnd > MAX_BANDS)
{
    sprintf(message, "Invalid band number: %d", bnd);
    return(ERROR);
}
}
return(OK);
/*******************/
/* submodule getline:
*/
/* this submodule fetches a line from a text file.
*/
/*****************************
*/

getline( fp, s, lim ) /* get a line from file with file pointer fp */

FILE *fp;
char *s;
long lim;
{
    long c, i;
    i = 0;
    while ( --lim > 0 && ( c = getc( fp ) ) != EOF && c != LINEFEED )
        s[i++] = c;
    if ( c == LINEFEED )
        s[i++] = LINEFEED;
    s[i] = '\0';
    return(i);
}

/*****************************/
/* submodule readspec:
*/
/* this submodule reads the files containing the spectra
*/
/*****************************/

#include <stdio.h>
#include <string.h>
#include <stdlib.h>
#include "define.h"
#include "specmodel.h"

readspec()
{
    char text[80];
    char buf[BUFFERSIZE];
    int i, j, k, x, y;
    float w, r, w_old, r_old;
    for (i=0; i < xblocks; i++)
    {
        for (j=0; j < yblocks; j++)
        {
            /* Read x,y block numbers and spectra file name */
            do
            {
                if (getline(infp, text, 3*BUFFERSIZE) <= 0)
                {
                    strcpy(message, "Error reading input parameter file: spectra file");
                    return(ERROR);
                }
while (text[0] == '#');
sscanf(text, "%d%d%s", &x, &y, specfile);
sscanf(text, "%d%d%s", &x, &y, specfile);
printf("x = %d y = %d %s
", x, y, specfile);
if (x != i+1)
{
    sprintf(message, "Invalid x block number: %d", x);
    return(ERROR);
}
if (y != j+1)
{
    sprintf(message, "Invalid y block number: %d", y);
    return(ERROR);
}

/ * Open spectra file */
if (! (specfp = fopen(specfile, "r")))
{
    sprintf(message, "Error in specread: can't open %s", specfile);
    return(ERROR);
}

/ * Read spectra file and interpolate wavelengths */
for (k=0; k < bands; k++)
{
    w_old = 0.0; r_old = 0.0;
    while (fgets(buf, BUFFERSIZE, specfp))
    {
        buf[strlen(buf)-1] = '\0';
        if (strlen(buf) > 0)
        {
            sscanf(buf, "%f%f", &w, &r);
            if (wav[k] > w_old && wav[k] <= w)
            {
                /* interpolate */
                ref[i][j][k] = r_old +
                    (wav[k] - w_old)*(r - r_old)/
                    (w - w_old);
                break;
            }
        }
        w_old = w;
        r_old = r;
    }
}

fclose(specfp);
}

return(OK);
}

/ *************************/
/ * submodule writeimage:
/ */
/ * this submodule writes out the final image and adds noise
/ */
/ *************************/

#include <stdio.h>
#include <stdlib.h>
#include "define.h"
#include "specmodel.h"
writeimage()
{
    int   i, j, k;
    int   px, py;
    float pix, rt, rn;

    /* Seed the random number generator with a different value each time the program is run.
     * To get the same series each time, omit this call. */
    srand(time(NULL));

    /* Write out the SIP image */
    for (i=0; i < xblocks; i++)
    {
        for (px=0; px < numpix; px++)
        {
            for (j=0; j < yblocks; j++)
            {
                for (py=0; py < numpix; py++)
                {
                    rt = (float) rand()/(float)RAND_MAX;
                    for (k=0; k < bands; k++)
                    {
                        /* add topographic effects */
                        pix = ref[i][j][k] + topo*(2*rt - 1);
                        /* add noise */
                        rn = (float) rand()/(float)RAND_MAX;
                        pix = pix + pix*noise*(2*rn - 1)/100.0;
                        if (pix < 0) pix = 0.0;
                        if (pix > 100) pix = 100.0;
                        fwrite(&pix, sizeof(float), 1, outfp);
                    }
                }
            }
        }
    }

    return(OK);
}
/*******************
/* submodule terminate:
/*
/* this submodule terminates the utility writing out the
error message */
/******************

/* include table definitions */

#include <stdio.h>
#include "define.h"
#include "specmodel.h"

void terminate(error)

char error;
{
  /* write error message to screen and exit if error */
  printf("%s\n", message);
  if (error == ERROR)
    exit(1);

  fclose(infp);
  fclose(outfp);
}

## Example input parameter file

# percentage noise to add
0
# +/- range for topographic effect to add
5
# no. rows of spectra blocks
2
# no. columns of spectra blocks
6
# square block size for each spectra (ie no. pixels)
100
# no. bands
6
# band no. & wavelength (nm)
1 487
2 571
3 661
4 837
5 1677
6 2215
# block coordinates & spectra file name (comma-delimited text file)
1 1 spectra/Iron_jpl_sc.csv
1 2 spectra/goethite_jpl_sc.csv
1 3 spectra/hemat_jpl_sc.csv
1 4 spectra/calcite_jpl_sc.csv
1 5 spectra/kao_iron_jpl_sc.csv
1 6 spectra/kao_veg_jpl_sc.csv
2 1 spectra/kaolin_jpl_sc.csv
2 2 spectra/TM_saponite_jplX.csv
2 3 spectra/quartz_jpl_sc2.csv
2 4 spectra/muscov_jpl_sc2.csv
2 5 spectra/dry_veg_jpl_sc.csv
2 6 spectra/green_veg_jpl_sc.csv

