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Cooperative Research Centre for Landscape Environments and Mineral Exploration

Australian National University/University of Adelaide

Fowlers Gap Regolith Field Class

National Undergraduate Regolith Geology school (NURGS)

Course history

The National Undergraduate Regolith Geology School (NURGS) commenced as an initiative of the CRC for Landscape Evolution and Mineral Exploration (LEME-1) and was carried over into the CRC for Landscape Environments and Mineral Exploration (LEME-2).

Initially, NURGS was designed to bring one invited student from each Australian university Earth Sciences department to a location anywhere in Australia to spread the regolith geoscience word. NURGS operated successfully in this fashion for a number of years.

After a short hiatus between 2002 and 2004, NURGS was modified to become an undergraduate field school for students from the Australian National University and the University of Adelaide, based at the University of New South Wales' Fowlers Gap Arid Zone Research Station, where it successfully continued until 2007.

NURGS was held in the following places:

- 1998 - Charters Towers;
- 1999 - Broken Hill;
- 2000 – Kalgoorlie;
- 2001 – Darwin;
- 2005-2007 - Fowlers Gap.

Teaching staff for NURGS included professionals drawn from LEME-1 & LEME-2 core parties, the minerals industry and postgraduate students, under the direction of successive CRC LEME Education & Training Program Leaders Prof. Graham Taylor, Prof. Pat James, Dr Steve Hill and Dr Ian Roach.

Dr Ian Roach
CRC LEME Education & Training Program Leader
January 2008

Cooperative Research Centre for Landscape Environments and Mineral Exploration

Australian National University/University of Adelaide

Fowlers Gap Regolith Field Class

National Undergraduate Regolith Geology school (NURGS)

Lecture notes and reading material

Written and compiled by:

Dr Ian Roach **CRC LEME Education & Training Program Leader** **Research School of Earth Sciences** **Australian National University** **Canberra ACT 0200** **Ian.Roach@anu.edu.au**	**Dr Steven Hill - CRC LEME** **Lecturer in Regolith Geoscience** **Department of Geology and Geophysics** **School of Environmental Sciences** **University of Adelaide** **SA 5005** **Steven.Hill@adelaide.edu.au**

Field Trip

Location: Broken Hill region (Fowlers Gap)
Duration: 9 days (7-15 July 2007)

The aim of this fieldtrip is to provide students with a first-hand experience of describing and then interpreting landscapes and associated regolith materials. The Broken Hill region is a well-studied and established regolith and landscape evolution framework typical of many parts of semi-arid Australia. It also hosts the world-class Broken Hill Line of Lode mineralisation. These attributes make it a valuable field teaching laboratory.

The first few days of the field trip include a tour and introduction to the major regolith and landform features of the region, including consideration of the landscape expression of the Broken Hill Line of Lode and the implications of this for future mineral discovery in the region. Other field sites include remains of ancient river systems that record environmental change from moister climates of the early Cainozoic through to the contemporary semi-arid climate. We also visit some of the most spectacular recently active fault scarps in Australia and consider the field evidence that tells about their ongoing tectonic history. The second half of the week includes a major field study, where students first produce a regolith-landform map of a defined field site and construct an interpretive model for that area's regolith and landscape evolution. Once this has been established the students then conduct a regolith and plant biogeochemistry sampling program that includes sampling a transect of surface soils and the dominant vegetation species and conduct on-site soil tests to determine possible changes in soil chemistry across the landscape. These samples are later prepared for analysis, followed by exercises on the presentation and interpretation of results during practical sessions later in the semester.

More information about regolith and landscape evolution research at Fowlers Gap is located on a website at **http://ems.anu.edu.au/staff/icr/fowlers/**. Here you'll find papers about Fowlers Gap, satellite and geophysical images, an illustrated plant database, maps and photos from previous field trips. You can also submit your own photos and they'll be featured when we get back!

ANU GEOL3030 Seminar A Fowlers Gap Regolith Field Class	UNIVERSITY OF ADELAIDE Surficial Geology II Regolith and landscape evolution field trip

FOWLERS GAP

7-15 July 2007

Departure

A bus will be departing from the rear of the Department of Earth and Marine Sciences (Linnaeus Way carpark) at 8 am Saturday 7th July. You will overnight in Balranald, and arrive in Broken Hill at about 1 pm Sunday 8th July. You will arrive back in Canberra late on the afternoon of Sunday 15th July.

Location

The field trip is being conducted at the Fowlers Gap Arid Zone Research Station, which is run by the University of NSW. Fowlers Gap is approximately 100 km north of Broken Hill, within the northern Barrier Ranges. Access is via the Silver City Highway between Broken Hill and Tibooburra. Further details about the station can be found on its website (http://bioscience.babs.unsw.edu.au/fgap). Contact details for the station are: Telephone 08 8091 2511; Fax 08 8091 2510

Telstra CDMA/NextG mobile phones give patchy coverage within the area, best on hilltops. Digital GSM mobile coverage only extends as far as the outskirts of Broken Hill. Phone cards are available for purchase for phone use from the station (or pre-purchase one before you leave if you really need to use the phones). Email access may also be available.

Costs

The field trip will cost students **$100 for under-cover accommodation**, or **$25 for campers**, to help cover the costs of accommodation and transport. Students are to provide their own food for the field trip, which can be purchased in Broken Hill on Sunday 8th and Tuesday 10th if necessary.

Under-cover accommodation will be strictly limited. At least 25% of course participants must camp. Of course, you can still use all the facilities at Fowlers Gap.

WARNING: WE WILL BE PASSING THROUGH THE MURRUMBIDGEE IRRIGATION AREA FRUIT FLY QUARANTINE. YOU MUST NOT BRING FRUITS OR VEGETABLES FROM CANBERRA. HEAVY FINES EXIST IF YOU ARE CAUGHT. THESE MUST BE PURCHASED IN BROKEN HILL.

What to bring

We will be mostly staying within bunk-style accommodation (unless you're camping). You will need to bring:

- Clothing suitable for fieldwork (allowing for either sunny or cold and rainy conditions)
- Raincoat (just in case you didn't realise that from the last point)
- Hat & sunscreen (yes, you can get sunburned in winter!)
- Stout footwear
- Warm sleeping bag, pillow etc
- Toiletries & towel
- Small first aid kit (large ones will come with the buses)
- Water bottle (2 L recommended)
- A4 mapping board (or clipboard)
- Drawing equipment (pens, pencils, paper etc)
- Field notebook or similar
- Optional camera
- Optional GPS if available
- GSOH
- FOOD. At Fowlers Gap you will need to cater for Breakfast, Lunch and Dinner every day except the first night (there'll be a barbie!).

We recommend that you form food groups to assist with access to the kitchen facilities (it can also be fun). The camp kitchen provides crockery, cooking equipment and cutlery. There are also fridges and rainwater tanks at the station.

There will be an opportunity to buy food at the supermarket in Broken Hill on the way to Fowlers Gap. Lunch may* also be purchased in Broken Hill on Tuesday July 10th (this will also be a second chance to purchase supermarket food).

*Depending on the ultimate itinerary. *It is also necessary to keep an emergency supply of food equivalent for 1 extra day of meals should the road be closed by wet weather.*

Provisional Program

We will join the 2nd year student group from University of Adelaide on Sunday 8th, once we arrive at either Broken Hill or on the way to Fowlers Gap.

Saturday July 7

- Depart Canberra 0800
- Arrive Balranald late afternoon

Sunday July 8

- Depart Balranald 0800, arrive Broken Hill about 1300
- Arrive Fowlers Gap late afternoon

Monday July 9

- Regolith and Landscape Evolution of Fowlers Gap Station

Tuesday July 10

- Broken Hill Line of Lode and environs

Wednesday July 11

- Regolith and Landscape of Fowlers Gap Station
- Biogeochemical & soil sampling, soil testing

Thursday July 12

- Regolith-Landform mapping

Friday July 13

- Regolith-Landform mapping

Saturday July 14

- Depart Fowlers Gap 0800, arrive Balranald about 1600

Sunday July 15

- Return to Canberra, arrive about 1700

Assessment

Assessment for 3 credit points* will be by a completed map and report:

1. a regolith-landform map (40%); and,
2. a report which includes two main parts (60%):
   - the regolith-landform description and interpretation; and (time permitting),
   - the geochemistry, biogeochemistry and soil testing program within the mapping area (if time permits at Fowlers Gap).

REGOLITH-LANDFORM MAP

Maps will be marked based on the accuracy of presentation of mapping polygons, the presence of a map scale, map grid and north arrow, plus the RLU descriptions in your map legend. Map legend descriptions should include information on: dominant regolith lithology; landform expression; minor regolith attributes (including surface lags); dominant vegetation community and species; and, potential geohazards (e.g., erosion risk, weeds, rabbit warrens etc).

REGOLITH-LANDFORM REPORT

This report should include the following sections:

- Introduction. Including the location and setting (briefly outline climate, landuse, geology, landscape setting), and the nature of this study (i.e., 2 day regolith-landform mapping study etc). This section should be no more than one page of text (single-spaced) and should include a regional location map.
- Description and outline of RLUs. This should include written descriptions of dominant regolith lithology; landform expression; minor regolith attributes (including surface lags); dominant vegetation community and species; and, potential geohazards. It will therefore be very similar to the text in your map legend. An interpretive paragraph may be included for each RLU outlining an interpretation of processes and significance. You may wish to include photographs or sketches of the features of each RLU. The text for each RLU should not exceed 2 paragraphs (one descriptive and one interpretive)
- Interpreted Regolith and Landscape Evolution. An approximately 1 page of text (single-spaced) discussion outlining your interpretation of the regolith and landscape evolution of the area. This would include the ages of the main features and how (and when) they formed. Aspects such as tectonism, weathering, induration, sedimentation, erosion, and controls on these could be

included here. Additional diagrams illustrating some of these points may help.

- (Time permitting: Geochemistry, Biogeochemistry and Soils. We may work on these data at Fowlers Gap and further details of how to tackle this will be given then).
- Conclusion. Briefly outlining what the study shows to wrap it all up. This should be about 1 paragraph long.
- References. If you have used them, cite them!
- Regolith-Landform map. Please resubmit your regolith-landform map with your report. This can be submitted as you did on the field trip or you can redo it (its up to you).

The map and report are due for submission before 5 pm Monday 13th August. Late submissions will be penalised 1% per day. Penalties for exceeding the suggested page/paragraph limits are at the discretion of the lecturer but may be up to 1% per page.

***For an additional 3 credit points (to make 6 cp), students may process and analyse soil samples collected during the field class for texture, Ph and EC, and compare these data against the phytogeochemical data collected during the camp. These data and interpretations will be presented as a report including a regolith-landform map with sections describing methods, soils and phytogeochemical data, interpretations and conclusions of no longer than 5000 words, due 26 October.**

BACKGROUND READING

Some background reading can be found in your lecture notes. There is also a selection of articles available on the CRC LEME website where there is a page dedicated to background Fowlers Gap field trip material. The address for this is: **http://crcleme.org.au/.**

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What is Regolith?

Steve Hill and Ian Roach

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Minerals Council of Australia

People & Landscapes

- There are few landscapes on Earth that have not been influenced by people in some way

People & Landscapes

- In fact its hard to imagine what many landscapes would be like without people

People & Landscapes

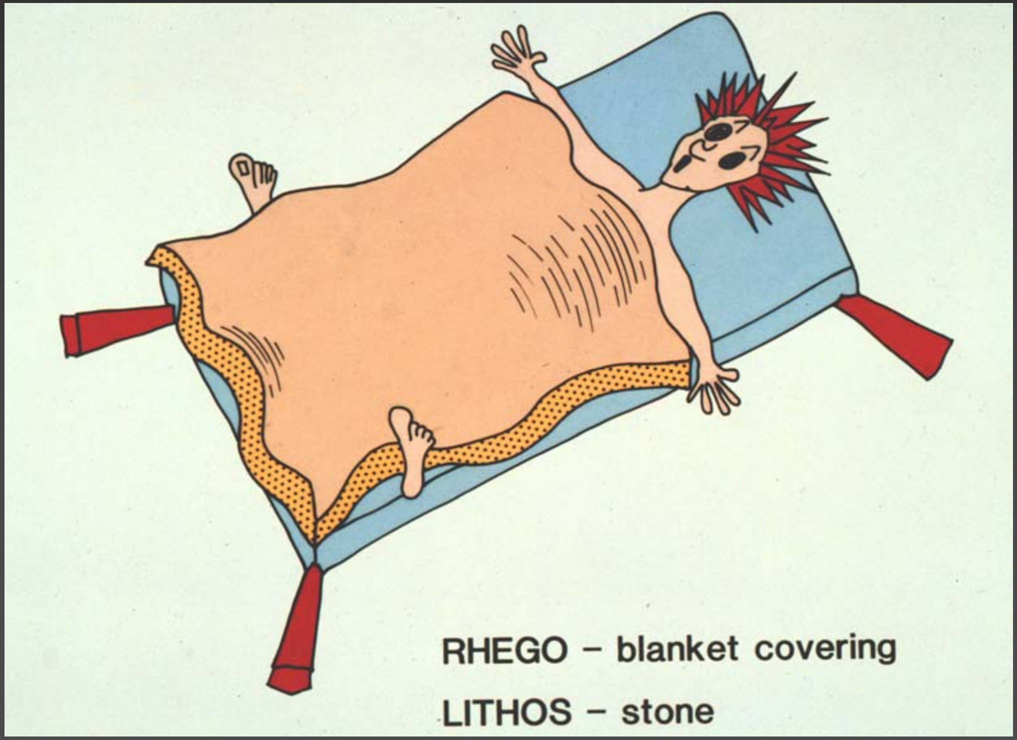
People & Landscapes

- It is sometimes very difficult to isolate changes caused by people from other changes to the landscape
- Nonetheless, landscapes are what we live with and what we are part of

