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An integrated remote sensing study for the Western Water Study (*Wiluraratja Kapi*) Papunya–Kintore region, Northern Territory

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DEPARTMENT OF PRIMARY INDUSTRIES AND ENERGY

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ACRONYMS

ACRES	Australian Centre for Remote Sensing
AGS	Airborne Gamma-Ray Spectrometry
AGSO	Australian Geological Survey Organisation
AMG	Australian Map Grid
ATSIC	Aboriginal and Torres Strait Islander Commission
CLC	Central Land Council
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DEM	Digital Elevation Model
DN	Digital number
EST	Eastern Standard Time
GIS	Geographical Information Systems
K	(the element) Potassium
NaI	(the compound) Sodium Iodide
NOAA-AVHRR	National Oceanic and Atmospheric Administration - Advanced Very High Resolution Radiometer
NTDLPE	Northern Territory Department of Lands, Planning and Environment
RGB	Red/Green/Blue false colour composite image
Th	(the element) Thorium
TIR	Thermal Infrared Radiation
TM	Landsat Thematic Mapper
TMI	Total magnetic intensity with the magnetic field of the earth removed
U	(the element) Uranium
UNIX	Operating system
WRS	World Reference System
WWS	(the) Western Water Study (*Wiluraratja Kapi*)

An Integrated Remote Sensing Study for the Western Water Study (*Wiluraratja Kapi*) Papunya-Kintore Region, Northern Territory.

SUMMARY

New insights into regional geology and geomorphology are apparent from an interpretation of multi-layer digital imagery for 70,000 km^2 of arid central Australia, and are applied to regional groundwater assessment, which is needed for the future development of water resources for Aboriginal communities. Enhanced Landsat (TM) imagery combined with a Digital Elevation Model (DEM) have been used in delineating an extensive network of palaeodrainage channels, that probably dates back to the Mesozoic or earlier. This system contains widespread calcrete deposits which contain important potential groundwater resources, and which overlie thick sand and gravel aquifers. Previously unrecognised alluvial fan deposits have been delineated with Airborne Gamma-Ray Spectrometry (AGS) overlain on the DEM, and these deposits are also of considerable hydrogeological significance. An extensive area of ferricrete has been identified east of Lake Mackay using a combination of AGS and Landsat TM imagery; the groundwater potential of this area has not yet been evaluated. The integrated remote sensing study is considered to be a cost effective method of mapping regolith materials and hydrogeological features rapidly over a large and relatively unknown area, such as that of the Western Water Study.

1.0 INTRODUCTION

1.1 The Project

The Western Water Study (*Wiluraratja Kapi*) is a collaborative project between the Australian Geological Survey Organisation (AGSO), the Water Resources Division of the Northern Territory Department of Lands, Planning and Environment (formerly within the Northern Territory Power and Water Authority) (NTDLPE), the Central Land Council, Northern Territory (CLC) and the Aboriginal and Torres Strait Islander Commission (ATSIC). It covers an area of approximately 68,000 square kilometres of Aboriginal Lands in the arid zone of central Australia.

1.2 Objectives

The objectives of the Western Water Study (WWS) are to provide information for the assessment of groundwater resources occurring beneath Aboriginal Lands, to highlight health parameters through water quality analyses, to promote equity of access to safe drinking water in remote arid areas, and to develop a rapid methodology that will provide these objectives through the development of a Geographical Information System (GIS).

1.3 The Papunya-Kintore Region, Northern Territory

The Papunya-Kintore region covers approximately 68 000 square kilometres of Aboriginal Land in central Australia (Fig 1). In the Papunya region, 80 out of 86 communities depend on bore water; of these communities, 61 perceive that they have insufficient water supply for the next five years (ATSIC, 1993). The remote communities in arid areas need groundwater for any future development as surface waters are inadequate or non-existent. However groundwater sources are sometimes of poor quality and location of acceptable water supplies is limited. A collaborative effort by the project partners begun in 1994-5 to assess the sustainability and accessibility of safe drinking water, in addition to water sought for other purposes such as reafforestation, horticulture and alternative land use.

2.0 AIM

The aim of the present investigation was to investigate geomorphological and hydrogeological aspects of the study area using remotely sensed techniques and a digital elevation model, and thereby enhance the rapid assessment of groundwater resources. We sought a cost effective method of mapping regolith materials and hydrogeological features over such a large and relatively unknown area as the Western Water Study. This study took an image interpretation approach, and the present report describes visual correlations identified between or within the datasets. The present study focused on potential aquifers in the Cainozoic units in the study area; a companion study by English (1997) focussed on potential aquifers in fractured bedrock.

3.0 REMOTELY SENSED DATA

The Australian Geological Survey Organisation (AGSO) is the national geoscientific mapping and information agency and holds significant geological, geophysical and geochemical map data for the pilot study area (Fig.1). These data form a useful starting point for the development of a groundwater resources information base.

Remotely sensed data can be used to visualise broad scale features that may or may not be presently mapped. This paper documents highlights and insights that contribute to the understanding of geomorphological and compositional aspects of the study area.

The datasets were chosen for their availability and unique spatial and spectral attributes. By examining remotely sensed data in relation to other digital data, such as a DEM and geology, new insights can be gained into the information content of both airborne and satellite data.

3.1 Landsat Thematic Mapper (TM) Unmixed Mineral and Vegetation Imagery .

The Landsat TM scanner is a space-borne sensor detecting visible, near infrared and thermal electromagnetic radiation from the earth's surface. The reflectance and absorption properties of surface materials, as well as atmospheric effects, determine the sensor digital number (DN) of a pixel which has been quantised to 256 intensity levels.

A processing technique is required to remove atmospheric effects and identify surface reflectance components in the data. A spectral unmixing process using the six non-thermal

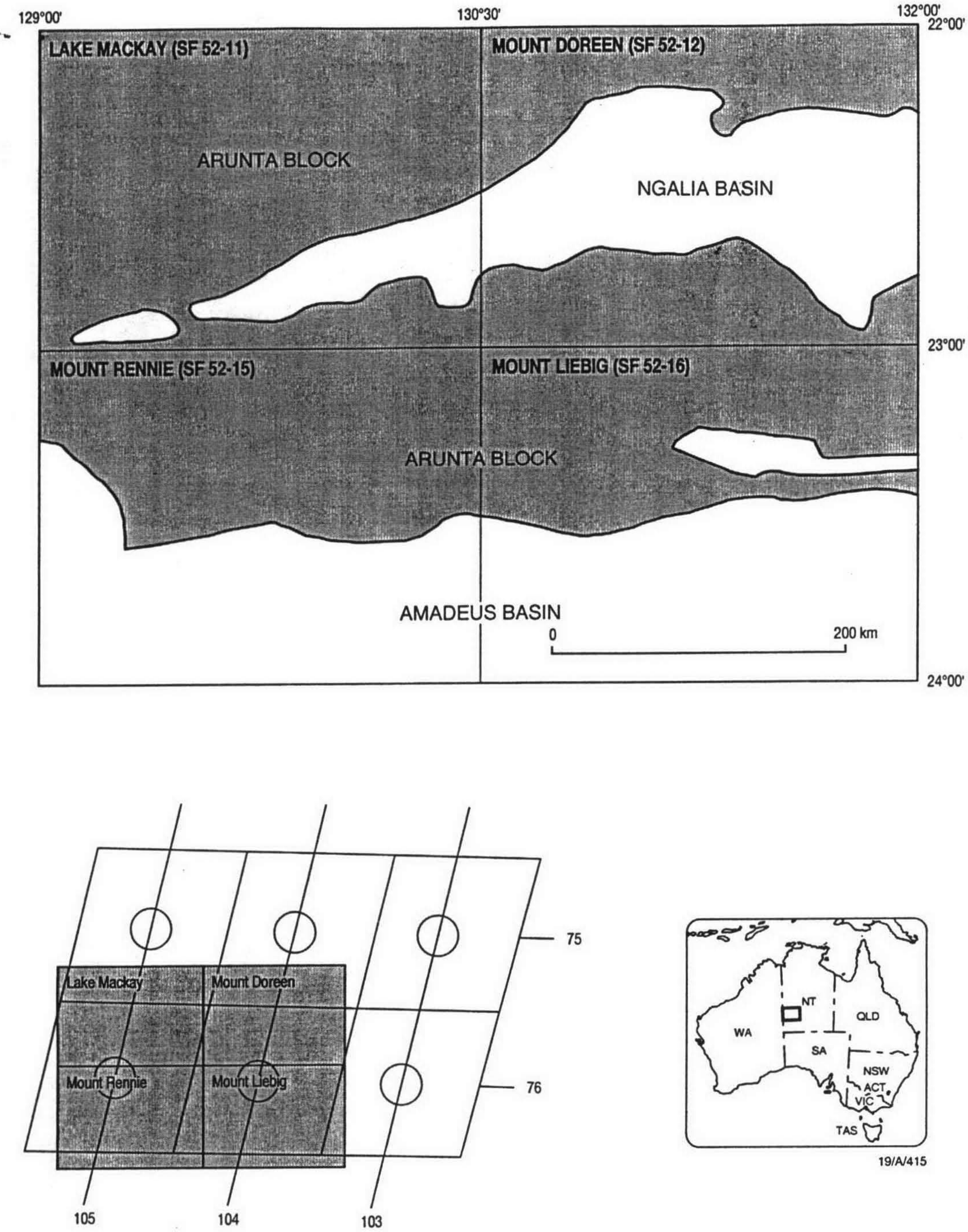


Figure 1. Western Water Study area. Location of the four 1:250 000 sheets relative to the main geological provinces. Landsat TM coverage with path and row numbers and image centres.

Landsat TM bands was used to separate the data into three geological and two vegetation end-member images based on known reflectance characteristics of surface components (Bierwirth, 1990). The result is a false colour composite image where red = clay (or carbonate, or water); green = iron oxide; and blue = quartz (or halite). Figure 2 shows the spectral reflectance curves for these common cover types. A greyscale image of the green vegetation abundance is also used for interpretation.

3.2 National Oceanic Atmospheric Administration - Advanced Very High Resolution Radiometer 11 Night Thermal image

The NOAA-AVHRR 11 satellite has been used in hydrologic, oceanographic and meteorologic studies, along with solid earth monitoring (Richards, 1993). It has a ground resolution of approximately 1.1 kilometres (1100 metres) at nadir, and records radiation in five spectral bands including one channel in each of visible red and near infrared, and three channels in the thermal infrared wavelengths (Richards, 1993). Table 1 lists the spectral bands or channels recorded by the NOAA-AVHRR satellite. Figure 3 displays the diurnal radiant temperature curves for some typical materials such as rocks and soil, vegetation or standing water. Band three of the thermal infrared spectrum was chosen for the purpose of this study.

Table 1 NOAA-AVHRR Spectral Bands

NOAA-AVHRR Spectral Bands:

Band	Wavelength (micrometres)	Electromagnetic Spectrum
1	0.58 - 0.68	visible red
2	0.72 - 1.1	near infrared
3	3.55 - 3.93	thermal infrared
4	10.3 - 11.3	thermal infrared
5	11.5 - 12.5	thermal infrared

Tapley (1988) undertook a study of the application of NOAA-AVHRR satellite imagery to assist in the interpretation of palaeodrainage and geological structures over the Canning and Officer Basins in South Australia. Thermal imagery was found to be useful to identify structural components as "...warm target must be composed of much denser, older rocks with relatively higher thermal inertia properties than the overlying present-day sands" (Tapley, 1988:422). The night-time thermal image has been found to be useful to reconstruct palaeodrainage networks and to identify unmapped lineaments that appear to be controlled by the alignment of local flow direction of palaeochannels (Tapley, 1988). This topic will be discussed in more detail later (See section 6.1.2).

3.3 Airborne Gamma-Ray Spectrometry (AGS - also known as Radiometrics)

The AGSO operates an aircraft that carries out regional airborne geophysical surveys which collect both gamma-ray and magnetic data simultaneously. Concurrent with the acquisition of geophysical data, surface elevations are derived by comparing radar altimeter readings measuring height above ground with GPS altitude (Grasty and Minty, 1995). Ground

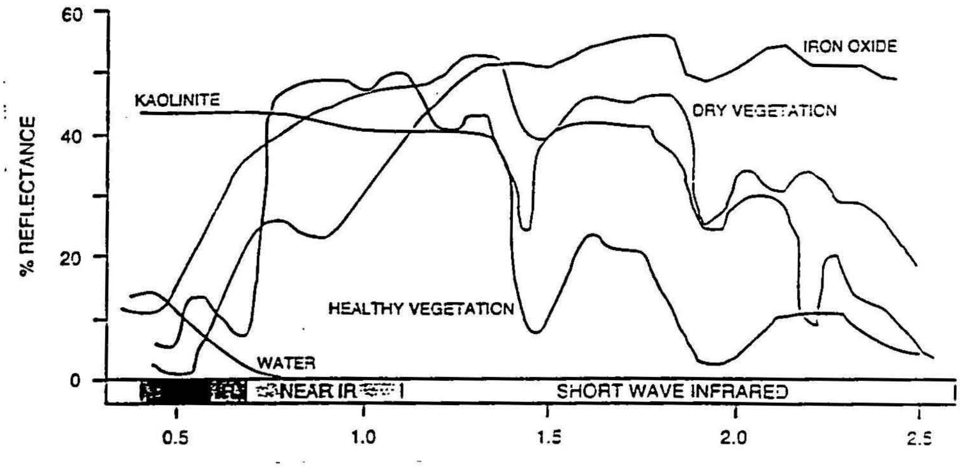


Figure 2 Spectral reflectance curves for common cover types.

