Regolith landform mapping in the Paralana Creek catchment from remotely sensed data, Northern Flinders Ranges, South Australia

Dharmarajah, M.

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Abstract

This study creates three regolith-landform maps of the Paralana Creek catchment on the north-eastern margin of the Flinders Ranges using three readily available remotely sensed data types: a 2D digital elevation model, an airborne gamma ray radiometric response image, and a QuickBird satellite image, each method providing data about different aspects of the landscape.

The regolith-landform map based on the digital elevation model provided an overview of the major landforms, with a basic understanding of the regolith and landform types. The regolith-landform map based on the airborne radiometric image provided data about the concentration and distribution of radioelements within the landscape, as well as a basic understanding of regolith and landform types and processes within the study area. The regolith-landform map based on the QuickBird image provided the most data about the regolith-landform units of the area, as well as current and previous landscape processes and evolution. Using these remote sensing methods this study created three regolith-landform maps, as well as identifying regolith-landform units, how landforms affect regolith type, distribution and succession, along with radioelement composition, transport and distribution within the study area. Map interpretation used the understanding of the landscape gained from all three maps in combination.

KEYWORDS; regolith landform unit, Paralana Creek, Flinders Ranges, Frome Plains, digital elevation model, radiometrics, QuickBird

1. Introduction

This Honours project characterises and maps the regolith-landforms of the Paralana Creek catchment, in the Mount Painter Inlier of the Northern Flinders Ranges and the adjacent Frome Plains of the Curnamona Craton. The 32 x 25 km study area encompasses part of the creek within the Mount Painter Inlier on the edge of the ranges to 30 km east into the Frome Plains.

The aim of this project is to compare and contrast three maps of the Paralana Creek catchment study area created using different remote sensing techniques. This includes:

1. characterisation of regolith-landforms and regolith-landform units;
2. synthesis of remotely sensed data to produce a regolith-landform map of the Paralana Creek catchment area; and,
3. assessment and evaluation of this use of different remotely sensed data sets for characterising regolith-landforms and therefore consideration of the suitability of different data sets for further regolith-landform mapping programs in the region.

This area has not been previously studied for the purposes of detailed regolith-landform mapping, though Gibson (1996) created a 1:500 000 regolith landform map of the Curnamona that covers the mapping area. However, due to the scale of mapping is only identifies four regolith landform units (Gibson 1996). Heathgate Resources has also carried out extensive geophysical and remote sensing surveys in parts of the study area (McAvaney 2008).

This project involves creating regolith maps using a 2D digital elevation model image, a radiometric response image, and a QuickBird satellite image of the northern Flinders Ranges. The QuickBird image was printed out to A1 size and the regolith-landform map interpreted by eye and drawn onto a map overlay. The digital elevation model and radiometric response images were treated in the same way, at A3 size.

Each remote sensing technique had strengths and weaknesses for regolith mapping, so their use in combination created a better overall representation of the study area. The QuickBird image was the most detailed as it provided an image of the land surface and groundcover at a high resolution, but the digital elevation model and radiometric response images provided an understanding of the underlying landscape processes active in the area and so supported the QuickBird image based regolith-landform unit interpretation. The QuickBird image was the best suited for regolith landform mapping, becoming the base for the regolith-landform unit map of this study.

2. Setting

2.1 Location and Land Use

The study area is situated in east central South Australia, approx 530 km northeast of Adelaide, at the northernmost tip of the Flinders Ranges (Figure 1).

The western portion of the study area is within the Arkaroola – Mt. Painter Wildlife

Sanctuary and the eastern portion within Wooltana Station. Arkaroola currently is run as an environmental preserve and tourist attraction, while there is some mineral exploration and mining on Wooltana (Sprigg 1984, McAvaney 2008). Previously both stations were under pastoral use, with sheep grazing from 1857 intermittently until 1967 when Arkaroola was bought by the Sprigg family for environmental conservation (Sprigg 1984). There has also been some mineral prospecting and small scale mining of copper, gold, uranium ores, lead, zinc and gemstones (Sprigg 1984, Hore *et al.* 2005).

2.2 Geological Setting

The study area includes a portion of the eastern edge of the northern Flinders Ranges including part of the Mount Painter Inlier and the western part of the Lake Frome plains in the north-western portion of the Curnamona Province (Hore *et al.* 2005).

2.2.1 Northern Flinders Ranges

The northern Flinders Ranges include the Mt. Painter and Mt. Babbage Inliers, which are unconformably surrounded by Mesozoic and younger sediments to the east and Palaeo-Mesoproterozoic metasediments to south and west (Mildren & Sandiford 1995, Brugger *et al.* 2003, Hore *et al.* 2005, Long *et al.* 2005, Davey & Hill 2007, Paul *et al.* 2009). The ranges are geomorphically young, much of the ranges having elevations above 300 m and some peaks reaching ~1100 m (Sprigg 1984, Célérier *et al.* 2005, Quigley *et al.* 2007a, Quigley *et al.* 2007b). They are currently seismically active, with hundreds of minor quakes detected annually (Sprigg 1984, Célérier *et al.* 2005, Davey & Hill 2007, Dubieniecki & Hill 2007, Quigley *et al.* 2007a, Quigley *et al.* 2007b).

The Mt. Painter Inlier (MPI) is largely composed of arenaceous Palaeoproterozoic to Mesoproterozoic gneisses, granites and metasediments (collectively called the Radium Creek Metamorphics) that have been intruded by Mesoproterozoic granites as well as Ordovician granites, pegmatites, leucogranites and granodiorites (Coats & Blissett 1971, Mildren & Sandiford 1995, Paul *et al.* 1999, Neumann *et al.* 2000, Brugger *et al.* 2003, Hore *et al.* 2005, Long *et al.* 2005). The rocks of the Mt. Painter Inlier contain high levels of Th and U (10-100ppm), which produce large amounts of heat due to radioactive decay (Brugger *et al.* 2003, Long *et al.* 2005). Both the Mt. Painter Inlier and ranges were affected by the Cambro-Ordovician Delamerian Orogeny (520-490 Ma), causing partial metamorphism and deformation with about 10-20% shortening (Neumann *et al.* 2000, Célérier *et al.* 2005, Hore *et al.* 2005, Long *et al.* 2005, Paul *et al.* 2009).

2.2.2 Lake Frome Plains

The study area extends approx. 30 km east from the edge of the ranges into the Frome Plains. The plains have low elevation and relief, with the uppermost portion being dominated by Tertiary to Quaternary age material (Long *et al.* 2005, Quigley *et al.* 2007a, Quigley *et al.* 2007b, McAvaney 2008). The surface sediments are largely recent colluvial and alluvial material derived from the ranges, with angularities varying from sub-rounded to angular indicating ongoing erosion and weathering processes. Also present are fine sandy to silty sediments, yellow-orange-brown or whitish in colour, likely derived from eroded materials as well as some aeolian sources.

The Frome Plains have formed in distinct layers, with the uppermost being recent colluvial and alluvial material, overlying the Quaternary Willawortina Formation, the Tertiary Namba and Eyre Formations, the Mesozoic Bulldog Shale and Cadna-Owie Formation and the basement rocks (Célérier *et al.* 2005, Long *et al.* 2005, Märten 2006, Dubieniecki & Hill 2007, Neimanis *et al.* 2007, McAvaney 2008). The Namba and Eyre Formations contain uranium mineralisations which are thought to be derived from the uraniferous granites of the Flinders Ranges (Märten 2006, Davey & Hill 2007, Neimanis *et al.* 2007, McAvaney 2008, Hill & Hore 2009). There is also evidence of post-depositional tectonic movement such as faulting and tiling of the formations (Davey & Hill 2007, Dubieniecki & Hill 2007, Hill & Hore 2009).

2.3 Structural Setting

The geomorphologic structures within the study area have a strong control on the regolith-landforms that developed (Quigley *et. al.* 2007a, Quigley *et. al.* 2007b). The major control in the study area is the sharp transition from the ranges to plains defined by the Paralana Fault (Hore *et al.* 1999, Paul *et al.* 1999, Quigley *et al.* 2007a).

There are also multiple small faults crosscutting this main fault that trend approx. NW-SE, and are likely the major control on the main drainage channels in the study area, including Paralana Creek.

2.3.1 Paralana Fault

The Paralana Fault delineates the edge of the Flinders Ranges in the study area (Paul *et* *al.* 1999, Hore *et al.* 2005, Quigley *et al.* 2007a). It is a major structure, penetrating the basement and being intermittently active since the Neoproterozoic (Paul *et al.* 1999, Célérier *et al.* 2005, Hore *et al.* 2005, Quigley *et al.* 2007a). It became a reverse fault due to SE-NW compression during the Delamerian Orogeny and was again affected by compression during the Alice Springs Orogeny (330 Ma) (Célérier *et al.* 2005, Hore *et al.* 2005, Quigley *et al.* 2007b).

2.3.2 Paralana Hot Springs

Paralana Hot Springs is the only active hot spring in the area, though there are many fossil hydrothermal/epithermal systems in the northern Flinders Ranges indicating previous widespread activity (Hore *et al.* 2005, Long *et al.* 2005). It is situated in the basement rocks of the Mount Painter Inlier, close to an intersection of Paralana and Lady Buxton Faults (Coats & Blissett 1971). The hydrothermal activity is thought to be associated with the highly radioactive rocks of the Mount Painter Inlier (Coats & Blissett 1971, Brugger *et al.* 2003, Long *et al.* 2005). Hot water reaching temperatures of ~60 °C well up through faults and cracks to form the spring which flows into Paralana Creek and out onto Frome Plains (Coats & Blissett 1971, Paul *et al.* 1999, Brugger *et al.* 2003, Hore *et al.* 2005).

2.3 Climate

The climate of the area is semi-arid, with widely varying day-night temperatures (Coats & Blissett 1971, Sprigg 1984, BOM 2009). Summers are hot and have the highest rainfall, with cool winters that experience low to moderate rainfall (Coats & Blissett 1971, Sprigg 1984, BOM 2009). Rainfall is erratic, with low frequency but high intensity rains causing flash-flooding (Sprigg 1984, Quigley *et al.* 2007b). This has contributed to extensive erosion of upland settings and generally thin regolith cover over bedrock exposures within the range-front area (Coats & Blissett 1971, Sprigg 1984, Quigley *et al.* 2007a, Quigley *et al.* 2007b).

Annual average rainfall is difficult to calculate due to widely variable annual conditions (Sprigg 1984). From 1937-1970 the average annual rainfall was 216 mm, while from 1971-1998 it was 440mm, over double what it was previously (Sprigg 1984). Average daily temperatures range from 18-35 °C, with overnight temperatures of 22 – -3°C (Sprigg 1984). The Australian Bureau of Meteorology gives an average rainfall of 248.2 mm from 1938 to 2009, with average daily temperatures ranging from 16.5 - 34.2 °C and overnight temperatures of 3.4 - 20°C (BOM 2009).