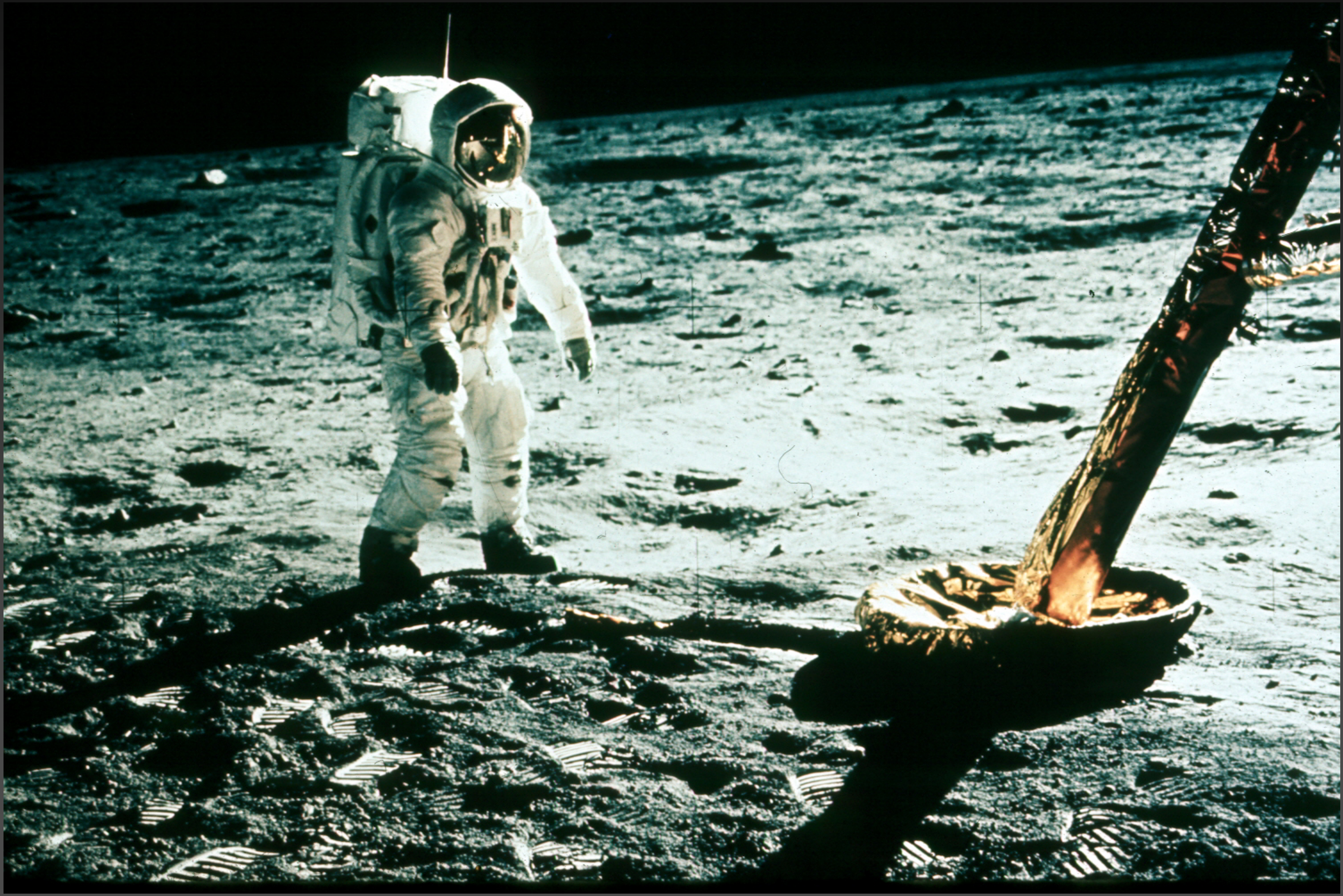
- In this component of SRES 3009 we will consider landscapes and the regolith materials with which they are composed

Regolith

- **What is the regolith?**
  - *Rhegos* = blanket or cover
  - *Lithos* = rock
  - Literally means "rock blanket"



Regolith?



Regolith

- **What is the regolith?**
  - Everything between fresh rock and fresh air!

- **Where is the regolith?**
  - Regolith is everywhere!

What is Regolith?

- **Term introduced by Merrill (1897).**
- **Redefined in Eggleton (2001):**

  "The entire unconsolidated or secondarily recemented cover that overlies coherent bedrock, that has been formed by weathering, erosion, transport and/or deposition of older material. The regolith thus includes fractured and weathered basement rocks, saprolites, soils, organic accumulations, volcanic material, glacial deposits, colluvium, alluvium, evaporitic sediments, aeolian deposits and groundwater."

- **Or: *"Everything between fresh rock and fresh air"!***

What is Regolith?

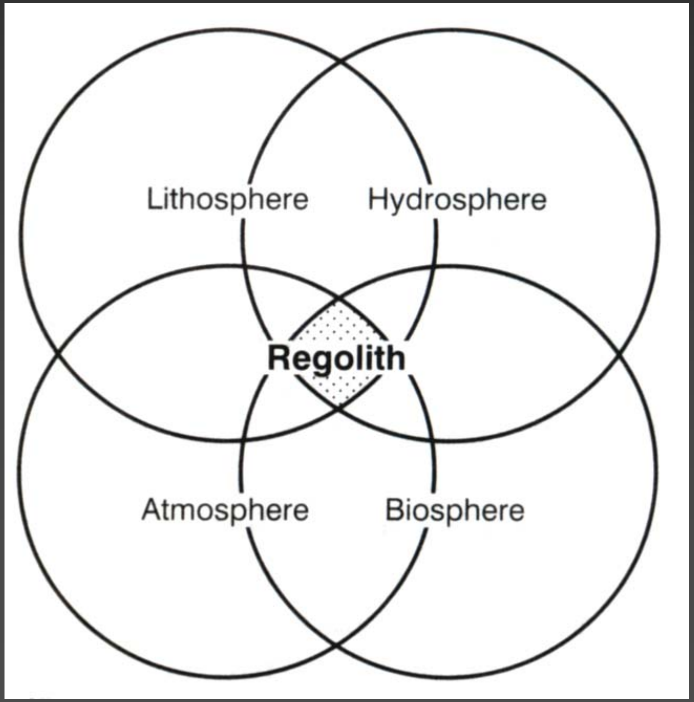
- **Rowley Twidale (1990):**

  "The Regolith is a mass of weathered material that is charged with salts and biota....it is a suppurating mass that gradually consumes any blocks enclosed within it, and is gradually gnawing away at....the bedrock. In general, the regolith is a discontinuous, festering veneer…". In: *Groundwater Geomorphology*. Geological Society of America Special Publication 252.

- **Is there an image problem here?**

Regolith

- **Why study the regolith?**
  - The regolith sustains our life and its resources. It is the interface upon which we live.
  - Implications for:
    - Ecology
    - Land management
    - Engineering
    - Agriculture
    - Mineral Exploration
    - Resources



From Taylor & Eggleton 2001

Landscapes

- **What is the landscape?**
  - “Landscape” derived from the 16 century Dutch word ‘landschap’, meaning a unit of human occupation
  - Its is all around us and we are part of it

Landscapes

- **Regolith and landscapes are intimately related**
  - Regolith refers to the materials that make up landscapes
  - Their form and development are intimately inter-related

LANDSCAPE CONNECTIONS

- **When you gaze around you…**

- **Do you SEE the landscape or do you just LOOK at it?**

– Some people feel the rain,

– but some just get wet!

LANDSCAPE CONNECTIONS

- **It is often felt that much of the time we push aside the landscape around us…perhaps we can be afraid to connect with it…maybe we don't know how?**
  - Do we live with the land? Or from the land? "Man on the land???"

LANDSCAPE CONNECTIONS

- *“The strange, as it were, invisible beauty of Australia, which is undeniably there, but which seems to lurk just beyond the range of our white vision. You feel you can’t see it - as if your eyes hadn’t the vision in them to correspond with the outside landscape. For the landscape is so unimpressive…it hangs back so aloof. And yet, when you don’t have the feeling of ugliness or monotony…you get a sense of subtle, remote, formless beauty more poignant that anything ever experienced before…”*
    - D.H.LAWRENCE, *Kangaroo*

Reading Regolith-Landforms

What can you see here?

Reading Regolith-Landforms

What about here?

Reading Regolith-Landforms

- **What we see in landscapes perhaps depends on our perceptions and interpretations…**
  - *"Before it can ever be a repose for the senses, landscape is the work of the mind. Its scenery is built up as much from strata of memory as from layers of rock"*

– Simon Schama

Regolith-Landform Perceptions

- ***"Sand, flies and wild natives.."***
  - William Dampier's first description of Australia in the 17th century

"At the Pinnacles the marnpi sat down three times there. The three hills or peaks are the neck and head of the marnpi as he sat down and rested…."

As told by an Adnyamathanha elder

“They exhibit a regularity that water alone could have given, and to water, I believe, they plainly owe their first existence” (Sturt, 1849)

“One might have imagined that an ocean washed their base…”
(Sturt, 1849)

"…the gloomy and burning deserts over which I wandered during more than thirteen months" (Sturt, 1849)

- **Land manager / lease-holder**

Stock units and production?

Landscape as a long-term investment?

Landscape as a long-term investment?

- **Geologist / Minerals Explorer**

Drilling through regolith near Galena Hill, Broken Hill

An eye for bedrock and mineralisation

The “Hill of Mullock”!!!
Too weathered to be of any use???

- **Geologist / Minerals Explorer**
  - Most of the landscape is covered by regolith
  - Most exploration is centred on areas of bedrock exposure

Mineral exploration options...

1. Ignore it
2. “punch” through it with either drilling or geophysics
3. Try to READ it and explore with it and within it

Regolith-Landform Perceptions

What am I not doing here?

Regolith-Landform Perceptions

I can’t see a landscape here, its all the same!

Regolith-Landform Perceptions

What do you think of this then? An ideal holiday destination???

Regolith-Landform Perceptions

- **Description vs Interpretation**
  - We need to recognise the different between description of the landscape and its interpretation
    - Description states what is there….it should be our fundamental data
    - Interpretations are hopefully developed from sound descriptions. They invariable involve some influence from our perception.

Regolith-Landforms

- During this course component we will examine regolith materials and associated landscapes, and hopefully understand and see them better.
- This may help us decide how to best live with them

Course Component Program

- **Fowlers Gap Field Trip**
  - July 8-16
  - See Handout for more detailed information, but…
    - You must provide your own food.
    - There will be a BBQ provided free on 1st night (vegetarian options will be limited).
    - We will be passing through Broken Hill on the 9th and 11th. Opportunities to top up your supplies.
    - Be warned! Make sure you have a couple of days food in reserve in case of rain. The roads are CLOSED if it rains and we may not get to BH until Tuesday or Wednesday!
    - Pack light!
    - Accommodation will be cramped. You may wish to take a tent.

Assessment

- **Includes:**
  - Final Field Report (30%)
  - Includes:
    - Regolith-landform map
    - Regolith-landform report

REGOLITH MAPPING

Reading and presenting the regolith and the associated landscape

Steve Hill
CRC LEME
University of Adelaide

Ian Roach
MCA Lecturer, CRC LEME
Australian National University

What’s all this then?

- The regolith and landscape are all around us
- We are even a part of the landscape
- If we are going to live and function in the landscape, we need to be able to:
  - read it;
  - record this information; and,
  - then present it.
- The variations in regolith and associated landscape features are most conveniently presented in **maps**

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Towards Regolith-Landform Mapping

- Regolith-landform mapping has its similarities and differences with other forms of mapping that you may be more familiar with:
  - Geology Maps
  - Geomorphology Maps
  - Soil Maps
  - Land System Maps

Regolith Maps / Geology Maps

- Primarily represent bedrock
- Many have a strong stratigraphic basis for presentation
- Bedrock units may be extrapolated beneath regolith cover or else appear as ‘islands’ of rock in a ‘sea’ of cover

- Regolith maps are more than just added detail to areas without bedrock exposure!

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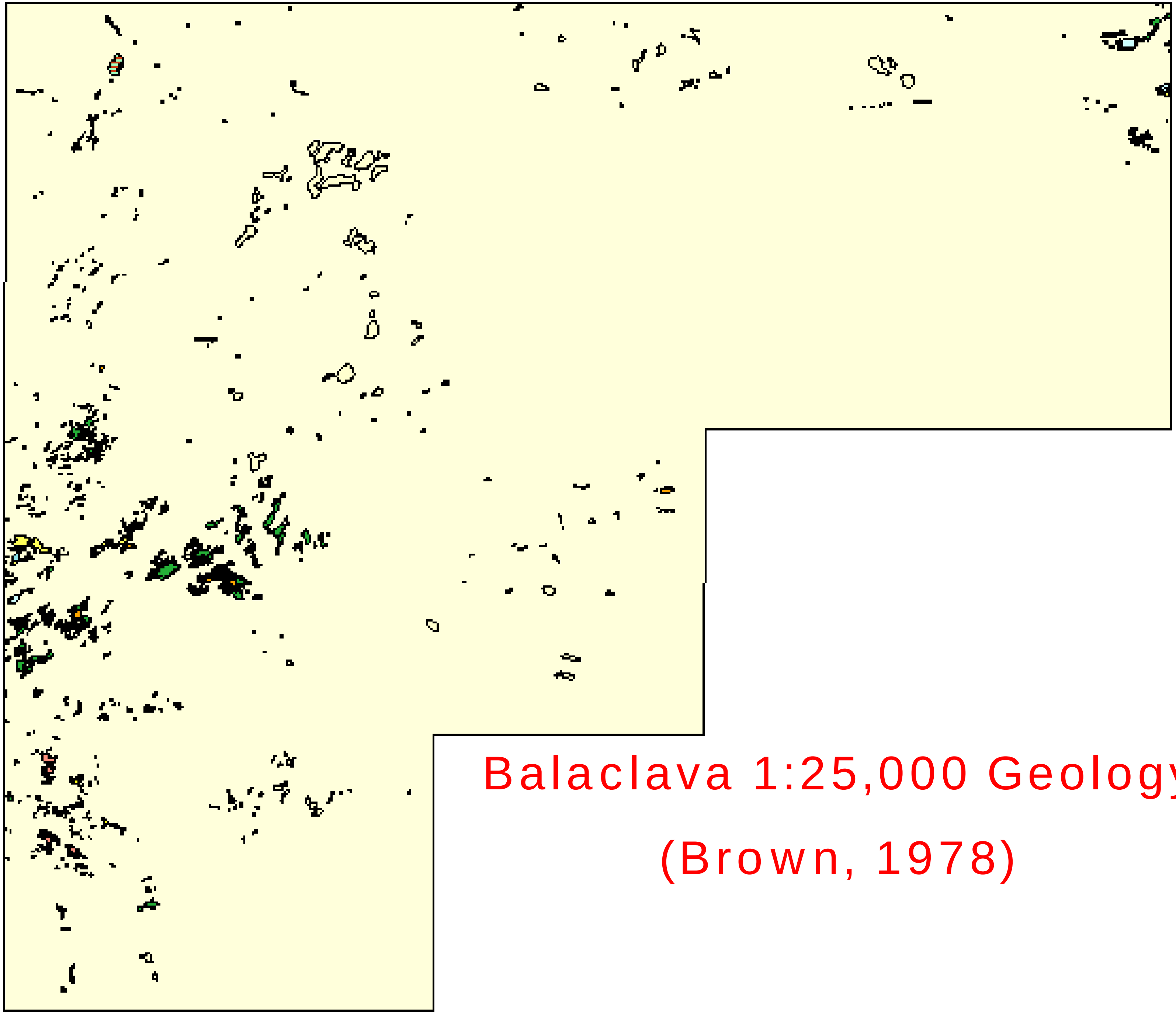
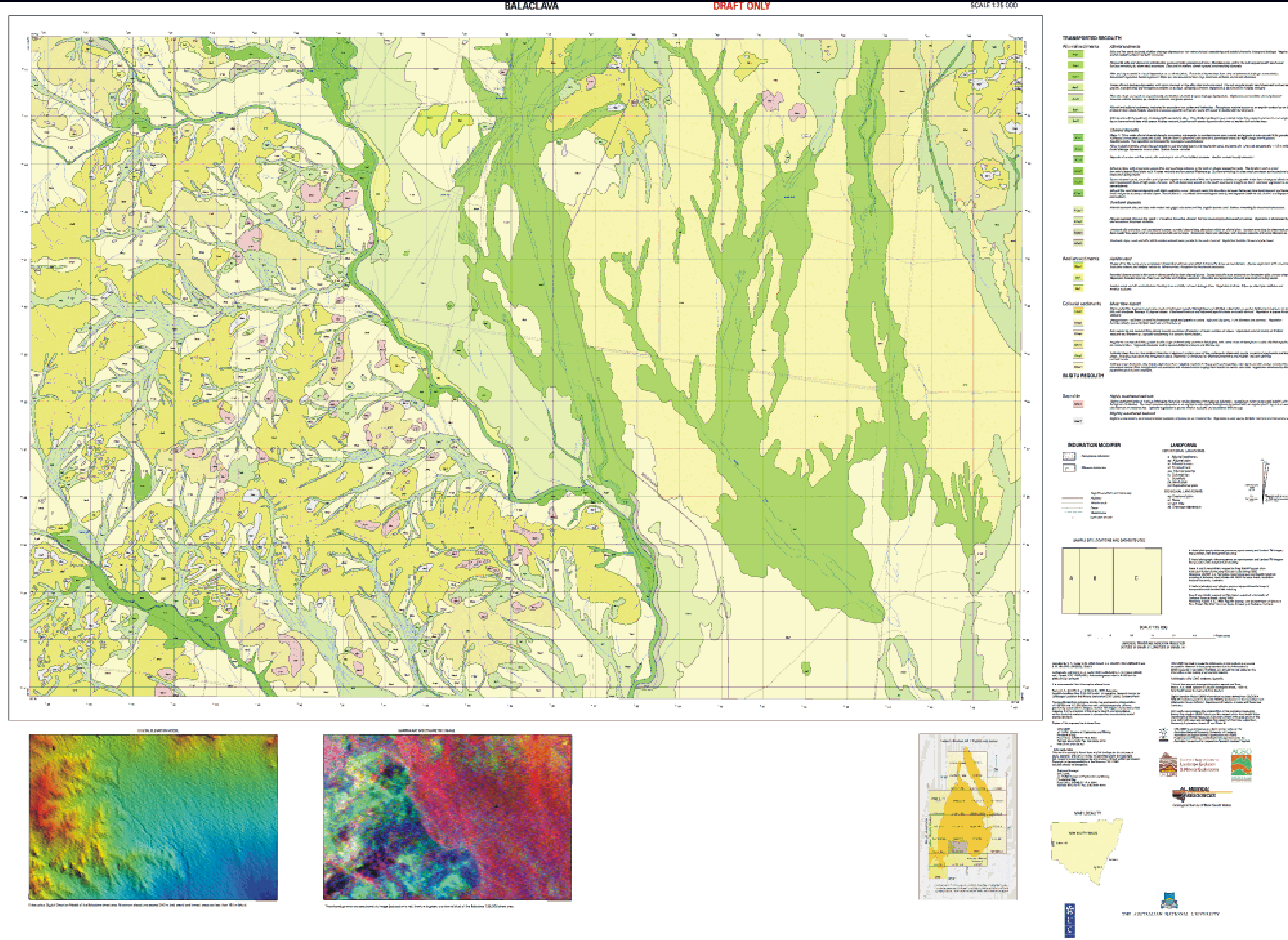


