SPECTRAL PROPERTIES OF SOIL AND LAG OVERLYING THE SITE OF THE BEASLEY CREEK GOLD MINE, LAVERTON REGION, WESTERN AUSTRALIA

Volume I

T.J. Cudahy, I.D.M. Robertson and A.R. Gabell

CRC LEME OPEN FILE REPORT 69

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RESEARCH ARISING FROM CSIRO/AMIRA REGOLITH GEOCHEMISTRY PROJECTS 1987-1993

In 1987, CSIRO commenced a series of multi-client research projects in regolith geology and geochemistry which were sponsored by companies in the Australian mining industry, through the Australian Mineral Industries Research Association Limited (AMIRA). The initial research program, "Exploration for concealed gold deposits, Yilgarn Block, Western Australia" (1987-1993) had the aim of developing improved geological, geochemical and geophysical methods for mineral exploration that would facilitate the location of blind, buried or deeply weathered gold deposits. The program included the following projects:

P240: Laterite geochemistry for detecting concealed mineral deposits (1987-1991). Leader: Dr R.E. Smith. Its scope was development of methods for sampling and interpretation of multi-element laterite geochemistry data and application of multi-element techniques to gold and polymetallic mineral exploration in weathered terrain. The project emphasised viewing laterite geochemical dispersion patterns in their regolith-landform context at local and district scales. It was supported by 30 companies.

P241: Gold and associated elements in the regolith - dispersion processes and implications for exploration (1987-1991). Leader: Dr C.R.M. Butt. The project investigated the distribution of ore and indicator elements in the regolith. It included studies of the mineralogical and geochemical characteristics of weathered ore deposits and wall rocks, and the chemical controls on element dispersion and concentration during regolith evolution. This was to increase the effectiveness of geochemical exploration in weathered terrain through improved understanding of weathering processes. It was supported by 26 companies.

These projects represented "an opportunity for the mineral industry to participate in a multi-disciplinary program of geoscience research aimed at developing new geological, geochemical and geophysical methods for exploration in deeply weathered Archaean terrains". This initiative recognised the unique opportunities, created by exploration and open-cut mining, to conduct detailed studies of the weathered zone, with particular emphasis on the near-surface expression of gold mineralisation. The skills of existing and specially recruited research staff from the Floreat Park and North Ryde laboratories (of the then Divisions of Minerals and Geochemistry, and Mineral Physics and Mineralogy, subsequently Exploration Geoscience and later Exploration and Mining) were integrated to form a task force with expertise in geology, mineralogy, geochemistry and geophysics. Several staff participated in more than one project. Following completion of the original projects, two continuation projects were developed.

P240A: Geochemical exploration in complex lateritic environments of the Yilgarn Craton, Western Australia (1991-1993). Leaders: Drs R.E. Smith and R.R. Anand. The approach of viewing geochemical dispersion within a well-controlled and well-understood regolith-landform and bedrock framework at detailed and district scales continued. In this extension, focus was particularly on areas of transported cover and on more complex lateritic environments typified by the Kalgoorlie regional study. This was supported by 17 companies.

P241A: Gold and associated elements in the regolith - dispersion processes and implications for exploration. Leader: Dr. C.R.M. Butt. The significance of gold mobilisation under present-day conditions, particularly the important relationship with pedogenic carbonate, was investigated further. In addition, attention was focussed on the recognition of primary lithologies from their weathered equivalents. This project was supported by 14 companies.

Although the confidentiality periods of the research reports have expired, the last in December 1994, they have not been made public until now. Publishing the reports through the CRC LEME Report Series is seen as an appropriate means of doing this. By making available the results of the research and the authors' interpretations, it is hoped that the reports will provide source data for future research and be useful for teaching. CRC LEME acknowledges the Australian Mineral Industries Research Association and CSIRO Division of Exploration and Mining for authorisation to publish these reports. It is intended that publication of the reports will be a substantial additional factor in transferring technology to aid the Australian Mineral Industry.

This report (CRC LEME Open File Report 69) is a Second impression (second printing) of CSIRO, Division of Exploration Geoscience Restricted Report 160R, first issued in 1992, which formed part of the CSIRO/AMIRA Projects P243, P240A and P241A.

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Colour aerial photograph of the Beasley Creek area prior to mining. The dark colours of the lag covered hill and the bright patches of calcrete are prominent. The sample traverses and the outline of the pit are shown. Approximate scale 1: 13 400. Photo by Kevron Aerial Surveys, published by permission of METEX Resources NL.
PROJECT LEADERS PREFACE

The CSIRO-AMIRA Research Program "Exploration for Concealed Gold Deposits, Yilgarn Craton, Western Australia" has, as its overall aim, the development of improved geological, geochemical and geophysical methods for mineral exploration, that will facilitate the location of blind, concealed, or deeply weathered gold deposits. The research has been undertaken by three modules - Laterite Geochemistry (AMIRA Project P240), Weathering Processes (AMIRA Project P241) and Remote Sensing (AMIRA Project P243).

The Remote Sensing Project's primary aim is to develop, evaluate and demonstrate new remote sensing techniques, tailored to exploration in the deeply weathered terrains of Western Australia. An important part of this strategy is understanding the spectral characteristics of natural materials. These spectra are needed for the selection, processing and interpretation of remotely sensed data. To address this problem, several studies have examined the spectral behaviour of a wide range of regolith materials, including weathered gold alteration systems and unmineralised geology (reports 160R, 169R, 234R, 235R, 240R and 244R). These spectral studies have generally proceeded in conjunction with various mineralogical and geochemical investigations by Gold Project P240 and P241 scientists so that relationships have been established between spectral reflectance and mineralogical/geochemical/physical information. This study details the results from one of these collaborative investigations for the Beasley Creek gold deposit and explains the relationships in terms of the regolith model described in P243 report 243R.

A.R. Gabell
Project Leader

September, 1992
SUMMARY

Gold exploration, using spectral remote sensing in the Yilgarn Craton, is difficult for at least two reasons. Firstly, very deep weathering has changed the complex fresh rock mineralogy to a surface mantle, largely consisting of ferric oxides, clays and quartz. Secondly, there is little detailed knowledge of the reflectance properties of these weathered surface materials, of very variable crystallinity, overlying gold mineralisation and in background areas. To address these problems, some of the studies in the P243 project have concentrated on the measurement and analysis of 0.4 to 2.5 \( \mu \text{m} \) reflectance spectra of a large range of regolith materials overlying gold deposits at Beasley Creek (this study), Bounty (in the Forrestania region, report 169R) and Panglo (in the Ora Banda region, report 234R). Background areas have included studies at Laverton (report 235R), Lawlers (report 240R) and Ora Banda.

The Beasley Creek gold mine is located in the Laverton area, north-eastern Yilgarn Craton. Before disturbance of the ground by open-pit mining, the Beasley Creek gold deposit was situated under the crest of a small, 3.5 m high rise. Gold mineralisation was related to deeply weathered carbonateous shale and chert rocks, within an Archaean greenstone sequence. Laboratory reflectance spectra were measured of surface samples collected from two east-west traverses across gold mineralisation and extending into background areas. The samples comprised soil and ferruginous lag overlying subcropping lateritic duricrust, exposed saprolite and mottled zone.

The spectral results show no evidence for sericite or other primary minerals related to the original fresh rock. Instead, the spectra show information related to the products of weathering, namely, ferric oxides (hematite and goethite) and kaolinite.