# Example of input spectra file, from Excel spread sheet - output as .csv file.

<table>
<thead>
<tr>
<th>wavelength (nm)</th>
<th>reflectance percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>2102</td>
<td>45.1393</td>
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<td>2112</td>
<td>42.9575</td>
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<tr>
<td>2123</td>
<td>40.857</td>
</tr>
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<td>2133</td>
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<td>2143</td>
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<td>33.9096</td>
</tr>
</tbody>
</table>

APPENDIX 3
APPENDIX 4

GEOSCAN MkII CALIBRATION

1.0 INTRODUCTION

This appendix has been edited from a draft paper supplied by N Adronis the principal engineer involved with the development of the GEOSCAN MkII scanner. It provides useful background information on the system. The information in this document together with data supplied by N Adronis was used by Dr A Becker to write a program (Page 18) to convert ground spectral readings obtained with the GEOSCAN MkII scanner to reflectance values. This results of using this program are discussed in Chapter 9 of the thesis.

This paper describes the Spectral and Radiometric calibration procedures that can be used on the GEOSCAN MkII Scanner.

The GEOSCAN MkII Scanner has been designed to discriminate reflectance and emittance to the maximum sensitivity possible using the latest Scanner design techniques and component technologies over three spectral regions. The measured sensitivity in the three spectral bands are as follows:

<table>
<thead>
<tr>
<th>Spectrometer Type</th>
<th>Max Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visible Spectrometer</td>
<td>Max of 0.25% reflectance</td>
</tr>
<tr>
<td>SWIR Spectrometer</td>
<td>Max of 0.4% reflectance</td>
</tr>
<tr>
<td>Thermal Spectrometer</td>
<td>Max of 0.05 degrees temperature</td>
</tr>
</tbody>
</table>

Typically reflectance can not be measured in a controlled environment of better than 1%. Assuming only the AC component of a reflectance signal is recorded then a 8 bit digitising system or 256 discrete levels is adequate. The high sensitivity has been achieved by using large optics and the highest quality optical components.

The reflectance and temperature sensitivity degrades with the amount of induced instrument noise and the ground illumination conditions. For example a visible channel with a airborne signal to noise of 180:1 (Maximum 8 bit signal to noise ratio) will have a reflectance sensitivity of approximately 1%. As the energy illuminating the ground decreases due to a low sun angle or poor atmospheric conditions the amount of instrument induced noise will increase and degrade the instrument sensitivity.
The GEOSCAN MkII Scanner does not digitise the entire target reflectance curve, (ie from 0% to 100% reflectance) but only digitises the portion of the reflectance curve which contains information. For example in the SWIR region a typical soil sample for a particular survey may have a variation in reflectance of between 30% to 60% and the Scanner digitises this reflectance range using 8 bit quantisation over 30% to 60% reflectance. The background illumination level or the DC component of the signal is not recorded as there is no information in the DC component. Atmospheric back scatter, instrument black body temperature and electronic DC offset also contribute to the recorded signal DC component which tends to invalidate the information content of the signal DC component.

2.0 SPECTRAL CALIBRATION

Calibration Procedures

Spectral calibration has been achieved using an ORIAL wide bandwidth monochromator. A quartz halogen lamp is used as a Visible and SWIR light source and a carbon heater rod is used as a black body source. Three diffraction gratings are used to generate monochromatic light:

<table>
<thead>
<tr>
<th>Spectrometer</th>
<th>Grating</th>
<th>Bandwidth</th>
</tr>
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<tbody>
<tr>
<td>Visible</td>
<td>500nm</td>
<td>1nm</td>
</tr>
<tr>
<td>SWIR</td>
<td>2.0nm</td>
<td>2nm</td>
</tr>
<tr>
<td>Thermal</td>
<td>8.0nm</td>
<td>8nm</td>
</tr>
</tbody>
</table>

Second and third order spectral blocking filters are not used on the monochromator as the Scanner spectrometer dichroic filters and detector array spectral blocking filters are more than adequate to filter out Grating orders.

The Monochromator Visible Spectrometer wave length calibration is verified using a red laser. The monochromator SWIR spectrometer calibration is verified by using a high power red laser and using the fourth order harmonic as a reference. The visible spectrometer optical path is blocked off during the SWIR monochromator wave length verification procedure to prevent damage to the visible detector. The Thermal
monochromator wave length calibration is verified by using the absorption lines of a polystyrene plastic film.