Balaclava 1:25,000 Geology

(Brown, 1978)


BALACLAVA
DRAFT ONLY
SCALE 1:25 000
TRANSPORTED REGOLITH
IN SITU REGOLITH
INDURATION MODIFIER
LANDFORMS

Geomorphology Maps

- Primarily record information on surface form
- Do not always represent regolith materials (although landforms and regolith may be closely related)
- Four main types:
  - – morphographic (shapes)
  - – morphogenetic (origin)
  - – morphometric (dimensions)
  - – morphochronological (time)

MORPHOLOGICAL MAPPING SYMBOLS

Angular convex break of slope	Cliffs (bedrock, 40° or more)
Angular concave break of slope	Breaks of slope } Convex and concave too close together to allow the use of separate symbols
Smoothly convex change of slope	Changes of slope } Convex and concave too close together to allow the use of separate symbols
Smoothly concave change of slope	Convex slope unit
6 Angle of slope (degrees)	Concave slope unit

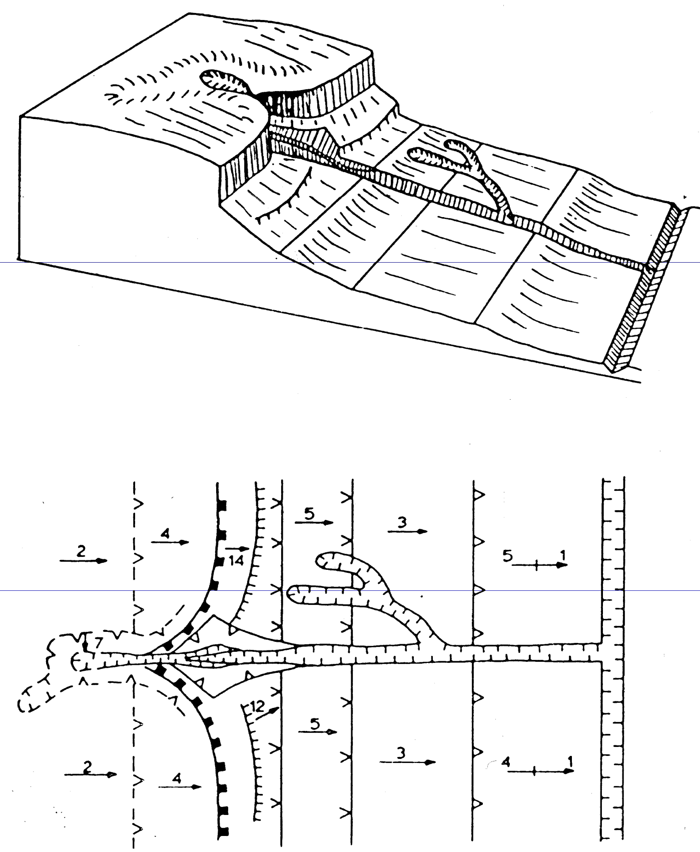


FIG. 14.3. A system of morphological mapping

Soil Maps

- Spatial pattern of soils in the landscape
- Dominated by classification schemes
- Describe ***Catenas*** -- the relationships between soil and landscape
- Soil is a part of the regolith but is typically restricted to the uppermost depths
- Do not consider the rest of the weathering profile nor materials

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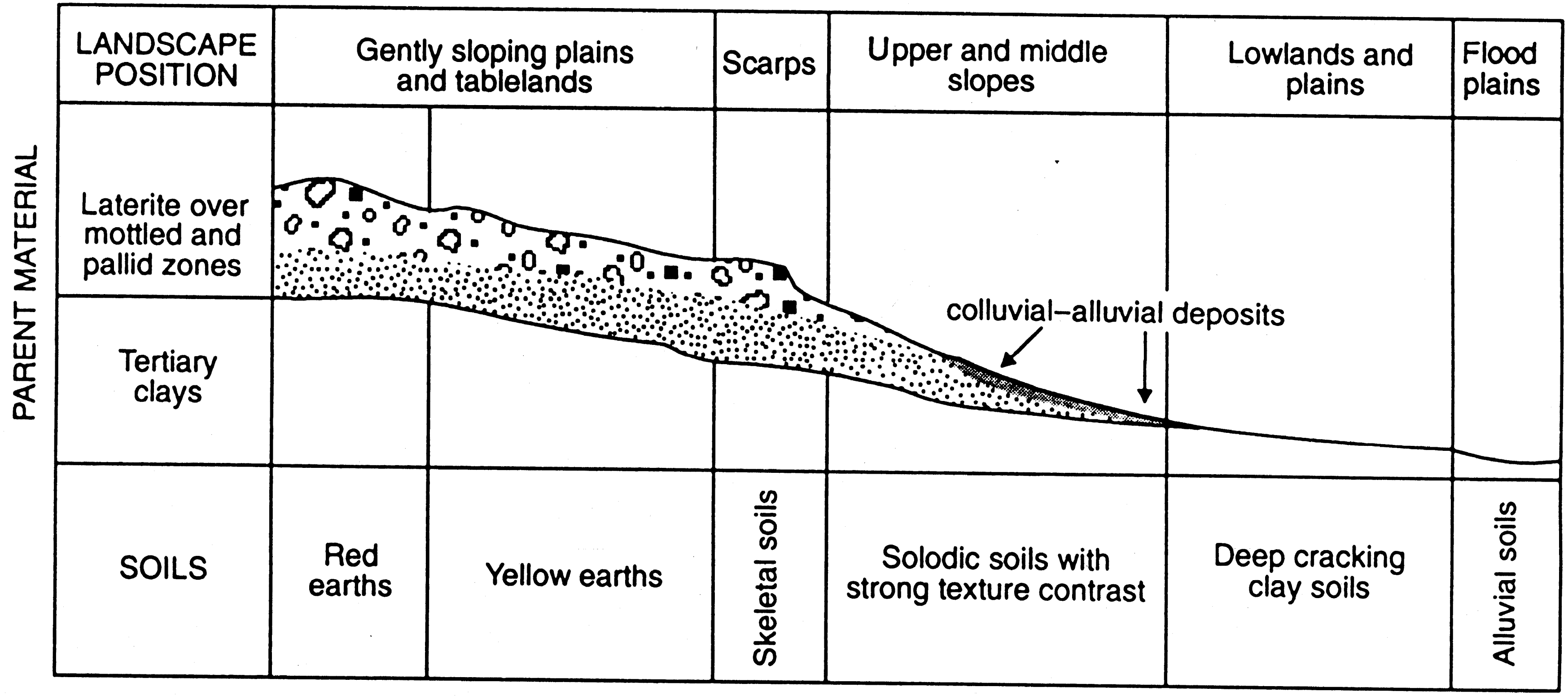
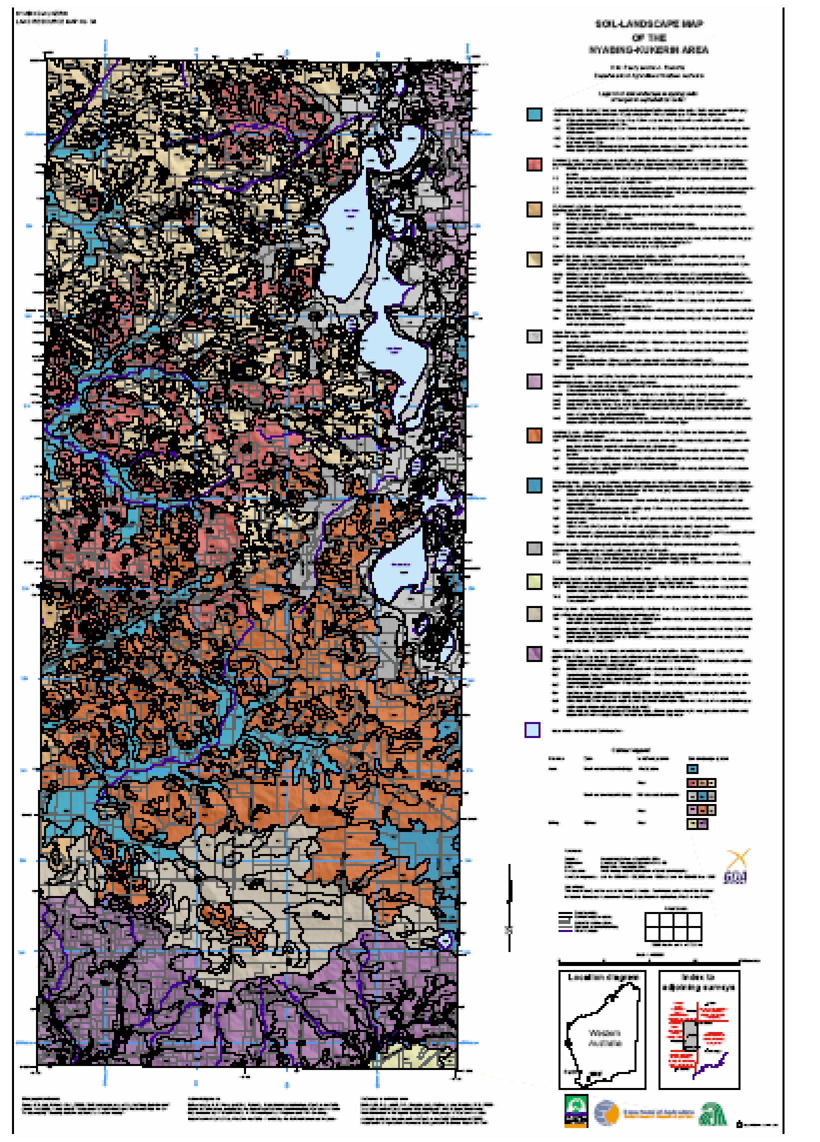
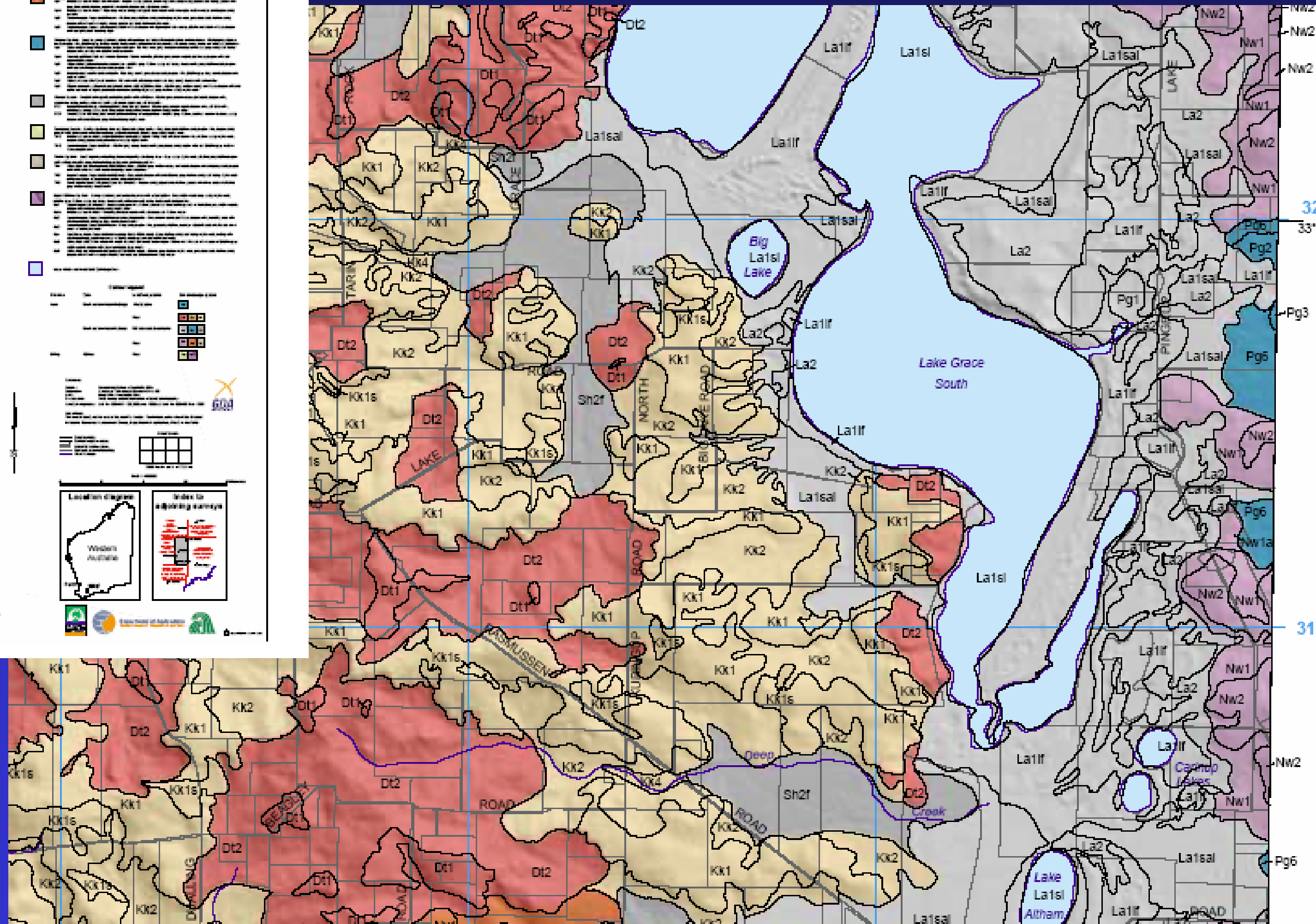


Soil catena from northern Queensland, showing variations in soil types with position in landscape (after Gunn, 1967).