2.4 Geomorphology

The study area is characterised by the Flinders Ranges to the west and the Frome Plains to the south, so the study area includes areas of up to ~300 m (above sea level) in the ranges to ~50 m (above sea level) on the plains (Geoscience Australia 1973, Geoscience Australia 1980).

2.5 Vegetation

Dominant vegetation includes spinifex (*Triodia basedowii*), curly mallee (*Eucalyptus gillii*) and gum-barked coolibah (*Eucalyptus intertexta)* on both the ranges and plains, with mallee (*Eucalyptus* sp.) and mulga (*Acacia aneura*) abundant in the ranges and bluebush (*Maireana.* sp.), bladder saltbush (*Atriplex vesicaria*), and Mitchell grass (*Astrebla* sp.) on the plains (Coats & Blissett 1971, Neimanis *et al.* 2007, Hill and Hore 2009). River Red Gums (*Eucalyptus camaldulensis*) are locally abundant in waterways on the plains and ranges (Neimanis *et al.* 2007, Hill & Hore 2009).

3. Remote Sensing

The majority of the project work was done using remotely sensed data in the office. The field component was walking and driving through part of the study area to record a basic understanding of the land surface, general conditions and biota.

Three remote sensing methods were used: a 2D digital elevation model image (Appendix A), an airborne radiometric response image (Appendix B), and a high resolution true colour QuickBird satellite image (Appendix C).

3.1 Mapping using a DEM image

Digital elevation models (DEMs) are 2D or 3D models to represent the topography and shape of the Earth's surface (Sefercik 2007). There are three methods of generating these, using geodesic methods (e.g. topographic maps), photogrammetric flight data or remote sensing such as radar (Belliss *et al.* 2000, Sefercik 2007).

While DEMs are not used for regolith mapping directly, they are commonly used in conjunction with mapping techniques such as radiometrics (Craig *et al.* 1999, Pickup & Marks 2001, Wilford *et al.* 2001, Wilford 2002, Sefercik 2007). This project used a 2D DEM image, with the elevations shown by the use of colour (McAvaney 2008).

3.2 Mapping using a radiometric image

Airborne gamma-ray spectrometry (i.e. radiometrics) is a passive remote-sensing method of measuring the abundance and therefore distribution of radioisotopes K, Th and U in rocks and regolith by measuring gamma-ray emittance from the radioactive decay of these elements (Duval 1990, Minty 1997, Wilford *et al.* 1997, Pickup & Marks 2001, Wilford *et al.* 2001, Wilford 2002, Wilford & Minty 2007, Munday 2008, Scott & Pain 2008). Gamma rays are generally detected from the upper 30-45cm of dry rock/regolith, though non-radiogenic cover can also reduce the response detected (Duval 1990, Minty 1997, Wilford *et al.* 1997, Craig *et al.* 1999, Pickup & Marks 2001, Wilford *et al.* 2001, Wilford 2002, Wilford & Minty 2007, Munday 2008, Scott & Pain 2008). Radiometric measurements are generally displayed in RGB false colour composites, with U = blue, Th = green, K = red, and a black to white hue indicating high or low concentrations (Wilford 2002, Wilford & Minty 2007).

Uranium and thorium are not measured directly, but extrapolated from the amount of gamma radiation from their daughter isotopes (Minty 1997, Wilford *et al.* 2001, Wilford 2002, Munday 2008, Scott & Pain 2008). U and Th are measured in ppm, K as a percentage (Duval 1990, Minty 1997, Wilford *et al.* 1997, Pickup & Marks 2001, Wilford 2002, Munday 2008). Given that the ranges in the study area are known to contain radioactive granites, it is expected to see a strong radiometric response in the ranges exposures (Célérier *et al.* 2005, Long *et al.* 2005, McAvaney 2008).

The spatial resolution of data is relatively low due to the diffuse nature of the gamma rays, with more than 20% of radioactivity detected from a height of 100m will be from an area of radius more than 300m (Minty 1997, Wilford *et al.* 1997). Other sources of error include disquilibrium, where one or more of the decay isotopes is concentrated or removed from the decay chain, moisture content of the regolith, and preferential K uptake by plants (Ollier & Pain 1996, Minty 1997, Wilford *et al.* 1997, Wilford 2002). The study area is generally arid with sparse vegetation, so these are unlikely to be sources of error.

As radioelement concentration can be affected by weathering processes, a radiometric response image of an active depositional system is more indicative of the geochemistry and composition of the source material, while in a less active or inactive depositional regime it is more indicative of weathering processes (Wilford *et al.* 1997, Scott & Pain 2008).

It is inadequate for regolith-landform mapping by itself, so should be combined with other remote sensing techniques, such as DEM and/or QuickBird imagery (Ollier &

Pain 1996, Wilford *et al.* 1997, Craig *et al.* 1999, Pickup & Marks 2001, Wilford *et al.* 2001, Wilford 2002, Wilford & Minty 2007). This study used an airborne radiometric survey (McAvaney 2008).

3.3 Mapping using a QuickBird image

QuickBird satellite imagery uses a multispectral remote sensing technique which measures the degree of reflectance in the visible to short-wave infra-red wavelength bands of materials on the Earth's surface to determine of composition, distribution, and characteristics of surface materials (Dauth 1997, Wilford & Creasey 2002). Multispectral remote sensing has been extensively used to map land surfaces, particularly regolith and geological mapping as well as vegetation mapping, agriculture, forestry and similar fields (Craig *et al.* 1999, Wilford & Creasey 2002, Benger 2003). This data can be displayed as a simple true colour high resolution image or be used to identify the unique spectral signatures of surface materials and therefore generate a regolith unit map using techniques such as principal component analysis or band ratios to distinguish between different regolith materials or highlight characteristics of interest (Wilford & Creasey 2002, Benger 2003). This study used a digital true colour high resolution visible light spectrum image for regolith landform interpretation and mapping.

4. Methods

The fieldwork was carried out in May with a total of one week in the field. It involved walking through part of the study area, taking notes about the landforms, regolith, biota and the general environment.

The remotely sensed data were provided by Steve Hill and Steve Hore, from PIRSA and Heathgate Resources Pty. Ltd.

The different regolith-landforms were interpreted largely from visual examination of the QuickBird image, with some input from DEM and radiometric imagery as well as from fieldwork. Map creation involved the interpretation of landforms and regolith types from colour and pattern changes of the land surface, the topography of the study area and radioelement distribution. All three regolith-landform maps used same general method for map creation – interpreting colour and pattern changes, boundaries and shape to provide data about the land surface.

4.1 Map compilation and production

Regolith development is strongly influenced by and related to the underlying landforms, therefore for regolith-landform mapping and interpretation an understanding of landscape processes is required (Pain and Ollier 1996, Quigley *et al.* 2007a, Quigley *et al.* 2007b).

Mapping has three purposes, to record data, to present data, and for research purposes (Pain & Ollier 1996). Recording includes collecting data and information such as regolith and landform type, landscape composition, and weathering extent which can then be visually presented in a map form (Pain & Ollier 1996). This visual format allows easier interpretation and use of the data, e.g. looking for drainage patterns and how they correlate with regolith and landform type (Pain & Ollier 1996). Research leads directly from this, with such maps being used for purposes such as examining and understanding landscape processes, or studying landform succession (Pain & Ollier 1996).

Regolith maps are created using regolith-landform units (RLUs) (Ollier & Pain 1996, Craig *et al.* 1999, Pain *et al.* 2007). A RLU is an area which has a homogenous regolith and landform attribute set at that mapping scale (Ollier & Pain 1996, Craig *et al.* 1999). The regolith type is strongly influenced by the landform, affecting both composition and location (Ollier & Pain 1996, Craig *et al.* 1999). RLUs are not necessarily only one type of regolith material, but can be groups of associated regolith materials and landform characteristics (Ollier & Pain 1996, Craig *et al.* 1999, Pain *et al.* 2007). The specificity of a RLU's composition is dependent on the mapping scale – the larger the scale the less specific the RLU, i.e. becoming more generalised as the map scale increases (Ollier & Pain 1996, Craig *et al.* 1999, Pain *et al.* 2007).

RLUs have a specific naming format which provides the basic regolith and landform data about that particular unit. The naming format is a letter or letter combination in capitals, a letter or letter combination in lower case, and occasionally a numeral e.g.

ACah1. The capital letters indicate the regolith type, the lower case the landform type, and the numeral is used to distinguish between units with a similar regolith and landform set (Craig *et al.* 1999, Pain *et al.* 2007). Each regolith and landform type has its own unique code (Craig *et al.* 1999, Pain *et al.* 2007).

The exact classification of RLUs is up to the individual(s) interpreting the landscape, so there is some flexibility in how landscapes are classified (Pain *et al.* 2007). For example, what may be called an erosional rise in a relatively flat landscape may be classified as part of a plain in a landscape with greater topographical variance (Pain *et al.* 2007).

4.2 Digital Elevation Model

The digital elevation model (DEM) image (Figure 2) was displayed as a colour image with the elevations displayed in colours, white and red being the highest elevation, and magenta the lowest. It showed outlines of major landforms as well as the progression of high to low-lying land surfaces of the ranges to the plains, providing an overview of landforms in that area.

The DEM based regolith landform map (Figure 3) was straightforward to interpret, showing only elevation and topography of the study area. To create the map the major colour changes indicating topographic changes were traced. These traced outlines correlated to the boundaries of the major landforms – the edge of the ranges, the uppermost part of Paralana and Four Mile Creeks, and the drainage depression in the upper centre of the study area. (Note the DEM image did not cover the whole study area).

4.3 Radiometrics

The radiometric image (Figure 4) provided was a simple airborne gamma ray radiometric response image, with colour and colour intensity indicating type and amount of radiometric response. The ranges have bright, strong colours, indicating a strong radiometric response and therefore a high concentration of radioactive materials, especially U. The plains are relatively dark in comparison, indicating little to no radioactive surface materials. Paralana Creek shows up moderately well, being reasonably well defined with a higher response closer to the ranges, decreasing as it moves out onto the plains and changes from a creek to a fan deposit. This provided a general indication of regolith-landforms of the area.

The radiometric image based regolith landform map (Figure 5) was relatively straightforward to interpret. The changes in colour were traced, showing easily recognisable outlines of major landforms such as the edge of the ranges, part of Four Mile Creek, Paralana Creek and alluvial fan, as well as a palaeochannel system. (Note the radiometric image does not cover the whole study area).