The spectra of the coarser, ferruginous lag (10-50 mm diameter) show variations in the wavelengths of the ligand-metal charge transfer shoulder, near 0.6 \( \mu \text{m} \), and the iron crystal field absorption minima, near 0.9 \( \mu \text{m} \), indicating hematite or goethite. The relative changes in the wavelength of these parameters are invariant over broad zones (>500 m wide), consistent with hematite-goethite relationships measured by XRD and spatially related to particular, exposed, lateritic units. The goethitic lag is located over saprolite and mottled zone and is interpreted to be the residual product of deflation of the upper, lateritic horizons. The hematitic lag is located over lateritic duricrust.

The soil shows a relatively consistent spectral mineralogy comprising hematite and poorly crystalline kaolinite. The poor kaolinite crystallinity is indicated by the weakly developed absorption doublets at 1.4 and 2.2 \( \mu \text{m} \). Within a 100m wide zone, over gold mineralisation, there is an 8 nm shift to shorter wavelengths of the charge transfer shoulder, indicating slightly more goethite-rich soil. This shift in wavelength is much less than that shown by the coarse lag.

The soil and lag data indicate a weak relationship between gold and the wavelength of the charge transfer shoulder. This relationship shows that the weathered materials, with more gold, are relatively goethite-rich though, there are too few data to consider this result as significant.
The associated P240/P241 investigations noted an increase in the overall abundance of iron-rich lag in the vicinity of gold mineralisation. The increase in the total ferric iron content of the soil and lag was examined, using the depth of the crystal field absorption near 0.9 μm. This spectral parameter showed weak correlation with the Fe₂O₃ content but no relationship to areas of gold mineralisation. However, this does not preclude gold being associated with higher ferric iron content at the surface. An increased amount of ferruginous lag at the surface will increase the total iron content, especially in the context of remote sensing applications.

According to a regolith model (report 243R), passage from saprolite and mottled zone to lateritic duricrust is hypothetically associated with a decrease in the abundance of clays. This relationship was tested for the soil developed over these particular units, using the depth of the AlOH-related 2.2 μm absorption. The depth of the 2.2 μm absorption was found to correlate with the Al₂O₃ content of the soil but there was poor correlation with the position in the regolith. The results showed soil mantling saprolite and mottled zone has relatively shallow 2.2 μm absorptions (lower clay abundances) compared to the soil covering lateritic duricrust. It is suggested that this anomaly is caused by increased winnowing of the soils, overlying saprolite and mottled zone on the western-side of the low rise, by the prevailing winds.

The associated P240/P241 studies found that powdery carbonates occur as patches within the soil. However, spectral examination of carbonate-rich soil showed no evidence of the diagnostic carbonate absorption at 2.33 μm, even though scanning electron microscope examinations showed calcium-rich particles were well exposed at the surface of the soil minerals. A related P243 study (report 169R) discovered more than 40% by weight of sub-75 μm carbonate powder was required in a soil before carbonates were spectrally recognisable. This is much greater than the maximum carbonate content of the Beasley Creek soil. The only indication of carbonate in the spectra was an increase in the albedo, particularly the visible brightness.

Spectral analysis of the depth, width and wavelength of the 1.9 μm, water-related absorption, can provide information about the content and site (free, adsorbed, trapped) of water molecules. The soil shows two distinct populations of 1.9 μm absorptions, one associated with free water (driven off after heating to 100°C), and the other associated with water trapped in quartz as fluid inclusions (unrelated to gold mineralisation).

The coarse, ferruginous lag commonly shows an upward ramp in reflectance from 0.9 and 1.3 μm which can dominate spectral properties in this region and will influence the geometry of the ferric iron absorption at 0.9 μm. Another P243 study (report 244R) found the intensity of this feature is correlated with the depth and width of the 1.9 μm absorption and suggested this water is either adsorbed on the surfaces of the iron oxide crystals, by hydrogen bonding, or is intimately associated with silica and iron oxide and formed after lateritisation (report 243R). This spectral property may be associated with the affects of desert varnish, though the underlying rock mineralogy is clearly evident in the spectra (for example, the hematite-goethite ratio).
The spectral results show that the soil and ferruginous lag overlying the Beasley Creek gold mineralisation are not mineralogically distinct from the background materials. An increased development of goethite (shorter wavelength charge transfer shoulder) appears to be associated with gold at Beasley Creek but goethite is pervasively developed in varying abundances throughout the regolith. Therefore, the significance of ferric oxide development to gold mineralisation needs to be further evaluated, especially in the context of the regolith. The spectral results appear to be useful for the regolith characterisation of the soil and lag and so could be used to help classify regolith materials to assist geochemical gold exploration.
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1.0 INTRODUCTION

Gold exploration in the Yilgarn Craton, using remote sensing techniques, is made difficult by the deep weathering of the regolith and the few detailed spectral studies on weathered materials from this environment. To address this problem, a significant portion of the P243 research has concentrated on determining the 0.4 to 2.5 $\mu$m reflectance properties of weathered materials that overlie gold deposits and background areas. This wavelength region provides information on two of the major weathering products, namely, the iron oxides and clays, and is covered by a variety of airborne and space-borne remote sensing systems. These remote sensing systems are available, or soon to be available, to the exploration industry and include Landsat Thematic Mapper, Daedalus Airborne Thematic Mapper, Geoscan Mk I and II and JERS-1. Therefore, understanding the reflectance characteristics of the weathered surface materials at high resolution would help evaluate the utility of these remote sensing systems for gold exploration in the deeply weathered mantle of the Yilgarn Craton.

High-resolution spectral studies of Yilgarn gold deposits have been completed for Beasley Creek, in the Laverton area (this study), Bounty, in the Forrestania area (Cudahy and others, 1992a) and Panglo, in the Ora Banda area (Cudahy and others, 1992b). Unlike most Yilgarn gold deposits, the surface environments of these deposits were undisturbed by mining activity at the time of sample collection, so the results of these studies can be applied confidently to remote sensing strategies which map only the surface characteristics. The background spectral investigations have been at Laverton (Cudahy, 1992b), Lawlers (Gozzard and Tapley, 1992) and Ora Banda (Hunter and others, in preparation).

Some of these spectral studies have been in association with Gold Project P240 and P241 mineralogical and geochemical investigations, generally using the same samples (for example, Robertson, 1989; 1990). This has allowed a direct comparison between spectral information and other analytical data. These comparisons have been supported by laboratory experiments aimed at establishing quantitative relationships between reflectance behaviour and physicochemistry (mineralogy, geochemistry and physical morphology) (Cudahy, 1992c; Cudahy and others, 1992a).

These field and laboratory studies, together with published information, have been incorporated into an empirical model, relating spectral-physicochemical properties to regolith characteristics and processes of the eastern Yilgarn Craton (Cudahy, 1992a). This model provides a mechanism by which unexpected spectral information can be isolated and enhanced as these may provide potential targets for gold exploration.

This study examines the 0.4 to 2.5 $\mu$m properties of the weathered surface materials of the Beasley Creek gold deposit and compares this information with the other physicochemical data, spectral-physicochemical relationships and regolith model. This will determine if reflectance information, associated with the Beasley Creek deposit, can be used in a quantitative and thematic way by explorationists for finding similar styles of gold mineralisation.
2.0 OBJECTIVES

The main objectives of this study were:

1. To investigate whether spectral techniques can be used to identify minerals related to gold mineralisation; and

2. To determine the relationships between spectral information and physicochemical characteristics of the regolith.

3.0 LOCATION, GEOLOGY AND GEOMORPHOLOGY

The Beasley Creek gold deposit is located approximately 10 km west-north-west of Laverton, in the north-eastern part of the Yilgarn Craton (Figure 1). The vegetation is sparse and the climate is semi-arid (Gower, 1976).