Soil-landscape map of Nyabing-Kukerin, WA. WA Department of Agriculture.





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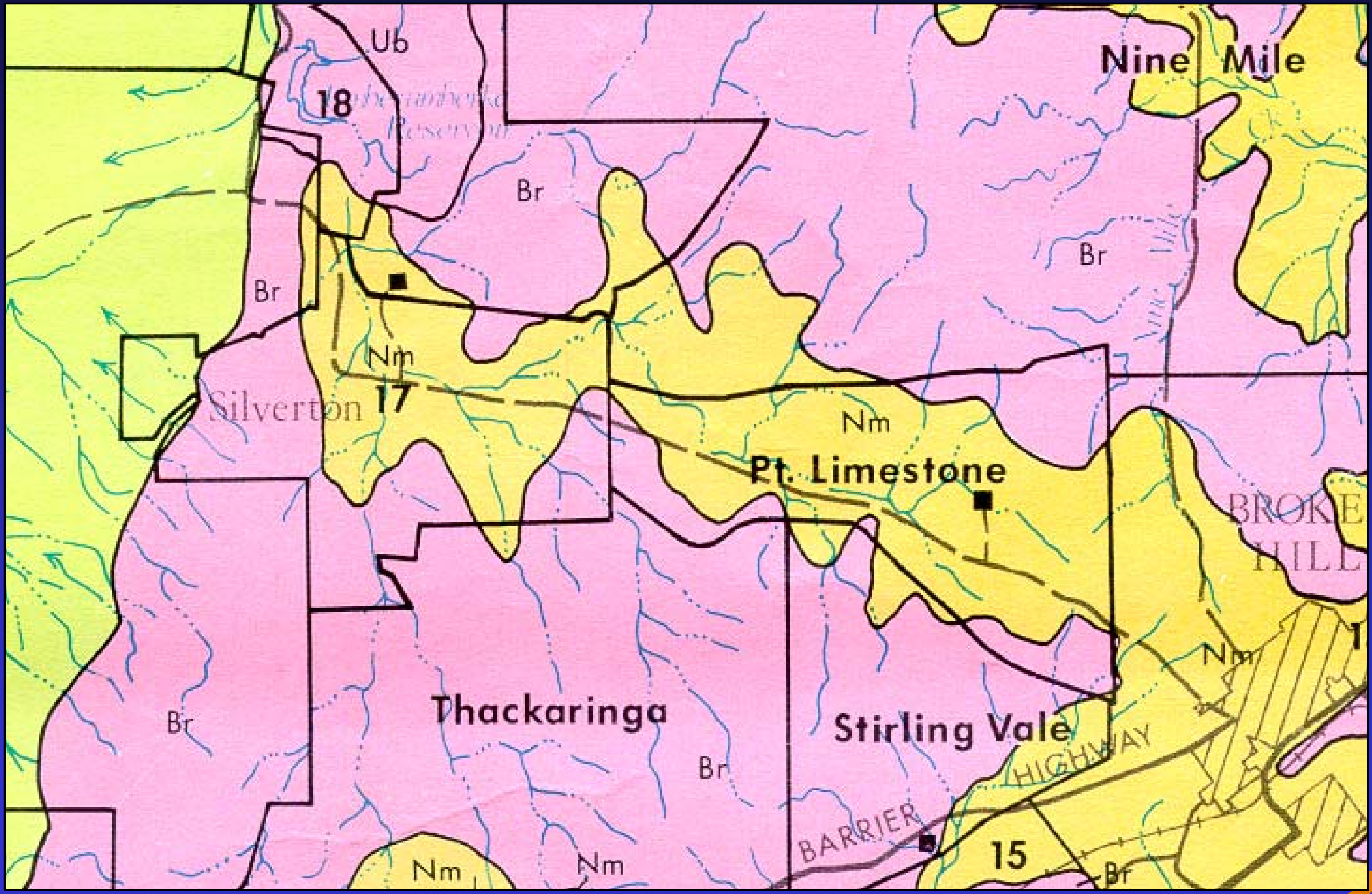
Land Systems Maps

- Show areas with recurring patterns of topography, soils and vegetation
- May be further sub-divided into land units
- Widely adopted as part of regional surveys in Australia, PNG, Africa etc.

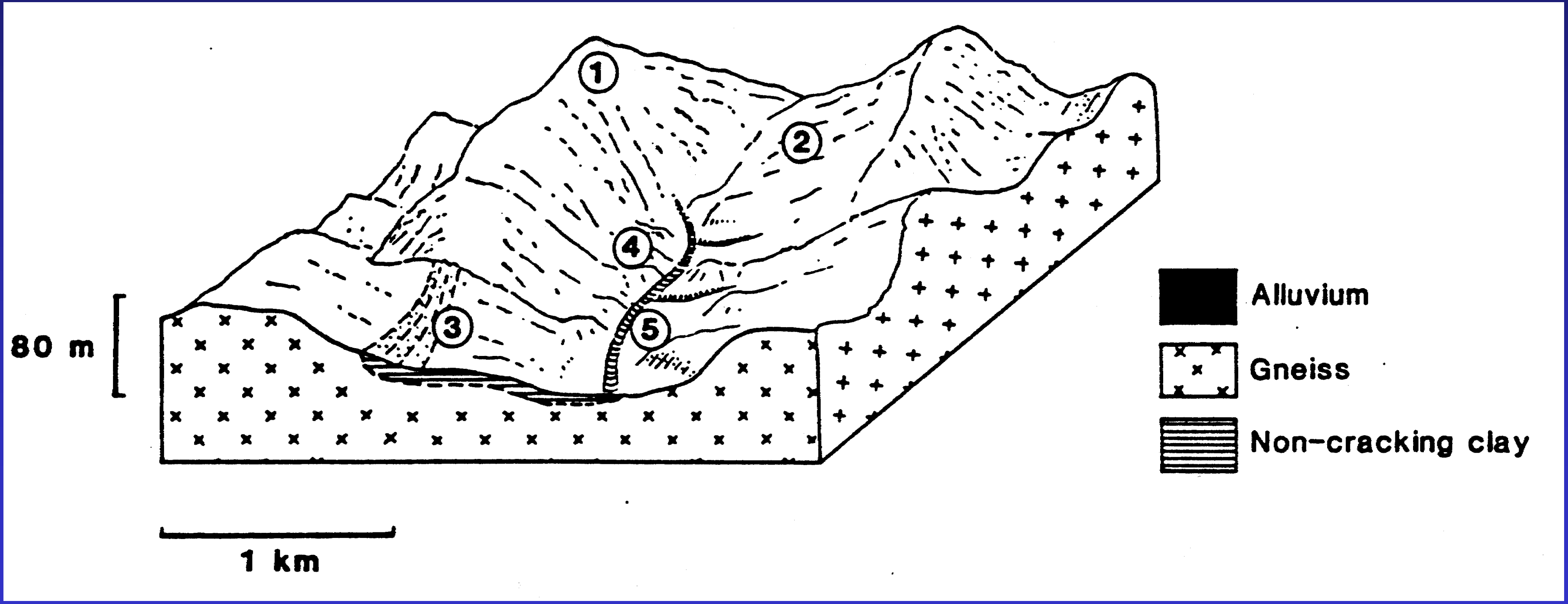
- Although the attributes of Land Systems may relate to regolith, these maps do not attempt to specifically show regolith

A portion of the Broken Hill 1:250k Land System map (Walker, 1991)



The Barrier (Br) Land System and associated Land Units (Walker, 1991):

1. Crests and upper slopes
2. Lower hills and slopes
3. Banded slopes
4. Footslopes and valleys



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What goes into regolith maps?

- Continuous coverage of regolith-landforms
  - Even in areas of bedrock exposure:
    - Bedrock near the Earth's surface is typically weathered to some degree
    - Bedrock exposures will have a landform associated with them
  - But why don't we just map bedrock units and have them on our regolith maps?
    - Inconsistent with regolith-landform presentation
    - Representation of degree of weathering can be later related to landscape expression and existing chemical surveys of bedrock units
    - Can be included in GIS derivative outputs

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What goes into regolith maps?

- Regolith mapping surrogates
  - Mappable features that can be related to the distribution patterns of regolith
  - Once relationship is established this can be a powerful, indirect method for mapping regolith
  - e.g.
    - landforms
    - soils
    - vegetation
    - lithology
    - geology
    - chronology
    - remotely sensed features (e.g. Landsat TM, radiometrics, air photos)

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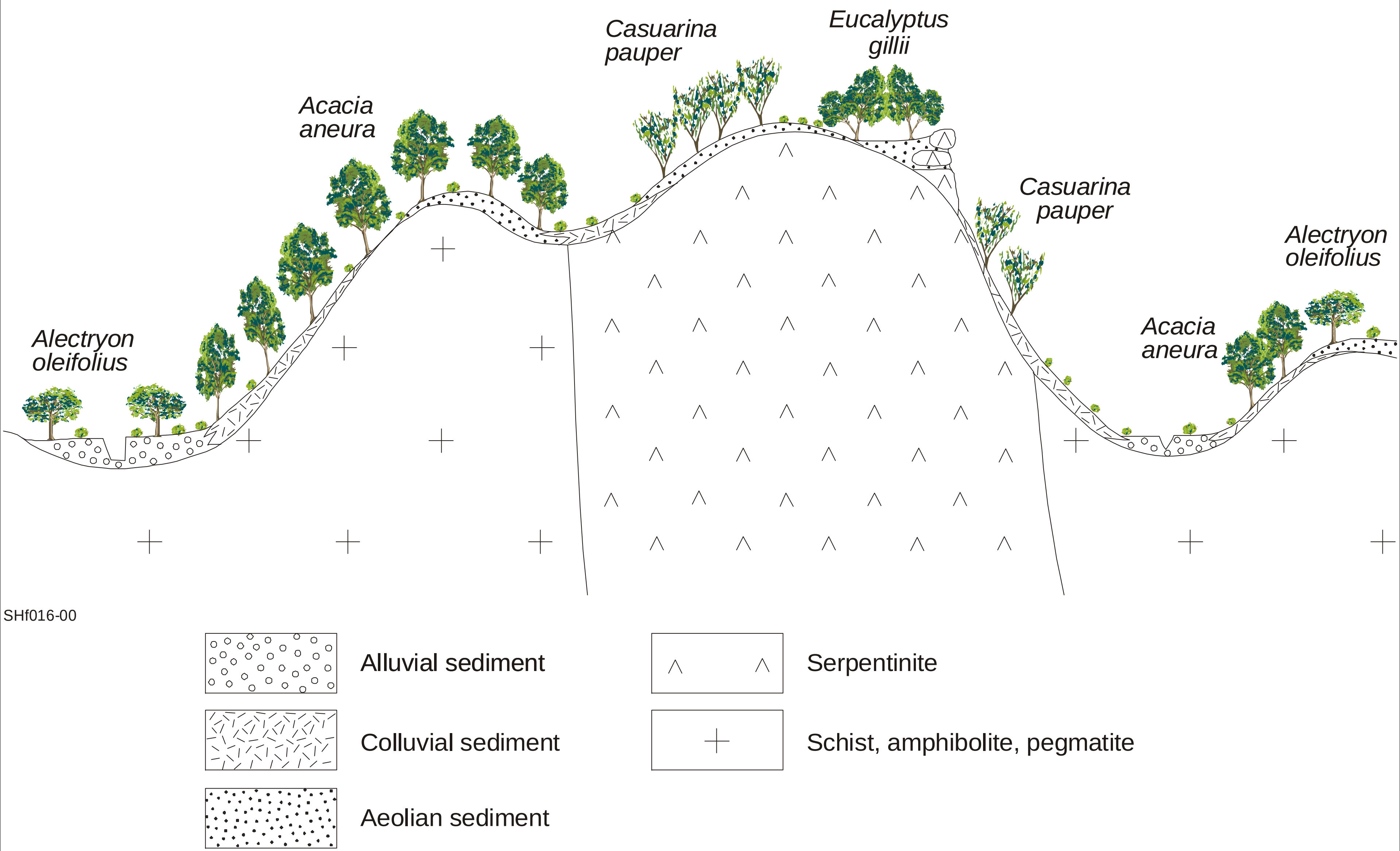
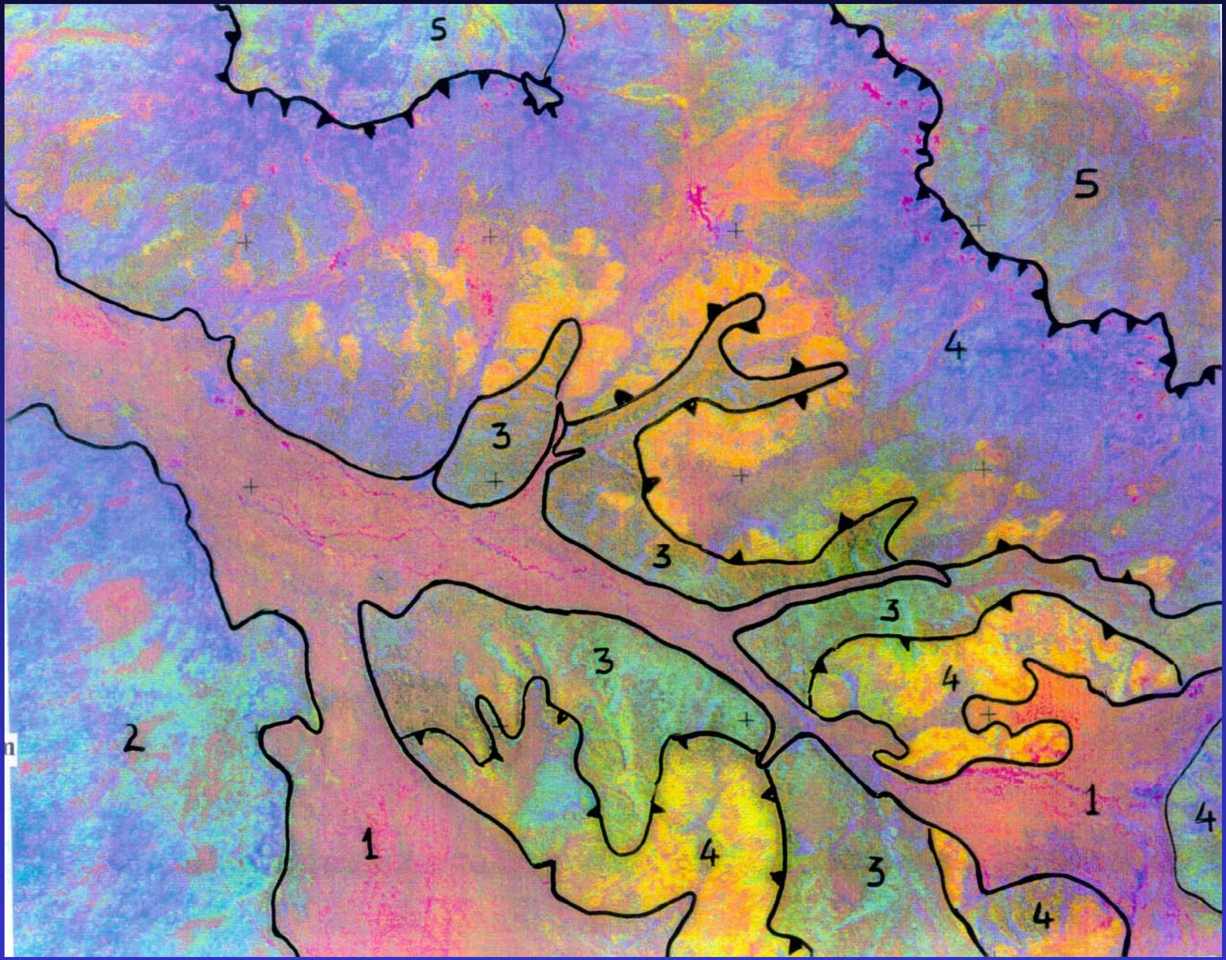
A vegetation surrogate associated with regolith developed on ultramafic bedrock at Thackaringa, NSW