4.4 QuickBird

The digital QuickBird image (Figure 6) covered a large area over 52 km high and up to 46 km wide. This was edited to create an image of only the study area which was then printed at high resolution on photo quality paper at A1 size. It was then laminated with a gloss finish to provide a clear, sharp image for interpretation. The interpreted regolith landform units were drawn with a non-permanent whiteboard marker onto transparent overhead projector sheets laid over the image, then traced onto a single large tracing paper overlay for scanning. The use of the overhead projector sheets allowed for accurate interpretation, especially in areas with indistinct boundaries.

The steps taken to identify the regolith landform units were based around systematic classification from the large to the small scale. To begin with, the major landforms were identified, being Paralana Creek and alluvial fan, the edge of the ranges, and the Frome Plains. Each of the landforms was examined individually, looking for RLU boundaries, changes in vegetation and colour, and evidence of underlying structures.

Paralana Creek was characterised by alluvial channel and depositional plain units withdense vegetation, showing as a strong green colour on the QuickBird image. The RLUs within the creek changed type, shape and composition the further the creek was from the ranges. As the creek changed to the alluvial fan, the RLUs became generally much larger and more irregular in shape than those in the creek. The units also changed from being alluvial channel and plain deposits to include sheet wash units as well. The part of Four Mile Creek within the study area exhibited similar RLUs.

The edge of the ranges was characterised by higher elevation, rocky exposures and drainage channels that fed into Paralana Creek. The channels themselves were obvious from the sinuous shape and vegetation pattern, while the drainage depressions less so due to the rocky nature of the area.

The plains were characterised by yellow-orange-brown coloured sediments and little to no vegetation. The eastern side of the study area was dominated by dendritic drainage depression channel systems, while the western half by aeolian and sheet wash deposits. The change from the complex drainage systems to the simpler sheet wash deposits suggests a change in the underlying structure of the area, probably a fault. It is likely that the fault activity and tectonic uplift constrained the dendritic drainage systems development.

Landform and RLU boundaries were determined by overall changes in the colours and patterns of the land surface, also considering how the boundary correlated with any changes in the underlying landform. This was well illustrated when determining the boundaries of Paralana Creek. There was both distinct colour and surface pattern differences between the creek and the plains, and from the DEM image and fieldwork the boundary between creek and plain was known to be sharp. The large amount of vegetation in the creek showed up as a dense green colour, contrasting strongly with the yellow-orange-brown colours of the plains where there is little to no vegetation. As colour indicates vegetation, it can identify areas where there is current and/or recent water flow i.e. creeks and drainage systems. Lesser and/or inactive waterways would have less vegetation and so be less green, which can be seen in the palaeochannel deposits just a little south of the main Paralana Creek waterway or the dendritic drainage systems in the eastern part of the study area.

Colour was also used to delineate topographic boundaries. The ranges were largely dark brown in colour, with a distinct colour change at the boundary with plains or drainage channel deposits.

Landform control on RLU succession is another aspect of landscape interpretation. Closer to the ranges (higher elevation as well as fault/uplift activity), there are likely to be channel and drainage depression type landforms, while out on the plains landforms would be dominated by depositional, sheet flow and aeolian type units. This RLU succession is seen in the study area, in the transition from the topographic high of the ranges to the low of the plains.

5. Results

5.1 Digital elevation model image

The DEM (Figure 2) indicated topographic height with colour. Areas of highest relief were white, progressively grading down through pink, red, yellow, green, blue, and magenta being indicative of the lowest-lying areas (Geoscience Australia 1973, Geoscience Australia 1980, McAvaney 2008).

The westernmost part of the image was white and red indicating the highest elevations and correlating with the edge of the ranges. Paralana Creek was seen clearly due to sharp changes in colour indicating the edges of the channel. The green in the centre of the image showed dendritic patterns, and correlated with the dendritic drainage system north of Paralana Creek.

Overall, this image showed how the elevation of the area drops from west to east, correlating with the change in landforms from the ranges to the plains.

5.2 Digital elevation model regolith landform map

The DEM regolith landform map (Figure 3) showed a reasonable correlation between topography and landform, with the edge of the ranges and the uppermost parts of Paralana and Four Mile Creeks being well-defined by outlines of colour (i.e. topographic) boundaries.

5.3 Radiometric image

The radiometric response image (Figure 4) showed the different responses in different parts of the landscape. The ranges exhibited the highest radiometric response being predominantly bright blue to white, indicating a large amount of U present. This was to be predicted, as the Mt. Painter Inlier has anomalously high radioelement concentrations, with levels of U and Th ranging from 10 – 100 ppm (Neumann *et al.* 2000, Brugger *et al.* 2003, Mildren & Sandiford 2005).

There was a strong correlation between Paralana Creek and its radiometric response, indicating the transport of radioactive materials from the ranges via the creek onto the plains. The predominately blue colour indicated it is largely U being transported. As the creek moved onto the plains the response became weaker and more K rich, suggesting that there is less radiogenic material (i.e. material from the ranges) being transported that far. The increased K response was likely due to K-rich material being windblown from further south by the same winds that created the dune field. It was unlikely to be due to vegetation concentration of K, as that area was sparsely vegetated.

The sheet flow plains closest to the ranges showed a low response, likely from the little colluvial material that eroded off the slopes, while the sheet flow plains further away exhibited little to no response. This indicated that the source of those sediments is non-radiogenic, and/or that any ranges-derived radiogenic sediments were covered by a layer of non-radiogenic sediments sufficient to muffle the radiometric response.

While the resolution of the image was only moderate, the shapes of Paralana Creek, alluvial fan and ranges were clearly evident. Overall this image showed how radiogenic material in the ranges weathers, erodes and was transported largely via alluvial means through the landscape.

5.4 Radiometric image regolith landform map

The radiometric regolith landform map (Figure 5) showed general outlines of the edge of the ranges, Paralana Creek and alluvial fan, the palaeochannel system and part of Four Mile Creek. The shapes and positions of these boundaries provided a basic understanding of the general regolith-landforms present in the study area.

5.5 QuickBird image

Within this image (Figure 6), the eastern edge of the ranges was visible along the western-most part of the image, with Paralana Creek flowing out onto the plains to the east.

Paralana Creek was very distinct on the image, appearing as a grey-green colour dotted with green. As it fanned out onto the plain, the green flecks became less numerous. The grey-green colour remained predominant for a little longer before mingling with the red-brown colour dominant on that part of the plains.

The predominantly green colour was due to the amount of vegetation, with the majority of green dots being River Red Gums. Generally the greener the colour, the denser the vegetation. Within the main creek there were multiple landforms, generally channel and depositional plain types. Some of the channels were more heavily vegetated than others, suggesting a possible correlation between depth of channel and amount of water flow and the density and the age and amount of the vegetation present – i.e. deeper channels where water is most likely to flow preferentially are more vegetated than shallower channels which would only experience water flow during heavier, rarer downpours.

Closer to the ranges the channel and depositional plain deposits within Paralana Creek were closely intermingled, but as the creek moved further downstream the depositional plain units became larger with the alluvial channel deposits smaller and thinner. As the creek turned into the alluvial fan the RLUs further increased in size and became more irregular in shape, with the loss of smaller alluvial channel deposits and a change to sheet wash dominated deposits. Just south of Paralana Creek was a palaeochannel system which was very similar is shape and close to the current creek course. While not as obvious as Paralana Creek, the main watercourse and associated alluvial fan could be identified on the image.

Whitish patches of regolith materials were predominant near the edge of the ranges. From previous field work it is probable these are material from exposures of the underlying formation.

The majority of the plains were a light tan colour, changing to a darker grey-green colour in the dendritic drainage systems. The colour change was due to a greater amount of vegetation within the drainage depressions and channels. These drainage systems were likely influenced by fault and block tilting in those areas.

In the easternmost part of the study area was dominated by sheet wash deposits, with aeolian dunes in the northern and southernmost areas.

5.6 QuickBird image regolith landform unit map

The RLU map (Figure 7) colours were chosen to act as a guide for RLU type - green and purple for alluvial deposits, yellow and orange for colluvial/sheet wash, red for the ranges, and light pink for the dunes. Using this colouration, major landforms and associated regolith types were made distinct from each other and obvious to the eye.

The shape of Paralana Creek and its fan was obvious from the overall green colour of the RLUs. The palaeochannel system associated with Paralana Creek was also made obvious, showing up as a smaller, less defined green dominated system below it. The fans were partially obscured by the sheet wash (orange colours) and the longitudinal dunefields (light pink), but the overall shape of those RLUs illustrated their general extent.

Other, smaller alluvial systems, such as part of Four Mile Creek in the northernmost part of the study area, and the dendritic drainage systems were also characterised by greens. The dendritic drainage systems were made obvious due to their distinctive complex boundaries, as well as the colouration of the units. Due to this their shape could be seen, showing how they drained into lower lying parts of the study area (i.e. the western portion).

The other main features are longitudinal dune fields and anthropogenic structures. The shape and position of the longitudinal dunefields also provided an indication of dominant wind direction (southerly), as the dunes are aeolian in nature. The only anthropogenic RLU described in the study area is the airstrip and associated structures of the Beverly Uranium Mine (hot pink) in the central upper part of the study area.

5.7 Regolith landform units

A full description of the regolith landform units of Figure 7 are given in tables 1-4.

6. Discussion: Evaluation of remote sensing methods for regolith-landform mapping

The three remote sensing methods could all be used for regolith landform mapping. Using each method individually produces a map with limited regolith landform data, but combining understanding gained from the others produced the best results.

The DEM image provided limited regolith landform data, only showing the topography of the study area with some estimation of regolith type. The radiometric response image and its regolith-landform map provided data about the concentration, distribution, and transport of radioelements U, K and Th and a generalised idea of regolith-landforms. These two remote sensing methods are by themselves poor data sources to produce a regolith-landform map.

The QuickBird image was the best remote sensing technique to produce a RLU map, providing detailed imagery of the land surface in true colour. However, it didn't provide any data about landscape elevation, topography or the distribution of radioelements within the study area. Its high degree of detail means that RLU mapping and interpretation can be largely done in the lab, with a much smaller field component required. This would mean lower field costs for producing a RLU map.

The RLU map illustrates the regolith-landform interpretation of the landscape, making the landforms – creek, fan, palaeochannel system, drainage systems, dunes, sheet wash plains – all well defined and colour coded, so the shapes and relationships between them were easier to see. It also provided some information about the climatic conditions of the area, showing how vegetation was generally sparse and confined to waterways, indicating a low rainfall environment, while the shape and position of the longitudinal dunes indicated the dominant direction of the wind that formed them.