The geology of the Laverton region has been mapped at 1:250 000 scale by Gower (1976) and at 1:50 000 scale by Hallberg (1982, 1983) (Figure 1). The oldest rocks are Archaean in age and include:

1. Ultramafic rocks - komatiite, peridotite and dunite;

2. Mafic rocks - basalt, high-Mg basalt, dolerite, gabbro and norite;

3. Felsic rocks - dacite, rhyolite, andesite, granodiorite and syenite; and

4. Sedimentary rocks - chert, BIF, shales, siltstones, sandstones and conglomerates of felsic and mafic origin.

All the Archaean rocks have been metamorphosed such that the prefix "meta" is implied but not used in this report. Regional metamorphism reached greenschist facies with higher grades in the contact aureoles of some granitic plutons. Hydrothermal alteration was localised along brittle-ductile structures, and in places, introduced gold mineralisation (Hallberg, 1983).

The Yilgarn regolith is the product of prolonged weathering over a very long period possibly since the Permian (Butt, 1982). During the Oligocene-Miocene, the climate was humid, causing deep lateritic weathering (Kemp, 1978). This humid period turned to one of aridity which has continued to the present (Kemp, 1978). The regolith has been further modified by erosion, deposition and pedogenesis.

In the Laverton region, much of the original lateritic duricrust has been eroded. Saprock is well exposed, especially for the more resistant units, such as chert, which forms prominent strike ridges. In some places, the ferruginous mottled zone forms a resistant capping to erosion producing breakaway-like topography.
Figure 1: (a) Map of the granite-greenstone belts of the Yilgarn Craton and the location of Laverton study area; and (b) Regional geology of the Beasley Creek area (after Hallberg, 1982).
Figure 2:  (a) Geology of the Beasley Creek gold deposit (after WMC plan BCG/50/1); and (b) Cross-sections of the regolith and geology for the two traverses A-A' (38820 mN) and B-B' (38490 mN) (after Robertson and Churchward, 1989).
The geology of the deposit (Figures 2a and 2b) has been mapped by Western Mining Corporation and comprises an Archaean greenstone sequence of basalts, shales, cherts and talc-carbonate schists. These have been locally intruded by felsic and dolerite dykes. A granitic pluton is located less than 1 km to the north (Figure 1b). A set of northeast-southwest trending and steeply dipping faults offset the stratigraphy. Gold mineralisation is largely restricted to a unit of black shales and cherts. Remnants of Permian glacialis are located to the east of the gold deposit (Figure 2).

The gold deposit, prior to open-pit mining, was located beneath the crest a 3.5 m high rise (Figures 2, 3c and 3d), surrounded by low-lying wash plains. The depth of weathering extends to over 230 m within the mineralised zone but is much shallower (40 m) over the surrounding country rocks (Robertson, 1991). The laterite profile has been dissected with saprolite exposed on the western-side of the rise and remnants of lateric duricrust preserved on the crest and eastern-side of the rise (Figure 2b). Plate 1 shows exposed lateritic duricrust and Plate 2 shows ferruginous lag over the area of gold mineralisation (both photographs were taken prior to mining).

Figure 3: Variations in the soil pH, topography and soil depth across the two traverses, 38820 mN and 38940 mN (after Robertson, 1990).
Figure 4: Surface distribution of calcite (a), quartz (b), ferruginous coarse lag (c) and khaki lag (d) over the study area (after Robertson and Churchward, 1989).
Plate 1: Lateritic duricrust exposed in a shallow quarry on the eastern side of the low rise at Beasley Creek.

Plate 2: Ferruginous lag overlying the zone of gold mineralisation.
Calcrete (Figure 4a), quartz (Figure 4b) and ferruginous lag (Figures 4c and 4d) are distributed in varying abundances over the rise. No saprock float is evident at the surface. The lag represents an accumulation of larger fragments, after deflation of finer-grained materials by wind and water. Ferruginous gravels represent the most common type of lag. The coarsest ferruginous lag (10-50 mm in diameter) appears to be most abundant on the crest of the hill but these represent 10% or less of the total surface material. Coarse quartz lag appears to be dispersed around small quartz veins, unrelated to gold mineralisation (Robertson, 1989).

Red, friable, clay soil mantles the rise to a depth of 0.5-1.0 m - the thinnest soil is developed over the top of the rise (Figures 3e and 4f). The composition of the coarser soil fraction (greater than 710 \( \mu \)m) is similar to the fine lag, both are largely derived from the underlying parent materials (Robertson, 1990). The intermediate soil fraction (75-710 \( \mu \)m) consists of hematite coated, wind-blown, quartz sand, with minor grains of feldspar and small ferruginous granules (Robertson, 1990). The finest soil fraction (less than 75 \( \mu \)m) consists of quartz grains and smaller kaolinite and iron oxide particles (less than 1 \( \mu \)m) largely derived from the underlying parent materials (Robertson, 1990).

4.0 FUNDAMENTALS OF SPECTRAL PROPERTIES

Many of the reflectance characteristics of geological materials in the 0.4 \( \mu \)m and 2.5 \( \mu \)m wavelength region result from electronic/vibrational atomic/molecular processes and scattering affects. Electronic processes generally involve the movement of electrons associated with transition metals, such as iron, and produce relatively broad absorptions at wavelengths shorter than 1.2 \( \mu \)m (Hunt and others, 1971). Vibrational processes relate to the bending, rotation or stretching of particular anion-cation pairs, such as Al-OH, Mg-OH and H-O-H (Figure 5), and produce narrow absorptions at wavelengths greater than 1.2 \( \mu \)m. Scattering affects are generally related to the size of the scattering centres, such as individual crystals (Morris and others, 1985), or collections of crystals joined together as larger particles (Hunt and others, 1971). Scattering can cause changes in the depth and the wavelength of absorptions and the albedo.

![Diagram](attachment:image.png)

Figure 5: Schematic representation of the bending and stretching vibrations of water molecules (after Bishop, 1988).
Figure 6. Reflectance spectra of various minerals with the key absorptions indicated (from the CSIRO Remote Sensing Pure Mineral Library).
Two major products of weathering, iron oxides and clays, have characteristic spectral features in the 0.4 to 2.5 μm wavelength region. Quartz, the other major weathering product, does not have characteristic spectral properties in this wavelength region but there are diagnostic characteristics for quartz in the mid-infrared (9-14 μm) (Salisbury and D’Aria, in press). The iron oxides, hematite (αFe₂O₃) and goethite (αFeO(OH)), possess iron-related electronic absorptions (Hunt and others, 1971) near 0.5, 0.66 and 0.9 μm (Figures 6a and 6b). Cudahy (1992c) used the wavelengths of these features to approximate the hematite-goethite ratio and the depth of the 0.9 μm absorption to approximate the ferric oxide content. The clays (kaolinite, smectite and illite) have vibrational absorptions in the 1 to 2.5 μm wavelength region (Figures 6c, 6d and 6e), related to overtones or combination tones of fundamental stretches (ν) or bends (δ) of the Al-OH molecule, that occur in the 2.7 μm wavelength region. For example, kaolinite (Figure 6c) has overtone or combination tone absorptions at 1.394, 1.403, 1.413 (all related to 2νOH), 1.829 μm (νOH+2δOH), 2.167 μm (νOH+δOH), 2.207 μm (νOH+δOH), 2.32 μm (νOH+δOH) and 2.387 μm (νAl-O+νOH).

5.0 SAMPLING AND SAMPLE PREPARATION

The samples for spectral measurement were collected in November, 1987 by Robertson and Churchward (1989) along two east-west traverses, spanning the ore zone and extending into background areas. The location of these samples are shown in Figure 7. The sample spacing ranged from 25 to 100 m, with closer spacing located over the ore zone.