A collimated monochromatic light source is injected into the telescope aperture using a small off centred parabola. The scan mirror is rotated a 5Hz to minimise detector noise and scans across the aperture of the monochromator off centred parabola. The monochromator is set to the zeroth order to provide a broad band light source and the Scanning Telescope Pitch angle is adjusted to maximise the signal level. The monochromator offset error is determined by adjusting and maximising the zeroth order peak and the dial gauge zero setting. This offset is then applied to all monochromator readings to generate an absolute wave lengths for the particular grating used.

The Scanner single channel CRO display is used to measure the intensity of the calibration source. The CRO display calculated the maximum and minimum calibration peak values and averaged 16 readings to remove the detector noise component. By sweeping the monochromator wave length at 1 nanometre increments and recording the calibration peak high and low values a band pass curve can be generated. These curves are normalised as the signal value and the gain and offset settings between channels are not correlated. Because there are no filters in the monochromator optical path and a high temperature source is used then the energy generated by the monochromator over the narrow band pass of a detector channel can be assumed to be linear. The Radiometric calibration results can be used to generate a relative spectral response.

**Visible Spectral Calibration**

The Visible Spectral Calibration curves show that the position and shape of the band pass curves are all different. The Visible detector is made up of a 35 element linear array and by combining different detector elements channel a different band pass can be achieved. Channel 1 is made up of two detector elements, channels 2 and 3 are made up of three detector elements each, channels 4 to 6 are single adjacent detector elements and channels 7 to 10 are single detector elements with unused detector elements between the channels. Channels 4 to 10 are gaussian in their spectral distribution which is due to the rectangular detector elements imaging a rectangular field stop. Channels 2 and 3 should in theory have a flat on the top as they are a addition of thee gaussian detector channels. Due to the non linear frequency response of the dichroic filters used in the spectrometers to provide broad
APPENDIX 4

band frequency splitting and diffraction grating multiple order filtering the tops of channels 2 and 3 band pass curves map the non linear response of these filters. Channel 1 has a distorted band pass curve due to:

1. High attenuation of short wave lengths of Aluminium metal used in the front sufficed mirrors,
2. Poor response of the silicon detector at 400nm,
3. Square Visible camera lens aperture obstructing the short wave length.

SWIR Spectral calibration

The eight SWIR spectral response curves are mostly gaussian in distribution due to a rectangular detector elements imaging a rectangular field stop. Channel 17 and 18 have slightly distorted spectral response curves due to the non linear spectral response of the dichroic filters used as broad band filter and grating multiple order filters.

Thermal Spectral Calibration

The six thermal spectral response curves are mostly gaussian in distribution due to a rectangular detector elements imaging a rectangular field stop. Channel 20, 23 and 24 have a slightly distorted spectral response curves due to the non linear spectral response of the dichroic filters used as broad band filter and grating multiple order filters. Channel 24 has a distorted gaussian shape and is due to the fall in optical efficiency at the longer wave lengths.

3.0 RADIOMETRIC CALIBRATION

Warnings

To avoid misus of the Radiometric Calibration results, users of this information must note the following:
1. The GEOSCAN MkII Scanner optical performance has changed significantly since February 1992 and there has been an improvement in the signal to noise performance of between 50% to 200% in the three spectrometers.

2. Radiometric Calibration Results are not valid for imagery flown before February 1992 due to the resurfaced mirrors and higher quality detectors.

3. The Radiometric Calibration coefficients will only convert the recorded digital data to power entering the Scanning telescope. Absolute ground radiometric power can not be determined due to the known atmospheric absorption between the aircraft and the ground. Use of telescope input power as a indication of ground illuminated and radiated power must be qualified.

4. The Radiometric Calibration coefficients will not be valid after 12 months due to the accumulated degradation in performance of seven mirror surfaces.

5. The calibration coefficients may be used to produce a relative spectral signature for channels of the same spectral signature for channels of the same spectrometers but can be used to generate a relative spectral response between the three spectrometers.

6. Due to the complex optical path of the Scanner built in calibration sources and the effect of the Scanner Telescope temperature the contribution of the calibration signal the recorded calibration source curves can only be used as a stable reference for scan runs of the same altitude and date.

7. Only the radiometric Gain coefficients in this report can be used for calibration and the user must generate separate offset, bias, Black body and Bias coefficient for different images.

Instrument Sensitivity Measurements

The GEOSCAN MkII Scanner has been designed to measure reflectance to better than 0.5% and with a temperature resolution of better than 0.1 degree.

Assuming a calibration lamp current is roughly proportional to irradiance, a 1% change in lamp current the GEOSCAN MkII Scanner will detect a 4.5% change Visible spectrometer signal level and a 3% change in the SWIR spectrometer signal level. This translates to the Visible spectrometers sensitivity of better than 0.25% reflectance and a SWIR spectrometer sensitivity of better than 0.3% reflectance.
Assuming the radiated power of a body of water is roughly proportional to temperature to the power of four (i.e., Emissivity of water = 0.96) then for a 35 degree water temperature with a 0.1 degree temperature change, the GEOSCAN MkII Scanner registers a 3% change in signal level. This translates to a thermal spectrometer sensitivity of better than 0.05 degrees temperature.