Using these in combination provided the most complete regolith landform map. The DEM imagery provided a basic overview of the topography of the area, the radiometric image of the radioelement distribution and concentration, while the high resolution, highly detailed QuickBird image provided a visual representation of the land surface and a detailed RLU map. Using these techniques together combined their strengths of measuring different aspects of the landscape and compensated for weaknesses.

6.1 Implications for land use

These remote sensing techniques provided data and understanding that can be used for a wide range of applications, including: mineral exploration, lithological and regolith mapping, landscape evolution research, radioelement distribution, surface geochemistry, environmental and agricultural monitoring, natural disaster assessment, regional and urban planning, and salinity (Forster *et al.* 1987, Meyer-Roux & King 1992, Wilford *et al.* 1997, Lawrie *et al.* 2000, Wilford *et al.* 2001, Harris 2003, Bandyopadhyay *et al.* 2009).

DEM imagery can be used to contribute to general landscape understanding and for regional and urban development (Tapley 2002).

Radiometric imagery can be used for lithological mapping and mineral exploration, specifically uranium prospecting. However, radiometric response data does not necessarily indicate economically viable deposits, as airborne radiometric imagery only detects surface materials and sufficient non-radiogenic cover can mask radiometric response of any such deposits (Duval 1990, Ollier & Pain 1996, Minty 1997, Wilford *et al.* 1997, Craig *et al.* 1999, Pickup & Marks 2001, Wilford *et al.* 2001, Wilford 2002, Wilford & Minty 2007, Munday 2008, Scott & Pain 2008).

QuickBird imagery can be used for environmental and agricultural monitoring, mapping vegetation types and distribution, land degradation and recovery, as well as RLU interpretation (Forster *et al.* 1987, Meyer-Roux & King 1992, Jürgens 1997, Harris 2003, Bandyopadhyay *et al.* 2009).

However, there are many more land use applications when remote sensing methods are used in combination, such as determining regolith composition, classification and characteristics, landscape processes research, environmental and agricultural management, and infrastructure planning (Bierwirth *et al.* 1996, Wilford *et al.* 1997, Craig *et al.* 1999, Lawrie *et al.* 2000, Pickup & Marks 2001, Wilford *et al.* 2001, Wilford 2002, Sefercik 2007).

Combining DEM and radiometric imagery can be used to identify and/or predict salt stores and outbreaks in erosional landscapes, areas of active erosion and/or deposition for land degradation and salinity studies, areas of groundwater recharge and discharge, to investigate hydrological and geomorphic processes, and to determine organic matter content and pH (Bierwirth *et al.* 1996, Wilford *et al.* 1997, Lawrie *et al.* 2000, Wilford *et al.* 2001). For example, newly deposited channel sediments can display high K, Th and U responses that are similar to the source material, indicating that the weathering, erosion and transport happened quickly with little modification to the overall radioelement composition (Wilford *et al.* 1997). However, older overbank and alluvial terrace deposits in the same area would show lower K but original U and Th values, the K being leached away over time and the less mobile U and Th materials remaining (Wilford *et al.* 1997). Such studies could be used in landscape processes and evolution research.

Radiometric and DEM data can also be used to determine some level of regolith composition and classification (Wilford *et al.* 2001). In regolith units where specific radioelements were associated with regolith materials, radioelement response can be used to look for that regolith material e.g. radiometrics used to identify ferruginous lag where Th was closely associated with Fe oxides (Wilford *et al.* 2001).

This study used the three remote sensing techniques in combination. The DEM image was used to generally predict the location and general type of the landforms of the area, the radiometric image to gain an overall understanding of radioelement distribution and transport patterns within the study area, and the QuickBird image to identity and map the RLUs, basing the interpretation on land surface colour, pattern, and RLU size and shape in combination with the understanding of landscape processes gained from the DEM and radiometric images.

The QuickBird regolith landform map was the most suited to regolith-landform mapping, as it had the best resolution, the most detail about the land surface and the RLU map clearly classified and identified the RLUs of the study area. However, the DEM and radiometric maps still contributed towards its development, with the DEM image providing understanding about the topography of the area, and the radiometric image about radioelement distribution and therefore transport patterns. It also supported the interpretation of the palaeochannel system, as there was a correlating radiometric response in that area.

The three maps created in this study were all aimed at providing regolith-landform maps as well as data and understanding of the regolith and landform processes of the area. These maps could be used as a basis for further regolith landform research in the area, for preliminary mineral exploration, or for environmental management given the highly detailed nature of the RLU map.

7. Conclusion

The three remote sensing techniques of DEM, radiometrics and QuickBird satellite imagery were well suited for regolith landform mapping, each providing data an understanding about different aspects of the study area. The DEM image provided data about landscape elevation and topography, therefore providing a general idea of landform shape and an indication of the types of RLUs to be found in that area. The radiometric image provided data about the abundance and distribution of radioelements

K, U and Th in the land surface, with information about element mobility, weathering, erosion, transport and distribution behaviours, and how these can be linked with particular regolith and/or landform types. The QuickBird imagery provided data about the land surface in the visible light spectrum. This imagery was found to be the most useful in creating the RLU map as it had the best resolution of the three remote sensing types and the true colour representation made it easy to interpret, especially with the understanding from previous field work. Information about the study area gained from the DEM and radiometric imagery provided an understanding of underlying landscape processes and how they would affect the RLUs, their distribution, development and succession.

Practical applications of these regolith-landform maps are for further research into landscape processes, evolution and development, with uses for exploration, agriculture, conservation, and infrastructure. The QuickBird regolith-landform map was the most useful, providing a clear representation of the distribution and classification of regolith in that area.

8. Acknowledgements

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10. Figure Captions

Figure 1: Location of Paralana Creek catchment study area, northern Flinders Ranges in South Australia.

Figure 2: 1:50 000 DEM image positioned within study area (McAvaney 2008). Note that image does not cover entire study area. Colours indicate approximate elevations (metres above sea level): white > 300m, pink ~251-300m, red ~201-250m, yellow ~151-200m, green 101-150m, blue ~51-101m, magenta <50m (Geoscience Australia 1973, Geoscience Australia 1980).

Figure 3: Regolith landform interpretation map based on DEM image in Figure 2.

Figure 4: 1: 50 000 radiometrics image positioned within study area (McAvaney 2008). Note that image does not cover entire study area.

Figure 5: Regolith landform interpretation map based on radiometrics image in Figure 4.

Figure 6: 1:41 524 scale QuickBird image of study area.

Figure 7: Regolith landform unit map of study area based on Figure 6.

11. Figures

Figure 1

Figure 2

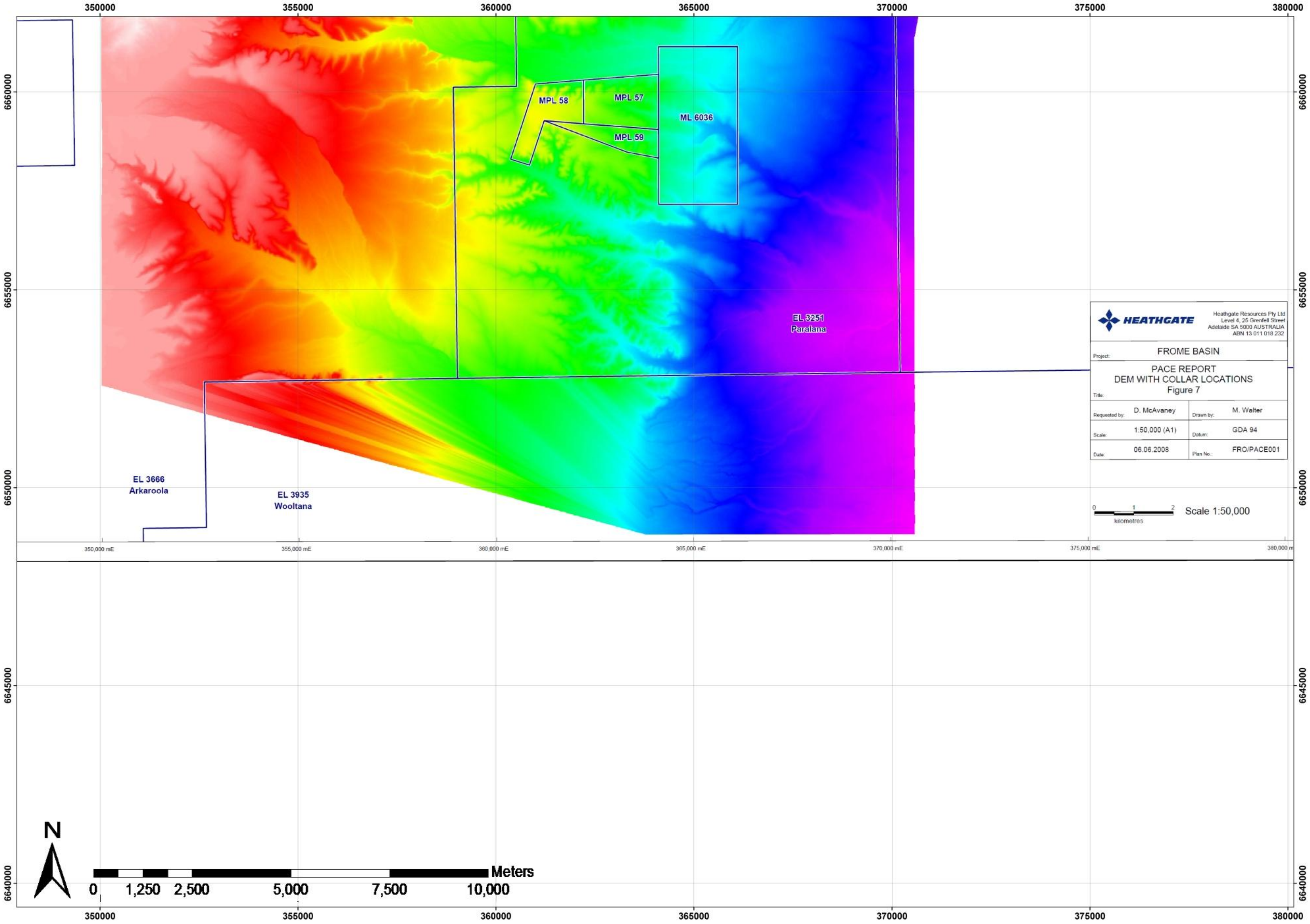

350000
355000
360000
365000
370000
375000
380000
6660000
6655000
6650000
6645000
6640000
MPL 58
MPL 57
MPL 59
ML 6036
EL 3251
Paralana
EL 3666
Arkaroola
EL 3935
Wooltana
350,000 mE
355,000 mE
360,000 mE
365,000 mE
370,000 mE
375,000 mE
380,000 m
HEATHGATE
Heathgate Resources Pty Ltd
Level 4, 25 Grenfell Street
Adelaide SA 5000 AUSTRALIA
ABN 13 011 018 232
Project:
FROME BASIN
Title:
PACE REPORT
DEM WITH COLLAR LOCATIONS
Figure 7
Requested by:
D. McAvaney
Drawn by:
M. Walter
Scale:
1:50,000 (A1)
Datum:
GDA 94
Date:
06.06.2008
Plan No.:
FRO/PACE001
0
1
2
kilometres
Scale 1:50,000
N
0
1,250
2,500
5,000
7,500
10,000
Meters