The coarse, generally ferruginous, lag (10-50 mm in diameter) was hand-picked whereas all the fine lag was swept into a sample bag without selection. The soil was sampled by discarding the top 25 mm (to avoid any contamination from exploration activity) and the underlying 150-250 mm of unconsolidated material was bagged.

The fine lag was further processed by wet sieving to retain the 0.2-4.0 mm fraction and remove the dust from exploration drilling. Thus, two groups of lag material were available for spectral analysis:

1. Coarse lag comprising ferruginous lag 10-50 mm in diameter; and

2. Fine lag comprising ferruginous and other lithic and mineral fragments 0.2-4 mm in diameter.

Preparation of the soil involved a few samples and comprised:

1. Drying the soils for up to 2 days at 100°C;

2. The addition of 0.1 M HCl to remove carbonate and iron oxide coatings from quartz grains;
3. Hand separation of quartz grains from ferruginous and lithic grains (710-2000 μm fraction); and

4. Sieving the soils to separate the 2000-710 μm, 710-500 μm, 500-250 μm, 250-142 μm, 142-75 μm and <75 μm fractions followed by ultrasonic cleaning (Robertson, 1989).

Figure 7: Map showing the location of the sample sites (after Robertson and Churchward, 1989).
6.0 REFLECTANCE MEASUREMENT AND PROCESSING

6.1 Spectrometer

Reflectance spectra of the soil and lag samples were measured using an "Infrared Intelligent Spectrometer" (IRIS) manufactured by Geophysical Environmental Research Limited (GER). The IRIS measures 875 separate channels between 0.35 and 3.0 μm. The sampling intervals are approximately 0.002 μm (2 nm) over the 0.35-1.0 μm region, 0.004 μm (4 nm) over the 1.0-1.8 μm region and 0.005 μm (5 nm) over the 1.8-3.0 μm region. The spectral resolution is approximately 0.010-0.012 μm (10-12 nm) in the 2.0 to 2.5 μm region.

The IRIS is a dual-beam instrument which simultaneously measures both the target and a reference. This reduces the effects of instrument drift and variations in lighting and humidity. Three diffraction gratings, mounted on a motor-driven axis, disperse the light into its different wavelengths. Silicon detectors measure the first (shorter wavelength) 460 channels and lead sulphide detectors measure the remaining channels.

Barium sulphate or Spectralon (halon or PTFE) plates were used as reflectance standards. A quartz-halogen photoflood lamp provided the illumination, angled approximately 20° to the vertical and positioned 800 mm from the target or reference. The target and reference plates were located approximately 400 mm from the IRIS optical head, such that the area viewed by the sensor was approximately 20 by 40 mm. The soil and lag samples were presented to the IRIS in washed, glass petri dishes.

6.2 Spectral Processing

Each spectrum was assigned a unique 9 character code, describing all the attributes for that measurement (Appendix 1). The reflectance data were processed using CSIRO's PCSpectra software, where the wavelength, symmetry and depth of absorptions were measured, to provide information about the mineralogy, abundance and crystallinity of minerals. In addition to reflectance spectra, hull quotient curves (HQ) were also investigated because this technique enhances absorptions (Green and Craig, 1985). Ratios of reflectances were also determined, to measure the relative depths of absorptions and changes in the wavelength of spectral characteristics. However, ratio information can be affected by changes in albedo (Cudahy, 1992c) and so they were used with caution.

6.3 Spectral Error and Other Difficulties

The errors involved in the spectral data were evaluated by performing multiple measurements (five times each) of representative samples. The sample was either rearranged or stirred before each measurement. The differences between the maximum and minimum values for each sample (ranges) were then used as an approximation for the within-sample variance. This range is presented as a bar in many of the graphs.
A major difference in relating reflectance information to other analytical data is knowing what part of the sample has been measured. For example, spectral reflectance and scanning electron microscope (SEM) techniques measure the outer few microns of a material (surface) whereas techniques such as X-Ray diffraction (XRD), inductively coupled plasma (ICP) and X-ray fluorescence (XRF) measure a bulk property (volume). No compensation can be made for this difference.

Any two variables were considered to be correlated if the resultant correlation coefficient \((r^2)\) exceeded the 99% confidence level for the number of samples used in the analysis (assuming gaussian distribution).

7.0 RESULTS

In total, approximately 150 laboratory reflectance measurements were made of coarse lag (Appendix 2.1), fine lag (Appendix 2.2), soil (Appendix 2.3), khaki lag (Appendix 2.4) and soil fractions (Appendix 2.4). The khaki lag are not considered in detail here because they were very restricted in their distribution (Figure 4d). Some of the general properties of the spectra are described first, then details of the relationships between spectral features and physicochemical information are described later.

The coarse lag spectra (Figures 8a and 8b) show the largest variation (sample and data set) in shape and albedo, particularly in the wavelength region beyond 1.0 \(\mu m\). Some of the coarse lag spectra show absorptions at 1.4, 1.9 and 2.2. \(\mu m\) (for example, ABLAAA.707 and ABLAAA.033 in Appendix 2.1) whereas other samples are featureless (for example ABLAAA.701 and ABLAAA.028 in Appendix 2.1). This spectral heterogeneity even occurs between individual ferruginous clasts from the same locality. This appears to be more pronounced for areas of exposed saprolite and mottled zone (Figure 9a), compared to areas of lateritic duricrust (Figure 9b). This spectral heterogeneity is, in part, influenced by the large size of individual clasts, some of which almost fill the entire field of view of the IRIS spectrometer.

In contrast, the fine lag spectra (Figures 8c and 8d) show lesser albedo, consistent in geometry and wavelength of absorptions and a very small within-site variation (Figures 9c and 9d). This relatively homogeneous spectral behaviour is probably a function of the finer particles (many fragments fill the field of view of the IRIS) and the nature of the material (mixtures of ferruginous, quartzose, carbonate and clay-rich fragments). There appear to be no differences between the spectra of the fine lag from over the exposed saprolite and mottled zone and the fine lag from over the lateritic duricrust.

The soil spectra (Figure 8e and 8f) show consistent shapes of their reflectance curves and absorptions. The soil shows a greater albedo compared to that of the fine lag, especially carbonate-rich soil (for example ABLSAA.429 and ABLSAA.430 in Appendix 2.3). The within-site variation of "whole" soil is small (Figures 9e and 9f) but there is a large
Figure 8: Composite reflectance spectra of the coarse lag, fine lag and soil samples.
Figure 9: Composite plots of several reflectance spectra taken from the same samples after stirring to show the spectral variation at any one site.
Figure 10: Spectra of whole soils and their various sieved fractions. The fractions are labelled 75 (<75 µm), 142 (75-142 µm), 250 (143-250 µm), 500 (251-500 µm), 710 (501-710 µm) and 2000 (711-2000 µm).
spectral variation among its different size fractions (Figure 10). This pronounced variation results from changes in the relative abundances of iron oxides, kaolinite, quartz and carbonate. Clay is concentrated in the finer soil fractions (less than 75 μm) and shows as deeper 2.2 μm absorptions. This fine soil fraction generally has longer wavelengths to its 0.9 μm crystal field absorption, indicating relative enrichment in goethite, especially on the eastern-end of the sample traverse (implications for this relationship are discussed in Section 8.1). On the basis of the depth and wavelength of the iron oxide absorptions at 0.9 μm (Cudahy, 1992c), the 75-142 μm fractions have the lowest iron oxide contents and are the most hematite-rich whereas the 710-2000 μm fractions have the highest iron oxide contents and are richer in goethite.