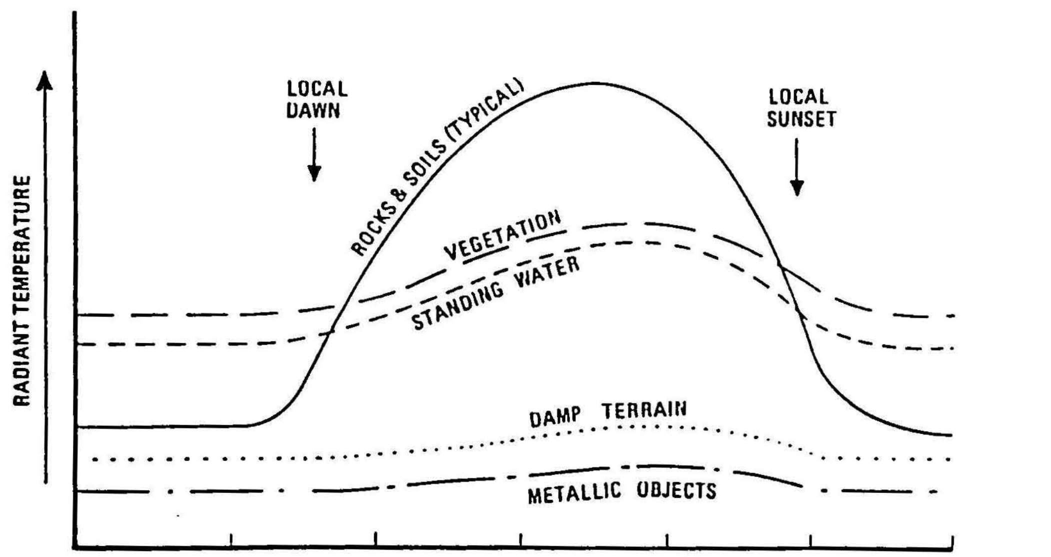


Figure 3 Diurnal radiant temperature curves (diagrammatic) for typical materials.

elevations become important as an input to the processing procedures, where correction for variations in aircraft altitude enable the conversion of airborne count rates to ground concentrations of potassium (K), thorium (Th) and uranium (U) (Grasty and Minty, 1995).

An AGS detector system holds a 32 litre volume of sodium iodide (NaI) crystals carried onboard a low-flying aircraft (for example 120 metres above the ground). When subjected to gamma-rays, the NaI crystals emit visible light or 'scintillations' that are converted to a measurable electric pulse (Grasty, 1976). These pulses are measurements of the natural radioactivity or the gamma-emitting isotopes of the decay series of the three elements K, Th and U. Equilibrium with their parent elements is assumed.

Spectral data is recorded in the range 0 - 3 MeV, a measure of the energy of the photon. Figure 4 shows the three windows of potassium, thorium and uranium. The isotopes are not measured directly from the windows but are mathematically resolved in the 'stripping process'. In modern surveys, actual concentrations of elements are determined by the use of a calibration range.

A total count measurement records overall radioactive levels and represents the combined measurements of potassium, thorium and uranium in counts per second. Figure 8 displays the total count radiometric image overlain on the DEM, for the Lake Mackay and Mount Doreen area of the Papunya-Kintore region. The three main photopeaks shown in Figure 4 and total count measurements are summarised in Table 2.

Table 2 Data channels acquired during airborne geophysical surveys

Channel/Element Window Analysed	Isotope sensed	Gamma-ray energy (MeV)	Wavelength (nanometres)	Energy (MeV)
1. Potassium	^{40}K	1.46	8.50×10^{-4}	1.37 - 1.57
2. Uranium	^{214}Bi	1.76	7.05×10^{-4}	1.66 - 1.86
3. Thorium	^{208}Tl	2.61	4.74×10^{-4}	2.41 - 2.81
4. Total Count				0.40 - 3.00

Spatial resolution will be determined by the survey altitude of the aircraft, flight line spacing, the sampling intervals along that line and the sensitivity of the spectrometer onboard the aircraft. In 1976, low-resolution (1.6 kilometre line spacing) airborne gamma-ray data was recorded over the Papunya-Kintore region of the Northern Territory. The survey was flown in a north/south direction with sampling at 70 metre intervals along the line of flight. Due to the broad line spacing, point data were interpolated to an image with a 300 metre pixel. Image processing techniques of the AGS will be described in section 5.1.3.

4.0 DIGITAL ELEVATION MODEL

The DEM used in this study covered an area equivalent to four 1:250 000 mapsheets - Lake Mackay, Mount Doreen, Mount Rennie and Mount Liebig - part of the arid zone in the southwest of the Northern Territory (Fig 5). The spatial coverage represented one quarter of a 1:1000 000 map sheet tile of the national DEM completed in 1996 (AUSLIG, 1996).

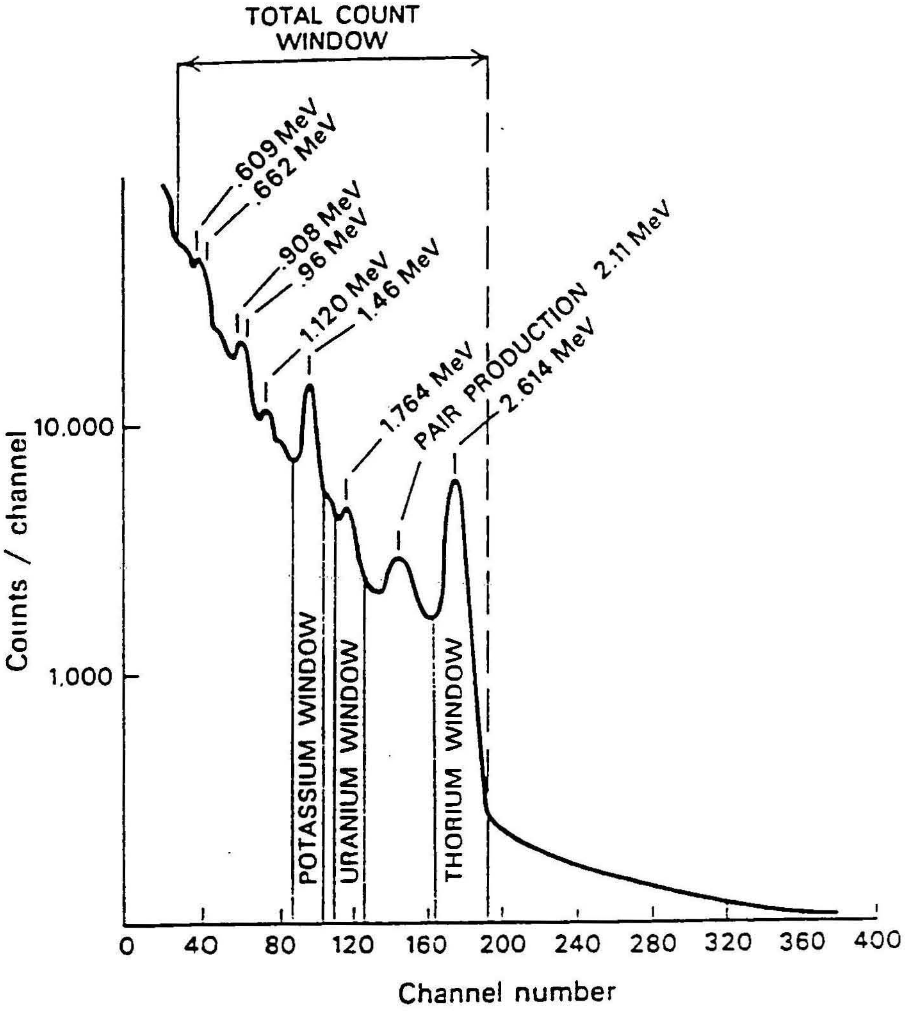


Figure 4 Gamma-ray spectrum showing the main photopeaks and channel positions for potassium, uranium and thorium.

The production of the Australia-wide DEM was a co-operative effort by the Australian Geological Survey Organisation, the Australian Land and Information Group, the Australian Heritage Commission and the Centre for Resource and Environmental Studies at the Australian National University. It has a grid spacing of nine seconds in latitude and longitude, approximating a 250 metre grid.

The DEM was created using the ANUDEM algorithm developed by the Centre for Resource and Environmental Studies at the Australian National University (Hutchinson, 1996). Source data for the DEM included more than 5 million spot heights taken from topographic contours from 1:250 000 digital maps, as well as observed spot heights from 1:100 000 map production where available. As well as elevation data, the program uses watercourses and waterbodies to enforce hydrological drainage which resolves to a large extent the problem of sinks forming in the created surface. Remaining sinks can be further removed or reduced by interactive editing, then the program re-run to recreate an elevation surface without sinks, thereby creating a depressionless DEM (Hutchinson, 1996).

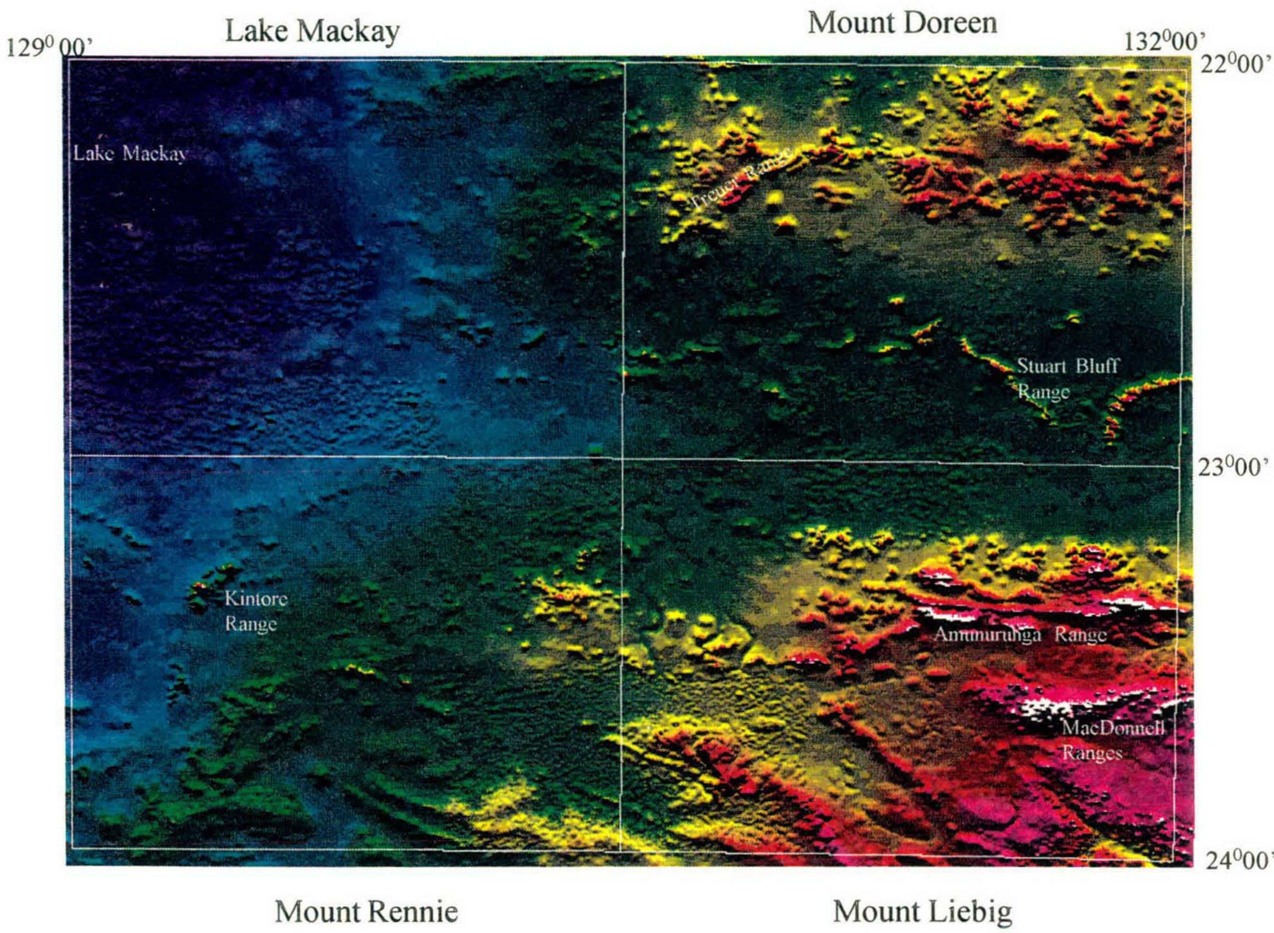
The capability of DEM's to be used for effective visualisation of data against terrain shape both in two and three dimensional space is widely practised and understood (Drury, 1990; Richards, 1993; Sabins, 1987). The DEM became the foundation dataset that allowed spatial visualisation of other spectral data by way of overlay. The functionality of ERMapper to zoom in and out, and filter the digital data to either smooth or edge enhance the imagery, facilitated effective observational capabilities to see detailed geomorphic or compositional aspects within the data.

5.0 METHODOLOGY

5.1 Data Acquisition and General Image Processing

Image processing was carried out using ERMapper 5.2 software run on an UNIX platform. Processing would vary depending on the data. For the purposes of interpretation and comparison, the aim was to enhance the spectral characteristics within each of the datasets. In most cases the digital datasets were first of all displayed by setting to the actual limits of the data thereby capturing the full range. This initial step was essential in the case of the digital elevation model, because to clip the highest and lowest values would mean the loss of ridge tops and valley floors.

Linear transformations were applied to stretch the data and use as many of the available colours in the lookup table to display the result. This technique proved in effect, to draw out information that could have otherwise been lost or overlooked. In some cases the resultant histogram was then equalised and either a 3 x 3 or a 7x7 low-pass averaging filter was applied to smooth the image. The comtal pseudocolour lookup table was used to display single band datasets where white/grey represented the highest values and dark blue represented the lowest values in a data range, see Table 3.



White = Topographic high   Blue = Topographic low

Figure 5. Digital Elevation Model (DEM), Western Water Study.

The study area covers part of the GEODATA NINE SECOND DEM, copyright Commonwealth of Australia (AUSLIG, 1996). Elevation ranges from 359 m (blue) at Lake Mackay to 1334 m (white) in the MacDonnell Ranges. The boundary between green and blue approximates the 500 m contour.