Figure 3

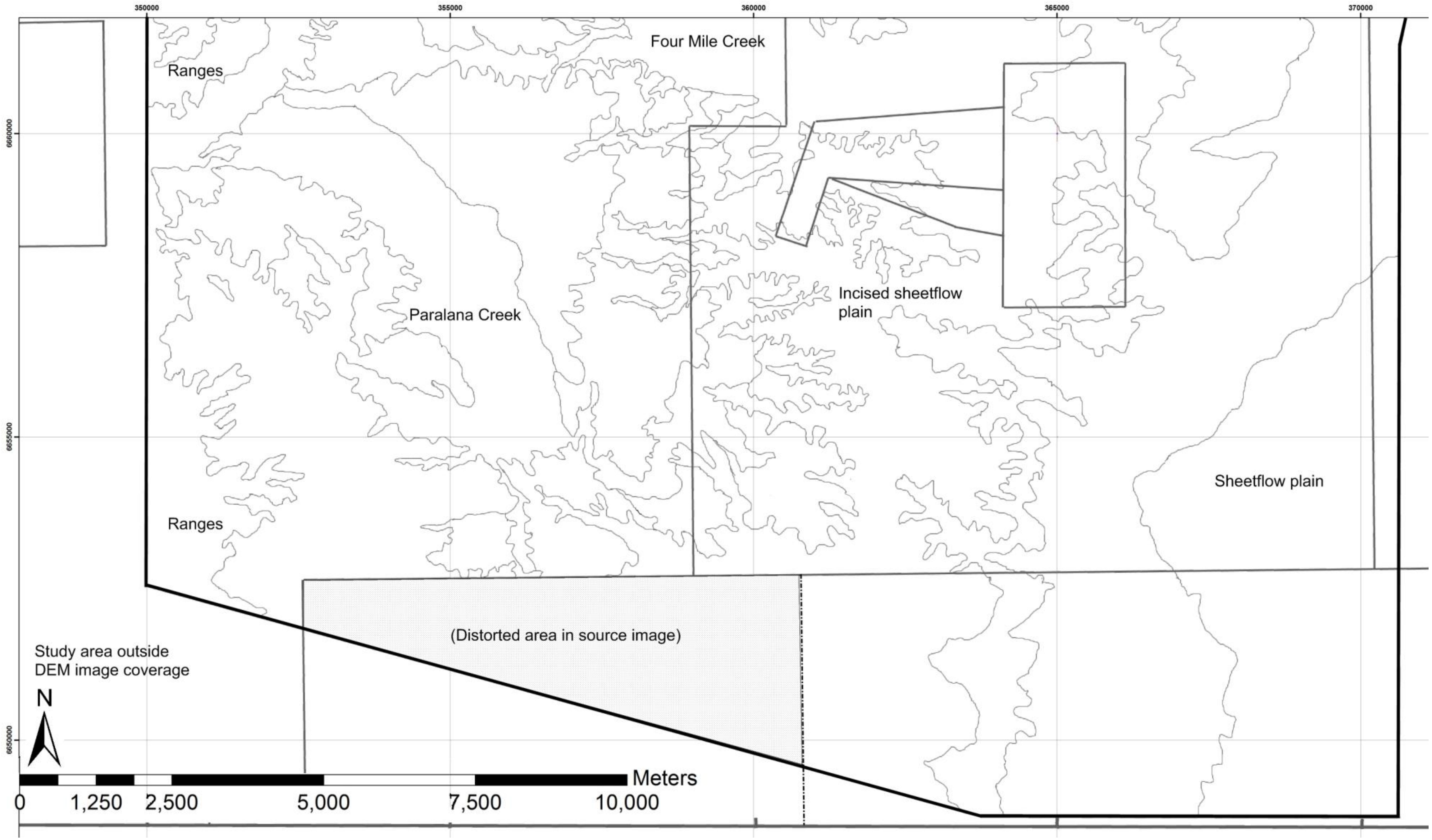
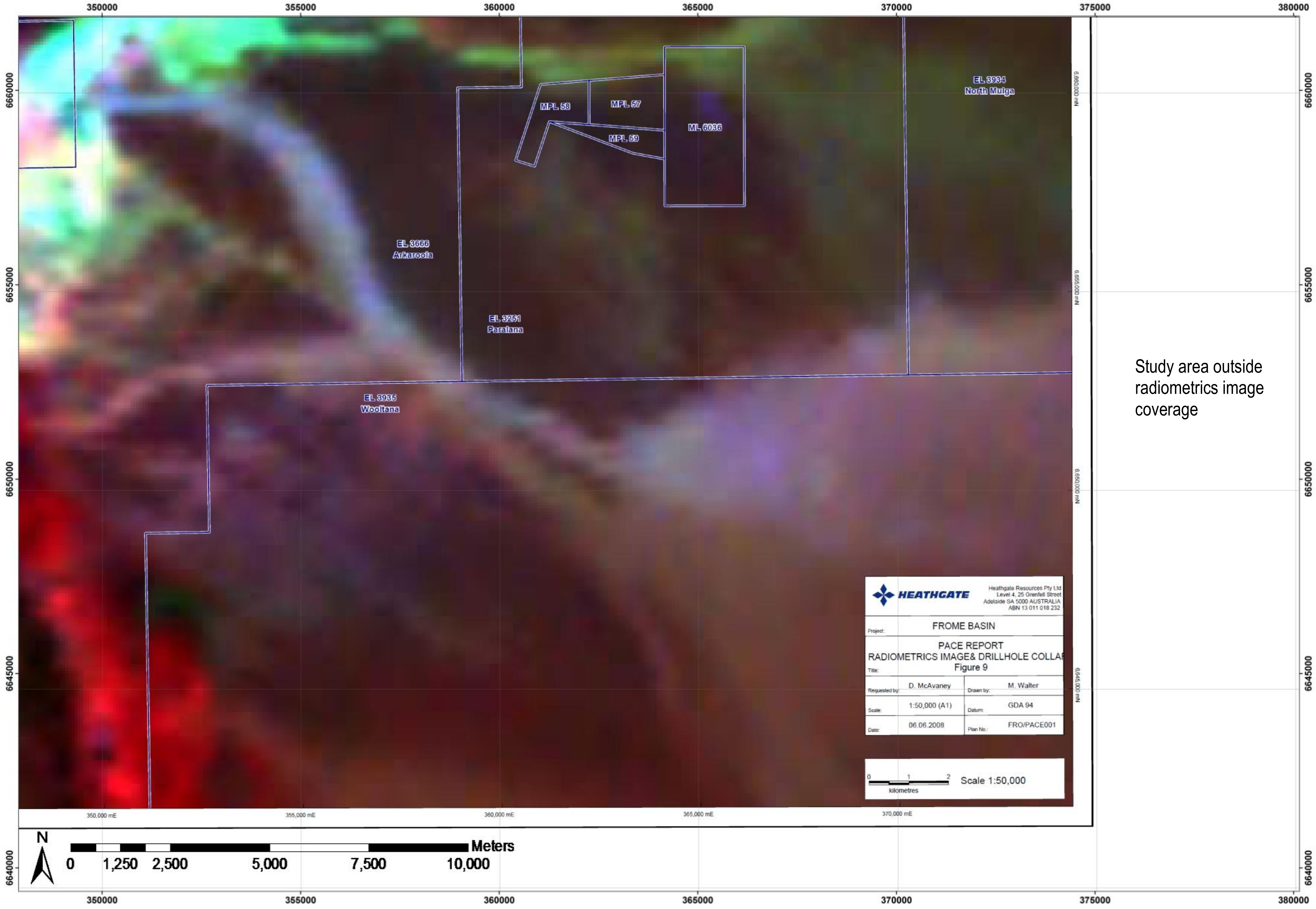
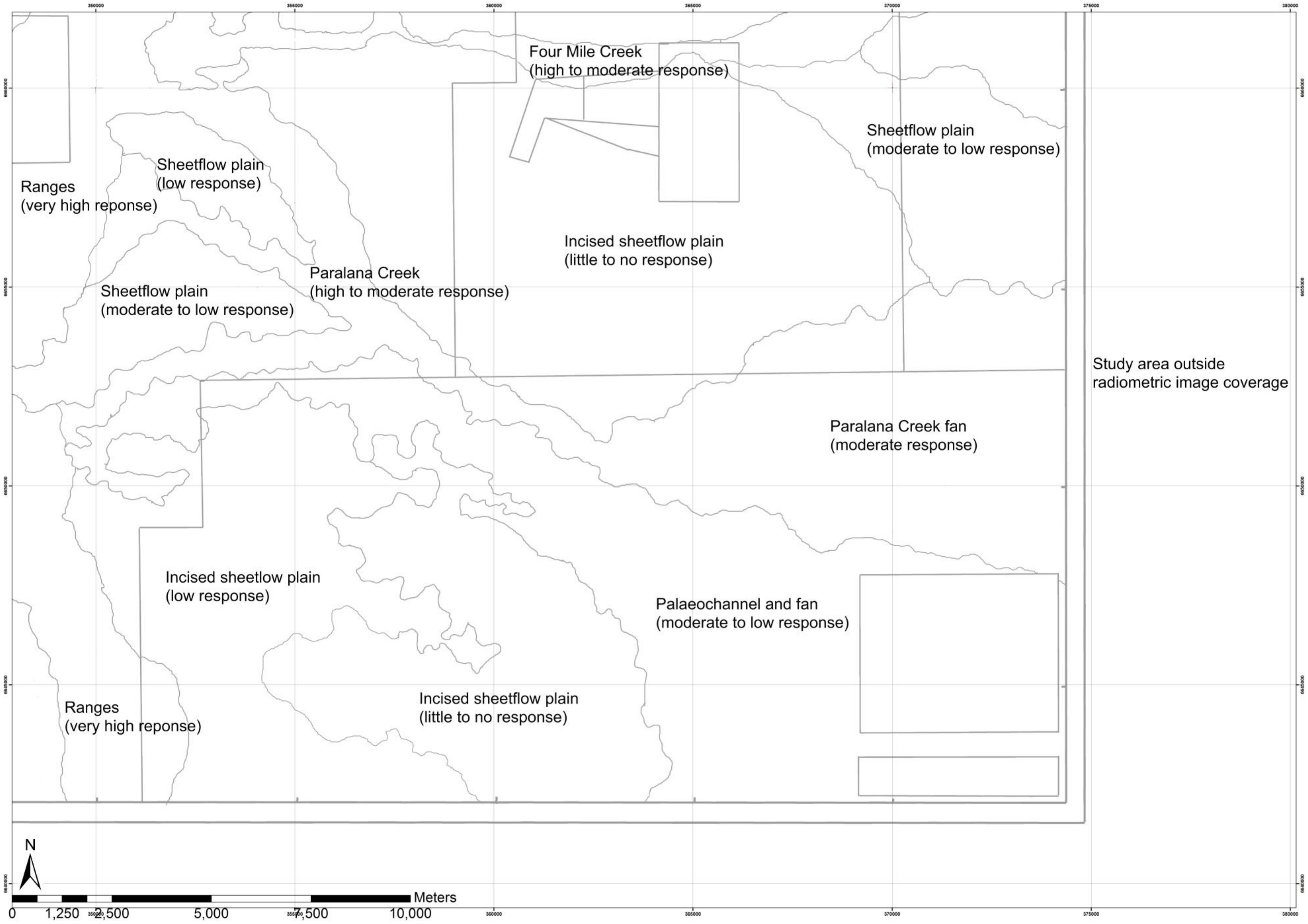