A vegetation surrogate associated with regolith developed on ultramafic bedrock at Thackaringa, NSW (from Hill, 2000)



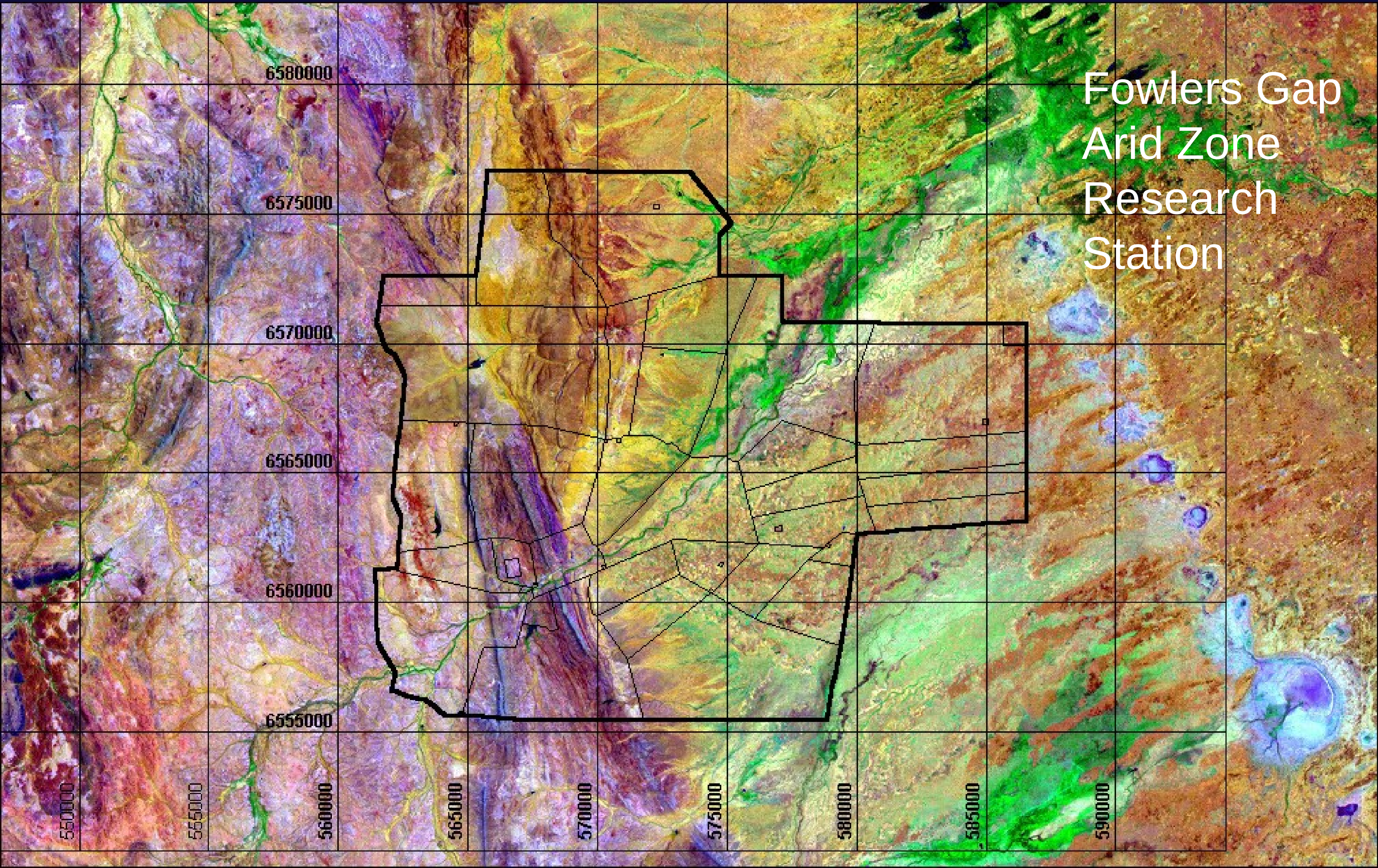
Landsat TM Surrogacy

CSIROREG Image near White Cliffs, NSW

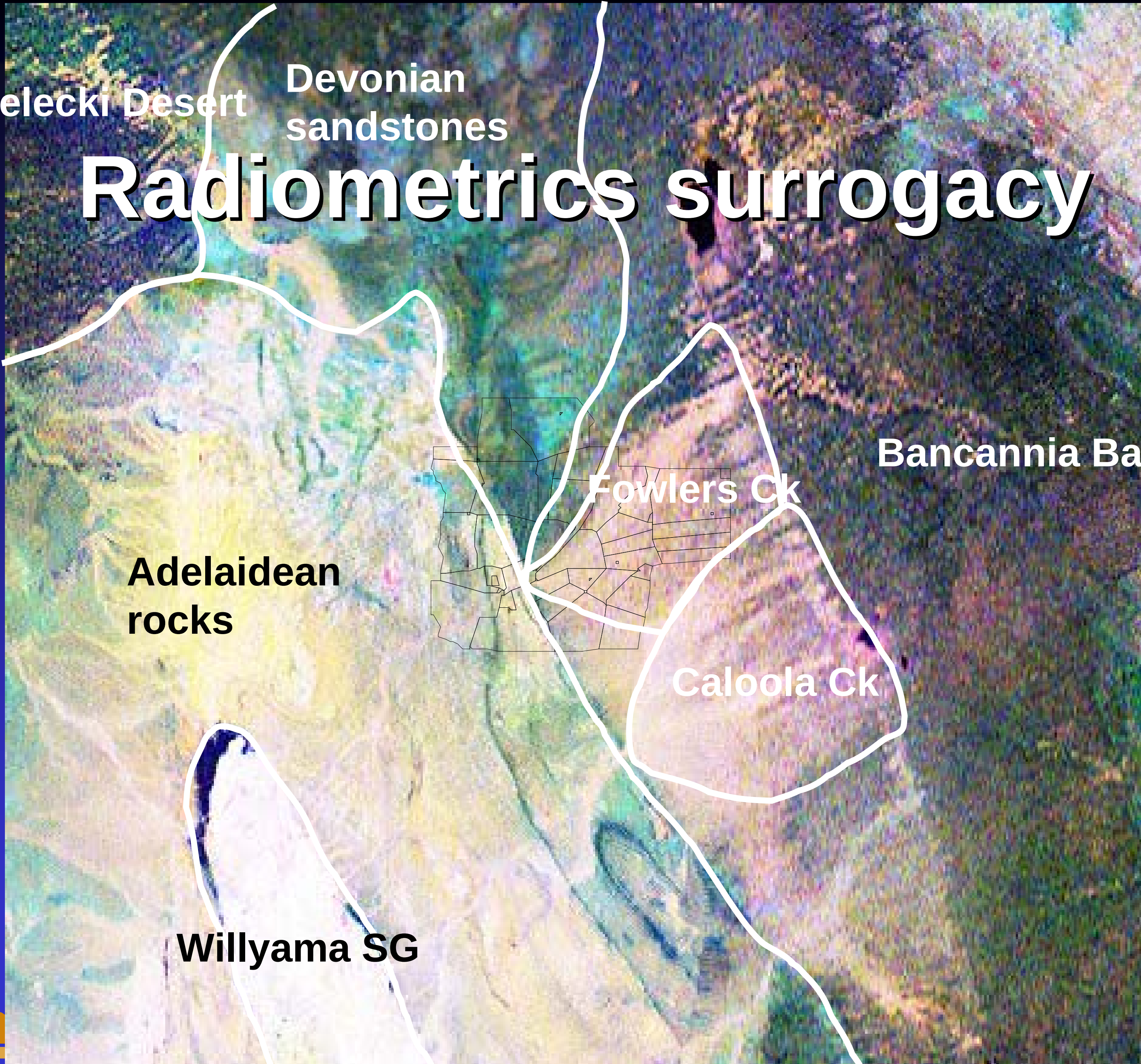


1. Aap
2. ISps
3. SHer (ferruginous)
4. SMer
5. Aer (silicified)

Landsat TM surrogacy



Radiometrics surrogacy



Regolith and Landforms

- Landform is the most popular surrogate used for mapping regolith:
  - regolith materials can be linked with particular landform assemblages
  - landforms can be conveniently observed in the field or remotely (e.g. stereoscopic aerial photographs, imagery, DEMs)
  - landforms cover the continents continuously

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Linear sand dune and adjacent alluvial plain - Merty Merty, SA

Regolith and Landforms

- Consider these two regolith-landforms
  - – Similar landform assemblages, but what about the associated regolith materials?

Mt Magnet, WA - ferruginous “breakaway”

Cue, WA - siliceous “breakaway”

A Regolith-Landform Mapping Framework

- GA regolith-landform units
  - Represents units based on:
    - Regolith Material (shown in upper-case letter codes)
    - Landform (shown in lower-case letter codes)
    - e.g. **$\mathbf{CHfs_1}$**
      - CH describes the main regolith type (sheetflow deposits)
      - fs describes the main landform type (sheetflood fan)
      - 1 is a modifier number used to divide between more subtle differences between units

A Regolith-Landform Mapping Framework

- GA regolith-landform units
  - Examples of regolith types and their codes
    - A alluvial sediments
    - C colluvial sediments
    - I aeolian sediments
    - SS slightly weathered bedrock
    - AC alluvial channel deposits
    - CH sheetflow deposits
    - O coastal sediments
    - SH highly weathered bedrock
  - Examples of landforms and their codes
    - ap alluvial plain
    - pd depositional plain
    - er erosional rise
    - aw alluvial swamp
    - cc beach
    - eh erosional hill
    - fa alluvial fan
    - ed drainage dpn
    - em erosional mtn

A Regolith-Landform Mapping Framework

- GA regolith-landform units
  - Induration
    - composition (e.g. ferruginous, carbonate, silica, manganiferous...)
    - morphology (e.g. nodular, hardpan, saprolitic…)

    - Included as a modifier to a particular regolith-landform unit
      - e.g. Aer1 (alluvial sediments on an erosional rise with siliceous induration)
      - e.g. Aer2 (alluvial sediments on an erosional rise with ferruginous induration)
    - May be shown as an over-print pattern too

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A Regolith-Landform Mapping Framework

- Possible minimum attributes to record for RLU field sites:
  - 1. Dominant regolith lithology (including induration modification)
  - 2. Dominant landform
  - 3. Surficial features (e.g. lag)
  - 4. Minor features
  - 5. Dominant vegetation community structure type and species

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An example of an RLU field site

Regolith: Colluvial seds [C]

Surficial Features: quartzose lag

Landform: Depositional Plain [pd]

Minor Features: red-brown fine sand

Vegetation: chenopod shrubland dominated by *Sclerolaena spp*.

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A Regolith-Landform Mapping Framework

- RLU information represented in:
  - – polygon pattern on map
  - – by letter codes
  - – non-interpretative description in map legend
  - – in accompanying GIS and/or report

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A Regolith-Landform Mapping Framework

- GA regolith-landform units
  - Some aspects to consider…
    - Is relationship between regolith and landforms always valid, and at all scales?
    - Can regolith materials always be satisfactorily grouped in this way (e.g. alluvial, colluvial, aeolian etc)?

Before you start

- Mapping Purpose
  - You need to know (or at least have thought about) the mapping objectives.
  - These could be:
    - general purpose
    - specialised (specific) purpose
      - e.g. mineral exploration, regolith-landform research, environmental management.