The Spectrometer sensitivity degrades with the amount of detector induced random noise. The spectrometer channel noise is proportional to the optical efficiency and a function of wavelength. The spectrometers efficiency has been designed to peak at the centre of channels:

- **Visible Spectrometer:** Channel 4
- **SWIR Spectrometer:** Channel 13
- **Thermal Spectrometer:** Channel 21

The spectrometer channel sensitivity can be determined by using the channel signal to noise figure for the recorded image. Most spectrometer channels have a signal to noise value of 180:1 to 100:1 which is the maximum signal to noise figure for a 8 bit digitising system.

From the signal to noise performance graphs it is apparent that the induced detector noise is proportional to the Scanner mirror speed or ground resolution. As the Ground integration time reduces the amount of induced noise increases. The Spectrometer noise performance tests indicate that the visible detectors generate white noise across the entire band pass. The SWIR detector noise power band width is roughly at the centre of the Scanning bandwidth. The thermal detector noise power bandwidth is mostly low frequency noise. The test flight airborne signal to noise figures indicate that most of the visible channels have a signal to noise of 180:1 and the SWIR and thermal channels have a signal to noise of between 50:1 to 100:1. Because the visible channels have a signal to noise of 180:1 which is the limit of the 8 bit digitising system the noise performance is constant until the mirror speed exceeds 20Hz.

The GEOSCAN MkII Scanner is designed to generate digital data that is proportional to optical input power at the Scanner telescope. Linear equations can be used to convert the recorded digital channel values to relative or absolute radiometric values.
Radiometric Calibration Procedures

Visible and SWIR radiometric calibration has been achieved using a standard calibrated lamp mounted 150mm from the centre of a white body target. A teflon based target is used as a white body source with a 96% to 99% reflectance efficiency. The Target is mounted at 45 degrees to the vertical axis of the Scanner telescope to position the calibration lamp outside the Scanner field of view. All the calibration source component spectral responses have been modelled to enable the telescope input power to be calculated for the 18 visible and SWIR channels. Two calibration peaks are generated by covering up 50% of the calibration target with a black body source. Different gain and offset settings are used to image the two calibration peaks which are used to calibrate the system gain and offset coefficients.

Thermal radiometric calibration is achieved by using two heated bodies of water at different temperatures. Knowing the emissivity of water and the black body equation the power at the six thermal wave lengths can be calculated. The two bodies of water are located at +/- 30 degrees from the telescope vertical axis.

Calibration Lamp Irradiance Calibration

The ORIEL calibration lamp No. 9_056 has been supplied with a list of course irradiance values from 400nm to 2500nm. The irradiance data can not be used to derive the black body equation due to the non back body lamp curve. Since we are not imaging the top of the black body curve and are effectively using the linear parts of both sides of the black body curve, we can use linear interpolation to calculate the irradiance at the 18 Visible and SWIR channels.

White Body Target Reflectance Calibration

The White body target used to generate a full aperture spherical light source is a SPECTRALON SRT-99-180 teflon based target. This target is supplied with coarse reflection data from 250nm to 2500nm and has a reflectance efficiency of between 95.5% to 99.3%. Since irradiance power can only be calculated to within 2%, linear interpolation is adequate to calculate the reflectance efficiency for the 18 Visible and SWIR channels.
The Calibration target reflectance efficiency spread sheet located in appendix A has been set up to calculate the reflectance for the 18 Visible and SWIR channels and the channel wave lengths have been linked back to the spectral response curves.

**Calibration Target Illumination Distribution**

The calibration lamp irradiance values have been measured 50mm from the lamp and since the calibration lamp is 150mm from the target the energy reflected off the target is approximately 10% of the published irradiance values. The calibration target is mounted 45 degrees to the telescope axis and the oval telescope foot print can be mapped on the calibration target using a 150mm and 20mm scanning mirror shape. Using the inverse square law the average target attenuation can be calculated by dividing the oval foot print into a 10mm grid and averaging the lamp attenuation at grid points. The Illumination distribution graph illustrates the illumination profiled of the Visible and SWIR calibration light source. The calculated average target attenuation has been linked to the Radiometric calibration spread sheets.