Table 3	ERMapper 5.2 Comtal Pseudocolour LookupTable Colour gradation for display of data range
White - Grey - Pink - Red - Yellow - Green - Blue - Dark Blue	
High values	Low values

5.1.1 Landsat Thematic Mapper (TM)

Data from the Landsat TM satellites is collected in a continuous stream as the satellite moves from north to south with orbit paths numbered from the west and image rows numbered from the south. The Landsat TM coverage for the study area was acquired from the Australian Centre for Remote Sensing (ACRES), ACT and comprised five 1994 scenes each containing seven spectral bands. The Landsat Worldwide Reference System (WRS) designates a path/row number eg. p103r76, to identify each scene. The Landsat TM scenes for the Western Water Study encompassing the Papunya - Yuendumu - Kintore region of the Northern Territory are p103r76, p104r75, p104r76, p105r75 and p105r76 (Fig 1). Evert Bleys (AGSO) registered and warped the raw Landsat TM scenes, then created a mosaic of those parts of the five scenes to produce a single Landsat TM image of the study area. Complete coverage was not possible in the Mount Rennie and Mount Liebig sheets and small portions in the south of both sheets is missing.

5.1.2 NOAA-AVHRR Night Thermal image

A pre-dawn NOAA-AVHRR 11 satellite image, pass time 4.00 a.m. EST, for the 21 August 1993 was obtained from the CSIRO, Division of Oceanography, Tasmania. The night thermal data was temperature calibrated 0.1 degree celsius for every increment increase in brightness value. ie. each increment of 0.1 degree celsius relates to a new class on the scale of brightness depicted as the thermal gradient on the image. The thermal data is represented as a corresponding colour gradient ranging white (warmest thermal radiance) through to dark blue (coolest thermal radiance), using the comtal pseudocolour lookup table in ERMapper 5.2, as described in table 3.

5.1.3 Airborne Gamma-Ray Spectrometry (AGS)

The AGS for the Lake Mackay and Mount Doreen mapsheets within the Papunya-Kintore region was collected in 1976. A reading was collected in each of the four channels of potassium, thorium, uranium and total count, every 70 metres, along a flight line spaced at 1.6 kilometres. There is no digital AGS data available for either Mount Liebig or Mount Rennie mapsheets as only analogue charts were completed using a much smaller detector system carrying a NaI crystal approximately 1/16th of 32 litres (Refer back to section 3.3 for a brief description of onboard AGS detector systems).

Tom Calvert (Water Resources Division, NTDLPE) wrote the software to extract the raw digital data from tape and convert to Australian Map Grid (AMG) coordinates. The data was converted to ERMapper 4 byte real BIL (Band Interleaved by Line). This data format is most appropriate for remotely sensed data since many processing operations require the analysis of both multiple channel values and groups of pixels. Using the capabilities within the ERMapper software it is a simple task to convert to other data formats such as Unsigned 8 bit integer for display in ArcInfo. The line data for the Papunya-Kintore region were interpolated to form a grid of values with a 300 metre pixel resolution (grid cell size = 300 x 300 metres).

There were eight digital images available for the Papunya-Kintore region, as two sets of four images, one set for each of the Lake Mackay and Mount Doreen mapsheets:
1. Lake Mackay - potassium, thorium, uranium and total count.
2. Mount Doreen - potassium, thorium, uranium and total count.

Tim Mackey (AGSO) used the Intrepid software package to de-stripe and grid-stitch each pair of the four digital radiometric datasets to produce single images of potassium, thorium, uranium and total count. The de-stripping process largely removed effects of spectral "noise" in the data, thus improving the visual impact and capacity for detailed interpretation.

5.2 Spectral unmixing of mineral and vegetation components

Natural systems are extremely complex. The response from each Landsat TM pixel (cell) is the result of the interaction of naturally occurring illumination of all the materials on the surface within a $30m^2$ area. This can include vegetation, leaf litter, soils and rocks, varying moisture contents and a shadow component. Therefore each pixel is a summation of a large number of these effects and will be dominated by the major surface components. Figure 2 shows the spectral reflectance curves for common cover types such as clay (as kaolinite), iron oxide and green or dry vegetation.

One problem for the analysis of remote sensing data is the fact that the reflectance properties of particular minerals may be mixed with other mineral and vegetation components. Given that mixtures comprise a typical pixel reflectance in data such as Landsat TM, a method is required to identify the individual components.

Based on previous research experience, a method known as 'spectral unmixing' was chosen for the analysis of the Landsat data. This method matches multispectral data to material reflectance-spectra known as end-members. These end-members or materials are then resolved mathematically as to their respective contributions to the overall reflectance (Bierwirth, 1990). Pixel unmixing based on known spectral reflectance of end-members such as clay, iron oxide and quartz was applied (Bierwirth, 1990). The unmixing procedure produced two maps. Firstly, a three band unmixed mineral map comprising clay, iron oxide and quartz, see figure 7; and a single band green vegetation map, see figure 17. Further image enhancement was achieved with the application of linear contrast stretching to visualise the actual range of data more clearly. For this study, the unmixing procedure involved the following steps:

1) conversion of the data to pseudo-reflectance
2) selection of appropriate laboratory end-member materials
3) unmixing analysis to resolve material abundances

The first step is required because sensor digital numbers (DN's) are strongly influenced by sensor gain settings, solar illumination and atmospheric effects. These need to be removed so that reflectance information can be obtained from the data. The method used for the conversion is detailed in Bierwirth (1990) and involves the use of band means and minimums together with an assumed reflectance mean. This circumvents the need for complex and generally inaccurate atmospheric correction models which require specific information about atmospheric components at the time of overpass.

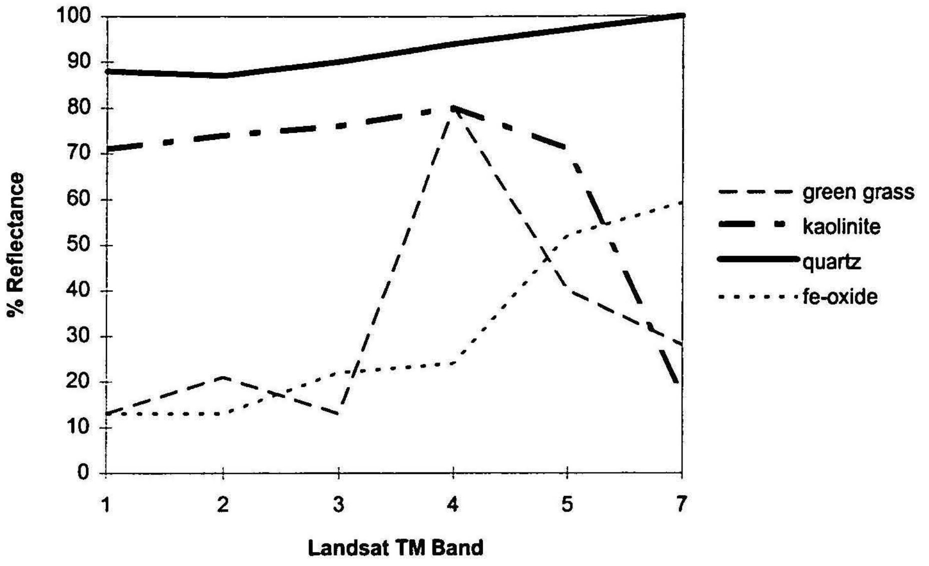


Figure 6. End-member material spectra, used in the unmixing analysis, convolved to Landsat TM wavelengths.

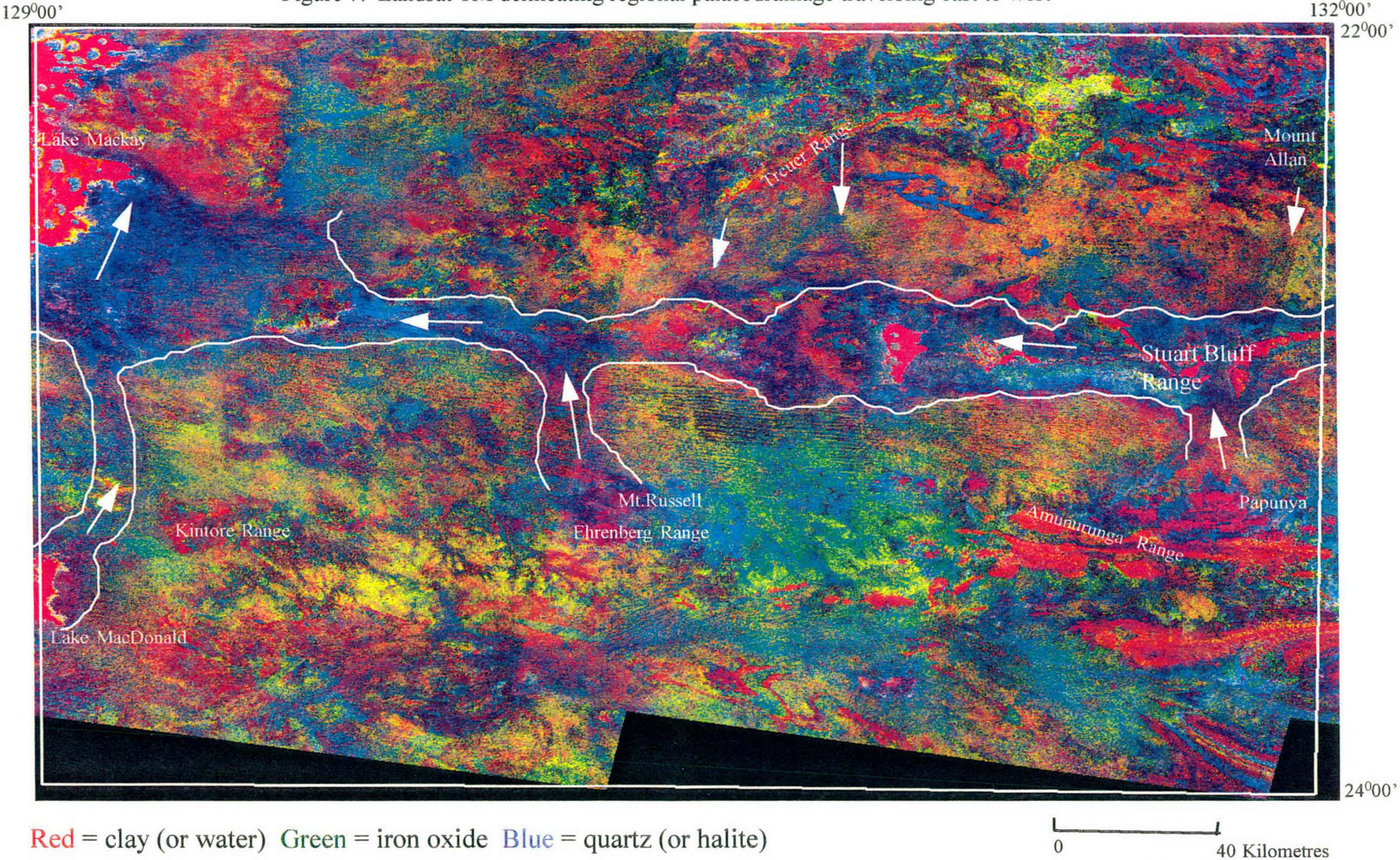
The second step is probably the most important in terms of obtaining useful results. The materials selected as spectral end-members should be spectrally separable for the wavelengths used and their vectors should span the boundary of the data points in n-band dimensional space. The distribution of values in the results actually indicates whether sensible end-members have been selected. However, the purity and accuracy of spectral targets should be defined by laboratory studies. End-members used for this study are shown in figure 6 reduced to Landsat wavelengths end-members.

The third step is an unconstrained solving of simultaneous equations. Shade is not used as an end-member so that illumination variations will be observed in the end-member images. Mineral abundance results will also be a function of the amount of vegetation which covers a pixel.

5.3 Image Interpretation Technique

This study was limited to visual observation and comparative reporting as formal statistical analyses were not performed. Also, there was no field component to this study, therefore observations discussed here were not ground-truthed. The value of close inspection of a variety of datasets comes from drawing together different pieces of information that

Figure 7. Landsat TM delineating regional palaeodrainage traversing east to west



Red = clay (or water) Green = iron oxide Blue = quartz (or halite)

Landsat TM data was used to delineate a regional palaeodrainage system within the Western Water Study area. It encompasses the southern area of the Lake Mackay and Mt. Doreen mapsheets. Groundwater enters the system from the ranges in the north and south then flows westward toward Lake Mackay, as indicated by the arrows.

contribute to building a firm understanding of geomorphological, geophysical and geochemical aspects.

Using the ERMapper 5.2 software, remotely sensed digital data was overlain onto the DEM to contribute terrain shape for inspection of spatial pattern. A north/west sun-angle filter illuminated the northwest-facing slopes of the DEM, thus shading southeast. This intensified the general low-relief of the Western Water Study area and highlights areas of granite and sandstone outcrop.

Work was carried out using digital data displayed on computer screen in conjunction with 1:250 000 topography and 1:500 000 geology maps. This technique proved adequate for visual inspection, interpretation and qualitative validation. Visual correlations found either between or within the datasets will be described and discussed in section 6.0.