Chenopod shrub

Surficial dispersion pathway

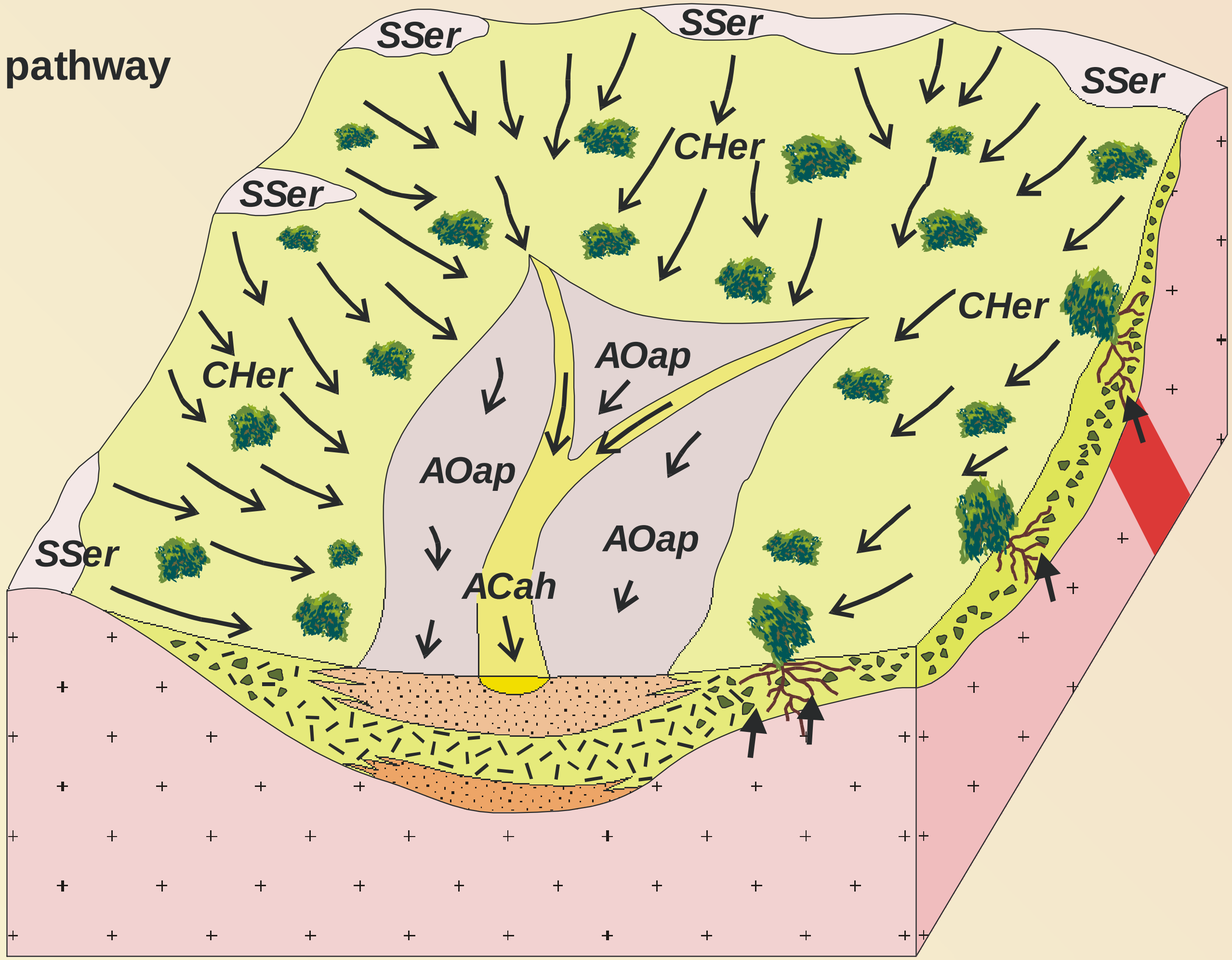
Regolith carbonate accumulation

ACah alluvial channel sediments in an alluvial channel

AOap alluvial overbank sediments on an alluvial plain

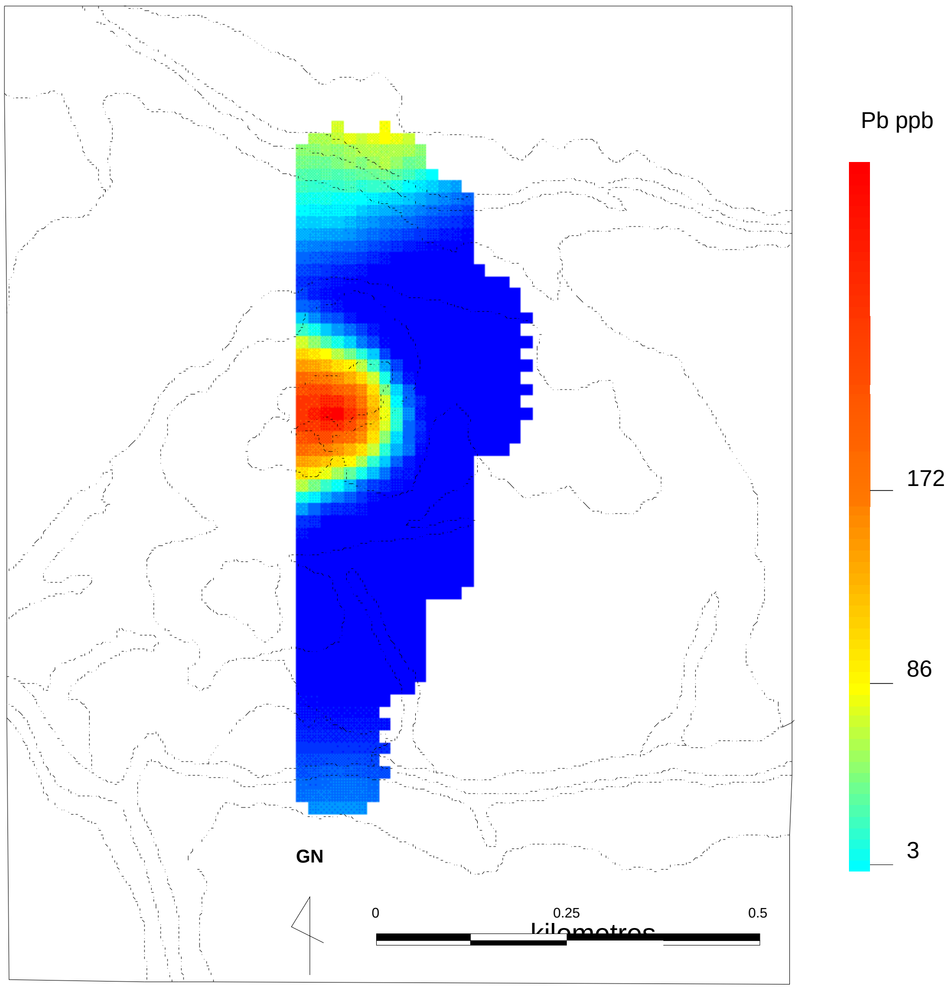
CHer colluvial sheetflow sediments on an erosional rise

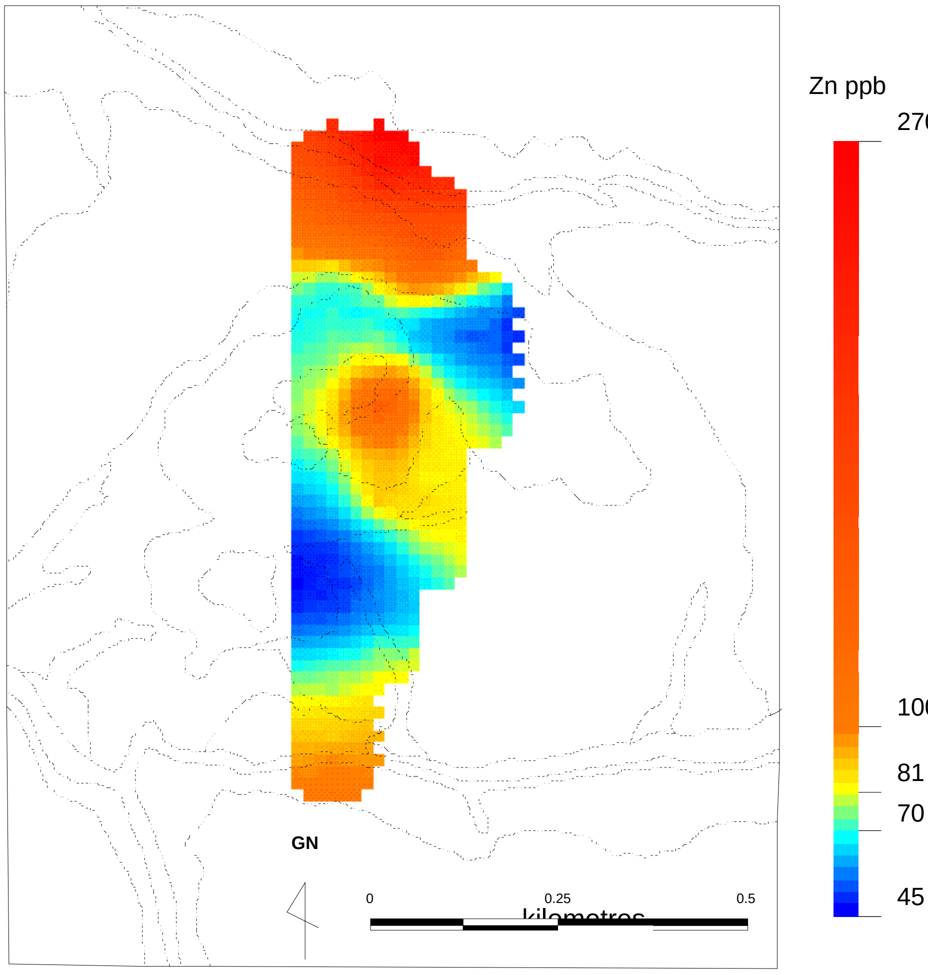
SSer slightly weathered bedrock on an erosional rise



SHs003-00

Regolith geochemistry and R-L maps

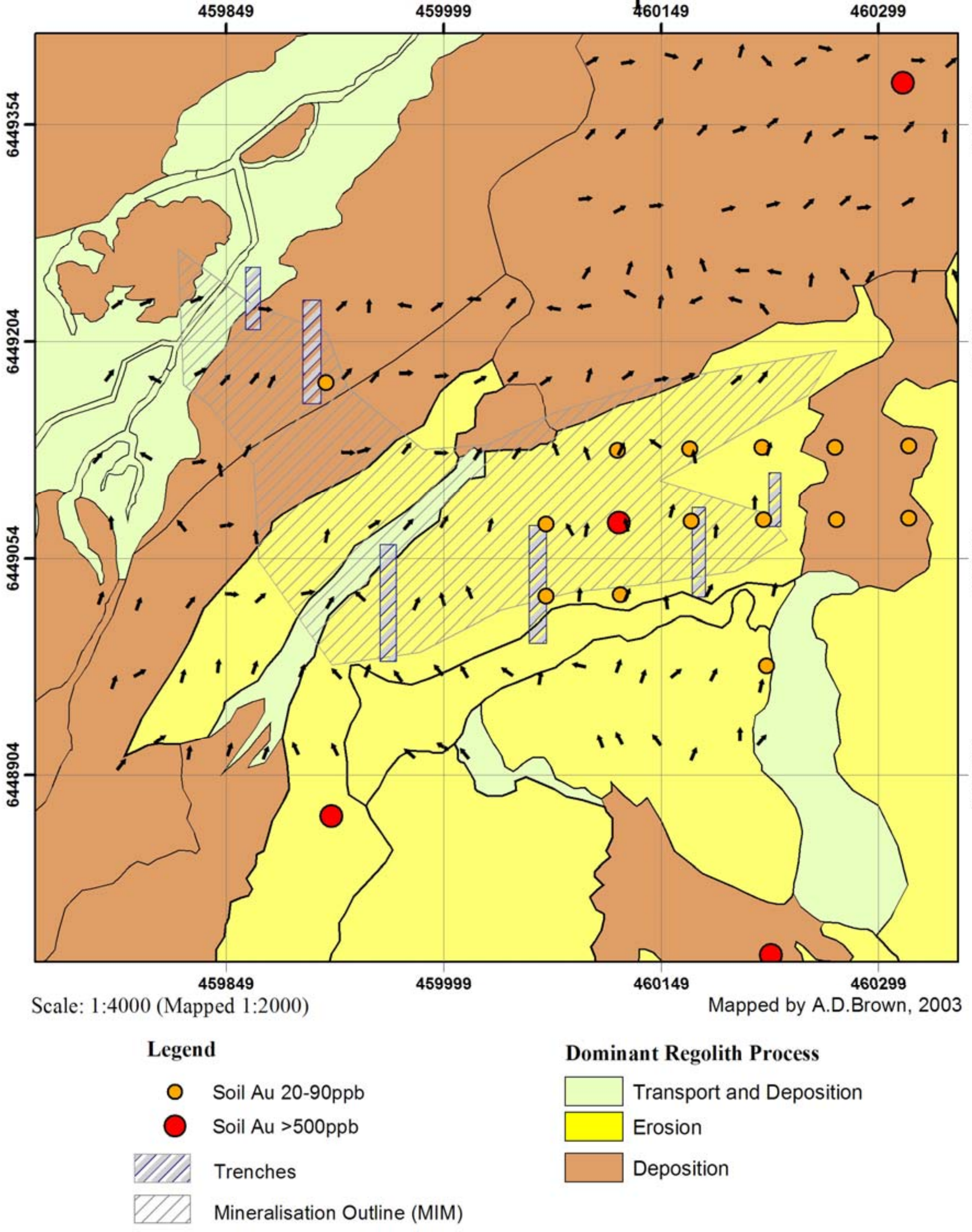




Deepleach 11 180 um Pb

Deepleach 35 180 um Zn

White Dam,
Curnamona Province SA
(Brown & Hill, 2003)



Can I start now?

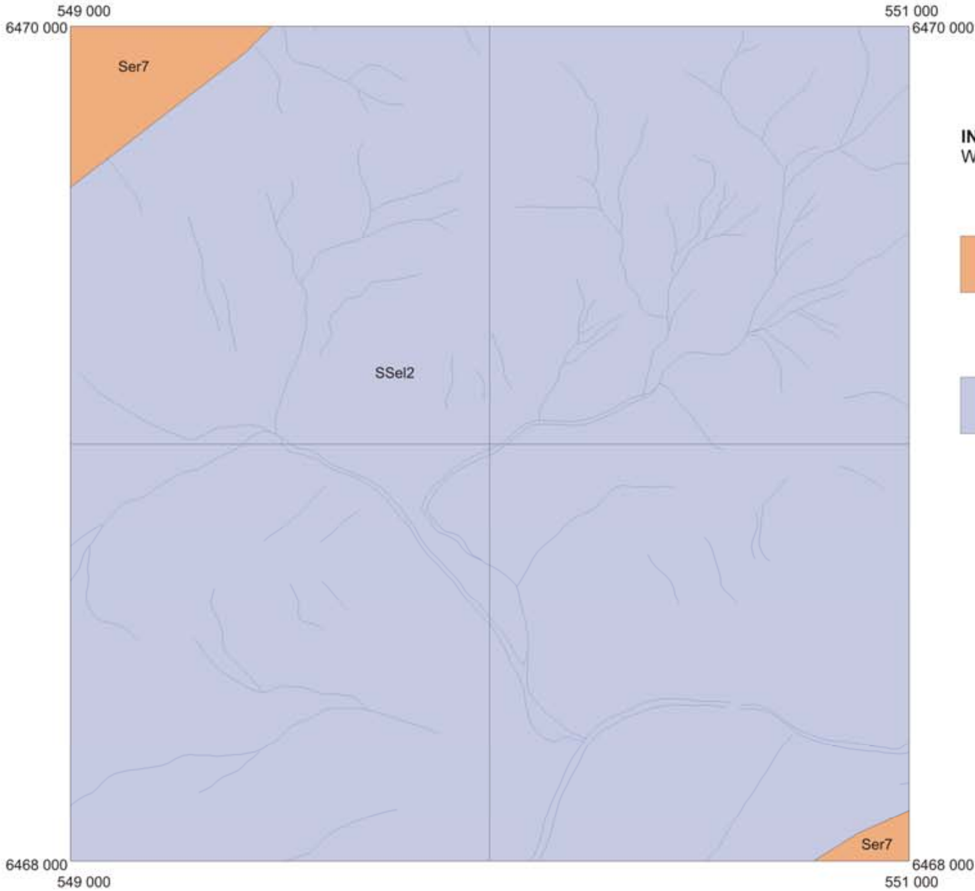
- What Scale are you going to be mapping at?
  - This relates closely to:
    - the general mapping objectives
    - the size of the area to be mapped and time / budget constraints
    - RLU homogeneity / heterogeneity to be presented
    - Size of RLUs to be represented
    - Precision of mapping boundaries

Mapping Scale Considerations

Map Scale	Min. Unit Width (> 3 mm polygon)	0.3 mm Line thickness equivalent
1:500 K	1500 m	150 m
1:250 K	750 m	75 m
1:100 K	300 m	30 m
1:50 K	150 m	15 m
1:25 K	75 m	7.5 m
1:10 K	30 m	3 m

Flying Doctor Catchment

Broken Hill 1:500 000 Regolith-Landforms (Gibson and Wilford, 1996) at 1:10 000



IN-SITU REGOLITH

Weathered rock — Palaeozoic and Precambrian rocks

Undifferentiated saprolite

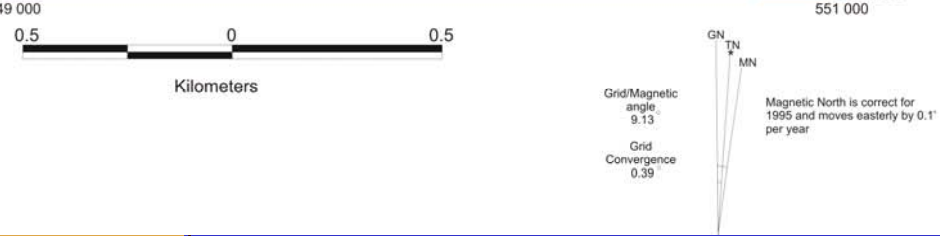
Ser7	Weathered Precambrian rocks in broad, relatively flat floored drainage basins forming erosional rises mostly surrounded by low hills and hills, but locally with scarp edges down to more dissected country. Alluvium and colluvium, calcareous in part, locally dominant. Broken Hill map area.