**Thermal Source Black Body Calibration**

Two heated water bodies are used as black body sources to calibrate the thermal spectrometer. Planck's formula for a black body can be used to determine the radiated power for the six thermal channels:

\[ M(1) = \frac{C1}{1**5*(exp(c2/1*T)-1)} \]

Where:

- \( M(1) \) = Black Body radiated power in Watts per square meter per wavelength
- \( C1 \) = 3.74E-16 Watts per square meter
- \( C2 \) = 1.44E-2 Meters per degrees Kelvin
- \( l \) = Wave length in meters
- \( T \) = Absolute temperature in degrees Kelvin

Spectral Emissivity can be calculated as follows:
\[ e(1) = \frac{M(1 \text{ material})}{M(1 \text{ black body})} \]

Where:

\[ \begin{align*}
E(1) &= \text{Spectral Emissivity of a material} \\
M(1 \text{ material}) &= \text{Radiated power of material} \\
M(1 \text{ Black body}) &= \text{Radiated power of a black body source as given in the above equation.}
\end{align*} \]

The emissivity of water is as follows:

- Distilled Water = 0.96 at 20 degrees C
- Smooth ice = 0.06 at -10 degrees C
- Frost Crystals = 0.98 at -10 degrees C
- Snow = 0.98 at -10 degrees C

The equation for the radiated power of a body of water can be derived from the above equation:

\[ M(1) = 0.96*\frac{C1}{1**5*(\text{ex(c2/1*T)}-1)} \]

Using this formula the radiated power for the six thermal channels can be determined using the water temperature.

**Gain Calibration**

The Scanner uses an eight bit digital gain system to amplify the spectrometer signal before digitising. The digital gain circuit has been wired up with an approximate exponential gain setting response and is required to handle the large dynamic range of detector signals generated. From the Gain calibration results and the Scanner digital gain circuit we can derive and verify the gain setting equation as being \[ y=1/(1-x) \].

**Offset Calibration**

The Scanner uses an eight bit digital offset system to remove the DC components or the background illumination components from the detector signals to allow maximum digitised
signal information content. From the Offset calibration results the offset setting response curve is linear.

**Raw Image Data Radiometric Conversion**

There are several problems in converting the spectrometer recorded digital value to an absolute power:

1. Calibration lamps with a calibration target can only be calibrated to within 2% reflectance. The Visible and SWIR spectrometers have a sensitivity of better than 0.5% reflectance.

2. Thermal calibration sources can only be held stable to within 0.1 degrees. The Thermal spectrometer has a sensitivity of better than 0.1 degrees.

3. The atmospheric absorption between the aircraft and the ground is unknown.

4. The Atmospheric absorption between the ground and the sun is unknown.

5. Atmospheric back scatter effects of the image illumination invalidate radiometric ground control points in the shorter wave lengths.

Until these problems are solved an airborne Scanner that measures absolute spectra can not be built. The value of absolute radiometric calibrated imagery has not yet been demonstrated.

**Visible Radiometric Calibration**

From the visible spectrometer optical, analog and digital circuits we can determine the relationship between the visible spectrometer spectral channel digital pixel value and the telescope input power:

\[
\text{Byte} = \frac{(\text{Signal} + \text{Bias} - 0\times(255 - \text{Offset}))}{\text{Gain}} / (255 - \text{Gain})
\]

or

\[
\text{Signal} = (\text{Byte} \times \text{Gain} \times (255 - \text{Gain})) - \text{Bias} + 0 \times (255 - \text{Offset})
\]
APPENDIX 4

Where:

- **Signal** = Telescope input power for the channel wave length in Micro Watts per square centimetre per nanometre wave length.
- **Byte** = Eight bit unsigned digit pixel value
- **G** = Optical and electronic gain coefficient
- **Gain** = Eight bit unsigned digital gain value
- **Bias** = Trans impedance amplifier offset error bias
- **O** = Electronic offset gain coefficient
- **Offset** = Eight bit unsigned digital offset value

Due to the high trans impedance amplifier impedance of greater than 1 Mega ohm any input offset error in the first stage of amplification in the spectrometer preamplifier is amplified and included in the detector signal. Unfortunately the bias voltage varied with amplifier temperature and since the Visible spectrometer is effectively in the aircraft airflow this value will vary according to the aircraft altitude. The bias voltage contributes about 5% to the total signal DC component.

Using a black body target as a zero reference and a white body source as a 100% and 50% calibration lamp source the value of the G, O and Bias coefficients can be calculated as follows:

\[
G = \frac{(\text{signall}-\text{signal2})}{(\text{byte1}-\text{byte2})/(255-\text{Gain})}
\]

For a signal level of zero and two different gain and offset readings:

\[
\text{Bias} = \frac{(\text{Byte2} \times G \times (255-\text{Gain2}) \times (255-\text{Offset1}) - \text{Byte1} \times G \times (255-\text{Gain1}) \times (255-\text{Offset2}))}{(\text{Offset2}-\text{Offset1})}
\]

\[
O = \frac{(\text{Signal}-\text{Byte} \times G \times (255-\text{Gain})+\text{Bias})}{(255-\text{Offset})}
\]

Because the radiometric tests were performed immediately after power-up there was a small amount of drift in the bias voltage during testing as the amplifiers heated up and resulted in a large variation in the offset coefficient for various gain and offset settings. A more accurate offset coefficient can be derived using gain and offset setting with larger than a 5% difference.