6.0 DISCUSSION

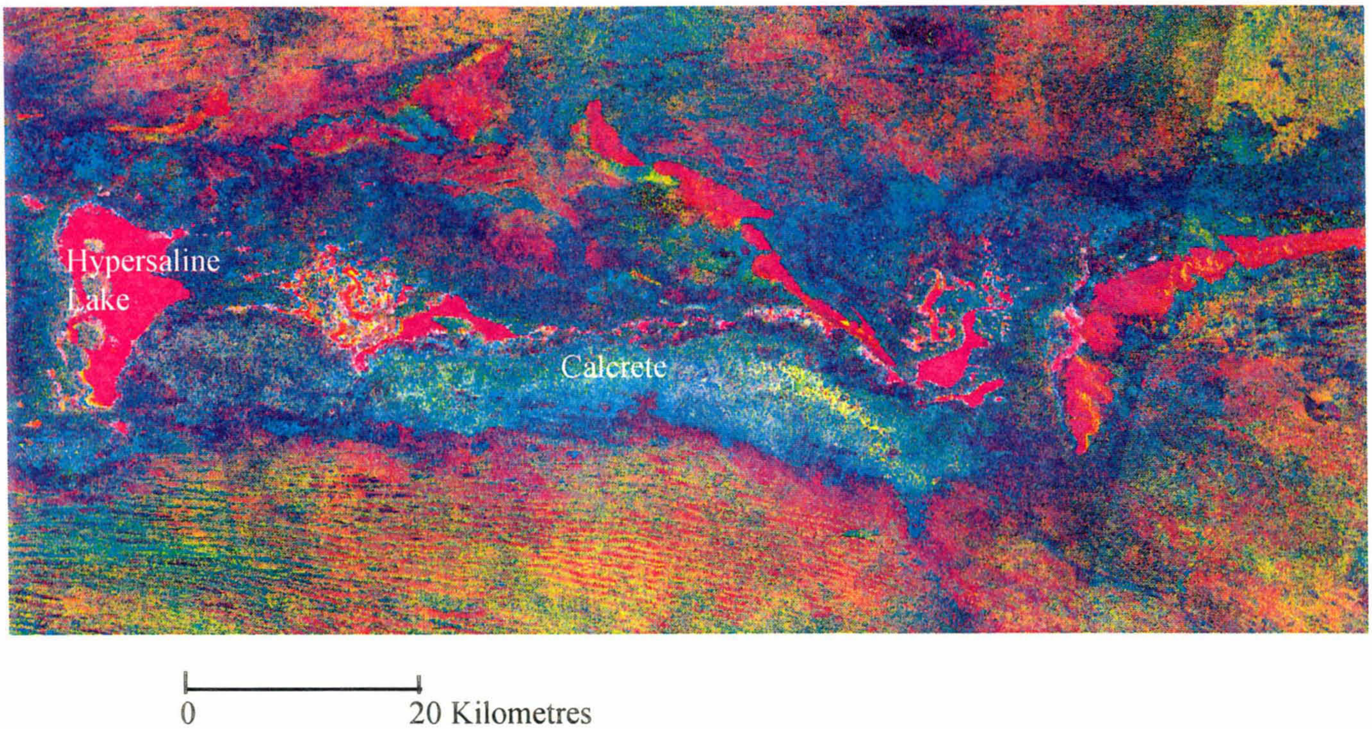
6.1 Image interpretation

6.1.1 Palaeodrainage Transversing the Study Area Including Hypersaline Lakes and Calcretes - Upward Seeping Groundwater Discharge

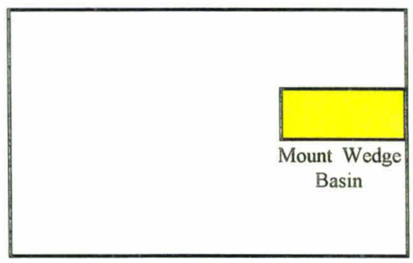
A broad east-west palaeodrainage system is visible in figure 7, and appears to be controlled by the underlying structural geology as well as the terrain shape at the surface. The high resolution Landsat TM brings clarity to the spatial as well as the compositional aspects of this broad scale feature. This palaeodrainage system completely spans the region to the south of both the Lake Mackay and Mount Doreen map sheets of the Papunya-Kintore region. Additional drainage moves north feeding into the central palaeochannel from the high country south of Papunya and Haasts Bluff, from Lake MacDonald and the Kintore Range and from Ehrenberg Range and Mount Russell (Fig 7).

Figure 8 shows a resistant ridge of Proterozoic sandstone which forms the Stuart Bluff Range (identified as reddish pink in the image), and a chain of salt lakes (brightest pink). These hypersaline lakes are present-day groundwater discharge playas and the colour reflects the crystalline gypsum and possibly halite in the lake beds. To the south is an extensive area of calcrete shown as yellow-green speckle on the image; this speckle depicts the karstic weathering on the surface of the calcrete formed by the dissolution of limestone. The weathering of the calcium carbonate allows water to permeate into the calcrete, which thus becomes important in this region containing unconfined aquifers with freshwater recharge. Linear sanddunes run east-west in this region and are on average between 8-10 metres high.

The high resolution TM imagery captures the geomorphic detail of sandridges, visible in figure 7 as light green/yellow stripes indicating an iron oxide component. The interdune swales contain silt and clay alluvium and have become stabilised by a significant vegetation cover. A distinct vegetation signal envelopes the calcrete in the southern part of the Mount Doreen sheet, seen as dark blue on the TM image (Fig 8).



Red = clay (or water)
Green = iron oxide
Blue = quartz (or halite)



Western Water Study Area

Figure 8. Landsat TM Unmixed Mineral showing hypersaline lakes and calcrete Mount Wedge Basin.

This figure covers that part of the whole study area marked in yellow (see inset). It shows hypersaline lakes (brightest pink) and calcrete (yellow/green speckle) which represents groundwater discharge in the lowest lying area of the Mount Wedge Basin, Mount Doreen mapsheet.

This broad palaeodrainage delineated in figure 7 as the dark blue feature interspersed with the bright pink of the salt lakes and yellow/green areas of calcrete, correlates with the low-lying part of the landscape. Subtle variation in surface elevation is apparent where the salt lakes and bands of calcrete are slightly raised above the lower floor of this broad palaeochannel.

The surface material that has infilled this broad palaeochannel appears as dark blue/green on the image and suggests a high iron content. The accumulation of silt and clay sized material that has been transported and deposited over time have carried sesquioxides of iron adsorbed to the surface of the transported material.

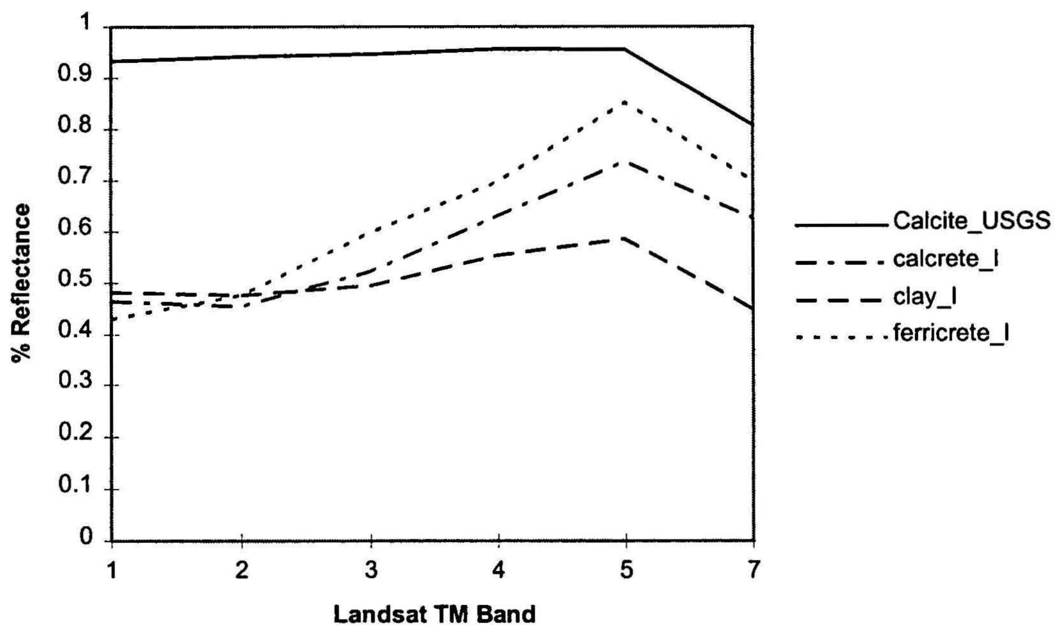


Figure 9. Average values of Landsat TM image data for surface components compared with laboratory measured calcite.

Figure 9 shows the spectrum of calcite obtained from the USGS spectral library convolved to TM wavelengths. This is compared with average TM image values for particular surfaces converted to pseudo-reflectance using the method of Bierwirth (1990). The calcrete image spectrum was collected from an area mapped as calcrete. The ferricrete and clay data was collected from the area of ferricrete and weathered granite east of Lake Mackay (see Figure 12a). All image spectra are dominated by the ferric iron absorption in the lower bands and associated increased reflectance in bands 5 and 7. The absorption in band 7 of calcrete is not as strong as clay and it appears that, in terms of the end-members shown in figure 6, the unmixing analysis has determined the calcrete to be more of a mixture of the quartz and fe-oxide spectra (relative to other materials). This has resulted in the blue-green colour in figure 7 than defines the extent of calcrete and the paleochannel.

Vegetation species such as spinifex appear in abundance considering the harshly arid conditions of this region. Sand dunes formed 20,000 years ago have stabilised. These sandridges lie in an east/west direction and abut the palaeodrainage but do not cover it, suggesting that this broad channel could have formed in the mid to late Miocene or earlier.

The hypersaline lakes and calcrete are depicted as part of the large external palaeodrainage system reconstructed by van de Graaff and others (1977) for the western half of the continent. This river system existed to carry runoff from past higher rainfalls, the last in the Eocene, to the sea. Sustained flow in these rivers ceased with the beginning of more arid conditions in the Miocene.

In the south of Western Australia the river system was initiated in pre-Jurassic time, perhaps as early as the Permian, before the Antarctic and Australian plates separated (Clarke, 1994). In the study area the catchment for the palaeodrainage system has had an equally long existence. Carboniferous orogenies created the ancestral Treuer and MacDonnell Ranges which still form its northern and southern boundaries today. The orogenies also created huge south-directed alluvial fans.

The Lake Mackay system is considered by van de Graaff and others (1977) to have drained north to the Bonaparte Gulf via the Lander River and the present-day Victoria River in a drainage basin covering much of the western half of the Northern Territory. Currently, drainage in the Lake Mackay system ceases at Lake White to its northwest. The palaeodrainages are most easily recognised on the West Australian Shield and in the Officer and Canning Basins where they are simple incised river systems infilled with up to 100m of sediment (Kern & Commander, 1993). Well-defined channels are further highlighted by secondary calcretes formed by modern groundwater discharge to the low points of the landscape (Fig 7). The divides between drainages can often be resistant ferricretes and silcretes.

The Lake Mackay-Lake Lewis palaeodrainage is a broader feature than many of the West Australian palaeodrainage systems because its boundaries have been formed by tectonics rather than by incision. It is likely that alluvial fans coming from these tectonic divides may be more significant in the sedimentary record than alluvial channel deposits. The calcretes may here have formed by groundwater discharge at the toes of discontinuous alluvial fans. The thickest sediments with the best aquifer characteristics and recharge potential are probably not directly beneath the calcretes but closer to the fan source (Fig 7). The eastern end of the palaeodrainage, from west of Lake Bennett to Lake Lewis outside the image, is recognised as the Mount Wedge Basin (Senior and others 1995). Here alluvial fans and extensive fresh to brackish water lakes existed, from the Miocene. The sediments deposited in the basin are more than 200m thick. They consist of a basal (possibly channel) sand, lacustrine clay and carbonate, and prograding alluvial fan deposits. A thin sequence, of the order of 10m thick, of playa deposits, calcrete, and aeolian sand occurs at the top of this sequence in the central area.

In figure 7 the palaeodrainage is clearly delineated by blue and green tones of calcretes interspersed with the magenta of playas and basement outcrop. This feature, winding in and out of a range formed by outcrop at the southern edge of the Ngalia Basin, appears to be controlled by its position midway between the Treuer and Walbiri mountain ranges to the north and the Amunurunga, Ehrenberg and Kintore mountain ranges on the southern half of the study area.

The eastern part of the palaeodrainage, where it is part of the Mount Wedge Basin, is shown in detail in figure 8. Calcretes, of the order of 10 m thick, are important local aquifers. The calcrete surface has been elevated above the water table through such processes as volume increase during calcite crystallisation and this has been followed by some dissolution and karstification of the calcrete. Freshwater recharge from rainfall is thus stored and ponded above denser more saline water, in and beneath the calcrete (Jacobson *et al*, 1989).

6.1.2 Palaeodrainage Northeast of Lake Mackay

The Thermal Infrared (TIR) band 3 of the NOAA-AVHRR 11 Night Thermal image (NOAA) was used to visualise palaeodrainage seen as the blue-green at the top right of the NOAA image (Fig 10). This image covers the 1:250 000 Lake Mackay mapsheet area. The low resolution at 1100 metre pixel size in the NOAA has given the image a pixelated appearance. The palaeodrainage spans approximately 180 kilometres, originating from the Treuer Range in the east and follows a northwesterly direction towards Lake Mackay (Fig 10).

TIR images record the radiant temperature of land surface materials. Radiant temperature is determined by a material's kinetic temperature and by its emissivity. Emissivity is the radiation emitted at various wavelengths depending on temperature. Temperature depends on the thermal inertia of the material which relates to its capacity for absorption and thermal conductivity. The diurnal temperature range of surface materials (change in temperature over a twenty four hour period) is a function of thermal inertia, which is directly related to the density of rock and land surface materials (Sabins, 1978).

According to Sabins (1978) TIR images can be useful to differentiate between rock types, to map surface moisture and geologic structure. Denser rocks, such as basalt and sandstone, have higher thermal inertia than less dense rocks, such as siltstone. On nighttime TIR images, rocks with higher thermal inertia values have warmer signatures. Damp ground has a cool signature on TIR images which is caused by evaporative cooling. Faults can be marked by cool linear anomalies caused by the evaporative cooling of moisture concentrated along the fault zone. Folds may be indicated by the thermal pattern caused by the outcrops of different rock types.

Thermal images are affected by environmental factors such as clouds, surface winds that may produce confusing thermal patterns and the time of data collection, for instance daytime images record the differential solar heating and shadowing of topographic features. Geologic and other interpretations may require nighttime images. Thermal inertia may provide insights into how and where groundwater is interacting with the land surface. Dense vegetation and surface moisture can effectively mask surface features therefore TIR imagery can be very useful in arid and semiarid terrain to distinguish cool low-lying areas in the landscape.