350000
355000
360000
365000
370000
6660000
6655000
6650000
Four Mile Creek
Ranges
Paralana Creek
Incised sheetflow plain
Sheetflow plain
Ranges
(Distorted area in source image)
Study area outside DEM image coverage
N
0
1,250
2,500
5,000
7,500
10,000
Meters

Figure 4



Study area outside radiometrics image coverage

Figure 5


Four Mile Creek
(high to moderate response)
Sheetflow plain
(moderate to low response)
Ranges
(very high reponse)
Sheetflow plain
(low response)
Incised sheetflow plain
(little to no response)
Paralana Creek
(high to moderate response)
Sheetflow plain
(moderate to low response)
Study area outside
radiometric image coverage
Paralana Creek fan
(moderate response)
Incised sheetlow plain
(low response)
Palaeochannel and fan
(moderate to low response)
Incised sheetflow plain
(little to no response)
Ranges
(very high reponse)
N
Meters
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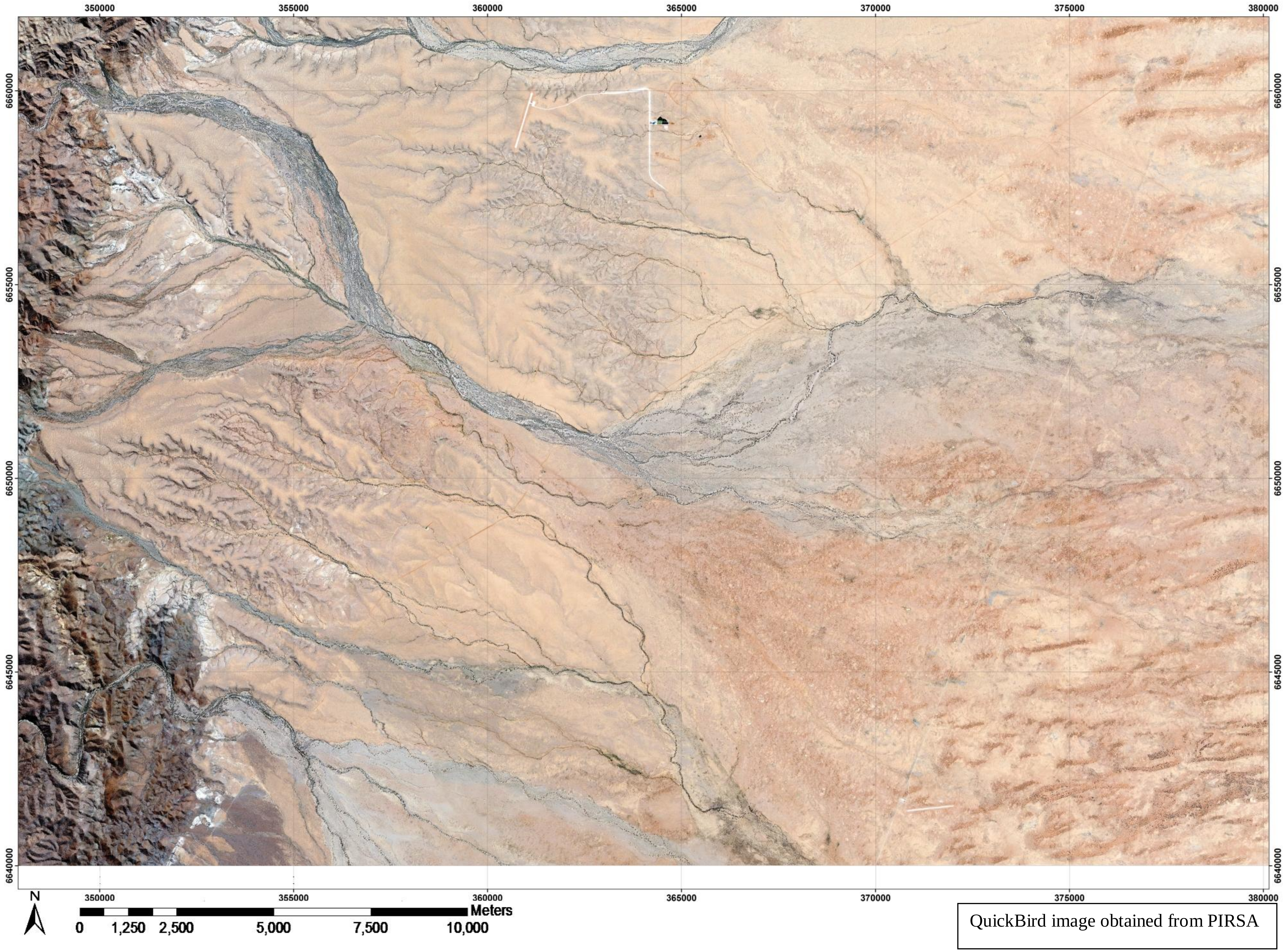
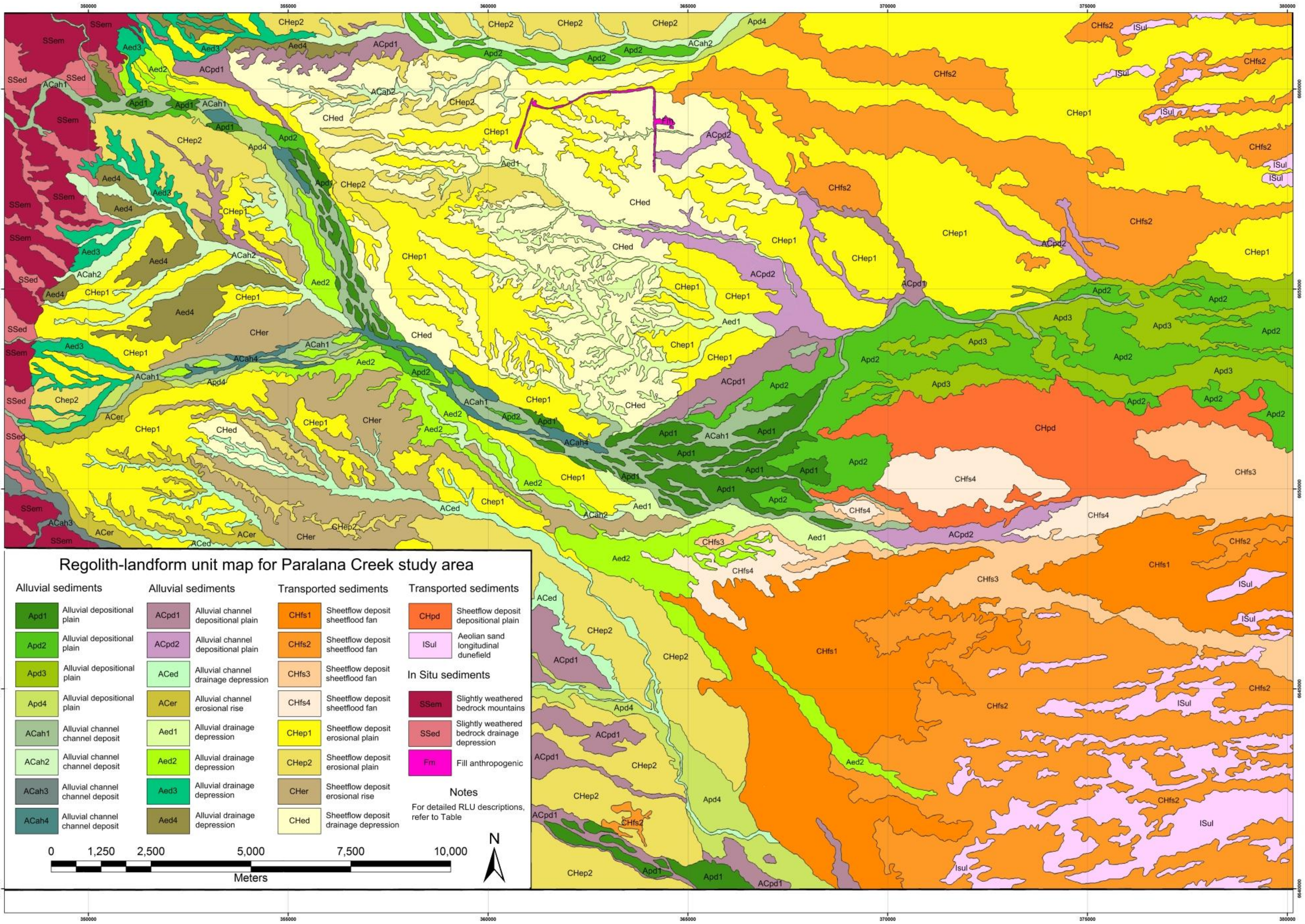
2,500
5,000
7,500
10,000

Figure 6



QuickBird image obtained from PIRSA

Figure 7


Regolith-landform unit map for Paralana Creek study area
Alluvial sediments
Apd1 Alluvial depositional plain
Apd2 Alluvial depositional plain
Apd3 Alluvial depositional plain
Apd4 Alluvial depositional plain
ACah1 Alluvial channel channel deposit
ACah2 Alluvial channel channel deposit
ACah3 Alluvial channel channel deposit
ACah4 Alluvial channel channel deposit
Alluvial sediments
ACpd1 Alluvial channel depositional plain
ACpd2 Alluvial channel depositional plain
ACed Alluvial channel drainage depression
ACer Alluvial channel erosional rise
Aed1 Alluvial drainage depression
Aed2 Alluvial drainage depression
Aed3 Alluvial drainage depression
Aed4 Alluvial drainage depression
Transported sediments
CHfs1 Sheetflow deposit sheetflood fan
CHfs2 Sheetflow deposit sheetflood fan
CHfs3 Sheetflow deposit sheetflood fan
CHfs4 Sheetflow deposit sheetflood fan
CHep1 Sheetflow deposit erosional plain
CHep2 Sheetflow deposit erosional plain
CHer Sheetflow deposit erosional rise
CHed Sheetflow deposit drainage depression
Transported sediments
CHpd Sheetflow deposit depositional plain
ISul Aeolian sand longitudinal dunefield
In Situ sediments
SSem Slightly weathered bedrock mountains
SSed Slightly weathered bedrock drainage depression
Fm Fill anthropogenic
Notes
For detailed RLU descriptions, refer to Table
0
1,250
2,500
5,000
7,500
10,000
Meters
N
350000
355000
360000
365000
370000
375000
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12. Tables

Table 1. In Situ regolith landform unit codes, descriptions, and supplementary descriptions from DEM and radiometric data for Figure 7.