From these test results we can use the gain coefficient to calibrate visible data for amplitude for images flown after February 1992. Since the electronic gain is fixed to within 2% components tolerance and the optical gain is fixed by the efficiency of the optical components then the gain coefficient will be valid for at least 12 months. Optical components efficiency tends to degrade rapidly in the shorter wave lengths.
Since the bias coefficient varies with Scanner temperature this value must be determined for every flight using a pixel of known black body value. Knowing the image bias coefficient, the offset coefficient can be adjusted accordingly.

**SWIR Radiometric Calibration**

From the SWIR spectrometer optical, analog and digital circuits we can determine the relationship between the SWIR spectrometer spectral channel digital pixel value and the telescope input power:

\[
\text{Byte} = \frac{(\text{Signal} + \text{BB} - O \times (255 - \text{Offset}))}{G} \times (255 / \text{Gain})
\]

or

\[
\text{Signal} = (\text{Byte} \times G \times (255 - \text{Gain})) - \text{BB} + O \times (255 - \text{Offset})
\]

Where:

- **Signal**: Telescope input power for the channel wave length in Micro Watts per square centimetre per nanometre wave length
- **Byte**: Eight bit unsigned digit pixel value
- **G**: Optical and electronic gain coefficient
- **Gain**: Eight bit unsigned digital gain value
- **BB**: Black body temperature of the SWIR spectrometer
- **O**: Electronic offset gain coefficient
- **Offset**: Eight bit unsigned digital offset value

Because it is difficult to shield a linear or two dimensional array from stray radiation outside, the field of view of the optics thermal energy radiated by mechanical components contribute to the SWIR detector DC component. For example, a black body source will radiate the same amount of energy at room temperature as the amount of energy recorded by the Scanner at 3000 meters altitude. The SWIR spectrometer Black body energy accounts for up to 80% of the SWIR DC component. The offset drift is graphically demonstrated in the GEOSCAN MkII Scanner operation as the Scanner must be flying at survey altitude for at least 40 minutes to allow the Scanner spectrometer temperature to stabilise. If this procedure is not followed then the SWIR signals will drift outside the eight bit signal digitising range within five minutes as the DC components accounts for more than 80% of the total signal.
Using a black body target as a zero reference and a white body source as a 100% and 50% calibration lamp source the value of the G, O and Bias coefficients can be calculated as follows:

\[ G = \frac{\text{signall}-\text{signal2}}{\text{byte1}-\text{byte2}}/(255-\text{Gain}) \]

For a signal level of zero and two different gain and offset readings:

\[ BB = \frac{\text{Byte2}\times G\times (255-\text{Gain2}) \times (255-\text{Offset1}) - \text{Byte1}\times G\times (255-\text{Gain1}) \times (255-\text{Offset2})}{\text{offset2}-\text{offset1}} \]

\[ O = \frac{\text{Signal}\times \text{Byte}\times G\times (255-\text{Gain}) + \text{Bias}}{255-\text{Offset}} \]

From the SWIR spectrometer Radiometric Calibration spread sheet you will note that the gain coefficient is within 5% for the different radiometric readings.

The offset and black body coefficients were not calculated as these results are only valid for the Scanner at room temperature.

From these test results we can use the gain coefficient to calibrate SWIR data for amplitude for images flown after February 1992. Since the electronic gain is fixed to within 2% components tolerance and the optical gain is fixed by the efficiency of the optical components, then the gain coefficient will be valid for at least 18 months. Optical efficiency degrades slowly for SWIR wave length.

Since the BB coefficient varies with Scanner temperature this value must be determined for every flight using a pixel of known black body value. Knowing the image bias coefficient the offset coefficient can be adjusted accordingly.

**Thermal Radiometric Calibration**

From the SWIR spectrometer optical, analog and digital circuits we can determine the relationship between the Thermal spectrometer spectral channel digital pixel value and the telescope input power:

\[ \text{Byte}=\left(\frac{\text{Signal-DC}+\text{Bias-O} \times (255-\text{Offset})}{G/(255-\text{Gain})}\right) \]
or

\[
\text{Signal} = (\text{Byte} \times G \times (255 - \text{Gain})) + \text{DC} - \text{Bias} + O \times (255 - \text{Offset})
\]

Where:

- \text{Signal} = \text{Telescope input power for the channel wave length in Micro Watts per square centimetre per nanometre wave length}
- \text{Byte} = \text{Eight bit unsigned digit pixel value}
- G = \text{Optical and electronic gain coefficient}
- \text{Gain} = \text{Eight bit unsigned digital gain value}
- \text{DC} = \text{Channel Signal DC component}
- \text{Bias} = \text{DC bias voltage}
- O = \text{Electronic offset gain coefficient}
- \text{Offset} = \text{Eight bit unsigned digital offset value}

Using two black body sources the value of the G, O, DC and Bias coefficients can be calculated as follows:

\[
G = \frac{(\text{signal1} - \text{signal2})}{(\text{byte1} - \text{byte2})/(255 - \text{Gain})}
\]

For a white body source and two different gain and offset readings the DC component and Bias coefficients can be calculated:

\[
\text{DC-Bias} = \frac{(\text{Byte2} \times G \times (255 - \text{Gain2}) \times (255 - \text{Offset1}) - \text{byte1} \times G \times (255 - \text{Gain1}) \times (255 - \text{Offset2})}{\text{(offset2} - \text{offset1)}}
\]

\[
O = \frac{(\text{Signal} - \text{Byte} \times G \times (255 - \text{Gain}) + \text{DC-Bias})}{(255 - \text{Offset})}
\]

From the Thermal spectrometer Radiometric Calibration spread sheet you will note that the gain coefficient is within 5% for the different radiometric readings.