One area where NOAA imagery does correspond well with topography and where it appears to delineate palaeodrainage beneath obscuring sand is to the northeast of Lake Mackay (Fig 10). The landscape of ferricretes and metamorphic rocks dissected by palaeodrainage channels is more similar to that of the Western Australian Shield and the

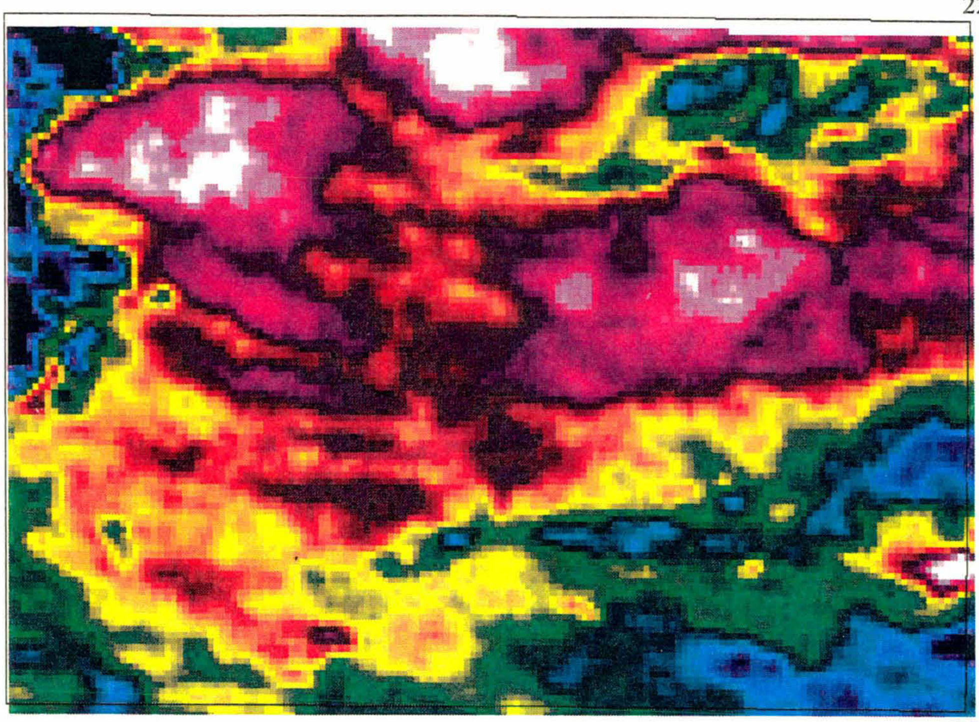


Figure 10. NOAA-AVHRR night thermal image showing the palaeodrainage, Lake Mackay.

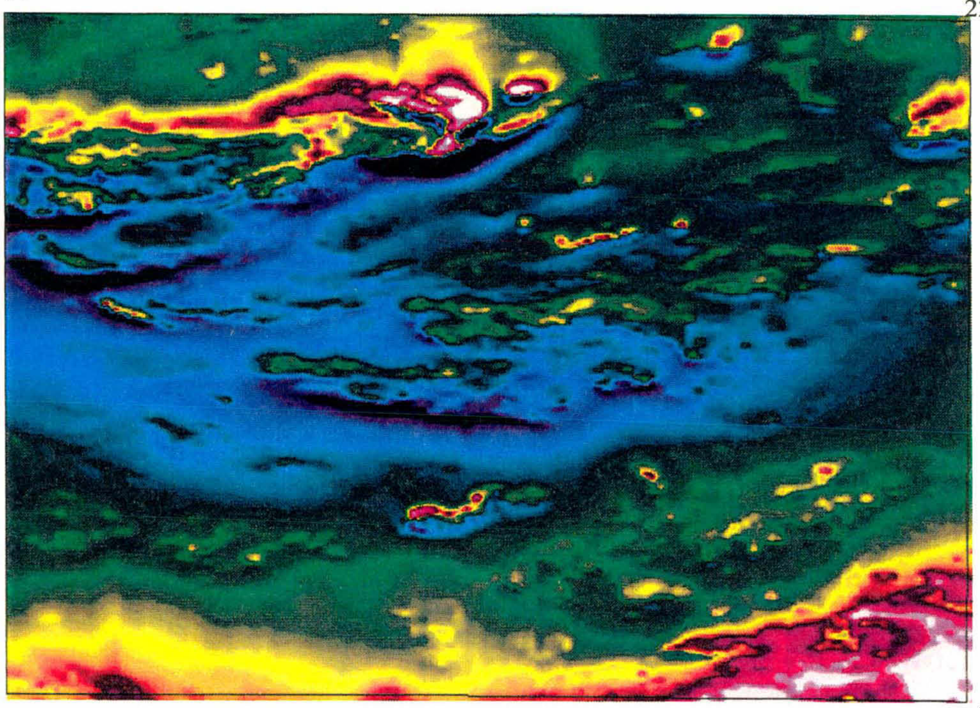


Figure 11. Total magnetic intensity with the magnetic field of the earth removed, Lake Mackay.

An apparent spatial correlation can be seen between the NOAA night thermal and the magnetics images. The warm signature seen as grey/pink/red in the NOAA image (Fig 10) maps the denser ferricretes and granites at or just below the surface. The TMI image shows a curvilinear fault system that follows a north-northeast direction across the mapsheet (Fig 11).

Officer Basin where NOAA has proved such a useful tool already (Tapley, 1988). Here igneous and metamorphic rocks of the Arunta Complex together with their younger ferricrete cappings (high temperature) have been dissected by Ethel Creek and its alluvial fan (low temperature) flowing west then northwest to Lake Mackay. An extensive unmapped northern tributary system to Ethel Creek is suggested by the crab-shaped low temperature feature (Fig 10). This northern system appears to be obscured by windblown sand seen as dark blue in the RGB gamma-ray spectrometry image (Fig 16a,b).

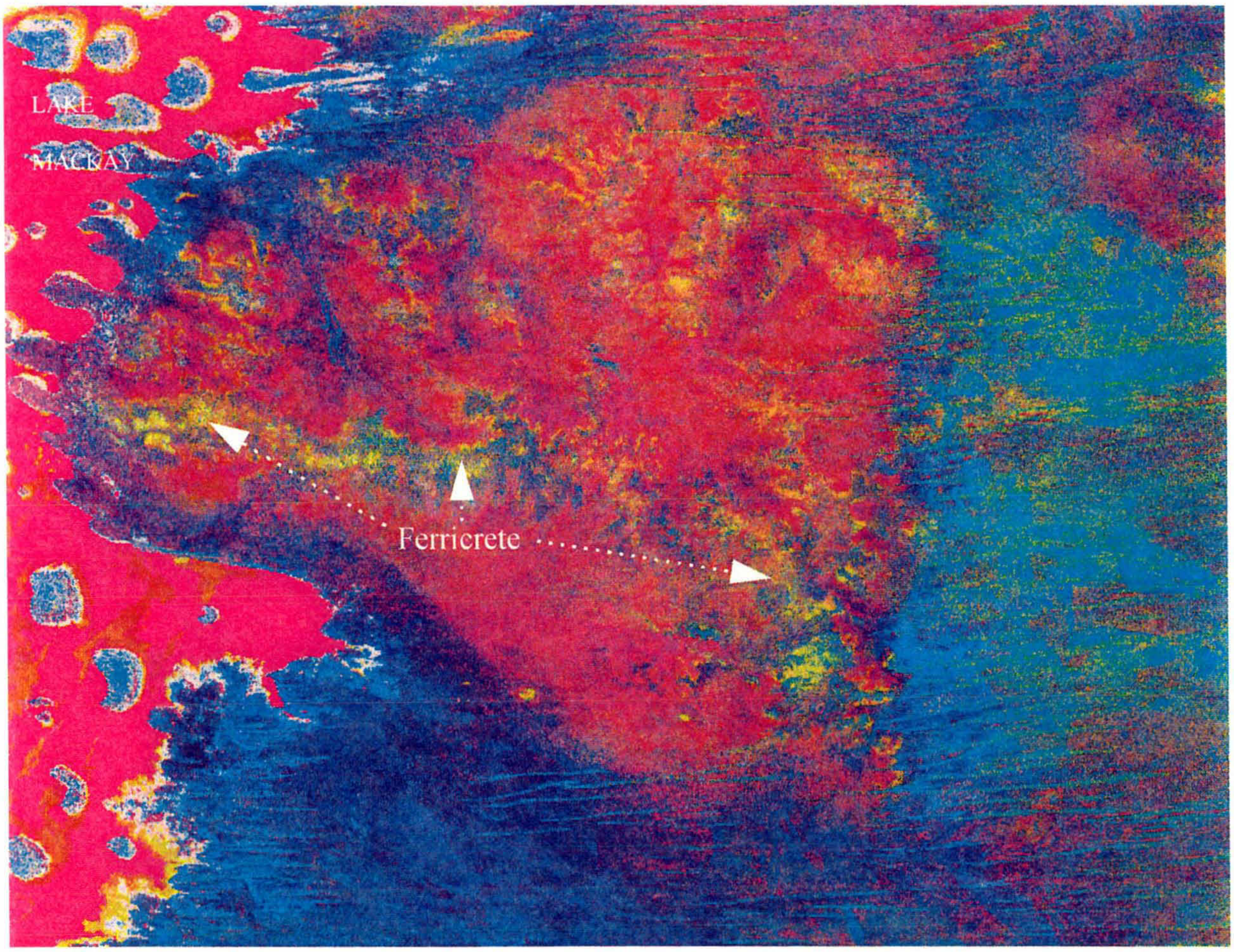
Although the alluvium at Ethel Creek is only 10m thick and unsaturated, the low salinity groundwater in the underlying metamorphic rocks suggests that it and its tributaries are an important site for groundwater recharge.

Total magnetic intensity (TMI) with the magnetic field of the earth removed has been used to contribute to mapping structural elements for the Western Water Study (English, 1997; Fig 11). A major "horsetail" splay fault system (English, 1997) predominates the image and correlates with a similar curved region which displays as a warmer, denser signature in the NOAA-AVHRR night thermal image (Fig 10). This would suggest a spatial correlation exists between the NOAA and the magnetics images, where the warm signature seen as grey/pink/red in the NOAA (Fig 10) maps the denser ferricretes and granites at or just below the surface. The TMI image shows a curvilinear fault system that follows a north-northeast direction across the mapsheet (Fig 11).

6.1.3 Ferricrete and granite east of Lake Mackay

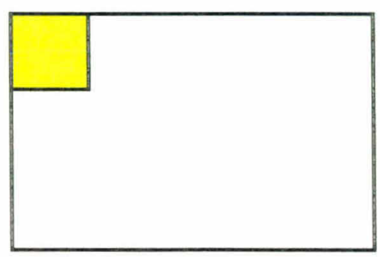
Two digital datasets were used to investigate an area of ferricrete and granite east of Lake Mackay (Fig 12 a,b). Laterites have been delineated in the Lake Mackay 1:250 000 geology. Figure 12(a) is a close up of part of the RGB false colour composite Landsat TM Unmixed Mineral image (Figure 7) that looks at the area east of Lake Mackay. The TM image offers a very good example of a distinct feature located adjacent to Lake Mackay. Areas of ferricrete are shown in green (see Figure 12a) and these areas are surrounded by yellow where the weathering of the ferricrete indicates an abundance of clay. This feature is also clearly visible as high thorium in the AGS (see Figure 12b). The Thorium is representing the presence of weathered granite, and the ferricrete can be associated with an accummulation of heavy metals.

This broad geological feature is all but invisible on the existing topographic and geological maps of the area at 1:250 000 scale. On the geology sheet it can be recognised in hindsight from a lack of sand dunes. The scattered rock outcrop mapped in the area consists of a spine of granite trending southeast with a surrounding apron of ferricrete, somewhat dissected. In the westernmost group of outcrops, closest to Lake Mackay, spot heights obtained from the digital elevation model (AUSLIG, 1996) show that ferricrete at 380-400m AHD form the highest points in the landscape, higher than nearby granite at 370-385 m AHD or the lake surface at 360m AHD. Stereoscopic examination of black and white airphotos at 1:80 000 scale proved inconclusive because it was impossible to locate the mapped outcrops on the photograph with certainty. The original annotated airphotos from field mapping in the 1960's were not available.