Spectrally, there appear to be three soil components:

1. A coarse-grained, goethite- and iron-rich but clay-poor fraction;

2. A medium grained, relatively hematite-rich but iron-poor fraction; and

3. A fine-grained, relatively goethite-rich and clay-rich but iron oxide-poor fraction.

These results are consistent with the petrographic observations of Robertson (1990) who found the medium-grained fraction consisted of hematite-coated aeolian quartz (and minor feldspar) sand, with the clay-rich, finer and iron oxide-rich, coarser fractions derived from the underlying material (Section 3.0).

7.1 Primary Minerals

The presence of "indicator" mineral absorptions for gold alteration were sought for in the reflectance spectra. This included absorptions related to the potassic micas (muscovite, sericite, illite), which are common alteration products in many mesothermal gold deposits of the Yilgarn Craton (Groves and others, 1985; Clarke and others, 1988). Micas were found by XRD in the soils overlying gold mineralisation at Beasley Creek (Robertson, 1990), although they were not regarded as from an alteration halo but from the metamorphosed, argillaceous rocks.

Potassic micas generally have a single absorption at 2.2 μm, a relatively shallow 1.9 μm water absorption and the minor development of absorptions at 2.35 and 2.45 μm (Figures 6e and 6f). The whole-soil reflectance spectra (Appendix 2.3) revealed no evidence for these absorptions, especially in the soils located over gold mineralisation (for example, ABLSAA.411, ABLSAA.430). In a related P243 study, Cudahy and others (1992b) found the K-mica content must be greater than 15% by weight of the total sample before the 2.35 μm absorption becomes apparent in the reflectance spectrum. This concentration is much greater than the K-mica content of these samples.
Small concentrations of K-mica may affect the geometry of the Al-OH absorption at 2.2 μm, especially if only one other AlOH-bearing mineral is present in the sample (Hauff and others, 1990). The geometry of the 2.2 μm absorption was tested, using a ratio of reflectances at 2.160 and 2.232 μm; higher 2.160/2.232 μm ratios should, theoretically, relate to increased proportions of sericite. Figure 11 shows this ratio versus a ratio of the XRD measurements of the relative abundances of sericite and kaolinite (Robertson, 1990). There is poor correlation with most of the results antithetic to the depth of the 2.2 μm absorption (Section 7.3). To remove this problem, the ratios were normalised to the depth of the 2.2 μm absorption. Though the results show that the affects of the 2.2 μm absorption have been removed (Figure 12), there is still no improved correlation with the XRD data. Therefore, sericite is not apparent in the soil reflectance data.

Figure 11: A comparison of the reflectance ratio 2.160μm/2.232μm (sensitive to the geometry of the 2.2 μm Al-OH absorption) and the XRD sericite/kaolinite ratio for the two traverses for soil samples. The location of the ore zone is indicated by a small box.
Figure 12: A comparison of the reflectance ratio $2.160\mu m/2.232\mu m/2.204\mu m$ (sensitive to the geometry of the 2.2 $\mu m$ Al-OH absorption and normalised with the depth of the 2.2 $\mu m$ absorption) and the XRD sericite/kaolinite ratio for the two traverses for the soil samples. The location of the ore zone is indicated by a small box.

The reflectance data show no evidence for Fe$^{2+}$ absorption at 1.1 $\mu m$ or Mg-OH absorptions in the 2.3 $\mu m$ region which indicates that no other primary minerals (such as amphibole), either associated with gold mineralisation or with the sedimentary, mafic and ultramafic rocks, are present.

7.2 Iron Oxides

This section examines, in greater detail, the reflectance data for iron oxides, including the hematite-goethite ratio, ferric oxide abundance and the degree of Al$^{3+}$ substitution in the lattices of the iron oxides.
Figure 13: Reflectance ratios $0.61\mu m/0.59\mu m$ (sensitive to the wavelength of the charge transfer shoulder) and $0.90\mu m/0.93\mu m$ (sensitive to the wavelength of the 0.9 crystal field absorption minima) for the two traverses for the fine lag, coarse lag and soil data. The interpreted zones of goethite have been annotated. The location of the ore zone is indicated by a small box.
The changes in the proportion of hematite to goethite were investigated using the wavelengths of the charge transfer shoulder near 0.6 μm and the crystal field absorption minima near 0.9 μm (Cudahy, 1992c). The wavelengths of these were either determined visually, from the reflectance and hull quotient spectra, or approximated, using ratios of reflectances at 0.61 with 0.59 μm and 0.90 with 0.93 μm; high values for the 0.61/0.59 ratio are related to more hematite-rich and high values for the 0.90/0.93 ratio are related to more goethite-rich materials. A comparison of the results, using these two techniques, showed similar variations in the hematite/goethite ratio.

The ratios are plotted for the coarse lag, fine lag and soil along the two traverses in Figure 13. The best separation is provided by the charge transfer shoulder, which consistently shows "goethite" over the crest of the rise and ore zone. The variations demonstrated by the coarse lag show broad zones of dominantly hematite or goethite consistent with the XRD results (Appendix 3.1, 3.4, 3.7 and 3.10). This relationship highlights an important but unexpected result. That is, the surface spectral mineralogy of these rocks is similar to their bulk mineralogy in spite of potential problems associated with coatings on nodules including desert varnish (Section 8.1). The soils show small, consistent changes in the wavelengths of the charge transfer shoulder and crystal field absorption, indicating an increased goethite content, within a 150 m wide zone, overlying gold mineralisation (Figures 13e and 13f). These changes are evident in both the reflectance ratios and visual interpretation of the reflectance and hull quotient spectra, but they were not detected by XRD. The shift in the wavelength of the charge transfer shoulder is approximately 8 nm shorter in the gold-related soils than in the background soils (Figure 14). At this stage, the relationship is not statistically significant and so further work is required to establish its consistency.

![Graph showing wavelengths of charge transfer shoulder and crystal field absorption](image)

**Figure 14:** Scattergram of the wavelength of the 0.9 μm crystal field absorption versus the wavelength of the charge transfer shoulder for ore zone-related and background soils.
Figure 15 shows gold content plotted versus the wavelength of the charge transfer shoulder for all samples. This shows significant correlation, the most goethite-rich coarse lag samples contain the highest gold contents and the most hematite-rich soil samples contain the lowest gold contents (Figure 15). However, the correlation between these variables is insignificant if the lag and soil are considered separately; the coarse lag show significant correlation at the 95% confidence level.

The relationship between goethite and carbonate in the soil is not clear. The soil along line 38940 mN shows an association between the wavelength of the charge transfer shoulder and the CaO (presumed carbonate) content (Figure 16b) but the soils along line 38820 mN show no such relationship (Figure 16b).

Figure 15: Scattergram of gold content versus the wavelength of the charge transfer shoulder (all samples).
Figure 16: Scattergram of the reflectance ratio $0.61\mu m/0.59\mu m$ (sensitive to the wavelength of the charge transfer shoulder) versus the CaO content (ICP) for the soils from line 38820 (a) and line 38940 (b). The expected hematite-goethite spectral variation is annotated.
An attempt was made to quantify the hematite-goethite ratio using the relationships established by Cudahy (1992c). The results, which were unsatisfactory, are not presented here. This is a poor result is possibly because of variations in the iron oxide crystal size (Morris and others, 1985), Al-substitution in the iron oxide structure (Buckingham and Sommer, 1983), the presence of other transition elements (Mn$^{2+}$, Fe$^{2+}$) and/or "bound" water (Cudahy, 1992c). Further work is required to understand the quantitative spectral-physicochemical relationships of the iron oxides.