The Thermal detector array is cooled using a Joule Thomson cooling which is a self regulating sacrificial nitrogen system. The long thermal wave length sensitivity of the thermal spectrometer makes the detector dewar act as a large black source and contributes 95% of the detector DC signal component. Due to the instability of the cooling system temperature (ie +/- 3 degrees at 70 degrees Kelvin) the thermal detector arrays must be AC coupled to 4Hz using a two poll Butter Worth high pass filter. The AC coupling effectively removes the signal DC component and a fixed DC bias is added to the signal to make it positive. When imaging a large target of constant temperature the AC coupling differentiates the average target temperature to produce an image with a sloping illumination. This non uniform thermal image illumination is compensated by using the same Visible and SWIR atmosphere back scatter correction algorithms. Due to the 4Hz
AC coupling the slope of the image illumination is a function of mirror speed and decreases as a linear function of increasing mirror speed. When the Scanner is operating in a airborne survey mode the mirror speed is constantly adjusted to be proportional to the aircraft ground speed. The Offset, DC and Bias coefficients were not calculated as these results are only valid for a constant mirror speed of 5Hz.

From these test results we can use the gain coefficient to calibrate Thermal data for amplitude response for images flown after February 1992. Since the electronic gain is fixed to within 2% components tolerance and the optical gain is fixed by the efficiency of the optical components then the gain coefficient will be valid for at least 24 months. Optical efficiency degrades very slowly for Thermal wave length. Offset, Bias and DC coefficients must be determined for each image using known radiometric ground control points.

**Scanner Built in Calibration Sources**

The GEOSCAN MkII Scanner has six calibration source that can be used as a stable reference between adjacent scanner runs. There are four visible and SWIR calibration peaks and two thermal peaks. The calibration peaks are organised in pairs and one peak is roughly 20% in magnitude of the other. The calibration curves are usually generated once before the start of a survey block and are used as a comparative reference. The calibration sources radiometric response changes as the optical components degrade with time. These calibration sources are not calibrated as there is a complex optical path between the light source and the telescope aperture and the light sources do not fill the telescope housing black body temperature contributing to the calibration signal. The calibration sources can be used to generate relative spectral signature curves for the three spectrometers but can not be used to generate a relative relationship between the three spectrometers. The image users must specify that a airborne calibration reference be recorded before each run as there is a time penalty in performing a calibration peak recording procedure.
4.0 GEOSCAN CALIBRATION (SWIR)

Program developed by Dr Anne Becker based on Nick Andronis draft report.

Algorithm

Signal = byte*G(255-gain) - BB + O(255-offset)

Where:
- Signal: unknown
- Byte: soil image pixel value
- G: parameter calculated by Nick for each channel. The original values provided by Nick in his draft report were revised by him
- gain: provided for each channel for each soil sample
- offset: provided for each channel for each soil sample
- BB: unknown
- O: unknown

To find BB and O in the above equation, assume that, for a black body:

Signal = O

Byte_{BB} = lowest pixel value in the black body image
Gain = same as above
Offset = same as above
G = same as above
O_{BB} = O

and so,

-BB + 0(255 - offset) = -byte_{BB}*G(255 - gain)

Therefore,

Signal = byte*G(255 - gain) - byte_{BB}*G(255 - gain)
= G(byte - byte_{BB})(255 - gain)

The white body images can be used to calibrate the soil samples relative to each other. This has not been done.
Program Code

IIS System 600 code to implement the calibration procedure algorithm described on the previous page:

/* Calibration Geoscan MkII data.
Designed to work on soil sample padded with a black body image section on
the left and a white body image section on the right.

Calibration parameters are read from a data file which lists, one per line, for each
channel, the G parameter which remains fixed and the gain values which are
changed for each samples. The parameter file also lists the sizes of the data image
and the black body image so that the correct sections can be read in.