0 15 Kilometres

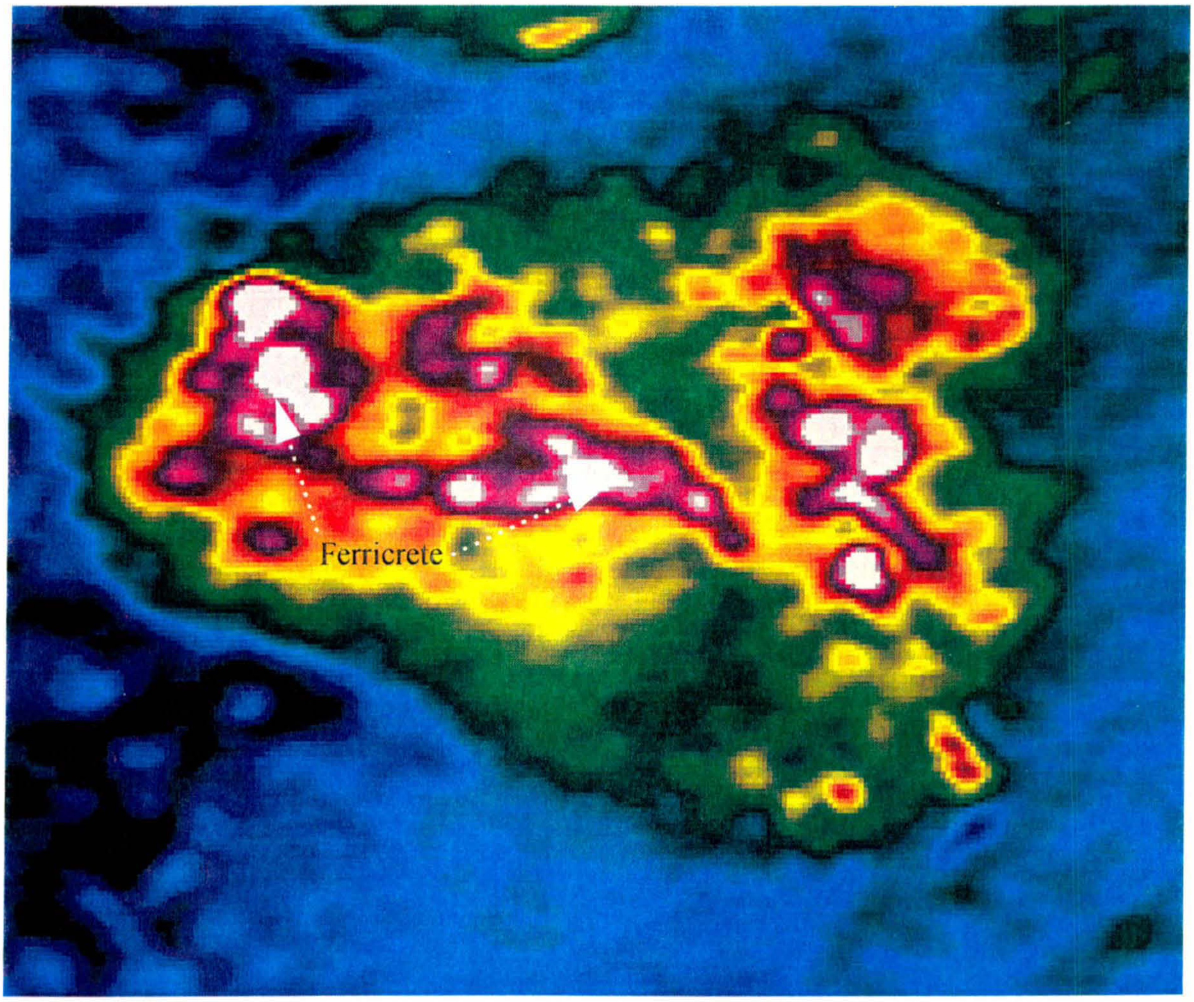
Red = clay
Green = iron oxide
Blue = quartz (or halite)



Western Water Study

Figure 12 (a). Landsat TM Unmixed Mineral image showing an area of ferricrete and granite east of Lake Mackay.

This figure covers that part of the whole study area marked in yellow (see inset). It shows an area of ferricrete not presently mapped, along with granite that has been mapped on the 1:250 000 Lake Mackay geology mapsheet.



0 15 Kilometres

White/Grey = High thorium
Blue/Black = Low thorium

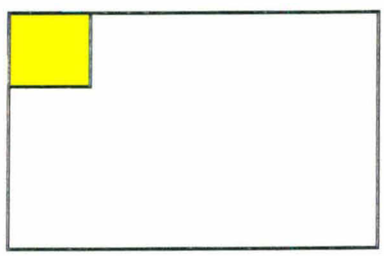


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Figure 12 (b). Thorium image showing an area of ferricrete and granite east of Lake Mackay.

This figure covers that part of the whole study area marked in yellow (see inset). It shows the area of ferricrete also identified in the Landsat TM image shown in Fig.12 (a).

Thorium is high over both granite and ferricrete but granite can be differentiated from ferricrete by its white signature on the RGB AGS image (Fig 16a). The TM image appears to show incised ferricretes and iron-rich red soil (green), granite (yellow) with clay (red) and calcrete (blue) in the topographic lows.

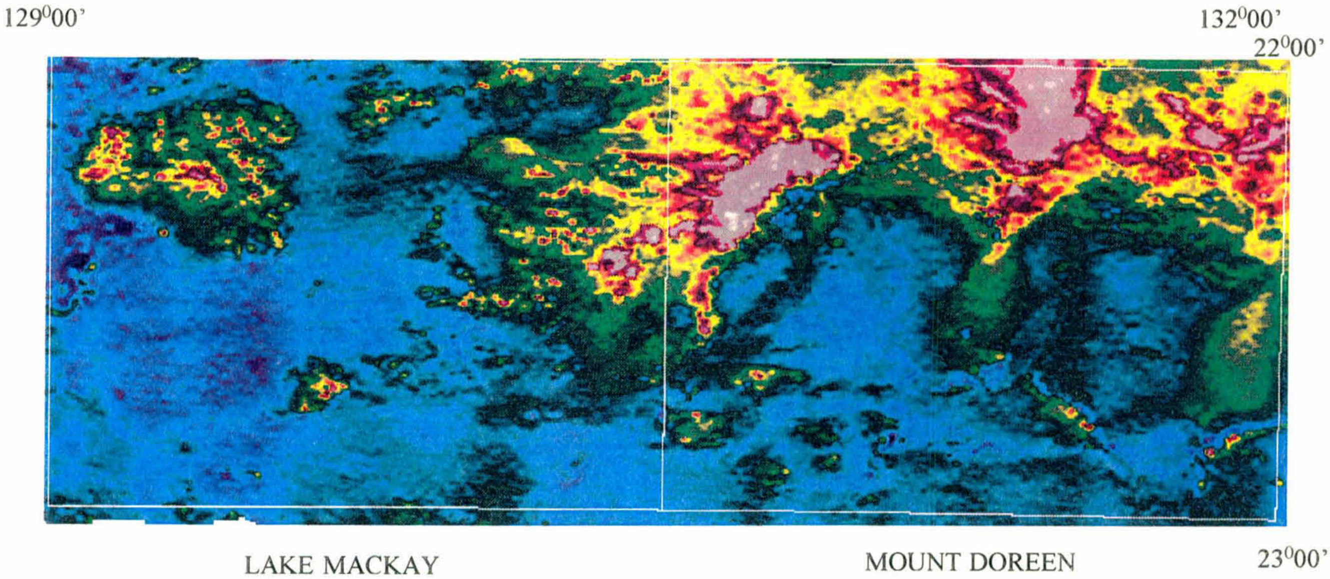
This broad feature together with the linear and more dissected ferricretes to the east and south of Lake Mackay may be a remnant of an older river system into which the younger palaeodrainage represented by Lake Mackay has been incised. This particular feature may, from its broad shape and its close association with the existing lake, have been deposited as a fan or a delta associated with an older, higher level Lake Mackay (J.R. Wilford, *pers.comm.*, 1996). Similar low ferricrete aprons in the Murray Basin at Scotia indicate groundwater discharge at higher lake levels (Ferguson *et al*, 1995).

6.1.4 Alluvial Floodouts

The single band AGS images of total count, potassium and thorium offer clear evidence of patterns of transported and deposited alluvial material which have formed modern low-energy floodouts (Figs 13 a,b to 15 a,b). A three band RGB AGS image depicts the presence of what appears to be four alluvial floodouts in the Papunya-Kintore region (Fig 16 a,b). Three alluvial floodouts can be identified originating from the granites of the Treuer Ranges in the Mount Doreen sheet area. A further area of alluvium extends eastward from Ethel Creek towards Lake Mackay. Potassium-rich alluvium, and the pathway of the mobilised material, can be traced in both the potassium and the total count images compared to the thorium image, where there is an absence of mobilised material (Fig 15 a,b).

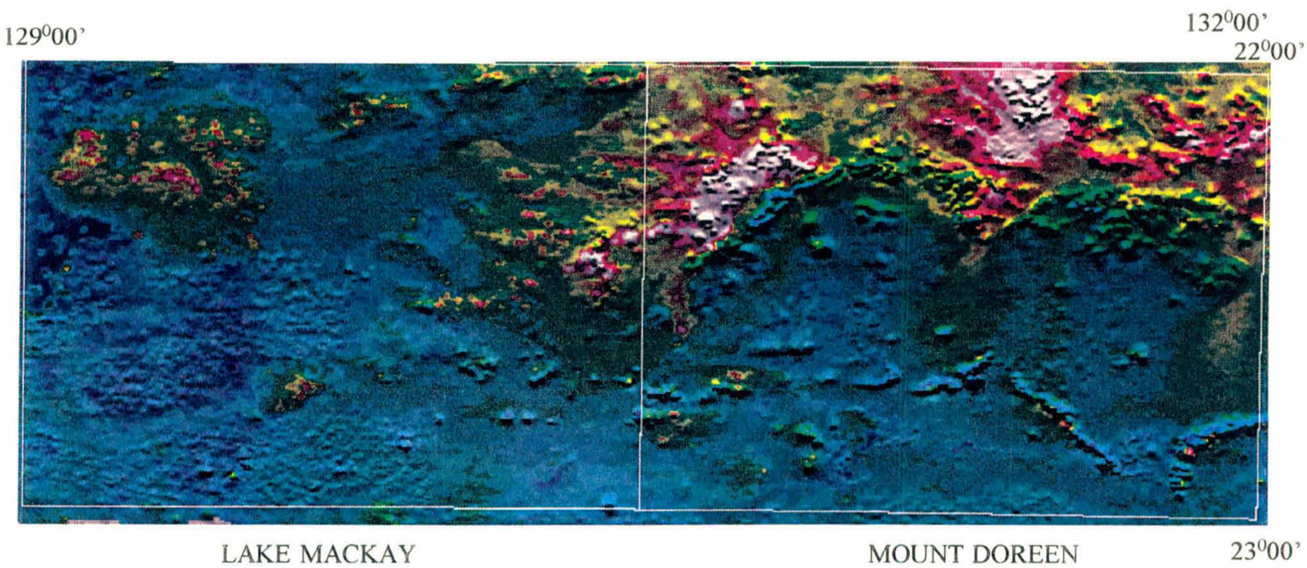
Alluvial floodouts are important in this region because the particle size of the material in these floodouts produce conditions of very high porosity and permeability, therefore becoming important for groundwater recharge. These granite-derived floodouts exhibit high potassium content and can be viewed well in the potassium AGS image (Fig 14 a,b). The shape of the floodouts are indicative of the flow processes driving their formation and direction of transportation and deposition. By overlaying the AGS onto the DEM, the direction pathway, area and shape of deposition of the potassium-rich alluvium can be traced and delineated in the potassium image as well as the RGB gamma image. AGS has been shown in the past to be useful to map regional regolithic features including soils (Wilford, 1992). Bierwirth (1996) found AGS to be useful as a rapid mapping tool in looking at soil and land degradation in the Wagga Wagga region in NSW. In the arid part of central Australia covered by the Western Water Study, the AGS details a similar story of erosion, transportation and deposition (Figs 13a,b & 14a,b). Secondary colluvial effects possibly caused by wind erosion and reworking of the alluvium deposits, can been seen in the imagery by the ovate shape of the floodout. The Mount Allan floodout in the east of the images, has travelled further and appears semi-linear to curved towards the west which could be due to a geomorphological influence.

Elongate sand dunes with an average height of 8-12 metres, transverse large areas in an east-west direction between the floodouts, but do not cover them. One explanation could be that the mapped alluvial fans are ephemeral Holocene floodplains (English, *pers. comm.*,



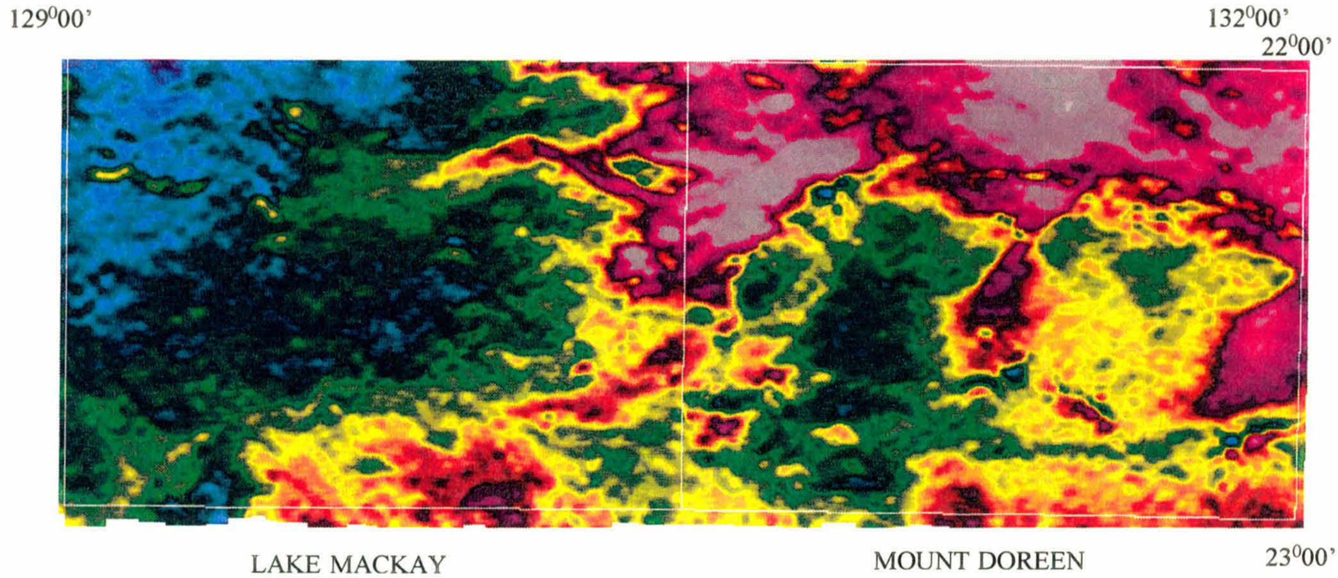
Grey = High total count   Blue = Low total count

Figure 13 (a). Total count of the gamma-ray for Lake Mackay and Mount Doreen.