Slightly weathered saprolite

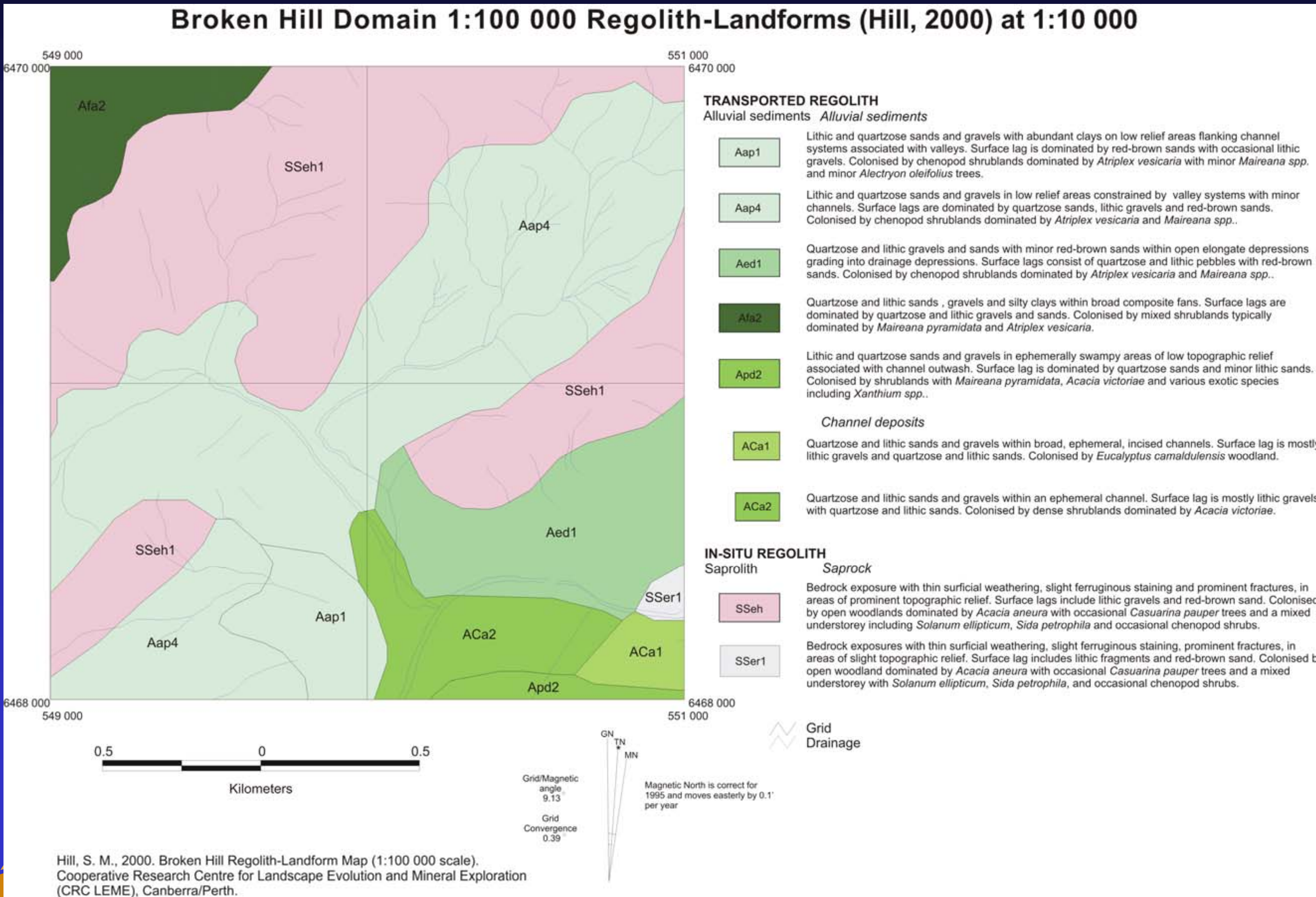
SSel2	Slightly weathered Palaeoproterozoic metamorphics in low hills and hills. Central west Broken Hill map area.

Grid
Drainage

D.L. Gibson & J.R. Wilford, 1996. Broken Hill Regolith Landforms (1:500 000 map scale) Cooperative Research Centre for Landscape, Evolution and Mineral Exploration (CRC LEME), Perth/Canberra.



Flying Doctor Catchment



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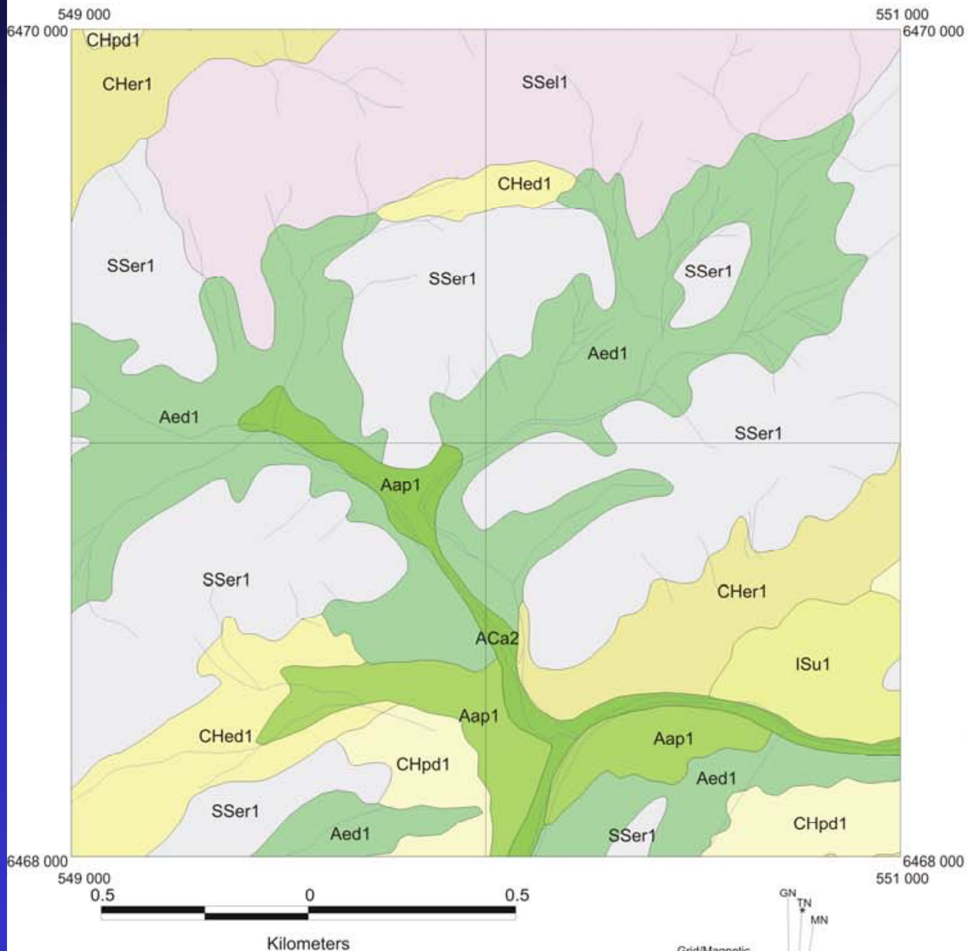
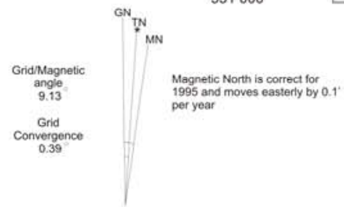
Flying Doctor Catchment

Mount Gipps 1:25 000 Regolith-Landforms (Lewis *et al.*, 2002) at 1:10 000





Lewis, A.C., Foster, K.A. & Hill, S.M., 2002. Mount Gipps Regolith-Landform Map (1:25 000 scale) Cooperative Research Centre for Landscape, Environments and Mineral Exploration (CRC LEME), Canberra/Perth.

TRANSPORTED REGOLITH

Alluvial sediments *Alluvial sediments*

Aap1 — Sub-rounded to sub-angular sands, silts and minor clays and gravels, mostly composed of quartz and lithic fragments. Low relief landsurface with minor shallow (<1m) incised channels. Coarse quartz sands with minor quartzose and lithic gravel surface lag. Powdery, rhizomorphic and minor hardpan regolith carbonate accumulations. Chenopod shrubland dominated by *Atriplex vesicaria* and minor *Maireana spp.*.

Aed1 — Sub-rounded to sub-angular quartzose and lithic sands, silts and occasional gravels. Depression with minor channel. Quartzose and lithic silts, sands and gravels. Rounded red-brown fine sands and silts, with powdery, rhizomorphic and minor hardpan regolith carbonate accumulations. Chenopod shrubland dominated by *Atriplex vesicaria* and minor *Maireana spp.* and *Enchylaena tomentosa*.

Channel deposits

ACa2 — Sub-rounded to sub-angular sands, silts and gravels, composed of quartz and lithic fragments with minor heavy minerals and clay. Ephemeral meandering and minor braided channels, with occasional levees. Imbricated gravel lags and sands. Minor exposures of slightly weathered bedrock. Open shrubland of *Acacia victoriae* and minor *Myoporum montanum*.

Aeolian sediments *Aeolian sand*

ISu1 — Sub-rounded to rounded fine quartzose, and minor lithic, sands. Transverse dunes and low relief landsurface. Rounded red-brown fine quartzose sands and silts with occasional coarser quartzose and lithic sands. Lithic, quartz and occasional indurated gravels within swales. Grassland dominated by *Stipa spp.* & *Astrebla spp.* with occasional chenopods and scattered *Casuarina pauper, Acacia spp.* and *Alectryon oleifolias*.

Colluvial sediments *Sheet flow deposit*

CHed1 — Sub-rounded to sub-angular lithic and quartzose sands with occasional gravels. Elongate landsurface depressions. Lithic and quartzose sands and gravels. Irregular contour banded surface pattern. Very minor powdery and hardpan regolith carbonates and rounded, fine red-brown sands and silts. Chenopod shrubland dominated by *Atiplex vesicaria, Maireana spp.* and *Enchylaena tomentosa*.

CHer1 — Angular to sub-rounded lithic and quartzose gravels, sands and silts. Areas with slight topographic relief. Angular to sub-rounded lithic and quartzose gravel lag. Minor powdery, nodular and hardpan regolith carbonates and rounded red-brown fine sands and silts. Chenopod shrubland dominated by *Maireana spp.*

CHpd1 — Sub-angular to sub-rounded lithic and quartzose sands, silts and gravels. Area with low topographic relief. Surface lag of coarse lithic and quartzose sands. Minor nodular and hardpan regolith carbonate accumulations, minor maghemite, rounded red-brown fine sands and silts. Chenopod shrubland dominated by *Maireana spp.*

IN-SITU REGOLITH

Saprolith *Saprock*

SSel1 — Bedrock exposure with thin surficial weathering, slight ferruginous staining and open fractures. Area of moderate topographic relief. Bedrock exposure and coarse, angular lithic and quartzose gravels, and occasional clasts of fragmented regolith carbonate accumulations. Minor rounded red-brown fine sands and silts with minor to extensive hardpan regolith carbonate accumulations. Chenopod shrubland dominated by *Maireana spp., Atriplex vesicaria,* with *Acacia aneura* trees.

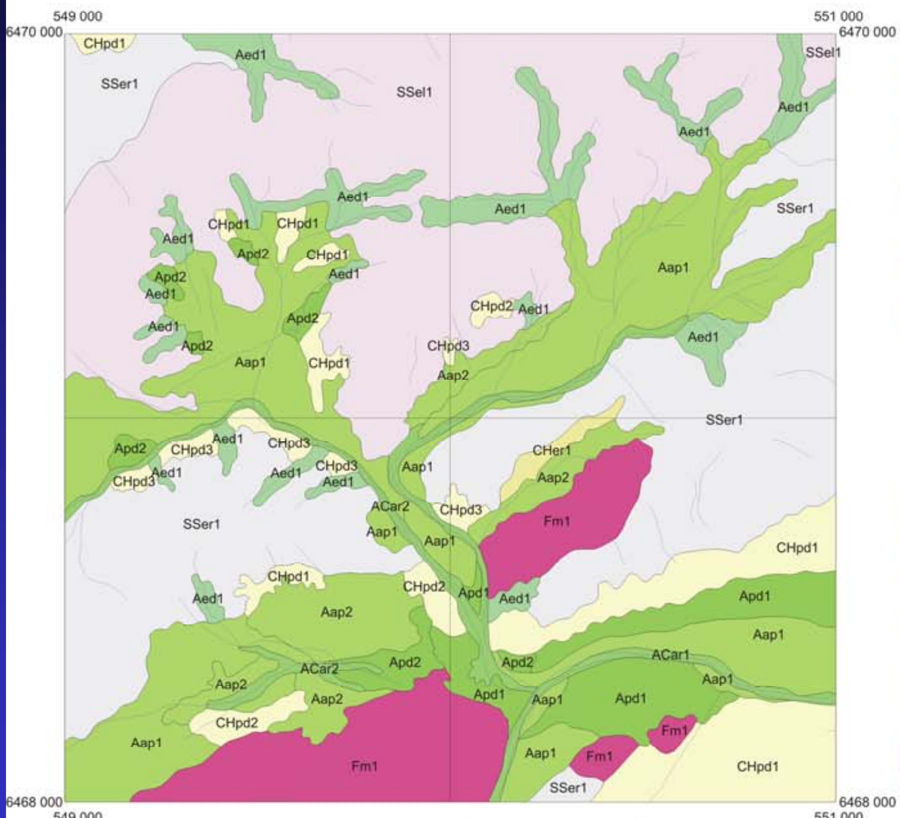
SSer1 — Bedrock exposure with thin surficial weathering, slight ferruginous staining and open fractures. Area of slight topographic relief. Bedrock exposure and coarse, angular lithic and quartzose gravels, and occasional clasts of fragmented regolith carbonate accumulations. Minor rounded red-brown fine sands and silts with minor to extensive hardpan regolith carbonate accumulations. Chenopod shrubland dominated by *Maireana spp., Atriplex vesicaria,* with *Acacia aneura* trees.

Grid

Drainage

Flying Doctor Catchment

The Flying Doctor Catchment 1:10 000 Regolith-Landforms



0.5 0 0.5

Kilometers

Compiled by K.L. Earl (GA/CRC LEME), M. Thomas (GA/CRC LEME), K.A. Foster (CRC LEME/GA) and S.M. Hill (CRC LEME/UC), 2002. Cartography and GIS by K.L. Earl (GA/CRC LEME) and K.A. Foster (CRC LEME/GA).

The regolith-landform polygons on this map are based on interpretation of 1:50 000 aerial photographs, and extensive field mapping. It is the intention of this map to identify and characterise surface materials and processes in the prospective area relatively void of bedrock. The drainage data was courtesy of Pasminco Mining.