The field mapping by Robertson and Churchward (1989) showed an increase in the abundance of coarse lag and iron segregations over the zone of mineralisation (Figure 4c). This increase may also be expressed in the iron oxide content of the soil or lag. This possibility was tested using a ratio of those reflectances sensitive to the depth of the crystal field absorption near 0.9 $\mu$m (Cudahy, 1992c). The selected wavelengths were from the top of the 0.78 $\mu$m reflectance peak and the base of absorption near 0.9 $\mu$m, with large ratios related to large iron oxide contents. The results show significant correlation with the Fe$_2$O$_3$ abundances for the lag and soil together (Figure 17) but no significant correlation when the soil and lag are considered separately. Neither the reflectance ratio nor the ICP information show an increase in the iron oxide content in either the soil or lag over mineralisation (Figure 18).

![Graph](image-url)

**Figure 17:** Scattergram of the reflectance ratio 0.78$\mu$m/0.90$\mu$m (sensitive to the depth of the 0.9 $\mu$m crystal field absorption) versus the Fe$_2$O$_3$ content (all samples).
Figure 18: Reflectance ratios of 0.78\(\mu\)m/0.90\(\mu\)m (sensitive to the depth of the 0.9 \(\mu\)m crystal field absorption) and the \(\text{Fe}_2\text{O}_3\) contents for the two traverses for the fine lag, coarse lag and soil.
Anand and others (1991) found the degree of Al$^{3+}$ substitution for Fe$^{3+}$ in the iron oxide lattice increased towards the top of the laterite profile. Buckingham and Sommer (1983) found increased Al-substitution shifted the 0.9 μm crystal field absorption for the ferric oxides to longer wavelengths. This relationship was tested for the coarse lag for which Robertson (1989) had estimated the degree of Al-substitution using XRD. However, the results proved inconclusive. This is demonstrated in Table 1, which presents the data for Al-rich and Al-poor hematite and goethite-bearing coarse lag, including their hematite-goethite ratios, percentage of Al-substitution and the wavelength of the 0.9 μm absorption. These data show that the Al-poor and goethite-rich samples ABLAAA.016 and ABLAAA.002 have longer wavelength 0.9 μm absorptions than the Al-rich and goethite-rich samples ABLAAA.030 and ABLAAA.031. The Al-poor and hematite-rich samples ABLAAA.034 and ABLAAA.023 have the same absorption wavelengths compared to the Al-rich and goethite-rich sample ABLAAA.035. These associations are inconsistent with the results of Buckingham and Sommer (1983). This anomaly may be caused by variations associated with "bound" water (Cudahy, 1992c), iron oxide crystal size (Morris and others, 1985), the presence of other transition elements, and the effect of desert varnish.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Hematite/goethite ratio (XRD)</th>
<th>Hematite (XRD) %Al substitution</th>
<th>Goethite (XRD) %Al substitution</th>
<th>0.9 μm crystal field absorption minima (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goethite-rich</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ABLAAA.016</td>
<td>10/57</td>
<td>0</td>
<td>2</td>
<td>0.887</td>
</tr>
<tr>
<td>ABLAAA.002</td>
<td>5/58</td>
<td>0</td>
<td>0</td>
<td>0.880</td>
</tr>
<tr>
<td>ABLAAA.705</td>
<td>8/33</td>
<td>3</td>
<td>1</td>
<td>0.877</td>
</tr>
<tr>
<td>ABLAAA.030</td>
<td>14/53</td>
<td>11</td>
<td>7</td>
<td>0.871</td>
</tr>
<tr>
<td>ABLAAA.031</td>
<td>7/57</td>
<td>10</td>
<td>7</td>
<td>0.877</td>
</tr>
<tr>
<td>Hematite-rich</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ABLAAA.034</td>
<td>18/14</td>
<td>2</td>
<td>9</td>
<td>0.870</td>
</tr>
<tr>
<td>ABLAAA.023</td>
<td>22/26</td>
<td>0</td>
<td>0</td>
<td>0.870</td>
</tr>
<tr>
<td>ABLAAA.708</td>
<td>22/4</td>
<td>12</td>
<td>13</td>
<td>0.877</td>
</tr>
<tr>
<td>ABLAAA.710</td>
<td>15/14</td>
<td>11</td>
<td>9</td>
<td>0.872</td>
</tr>
<tr>
<td>ABLAAA.035</td>
<td>20/16</td>
<td>14</td>
<td>10</td>
<td>0.870</td>
</tr>
</tbody>
</table>

A reflectance characteristic of the coarse lag is a progressive increase in brightness from 0.9 to 1.3 μm (for example ABLAAA.002, ABLAAA.016 and ABLAAA.704 in Appendix 2.1). This increase in brightness is less in the fine lag spectra (Appendix 2.2), is not present in the soil spectra (Appendix 2.3) and is possibly related to "bound" water
(Cudahy, 1992c). There appears to be no relationship between this feature and gold mineralisation. This feature may be related to desert varnish (Section 8.1).

7.3 Clays

This section covers the mineralogical and clay mineral abundances in soil and lag that can be obtained from reflectance data. The reflectance spectra of the coarse lag (Figures 8a and 8b) show a few samples with relatively pronounced 2.2 μm absorption doublets (for example ABLAAAA.029, ABLAAAA.033 and ABLAAAA.707 in Appendix 2.1). These seem to indicate relatively well-crystalline kaolinite and contrast with the fine lag and soil spectra, which show relatively shallow 2.165 μm absorptions, indicating poorly crystalline kaolinite and/or halloysite. XRD and SEM examination found only kaolinite.

Some of the spectra of soil from over the lateritic duricrust show a very weak absorption at 2.24 μm (for example ABLSAA.412 and ABLSAA.415). This could represent "noise" or possibly an Fe-OH or Si-OH vibration (discussed in Section 8.1).

The hull quotient depth of the 2.2 μm absorption could be used to indicate the Al-OH content if the crystal size, particle size and crystal order of the clay minerals remain invariant. The results for all the data show correlation between the 2.2 μm absorption hull quotient depth and the total Al₂O₃ content (Figure 19). The coarse lag data (Figures 20a and 20b) show significant correlation, indicating the surface Al₂O₃

![Graph](https://via.placeholder.com/150)

**Figure 19:** Scattergram of the 2.2 μm hull-quotient depth versus the Al₂O₃ content (all samples).
Figure 20: A comparative plot of the 2.2 μm huu-quotient depths and the Al₂O₃ contents for the two traverses for the fine lag, coarse lag and soil.
contents are similar to the bulk Al₂O₃ contents. The soil data (Figure 20e and 20f) show no correlation, though significant correlation is provided by the sub-four micron "clay" fraction (Figure 21). This suggests the reflectance of the whole soil is dominated by clay-size particles. Buckingham and Sommer (1983) found the depth of penetration of EM radiation through kaolinite powder is approximately 25 μm. A fine coating of clays could easily obscure underlying, larger particles of quartz, iron oxide and carbonate (discussed in Section 7.4).

The hull quotient depths of the 2.2 μm absorption for the soil spectra show changes across the two traverses (Figure 20), indicating variations in the Al₂O₃ content. These include a 200-400 m wide zone of shallow 2.2 μm absorptions for soil covering exposed saprolite and mottled zone on the western side of the low rise (Figure 2b). This is unexpected, as exposed saprolite should be associated with higher abundances of clay (discussed in Section 8.1).

![Graph](image)

**Figure 21:** A comparative plot of the 2.2 μm hull-quotient depths (whole soils) and the Al₂O₃ contents (<4 μm soil fraction) for the two traverses.
7.4 Carbonates

Robertson and Churchward (1989) and Robertson (1990) found powdery carbonate in some of the soils. The presence of carbonate in the soils was first investigated in the spectral data by looking for the characteristic CO$_3$ absorptions at 1.864 µm, 1.939 µm and 2.33 µm (Figure 6h). However, none of these absorptions were found in even the most carbonate-rich samples (Appendix 2.3 AFLSAA.428 and AFLSAA.429).