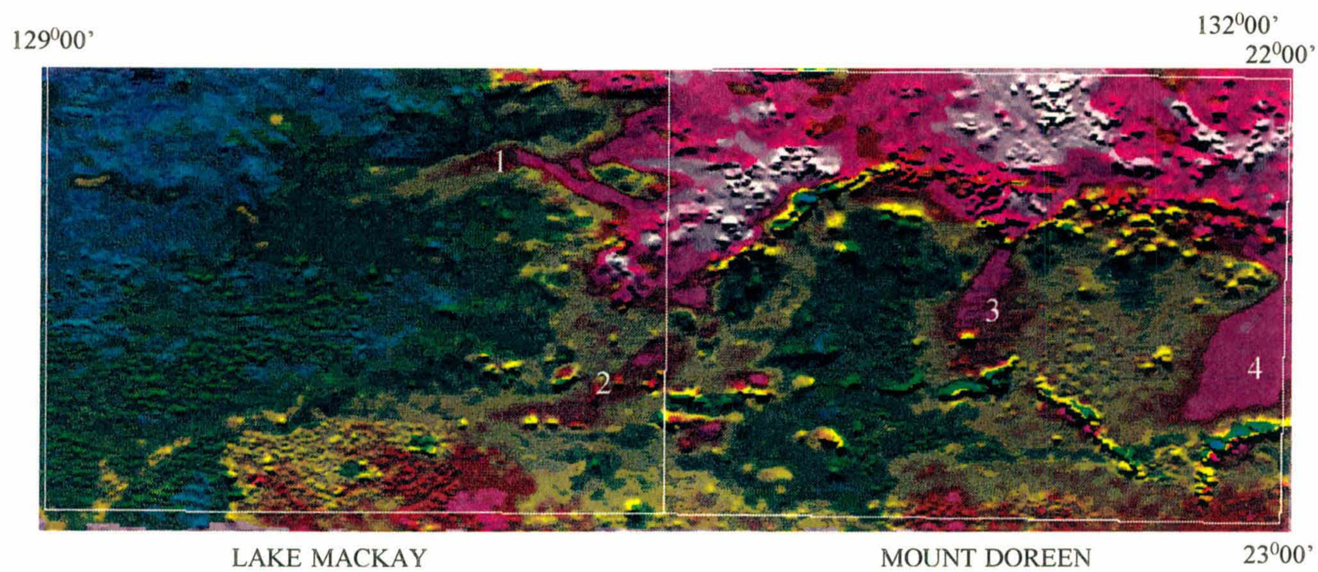
Grey = High total count   Blue = Low total count

Figure 13 (b). Total count of the gamma-ray for Lake Mackay and Mount Doreen overlain on the DEM.



Grey = High potassium Blue = Low potassium

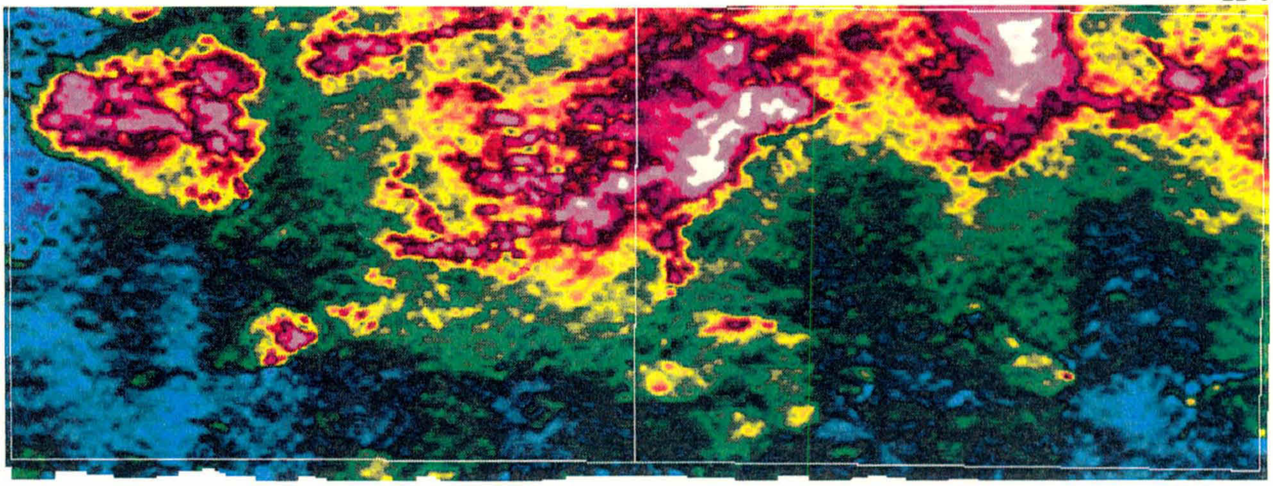
Figure 14 (a). Potassium band of the gamma-ray for Lake Mackay and Mount Doreen.



Grey = High potassium Blue = Low potassium

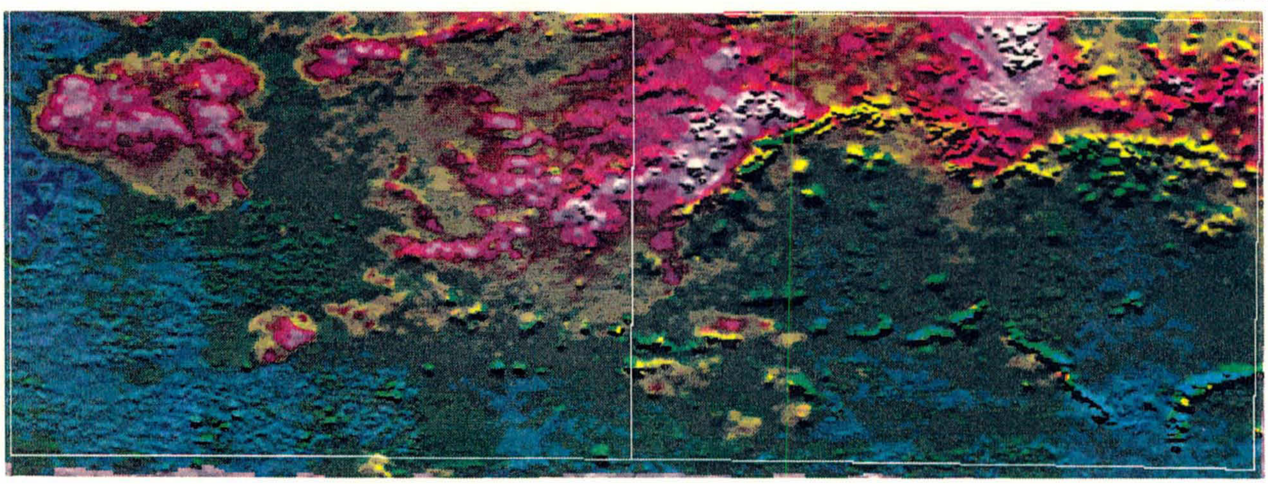
1 Ethel Creek Floodout
2 Waite Creek and Vaughan Springs Floodout
3 Djagamara Floodout
4 Mount Allan Floodout

Figure 14 (b). Potassium band of the gamma-ray for Lake Mackay and Mount Doreen overlain on the DEM.



Grey = High thorium Blue = Low thorium

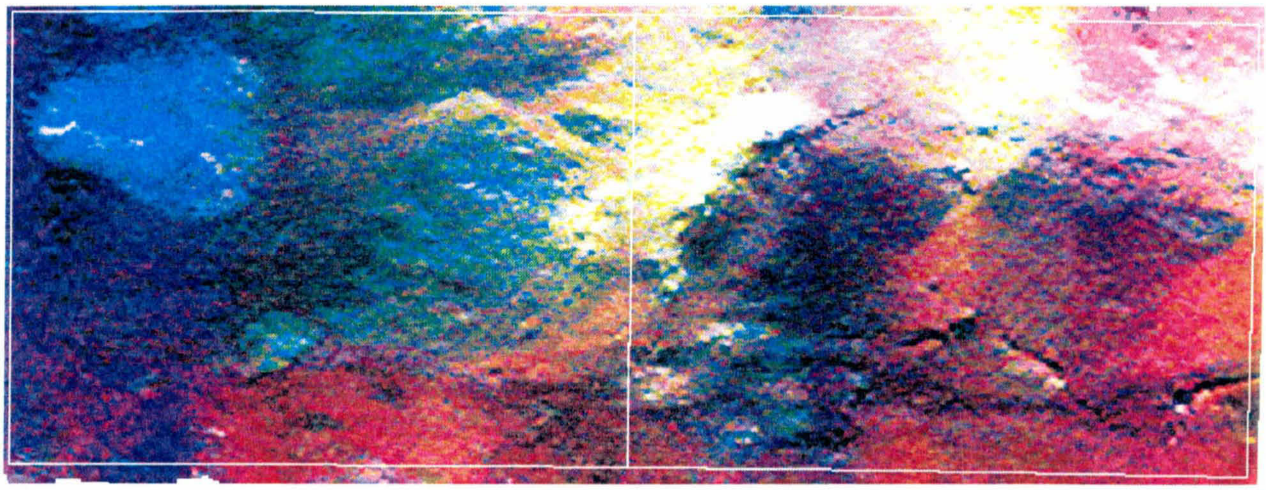
Figure 15 (a). Thorium band of the gamma-ray for Lake Mackay and Mount Doreen.



Grey = High thorium Blue = Low thorium

Figure 15 (b). Thorium band of the gamma-ray spectrometry for Lake Mackay and Mount Doreen overlain on the DEM.

129°00' 132°00' 22°00'

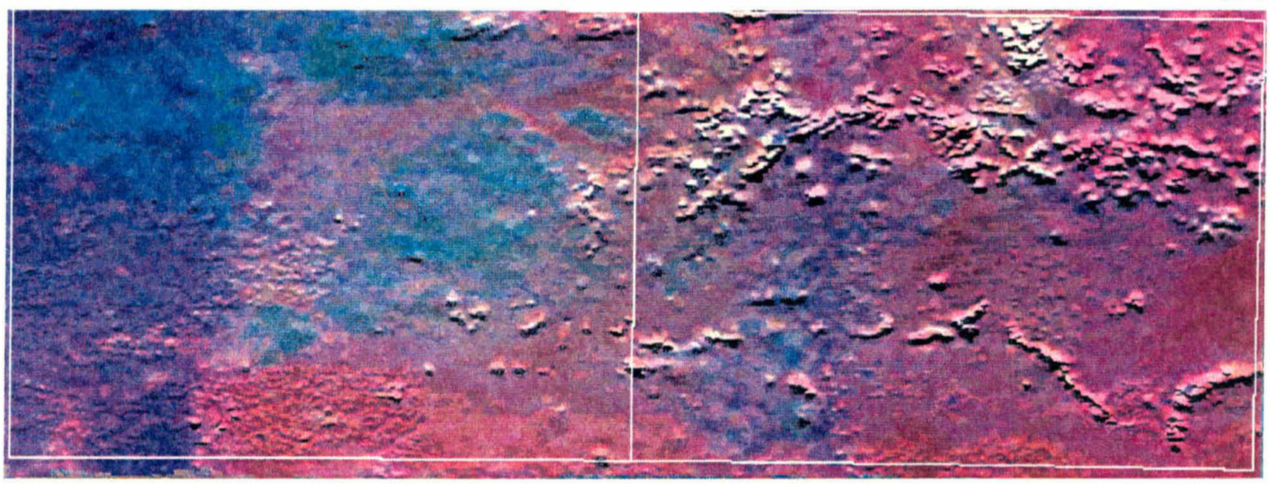


LAKE MACKAY MOUNT DOREEN 23°00'

Red = potassium Green = thorium Blue = uranium

Figure 16 (a). Red green blue gamma-ray for Lake Mackay and Mount Doreen.

129°00' 132°00' 22°00'



LAKE MACKAY MOUNT DOREEN 23°00'

Red = potassium Green = thorium Blue = uranium

Figure 16 (b). Red green blue gamma-ray for Lake Mackay and Mount Doreen overlain on the DEM.

1997), based on the observation that similar fan deposits cut through sand dune fields that are late Pleistocene in age elsewhere in central Australia.

On the 1:500 000 geological maps these surficial features are differentiated from the remainder of the aeolian sand unit (Qs) only by a lack of sand dunes. Surface samples taken from the Mount Allan floodout to the east consist of sandy clay or clayey sand which contain the element potassium as sand or silt size particles of potassium feldspar. Some potassium-rich illitic clay is a subordinate source of potassium (Fig 14a,b). These floodouts can sometimes be good indicators of underlying older high-energy fans with good aquifer and recharge characteristics. One example is the ovate Djagmara floodout in the centre-left of Figure 14a,b where gravel and sand more than 30 m thick occur consistently along an east-west seismic line extending over 20km. The eastern end of the line extends beneath dunes indicating that the older fan was more extensive laterally than the younger.