#include <stdio.h>
#include <stdlib.h>
#include "xanth/source/ind/inc/standard.h"
#include "xanth/source/ind/inc/errordef.h"
#include "iio/source/ind/inC/imdef.h"
define numchannels 8

CPUgeocalibrate (Ichan, Iname, Icount, Ochan, Oname, Ocount, prmfile, outfile)
int Ichan[], Icount, Ochan[], Ocount;
String Iname[], Oname[], prmfile, outfile;
{

int dtype, isx, isy, isz, isw;
int bufsize, channel, npix, n;
int image, line;
int BBss, BBns, BBsl, BBnl, IMss, IMns, IMsl, IMnl;
char strbuf[100], prmstr[25];
char calfile[100], uncalfile[100];
double G[10], gain[10];
double sum, BB, IM;
double bw[20];
Byte *buf, *p;
float callM;
float *realbuf, *realp;
FILE *prmfp;
FILE *calfp, *uncalfp;

/* Set bandwidth values */
bw[1] = 0.044;
bw[2] = 0.048;
bw[3] = 0.046;
bw[4] = 0.044;
bw[5] = 0.044;
bw[6] = 0.044;
bw[7] = 0.046;
bw[8] = 0.042;

/* Allocate buffer space */
bufsize = 50000;
buf = (Byte *) cMEMget(bufsize*4);
realbuf = (float *) cMEMget(bufsize*4);

/* Open the input image */
IMopen(Ichan, AZ(Iname[0]), 0, &dtype, &isx, &isy, &isz, &isw);
/* Open parameter file */
if ((prmfp = fopen(prmfile, "r")) == NULL)
    SYSError(Fatal, "Can't read parameter file!");

/* Open output spectra file */
strcpy(calfile, outfile);
strcat(calfile, ".cal");
if ((calfp = fopen(calfile, "a")) == NULL)
    SYSerror(Fatal, "Can't open calibrated spectra file!");

/* Open output spectra file */
strcpy(uncalfile, outfile);
strcat(uncalfile, ". uncal");
if ((uncalfp = fopen(uncalfile, "a")) == NULL)
    SYSerror(Fatal, "Can't open uncalibrated spectra file!");

/* Read data from parameter file */
channel = 1; line = 1;
while (fgets(strbuf, 80, prmfp))
{
    strbuf[strlen(strbuf)-1] = '\0';
    if (line == 1)
    {
        strcpy(prmstr, strtok(strbuf, " ");
        image = atoi(prmstr);
        strcpy(prmstr, strtok(NULL, " ");
        BBss = atof(prmstr);
        strcpy(prmstr, strtok(NULL, " ");
        BBns = atof(prmstr);
        strcpy(prmstr, strtok(NULL, " ");
        BBsl = atof(prmstr);
        strcpy(prmstr, strtok(NULL, " ");
        BBnl = atof(prmstr);
        strcpy(prmstr, strtok(NULL, " ");
        IMss = atof(prmstr);
        strcpy(prmstr, strtok(NULL, " ");
        IMns = atof(prmstr);
        strcpy(prmstr, strtok(NULL, " ");
        IMsl = atof(prmstr);
        strcpy(prmstr, strtok(NULL, " ");
        IMnl = atof(prmstr);
    }
    else
    {
        strcpy(prmstr, strtok(strbuf, " ");
        G[channel] = atof(prmstr);
        strcpy(prmstr, strtok(NULL, " ");
        gain[channel] = atof(prmstr);
        channel++;
    }
    line++;
}

/* Print output file heading */
fprintf(calfp,"Calibrated Soil%d: \n", image);
fprintf(uncalfp,"Uncalibrated Soil%d: \n", image);

/* Create the output image*/
IMcreate(Ochan, AZ(Oname[0]), IMmPreRead, IMdtReal, IMns, IMnl,
    numchannels, isw);

for (channel=1; channel<=numchannels; channel++)
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{
/* Read BB image and find average pixel value*/
IMread(lchan[0], buf, dtype, BBss, BBsl, channel+10, 1, BBns, BBnl, 1, isw, 0);
npix = BBns*BBnl;
sum = 0;
for (n = npix, p = buf; n; n--, p++)
    sum += *p;
BB = sum/npix;

/* Read soil sample image and adjust each pixel value*/
IMread(lchan[0], buf, dtype, IMss, IMsl, channel+10, 1, IMns, IMnl, 1, isw, 0);
npix = IMns*IMnl;
sum = 0;
for (n = npix, p = buf; n; n--, p++)
    sum += *p;
IM = sum/npix;

/* Print uncalibrated spectrum */
fprintf(uncalfp,"%d %d
",channel, (int) IM);

/* Calibrate */
caliM = G[channel] * (IM - BB) * (255 - gain[channel]) / bw[channel];
for (n = npix, realp = realbuf; n; n--, realp++)
    *realp = caliM;

/* Print calibrated spectrum */
fprintf(calfp,"%d %f
",channel, caliM);

/* Write out new image */
IMwrite(Ochan[0], realbuf, IMdtReal, 1, 1, channel, 1, IMns, IMnl, 1, isw, 0);

}/* Close image files and free up memory */
IMclose(lchan[0]);
IMclose(Ochan[0]);

fprintf(calfp,"\n\n");
fprintf(uncalfp,"\n\n");
fclose(calfp);
fclose(uncalfp);
fclose(prmfp);

MEMfree(buf);
MEMfree(realbuf);
}