Thin clay coatings, masking larger carbonate particles, could explain this, so a carbonate-rich soil and carbonate-poor soil were selected for SEM examination to test this hypothesis. A photomicrograph of the carbonate-poor sample (Figure 22a) shows Al-rich particles (<10 µm) covering up to 20% of the surface of Fe-rich particles (150 µm diameter). Similarly, the carbonate-rich soil (Figure 22b) shows large Ca-rich particles (200 µm diameter) spotted by smaller Al-rich particles which cover 10-20% of their surfaces. Therefore, finer Al-rich particles (clays) do not completely obscure the larger, underlying, Fe- and Ca-rich particles (iron oxide and calcite). This was confirmed by bulk SEM analyses, which show Ca to be abundant (Figure 22b). The lack of carbonate absorptions in the soil spectra must have some other cause.

A laboratory experiment, using mixtures of powdered calcite and soil, by Cudahy and others (1992a), determined how much carbonate was required before the characteristic CO$_3^{2-}$ absorption at 2.32 µm became apparent in reflectance spectra. The CO$_3^{2-}$ absorption only became apparent when more than 40% (by weight) of carbonate was present in the sample. This carbonate concentration is much greater than those found at Beasley Creek so explaining the lack of carbonate absorption.

It was also discovered that soil, rich in carbonate, had an increased albedo, especially at visible wavelengths. This is demonstrated in Figure 23 where the reflectance at 0.5 µm is plotted against the CaO concentration. An increase in CaO content from 0 to 4% equates with an increase in the visible brightness from 7 to 14%. This change in brightness is not diagnostic of the carbonate content. An increase in the clay content or a decrease in the iron oxide content could produce a similar affect, though these would also change other parts of the spectrum (Sections 7.2 and 7.3).

7.5 Sulphates

Robertson (1990, 1991) found sulphates and moderate S abundances (up to 0.074% by weight) in the weathered materials over the Beasley Creek gold mineralisation (Appendix 1.33). However, the reflectance spectra of these samples show no evidence for the diagnostic sulphate absorptions near 1.5 and 1.7 µm (Figure 6g). This problem appears to be similar to that of the carbonates, in that there is insufficient concentration of SO$_4^{2-}$ to produce recognisable absorptions.
Figure 22: A scanning electron backscatter image and point microbeam analyses of (a) Fe-rich nodule coated with finer Al-rich particles from a carbonate-poor soil, and (b) assorted Al-, Fe-, Si- and Ca-rich particles from a carbonate-rich soil.
Figure 23: A comparative plot of the reflectance at 0.5 μm and the CaO content (ICP) for the soils along the two traverses.

7.6 Water

The water-related absorption at 1.9 μm was examined because the wavelength and geometry of this absorption reveals information about the environment of the water molecules (free, trapped, adsorbed). For example, water, associated with hygroscopic clays, such as smectite (Figure 6d), produces characteristic absorptions at 1.45 and 1.96 μm, possibly related to hydrogen bonding of the water molecules within the smectite structure (Bishop, 1988).

Most of the free water, within the soil and lag samples, was driven off by heating to 100°C. After this treatment, only two forms of water remained. The first is only apparent in the soil samples and is characterised by relatively deep and narrow 1.9 μm absorptions (Appendix 2.3 ABLSAA.428 and ABLSAA.429). The second is found in the lag spectra and is related to a reflectance ramp between 0.9 and 1.3 μm (Section 7.2; Appendix 2.1 ABLAAA.006 and ABLAAA.703). Several experiments, which are described in Appendix 4, were carried out to determine the nature of the "bound" water in the soils. The results show that these water molecules are trapped within quartz, associated with unmineralised quartz veins, as fluid inclusions. The reflectance ramp, related to the "bound" water in the lag, has been suggested by Cudahy (1992c) to be related with water hydrogen bonded onto the surfaces of iron oxide crystals (Gast and others, 1974) or intimately mixed (trapped) with iron oxide and silica.
8.0 DISCUSSION

The reflectance data provide no evidence for "indicator" mineral absorptions associated with gold mineralisation but give some information about the physicochemical character of the regolith. When interpreted in the context of their position within the regolith, some of these spectral results appear to be anomalous and therefore are worthy of further investigation.

8.1 Regolith Characteristics

The spectral data provide information on the nature of ferric oxides (Section 7.2), clays (Section 7.3), carbonate (Section 7.4) and water (Section 7.5). Much of this information is consistent with the spectral-regolith model proposed by Cudahy (1992a), which relates spectral-physicochemical properties to four regolith processes, namely, lateritisation, aridity, erosion or deposition and pedogenesis. This model includes physicochemical attributes of iron oxide and clay abundances, the hematite-goethite ratio, the degree of Al-substitution in the iron oxide lattice, clay mineralogy, clay crystallinity, Fe-substitution in the kaolinite lattice, carbonate content and the type of water. These physicochemical properties, except for Al-substitution in the iron oxide lattice (Section 7.2), were found to affect the reflectance spectra of the soil and lag overlying the Beasley Creek study area.

The first, and predictable, conclusion that can be made from the spectral data is related to the lack of primary mineral absorptions (Mg-OH, Fe$^{2+}$) which indicates no fresh rock or saprock at the surface. This is consistent with field mapping by Robertson and Churchward (1989) and indicates the surficial materials are intensely weathered and derived from the upper parts of the laterite profile.

The affects of lateritisation are evident in these samples. According to the model (Cudahy, 1992a), lag, located over saprolite/mottled zone, is a residual product after removal and deflation of the upper lateritic units and so should contain hematite and goethite. In contrast, the lag covering lateritic duricrust should contain hematite. The spectral results are consistent are consistent with these relationships (Section 7.2). Clay developed during lateritisation should be well crystalline kaolinite in the saprolite/mottled zone and poorly crystalline kaolinite, with increased iron substitution, in the lateritic duricrust. These relationships are consistent with the spectral data. Some of the coarse lag samples have pronounced 2.2 $\mu$m absorption doublets, indicating well-crystalline kaolinite from deeper in the laterite profile. Soil, covering lateritic duricrust, shows a weak absorption at 2.24 $\mu$m, possibly associated with an Fe-OH vibration in poorly crystalline kaolinite.

According to Cudahy (1992a), a "mature" soil, developed in a semi-arid, well-drained environment, such as that at Beasley Creek, should be characterised by hematite and poorly crystalline kaolinite. The spectral information of the whole soils is consistent with this mineral assemblage, except for the slightly goethite-rich soils over gold
mineralisation. There are several possible explanations for this increased abundance of goethite, including:

1. Low pH (Schwertmann and Murad, 1983), possibly related to the oxidation of sulphides in the mineralisation zone;

2. High pH$_2$O (Voigt and Will, 1981), possibly related to poor drainage (past or present); and/or

3. The soils have a smaller contribution from hematitic, aeolian sand.

There is some evidence to support the third explanation. Robertson (1990) found the coarse- and fine-grained fractions were largely derived from the underlying parent material, whereas the intermediate fractions largely consisted of hematite-coated, wind-blown quartz sand. Section 7.1 showed the coarse- (>710 µm) and fine-grained (<75 µm) grained soil fractions are spectrally goethite-rich relative to the intermediate-grained soil fractions. Therefore, the relatively goethite-rich soils over gold mineralisation may represent a smaller contribution of aeolian sand. This hypothesis is consistent with the occurrence of relatively thin soils on the crest of the rise (Figures 3e and 3f).