RLU	Regolith Type	Landform Type	Regolith materials	Vegetation	DEM	Radiometrics	Notes
SSer	Slightly weathered bedrock	Erosional rise	Thin to no regolith cover, some fine sandy-silty material. Overall reddish-brown colour.	Dominated by shrubs and small trees (mallee *Eucalyptus* sp. and mulga *Acacia aneura* sp.) with native grasses and forbs.	Shows a distinct topographic high with sharp boundaries along the edge of the ranges.	A very strong radiometric response in the ranges, of all radioelements with some areas showing a greater concentration of U, Th or K. Probable source of the radioelement material found on the plains and in the creek.	The bedrock exposures are only found along the western edge of the study area.
SSed	Slightly weathered bedrock	Drainage depression	Thin regolith cover, some fine sandy-silty material. Overall reddish-brown colour.	Dominated by shrubs and small trees (mallee *Eucalyptus* sp. and mulga *Acacia aneura* sp.) with native grasses and forbs.			
Fm	Fill	Anthropogenic construction	Anthropogenic materials	None.	No response.	No response.	Beverley Uranium Mine.

Table 2. Transported alluvial regolith landform unit codes, descriptions, and supplementary descriptions from DEM and radiometric data for Figure 7.

RLU	Regolith Type	Landform Type	Regolith materials	Vegetation	DEM	Radiometrics	Notes
ACah	Alluvial channel	Alluvial channel	Coarse yellow-brown sands, some gravel/pebble clasts, moderate rounding, largely lithic with vein quartz component.	River Red Gums, mulga, some small shrubs, some groundcover of forbs and native grasses.	Paralana Creek is distinctly lower than the surrounding land surface, which fits as it a creek will cut down through the land surface.	The upper part of the creek closest to the ranges has a distinct radiometric response, the overall blue colour indicating the majority presence of uranium. Further down the creek the colour intensity becomes less, indicating a lower concentration of radioelements, as well as becoming more magenta, indicating a greater concentration of K than further upstream. A weaker radiometric response can be seen directly below the middle part of the creek and the fan, indicating a likely palaeochannel system (supported by Quickbird imagery).	While RLUs are very similar, they are best distinguished from the subtly different vegetation
ACah2	Alluvial channel	Alluvial channel	Largely coarse yellow-brown sands, some gravel/pebble clasts, moderate rounding, largely lithic with vein quartz component.	Small River Red Gums, sparse forb groundcover.			
ACah3	Alluvial channel	Alluvial channel	Coarse yellow-brown sands, some gravel/pebble clasts, moderate rounding, largely lithic with vein quartz component.	Some small River Red Gums, some small shrubs, dense forb groundcover.			
ACah4	Alluvial channel	Alluvial channel	Coarse yellow-brown sands, some gravel/pebble clasts, moderate rounding, largely lithic with vein quartz component.	Scattered River Red Gums, some forb groundcover.			
Apd1	Alluvial	Depositional plain	Medium to fine yellow-brown sands, some silty material, few gravel/pebble clasts.	Moderate to good vegetation cover, small shrubs and forbs.			
Apd2	Alluvial	Depositional plain	Medium to fine sands, some silty material, few gravel/pebble clasts, light yellow-brown colour when exposed.	Moderate patchy vegetation cover, small shrubs and forbs.			

Apd3	Alluvial	Depositional plain	Medium to fine yellow-brown sands, some silty material, few gravel/pebble clasts, overall light yellow-brown colour when exposed.	Minimal patchy vegetation cover, largely forbs and native grasses.			
Apd4	Alluvial	Depositional plain	Medium to fine yellow-brown sands, some silty material, few gravel/pebble clasts.	Moderate patchy vegetation cover, few scattered River Red Gums, forbs, shrubs and native grasses.			
Aed1	Alluvial	Drainage depression	Medium to fine yellow-brown sands, some lithic gravel/pebble clasts.	Little to moderate vegetation cover, largely native grasses and forbs			
Aed2	Alluvial	Drainage depression	Medium to fine yellow-brown sands, some lithic gravel/pebble clasts.	Little vegetation, some small River Red Gums largely restricted to small drainage channels.			
Aed3	Alluvial	Drainage depression	Medium to fine yellow-brown sands with a small white crumbly poorly-consolidated component. Moderate lithic component, gravel to cobble size clasts.	Moderately well vegetated, largely forbs and native grasses.			
Aed4	Alluvial	Drainage depression	Medium to fine yellow-brown sands with exposures of white crumbly poorly consolidated sediments. Some angular to sub-angluar lithic component.	Occasional small shrubs, sparse forbs and native grasses.			
ACed	Alluvial channel	Drainage depression	Fine yellow-brown sand to silty material, some lithic cobbles and pebbles.	Sparse small shrubs, some native grasses, some small River Red Gums restricted to small drainage channels.			
ACer	Alluvial channel	Erosional rise	Fine yellow-brown sand to silty material, some lithic cobbles and pebbles.	Moderately well vegetated, some native grasses and forbs.			

ACpd1	Alluvial channel	Depositional plain	Fine light yellow-brown sandy to silty material.	Moderately vegetated, largely small shrubs, some forbs and native grasses.			
ACpd2	Alluvial channel	Depositional plain	Fine light yellow-brown sandy to silty material.	Sparsely vegetated, small River Red Gums restricted to small drainage channels.			

Table 3. Transported colluvial regolith landform unit codes, descriptions, and supplementary descriptions from DEM and radiometric data for Figure 7.

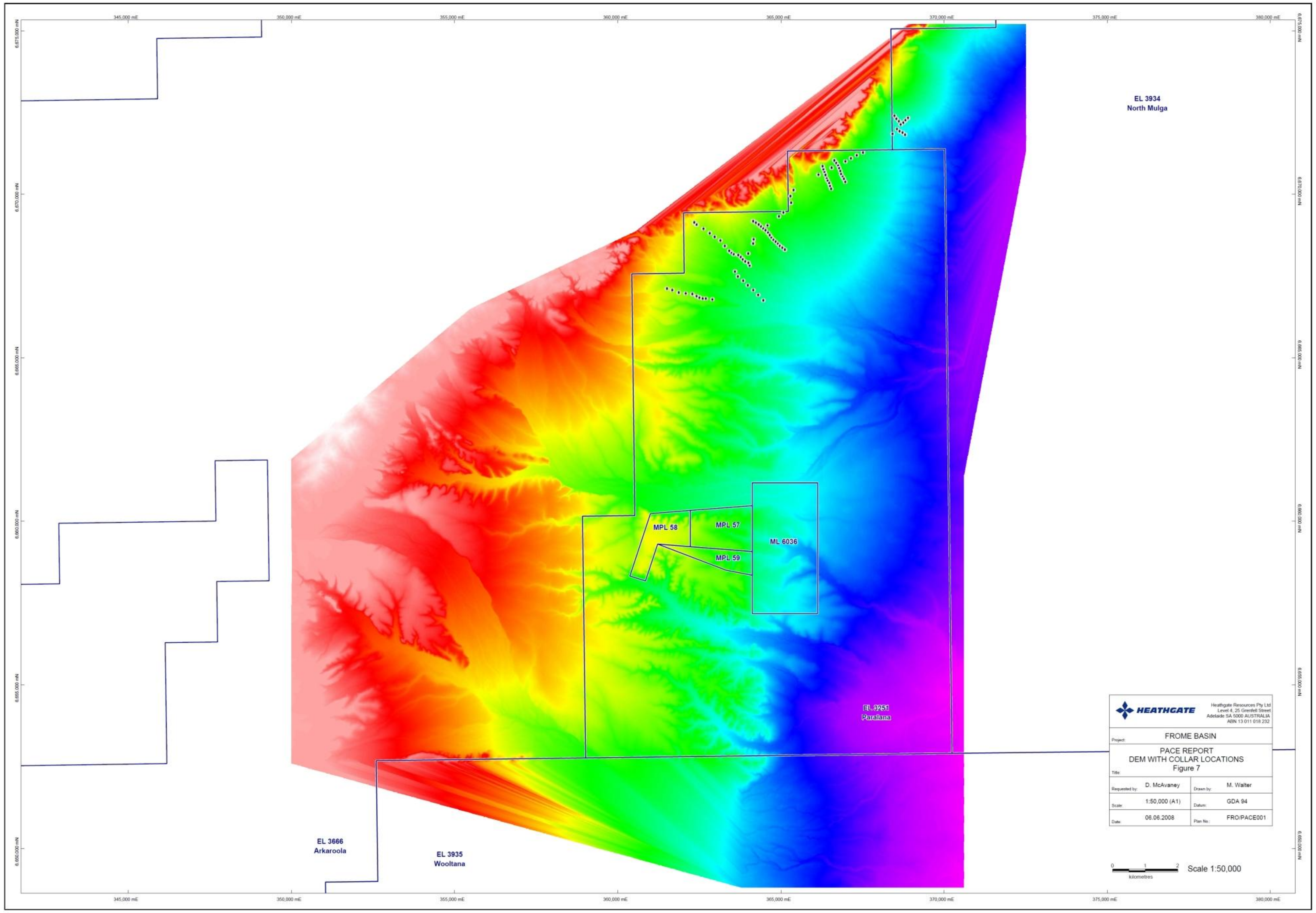
RLU	Regolith Type	Landform Type	Regolith materials	Vegetation	DEM	Radiometrics	Notes
CHfs1	Sheet flow deposit	Sheet flood fan	Fine yellow-brown sand to silty material, largely yellow-brown with some aeolian component.	Generally sparse, occasional small shrubs, some forbs and native grasses	Not a lot of detail to be found here, other than the change in topography is gradual.	To the north of the creek there is little radiometric response, indicating that there is little radioactive material in the ground surface there. To the south there is a generalised response, largely of K with some U component, indicating that there was some transport/movement of radioelements at some point	The sheet flow deposits are largely restricted to the areas north and south of the creek
CHfs2	Sheet flow deposit	Sheet flood fan	Fine yellowish sand to silty material with some aeolian component.	Sparse and patchy, some forbs and native grasses.			
CHfs3	Sheet flow deposit	Sheet flood fan	Fine yellowish sand to silty material with some aeolian component.	Patchy vegetation, few forbs and native grasses.			
CHfs4	Sheet flow deposit	Sheet flood fan	Fine yellow-orange-brown sandy to silty material, largely orange-brown with some aeolian component.	Sparse forbs and native grasses			
CHpd	Sheet flow deposit	Depositional plain	Fine yellow-brown sand to silty material, largely yellow-brown, with some aeolian component.	Generally sparse, occasional small shrubs, some forbs and native grasses.			
CHep1	Sheet flow deposit	Erosional plain	Fine yellow-brown sand to silty material, some aeolian component, sparse lithic/gravel clasts.	Largely sparse, small shrubs, some native grasses, occasional forbs.			
CHep2	Sheet flow deposit	Erosional plain	Fine yellow-brown sand to silty material, some aeolian component, sparse lithic/gravel clasts.	Moderate groundcover, occasional small shrubs, some forbs and native grasses.			
CHer	Sheet flow deposit	Erosional rise	Fine yellow-brown sand to silty material, some aeolian component, some areas of lithic gravel/pebble clasts.	Moderate to sparse, small shrubs and some native grasses.			
CHed	Sheet flow deposit	Drainage depression	Fine yellow-brown sand to silty material.	Moderate groundcover largely native grasses, occasional forbs.			