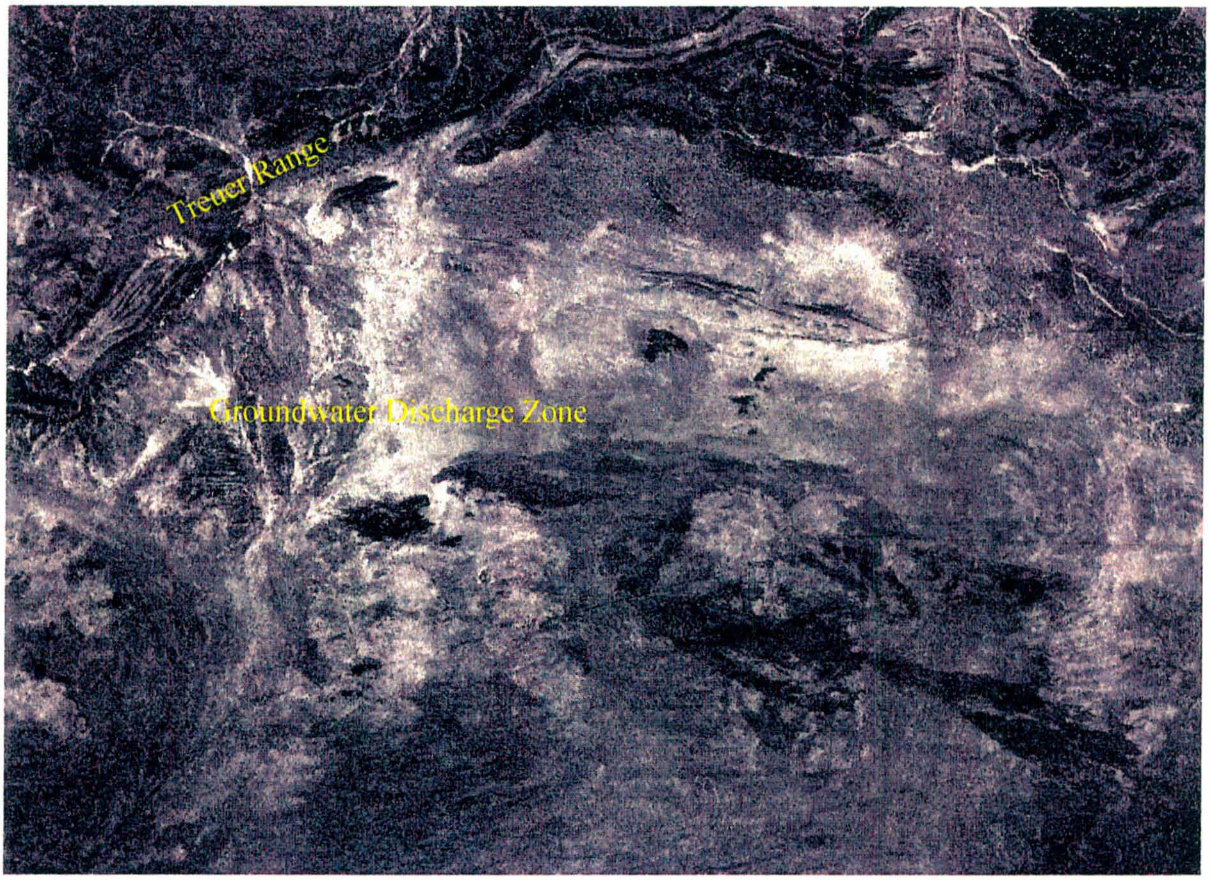
The floodouts are also useful indicators of direction of surface water flow. The Djagmara and Mount Alan floodouts (eastern half, Fig 14 a,b), show that surface water flows directly south toward the Lake Bennett - Currinya Lakes system. By contrast, the Vaughan Springs and Waite Creek floodouts running south-southwest from the Treuer Range (centre, Fig 14 a,b) and Ethel Creek floodout flowing east (upperleft, Fig 14 a,b), highlight the deflection of surface water flow westward toward Lake Mackay. The potassium image also shows the northern edge of floodouts coming off the Macdonnell Ranges to the south which provide groundwater to the Papunya and Mount Liebig communities (Woolley, 1966; Rooke, 1991).

6.1.5 Groundwater Discharge Zone Associated with Alluvial Floodouts

The single band greyscale image of the Landsat TM Unmixed Green Vegetation maps green vegetation abundance in an area of the Mount Doreen 1:250 000 mapsheet flanked to the north by granitic outcrop, being part of the Treuer Range (Fig 17). The white to light grey maps areas of higher abundance of green vegetation, and grades into darker greys as green vegetation becomes more scant. The footprint of a recent fire scar can be seen as a brush-like pattern of darker grey centred in the image (Fig 17). As previously burnt areas regenerate, the imprint of scarring becomes less visible to the naked eye in Landsat TM imagery.

The light coloured features are underlain by aeolian sand which is assumed to be shallow because bedding trends in the underlying Mount Eclipse Sandstone have been mapped through it. The only available waterbore confirms this: with less than 4m of aeolian sand above Mount Eclipse Sandstone. The midgrey feature to the north is underlain by shallow red slopewash (Qr) in turn overlying Mount Eclipse Sandstone. This medium vegetation signature is from mulga which is frequently used to map the slopewash unit in the area. The unit is clearly recognisable in the RGB TM image by its green/yellow (iron-rich) colour, speckled blue where dense mulga cover exists (Fig 7).

Surface drainage is clearly defined in this image due to the high vegetation values of the creeklines which can support a maximum density of vegetation where sufficient moisture and nutrient are concentrated. In the west of the image drainage networks converge and contribute to groundwater discharge. The pattern of drainage follows the gently sloping terrain to the south, then fans southwest to become part of the broader palaeodrainage



0 20 Kilometres

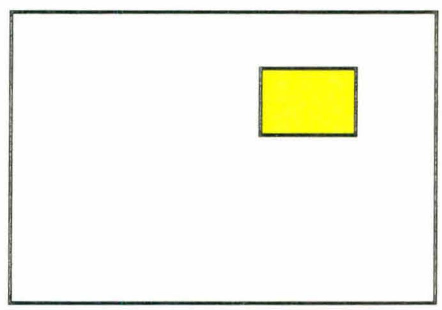


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Figure 17. Greyscale Landsat TM image of green vegetation abundance showing groundwater discharge south of the Treuer Range, Mount Doreen (yellow inset).

system visible in Figure 7. Potassium-rich clay alluvium derived from granites in the Treuer Range has become mobilised and transported to form fan-shaped alluvial deposits. The mineral-rich alluvium supplies nutrients and has a higher soil moisture holding capacity that could support vegetation growth. The abundance of green vegetation evident in Figure 17 has contributed to the stabilisation of surface material in the floodouts.

6.1.6 Windblown Features in Central Mount Wedge, Stuart Bluff Range

Figure 18 highlights what appears to be wind blown effects formed by prevailing easterly winds lifting silt and clay sized material and transporting it away to the west. This type of wind blown feature was not found in the Officer Basin area, where the thermal gradients appeared to correspond with topography (Tapley, 1988).

It is likely that silt and clay sized particles have been eroded by aeolian processes from the Proterozoic sandstone at Mount Wedge (Fig 18). This aeolian material (loess) has formed fan-shaped sediments on the leeside of Mount Wedge, a ridge rising 500 metres above the surrounding plain. This is a consistent feature in the NOAA nighttime image and the Mount Wedge example offers clear evidence of the known high thermal inertia of quartzite and sandstone (Sabins, 1978:131).

The large positive thermal anomaly north of Mount Wedge is underlain mainly by aeolian sand crossed by northwesterly dunes. Around its northern and eastern margins calcrete and red sheetwash are mapped. On its southwest margin, playa deposits of gypsum and halite occur. The Cainozoic sequence beneath these surficial units is more than 200m thick and consists largely of older lacustrine clays with some alluvial sand. The dunes were deposited in the last glacial maximum about 20 000 years ago from easterly winds at the northern edge of an anticlockwise system operating around the Central Australian highlands (Wasson, 1986). The mountain range is made up of extremely resistant quartzite, which overlies granite of the Arunta Block. The quartzite (Vaughan Springs Quartzite) is the basal unit of the Ngalia Basin sequence and dips gently to the northeast (Fig 1).

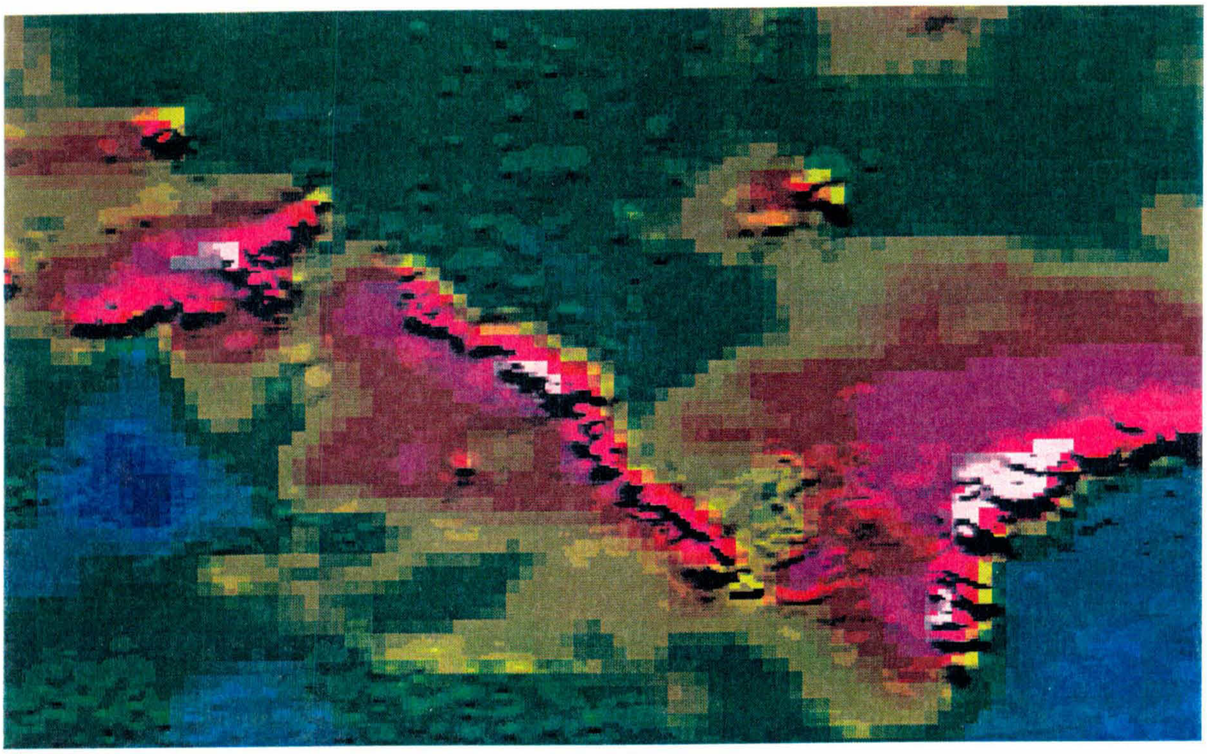
The strong negative thermal anomaly which exists to the south of the range - over apparently similar aeolian dune sands - may be a thermal effect caused by ponding of cooler air on the southern (cooler) side of mountain ranges (Fig 18).

6.2 Limitations of the Data

From the vantage point of hindsight, some limitations to the usefulness of remotely sensed data for a study such as this one will be outlined in brief. Such limitations can include scale, availability, cost and data integrity.

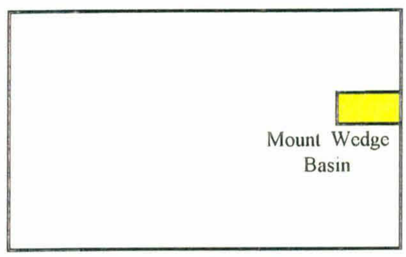
6.2.1 Scale

An important factor to consider when looking at a variety of digital data, is the scale of the data relative to the purpose of the study. The spatial coverage of the Western Water Study necessitated a regional approach. Data used for this study offered a range of resolutions from 30 metres with the Landsat TM to 1100 metres for the NOAA-AVHRR imagery.



0 20 Kilometres

Pink = High thermal radiance
Blue = Low thermal radiance



Western Water Study

Figure 18. NOAA-AVHRR night thermal image showing windblown effects at Mount Wedge Basin, Stuart Bluff Range.

This figure covers that part of the whole study area marked in yellow (see inset). It shows apparent aeolian transportation of sediment by prevailing easterly winds.

When looking at a range of environmental features, scale becomes one of the crucial factors when collating information. Something may be distinct at a pixel resolution of 30 metres, but become all but lost with a pixel size of 1100 metres. The low resolution of the NOAA-AVHRR limits its use to identifying broad scale features. If this data is used at a larger scale the result is a highly pixelated view that can introduce distortions in the data or a reduction in the integrity of the information.

6.2.2 Availability and Temporal Continuum

Acquisition of data can be hampered by the unavailability and/or paucity of quality. It is necessary to acquire cloud-free satellite data to ensure the best level of visibility. It may be necessary to accept data collected at different times, and there may not be the ideal temporal continuum.

6.2.3 Cost and Data Integrity

Remotely sensed data can range in cost and hence its availability can depend upon the budget constraints of a project. Furthermore, specialised staff may be required to process the data ready for use. Time taken in processing, checking for data quality, integrity, creating metadata documentation which will include lineage reporting are important considerations. Documentation can be crucial to trace what has been done to the data and this will give the user an indication of data integrity. Each step in processing can introduce change thereby creating a level of generalisation in the data.

7.0 CONCLUSIONS

The remotely sensed and digital datasets form a useful starting point for the development of a groundwater resources information base. Remotely sensed data overlain on a digital elevation model has been a useful tool to elucidate information about regional geologic and geomorphic features in the Papunya-Kintore region of the Northern Territory.

As a first pass reconnaissance study, features have been identified through visual interpretation and collation. The methodology developed in this study is transferable to future studies undertaken in the arid region. A regional palaeodrainage system divides the study area and forms part of a larger system that transverses a wider region of arid central Australia from Lake Lewis in the east, across the West Australian Shield. A large, significant area of ferricrete and granite east of Lake Mackay has been identified using the Landsat TM Unmixed Mineral image and the thorium band of the AGS. The NOAA-AVHRR 11 night thermal imagery correlates generally with topographic highs and lows. Regional magnetic highs across the Lake Mackay mapsheet appear to correlate with the warm thermal signature in the NOAA-AVHRR night image.

The spectral unmixing analysis was very useful to study the composition of geological features and surface material by reducing the masking effects of vegetation in Landsat TM imagery. Although the removal of the vegetation effects may not be complete, the much improved mineral image displayed the abundance of end-member materials of clay, iron oxide and quartz. The green vegetation image was useful to depict relative abundance and was found to indicate potential groundwater recharge.

Airborne gamma-ray spectrometry (AGS) has been useful to visualise and identify a number of geophysical features in the study area. The thorium band of the AGS was used to delineate an area of ferricrete east of Lake Mackay not presently mapped on the Lake Mackay 1: 250 000 geology mapsheet. Four separate floodouts were identified: (1) Ethel Creek, (2) Waite Creek and Vaughan Springs, (3) Djagmara and (4) Mount Allan floodouts. The single band images of potassium and total count, along with the three band false colour composite images were used to trace the form and flow direction of potassium-rich alluvial material that make up these floodouts. AGS along with Landsat TM imagery has also been shown to be a reliable tool in mapping regolith and soil degradation in other regions such as Wagga Wagga, NSW, and the Cape York Peninsula, Queensland.

Our approach is considered to be a cost effective method of reconnaissance mapping of regolith materials and hydrogeological features over a large and relatively unknown area as the Western Water Study area.

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8.0 ACKNOWLEDGMENTS

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