Aeolian activity appears to have also affected the abundance of clay in the soil. Section 7.3 showed that soil over saprolite and mottled zone had relatively shallow 2.2 µm absorptions compared to soil over the lateritic duricrust. This is anomalous as the saprolite/mottled zone would be expected to have relatively high clay abundances. This anomaly may be caused by increased aeolian erosion of clay material from the exposed western side of the topographic rise. This hypothesis is supported by the relatively shallower 2.2 µm absorptions (low clay content) and shorter wavelength crystal field absorption minima (hematite-rich) of the <75 µm soil fraction spectra, taken from the western end of line 38820 mN, compared to the <75 µm fractions from the eastern-end of this traverse (Figure 10). This indicates a smaller proportion of goethite-, clay-rich material from the underlying substrate and a greater proportion of hematite-rich, clay-poor aeolian material. This may be explained by aeolian removal of clay-size material and/or the aeolian addition of larger-size material.

In the context of the regolith model (Cudahy, 1992a), these soils over Beasley Creek are "mature" because their mineralogy and mineral abundances bear little relationship to the underlying substrate. This model-based conclusion contradicts the petrographic observations of Robertson (1990) but underlines the major affect of iron oxides and clays on reflectance properties.

Desert varnish is a process, related to arid areas, that can modify surface mineralogy, and hence spectral properties of exposed materials. Lyon (1990) examined desert varnish of lag collected from the Leonora region, 100 km to the west of Laverton. He described desert varnish as a surface coating of poorly crystalline aluminosilicate (possibly allophane) and iron oxide. Although many of the surfaces of lag clasts from Beasley Creek show desert varnish characteristics, including shiny, dark surfaces,
Section 7.2 showed the surface iron oxide mineralogy and clay abundances of the coarse lag are the same as the underlying rock mineralogy. This result is consistent with observations by Gozzard and Tapley (1992) and Anand and others (1991). It suggests that these shiny and generally dark surfaces could either be the product of aeolian polishing (no surface accumulation of minerals), or the varnish is sufficiently thin so as to allow the penetration of EM radiation to the underlying rock. It is unclear whether the development of a reflectance ramp between 0.9 and 1.3 \( \mu m \) (Section 7.2), and the low albedo of many samples, especially of the fine lag (Section 7.1), represents the latter.

8.2 Significance to Gold Exploration

The spectral data do not provide a simple mechanism for finding gold deposits such as Beasley Creek. No indicator mineral absorptions are present and the only anomalous feature, spatially related to gold mineralisation, is the shift in the wavelength of the charge transfer shoulder, indicating more goethite. The cause of this increased goethite in the soils may be related to aeolian action (Section 8.1). The relationship between increased goethite occurrence and gold in the coarse lag is not clear but may be related to changes in pH associated with the weathering of the sulphides in the mineralisation zone. However, it is stressed that goethite is pervasively developed in the weathered environment of the Yilgarn Craton and that this type of spectral information, as with most physicochemical information, should only be considered within the context of the regolith. Further work is required to establish the genesis and importance of iron oxide development in weathered gold deposits. Whether this wavelength shift of the charge transfer shoulder is measurable, using remote sensing systems, has yet to be established.

Spectral information can assist in the characterisation of regolith materials, useful for geochemical exploration. Much of the spectral information for the lag and soil is consistent with physicochemical properties and relationships described in the regolith model (Cudahy, 1992a). Spectral information could also be used to establish which physicochemical properties are responsible for the discrimination of regolith-landform units apparent in processed Landsat Thematic Mapper data (Tapley and Gozzard, 1992). Spectral information and an appropriate regolith model, could be used in forward modelling and a residual approach could be used to highlight anomalous spectral behaviour. For example, the localised, slight enrichment of goethite in mature soil is unexpected in the context of the regolith model and so might be a potential exploration target.

9.0 CONCLUSIONS

The 0.4 \( \mu m \) to 2.5 \( \mu m \) reflectance characteristics of soil and lag overlying the Beasley Creek ore zone were examined and compared with ICP, XRF and XRD physicochemical information from P240 and P241 studies to determine if gold mineralisation is associated with distinct spectral-physicochemical properties. There were no spectral characteristics specifically related to gold mineralisation. Sericite, which had been found in the soils by XRD, was not evident in the spectra. There is a shift in the wavelength of the 0.5 \( \mu m \)
charge transfer long-wavelength shoulder to shorter wavelengths, indicating more goethite in materials over gold mineralisation. However, goethite is pervasively developed in varying abundances throughout the regolith and so the significance of this result needs to be better understood geologically, before it is considered relevant to gold exploration.

The other spectral results include:

1. The spectra of lag and soil show information related to the weathering minerals (hematite, goethite and kaolinite) but no evidence of primary minerals;

2. Well-developed 2.2 μm absorption doublets in the coarse lag spectra indicate well-crystalline kaolinite. This contrasts with the poorly-developed 2.2 μm doublets of the soil spectra, which indicate poorly-crystalline kaolinite;

3. Some soil spectra show small 2.24 μm absorptions, possibly related to Fe-substitution in kaolinite developed over lateritic duricrust;

4. The depth of the 2.2 μm absorption may be accurately correlated with the Al₂O₃ content;

5. The depth of the 0.9 μm crystal field absorption is weakly correlated with the Fe₂O₃ content;

6. Soil spectra showing relatively shallow 2.2 μm absorptions (low Al-OH content) are located over exposed saprolite and mottled zone on the western side of the low rise;

7. The coarse lag spectra show changes in the wavelengths of the charge transfer shoulder and the 0.9 μm crystal field absorption, which correlate with semiquantitative XRD estimates of the hematite-goethite ratio;

8. The goethite-rich coarse lag is located over exposed saprolite and mottled zone and hematite-rich coarse lag is located over lateritic duricrust;

9. There was no apparent affect on the wavelength of the 0.9 μm crystal field absorption minima by Al³⁺ substitution in the iron oxide;

10. Many coarse lag spectra show a reflectance ramp from 0.9 to 1.3 μm, possibly related to bound water;

11. Spectra of carbonate-rich soils did not show a CO₃-related absorption at 2.32 μm but did show an increase in the visible brightness; and
12. Some of the soil spectra show a 1.9 μm absorption characteristic of water molecules trapped in fluid inclusions within quartz (unrelated to gold mineralisation).

These spectral results provide information on the characteristics of the regolith, consistent with a model proposed by Cudahy (1992a). The results emphasise the importance of aeolian activity on the soil mineral abundances.

10.0 FURTHER WORK

This study highlighted several gaps in our knowledge of the spectral behaviour of regolith materials, especially if spectral techniques (remote or proximal) are to be used in a quantitative manner for mapping the physicochemical properties of the regolith. This fundamental work requires detailed spectral studies, so as to:

1. Determine the spectral affects of Al-substitution in iron oxides;
2. Determine the spectral effects of clay crystallinity;
3. Determine the spectral affects of Fe-substitution in kaolinite;
4. Determine the reasons for the reflectance ramp between 0.9 and 1.3 μm;
5. Determine the spectral affects of quartz, carbonate, goethite and other regolith minerals on reflectance in the 9 to 14 μm wavelength region;
6. Determine the spectral characteristics of soils and soil components;
7. Determine the spectral characteristics of desert varnish; and
8. Determine the quantitative "mixing" relationships between the major regolith physicochemical properties.

Other questions identified in this study include:

1. What is the significance of the type of ferric oxide in weathered gold deposits;
2. Is the shift in the charge transfer shoulder of as little as 8 nm measurable, using currently available remote sensing systems. Landsat TM and airborne Daedalus 1268 data were collected over Beasley Creek prior to mining and so would be useful data sets to test this; and
3. How important is aeolian erosion and deposition on the spectral-physicochemical properties of soils.
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12.0 REFERENCES


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