Table 4. Transported aeolian regolith landform unit codes, descriptions, and supplementary descriptions from DEM and radiometric data for Figure 7.

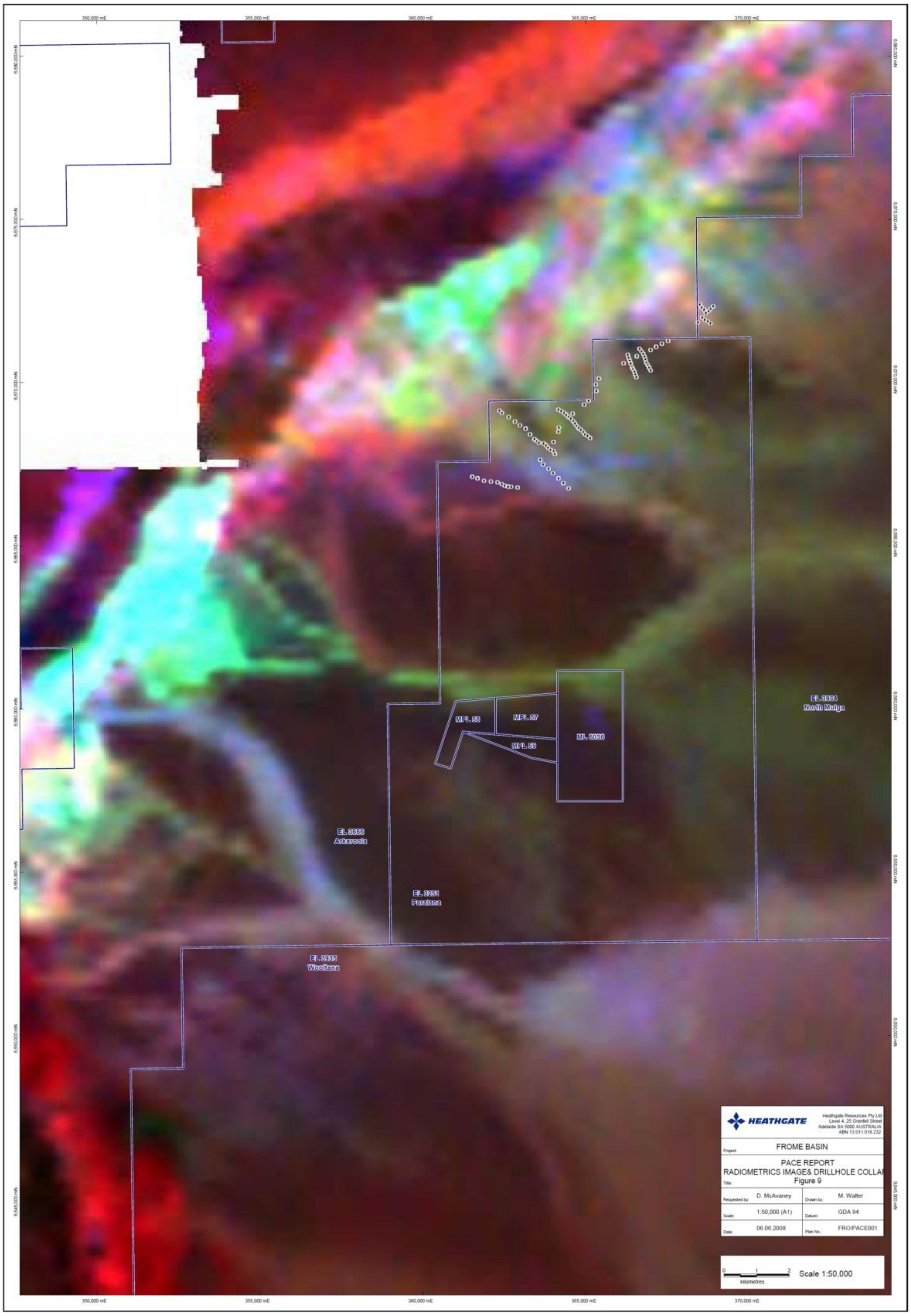
RLU	Regolith Type	Landform Type	Regolith materials	Vegetation	DEM	Radiometrics	Notes
ISul	Aeolian sand	Longitudinal dunefield	Fine sands-silts, largely reddish-brown colour	Sparse, generally native grasses	This area was not covered by the DEM	This area shows a generalised low level radiometric response, largely indicative of K	The aeolian deposits are only found in the south-eastern and north-eastern corners of the study area.

13. Appendix

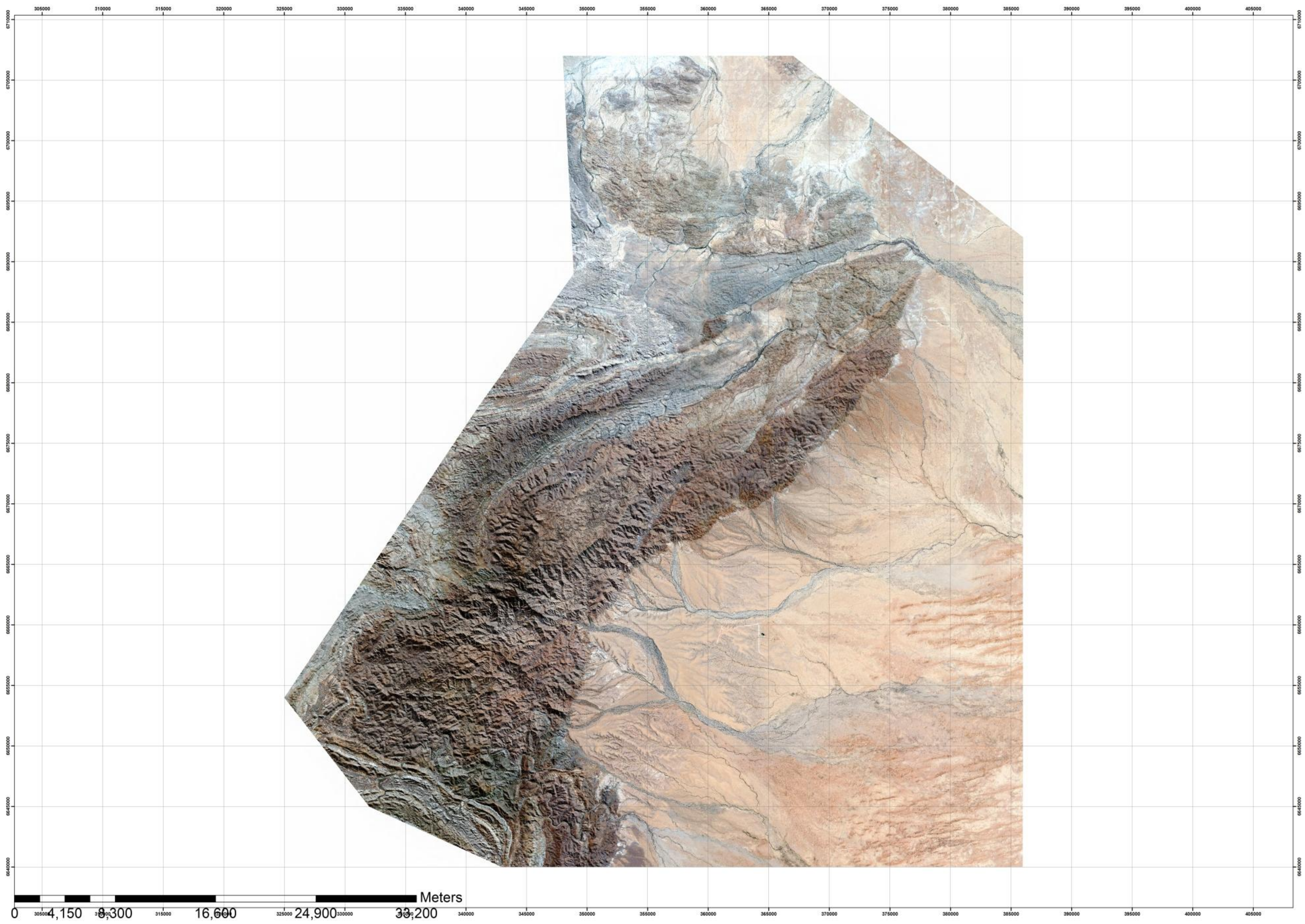
APPENDIX A - Entire DEM image (McAvaney 2008).



APPENDIX B - Entire radiometrics image (McAvaney 2008).



APPENDIX C – Entire QuickBird image (scale 1:135 979)



QuickBird image obtained from PIRSA