It is recommended that this map be referred to as: Earl, K.L., Thomas, M., Foster, K.A. & Hill, S.M., 2002. The Flying Doctor Catchment Regolith-Landform Map (1:10 000 scale) Cooperative Research Centre for Landscape, Environments and Mineral Exploration (CRC LEME), Canberra/Perth.

Grid/Magnetic angle 9.13°

Grid Convergence 0.39°

Magnetic North is correct for 1995 and moves easterly by 0.1° per year

GN TN MN

MINERAL RESOURCES

CRC LEME Cooperative Research Centre for Landscape Environments and Mineral Exploration

GEOSCIENCE AUSTRALIA

Grid Drainage

CRC LEME acknowledges the collaboration of the Geoscience Australia and the support of the New South Wales Department of Mineral Resources in the production of this map.

TRANSPORTED REGOLITH

Alluvial sediments — *Alluvial sediments*

- **Aap1** Red-brown quartzose silt and sand on a low relief land surface with numerous channels (<20 cm deep). Angular to sub-rounded fine quartz and lithic gravels. Chenopod shrublands dominated by *Acacia victoriae, Maireana pyramidata, Rhagodia spinescens* and *Atriplex vesicaria* with minor *Bassia spp.*.
- **Aap2** Red-brown quartzose silt and sand on a low relief land surface with numerous channels (<20 cm deep). Angular to sub-rounded predominantly quartz gravel lag. Chenopod shrubland dominated by *Acacia victoriae, Maireana pyramidata, Rhagodia spinescens* and *Atriplex vesicaria* with minor *Bassia spp.*.
- **Aed1** Red-brown quartzose silt and sand with fine quartz and lithic gravels, minor bedrock exposures and some sub-angular to sub-rounded lithic pebbles in elongate drainage depressions. Chenopod shrubland dominated by *Maireana pyramidata* and *Sida petrophila*.
- **Apd1** Red-brown quartzose silt and sand on low lying areas with very minor channels (<30 cm deep). Minor clay and sub-angular to sub-rounded quartz and lithic gravels, and pebbles. Chenopod shrubland dominated by *Atriplex nummularia*.
- **Apd2** Red-brown quartzose silt and sand on low lying areas between creeks with very minor channels (<30 cm deep). Minor clay and sub-angular to sub-rounded quartz and lithic gravels, and pebbles. Chenopod shrubland dominated by *Maireana pyramidata*.

Channel deposits

- **ACar1** Brown-grey quartzose silt and sand in an incised, meandering channel (<1.5 m deep). Quartz and lithic gravels and pebbles with minor bedrock exposure. Open woodlands dominated by *Eucalyptus camaldulensis*.
- **ACar2** Brown-grey quartzose silt and sand on an incised, meandering channel (<1.5 m deep). Quartz and lithic gravels and pebbles with minor bedrock exposure. Open woodlands dominated by *Acacia victoriae*.

Colluvial sediments — *Sheet flow deposit*

- **CHer1** Red-brown quartzose silt and sand on slight topographic relief. Surface lag of coarse lithic and quartzose sands and gravels conforming to a contour banding surface pattern. Chenopod shrubland dominated by *Maireana pyramidata*.
- **CHpd1** Red-brown quartzose silt and sand on a low relief land surface. Surface lag of quartzose and lithic gravels. Chenopod shrubland dominated by *Maireana pyramidata, Bassia spp.* and *Maireana sedifolia*.
- **CHpd2** Red-brown quartzose silt and sand on a low relief land surface. Surface lag of quartzose dominated gravels. Chenopod shrubland dominated by *Maireana pyramidata, Bassia spp.* and *Maireana sedifolia*.
- **CHpd3** Red-brown quartzose silt and sand on a low relief land surface. Surface lag of lithics dominated gravels. Chenopod shrubland dominated by *Maireana pyramidata, Bassia spp.* and *Maireana sedifolia*.

Fill — *Fill*

- **Fm1** Paved and landscaped area including the immediate surrounds of mine sites. Surface lags are highly variable. Vegetation is typically cleared and/or includes abundant exotic species.

IN-SITU REGOLITH

Saprolith — *Saprock*

- **SSel1** Exposed bedrock with moderate topographic relief (30 m to 90 m) and surficial weathering. Angular to sub-rounded fine quartz and lithic gravels, angular to sub-angular quartz and lithic pebbles. Chenopod shrubland dominated by *Maireana pyramidata, Acacia tetragonophylla, Acacia aneura* and *Maireana sedifolia*.
- **SSer1** Bedrock exposure with surficial weathering, minor silt and fine sand. Angular to sub-rounded fine quartz and lithic gravels, angular to sub-angular quartz and lithic pebbles. Chenopod shrubland dominated by *Maireana pyramidata, Acacia tetragonophylla, Acacia aneura* and *Maireana sedifolia*.

Regolith[1]	Landforms[1]
A - Alluvial Sediments	a - Alluvial Landform
AC - Channel Sediments	ap - Alluvial Plain
CH - Colluvial Sediments	pd - Depositional Plain
F - Fill	er - Erosional Rise
SS - Weathered bedrock	el - Erosional Low Hill

[1] C Pain, R Chan, M Craig, D Gibson, P Ursem & J Wilford (in press), RTMAP Regolith Database Field Book and Users Guide (Second Edition). CRC LEME Report 138.

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Field course assessment

- Regolith-landform map (40% of total)
- Regolith-landform report (60% of total):
  - Introduction (< 1 page);
  - Description and outline of RLUs (similar to legend entry, no more than 2 para, 1 descriptive, 1 interpretive);
  - Interpreted regolith and landscape evolution (ca. 2 pages, perhaps with descriptive diagrams);
  - Conclusion (1 para);
  - References (used them? Cite them!);
  - Regolith-landform map (resubmit completed map, or just the first one if you're happy with it).

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Field course assessment

- Includes:
  - Regolith-landform map
  - Regolith-landform report
- Reports due **18 September** (day after mid-semester break)

- **Decide now:**

  Final Field Report 30% or 40% of your total semester grade.

  Final exam 40% of 30% of your total semester grade.

Field course component

- Fowlers Gap Field Trip
  - July 8-16 (travel 8-9 & 15-16) depart 0800.
  - See Handout for more detailed information, but…
    - Cost $100
    - You must provide your own food.
    - There will be a BBQ provided free on 1st night (vegetarian options will be limited).
    - We will be passing through Broken Hill on the 9th and 11th. Opportunities to top up your supplies.

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Field course component

- DO NOT bring fruits and vegetables from Canberra. We will be passing through fruit fly quarantine areas
- Be warned! Make sure you have a couple of days food in reserve in case of rain. The roads are CLOSED if it rains and we may not get to BH until Tuesday or Wednesday!
- Pack light!

- Accommodation will be cramped. You may wish to take a tent.

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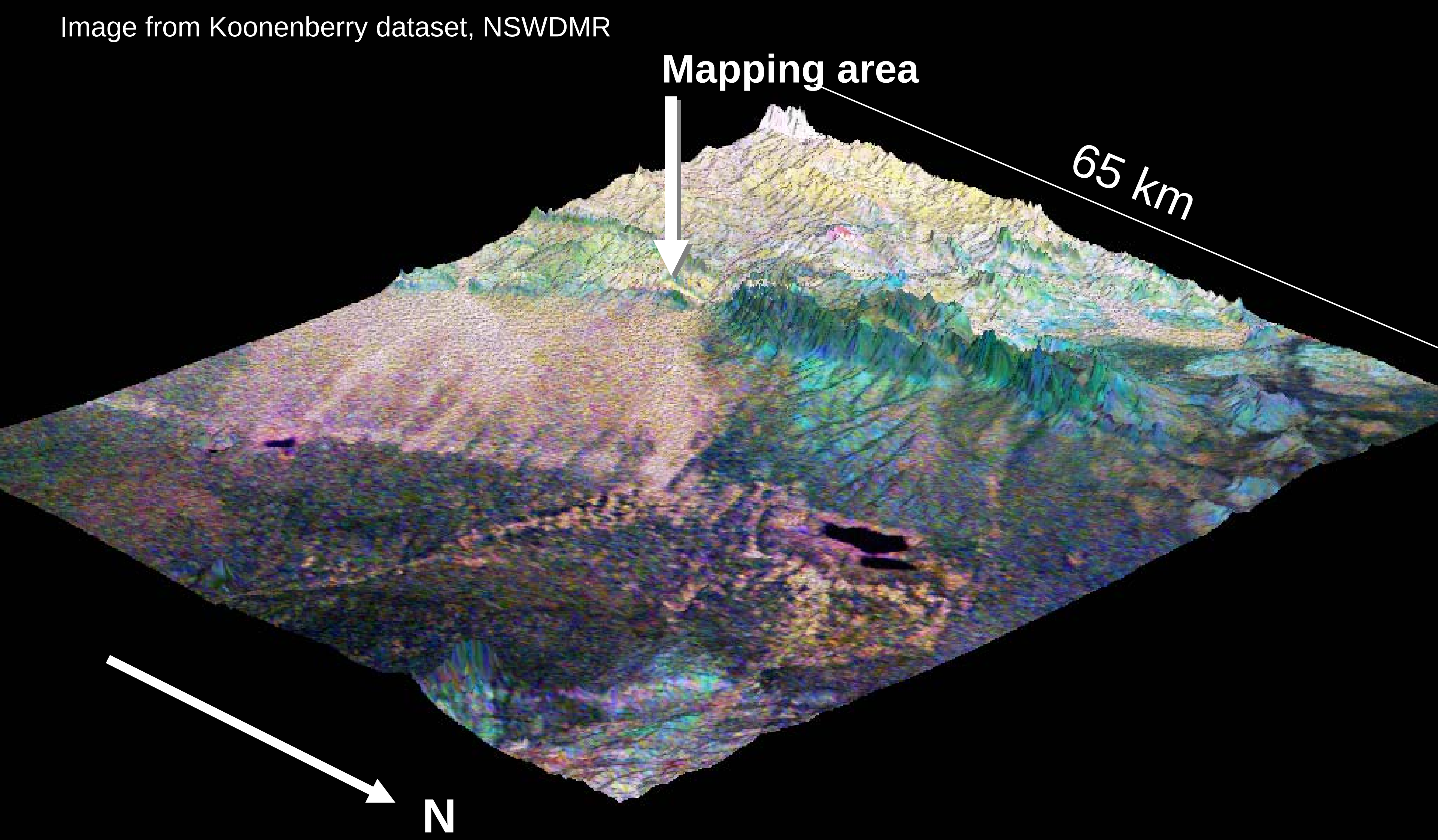
STOP!

Specifics of Fowlers Gap

- Let's look at some specific regolith-landforms at Fowlers Gap and see how they might be mapped…



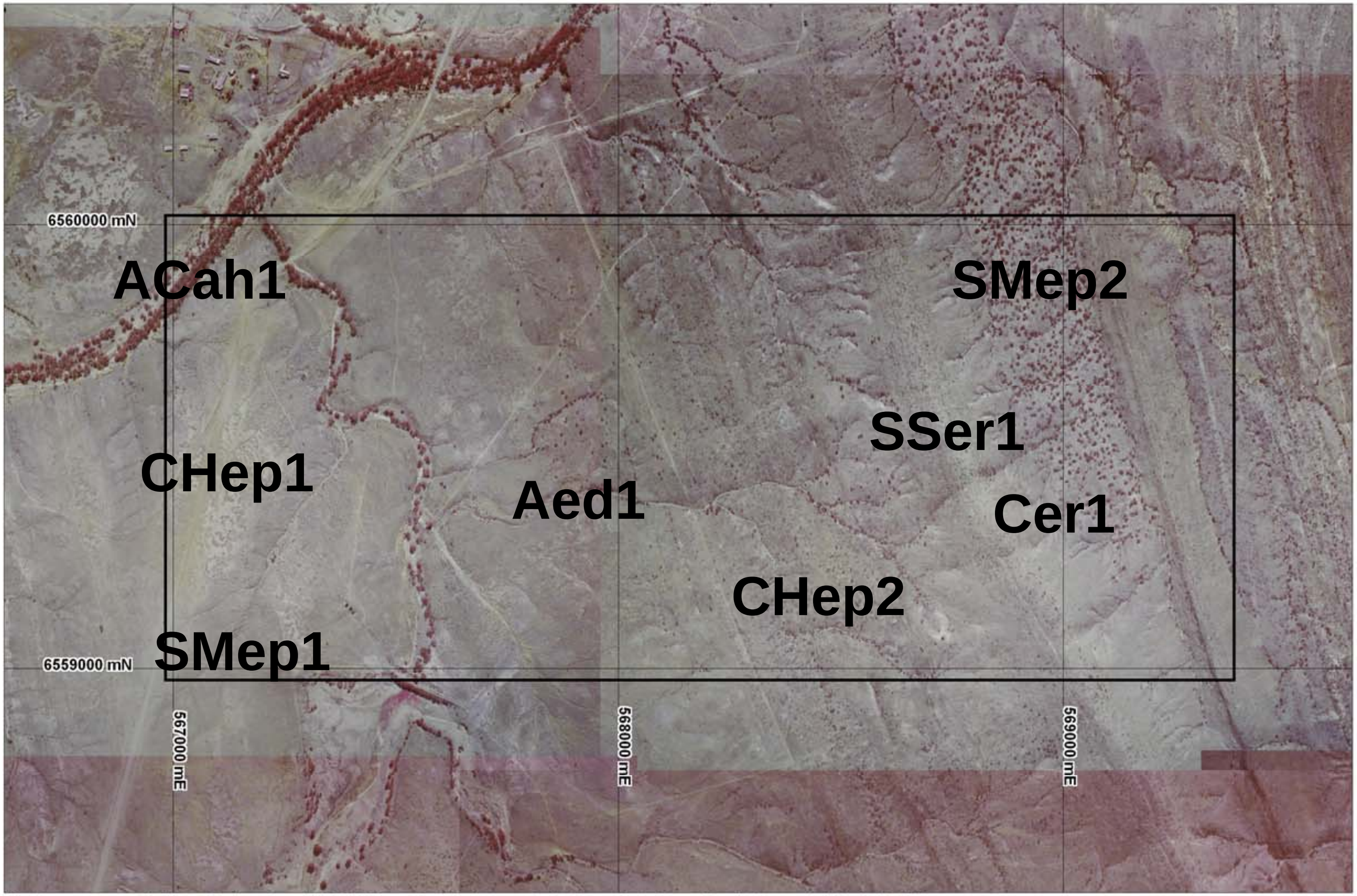
Fowlers Gap - Radiometrics draped over SRTM DEM

2005 ug mapping area

Fowlers Gap

Scale 1:12,500

Lake Paddock regolith-landform mapping area



Photobasemap compiled from Fowlers Gap 1:10,000 infra-red aerial photography by Qascophoto Runs 10 and 11, acquired 11 April 1981.
Map Grid conforms to the Australian Map Grid (AMG) using the Australian Geodetic Datum 1966 (AGD66), Universal Transverse Mercator projection Zone 54

2005 joint undergrad field class
dry weather mapping area

Image processed by Dr Ian Roach, MCA Lecturer CRC LEME, Australian National University, July 2005

Regolith-landform descriptions

- Lake Paddock regolith-landform units (RLUs) described using:
  1. Dominant regolith lithology (including induration modification)
  2. Dominant landform
  3. Surficial features (e.g. lag)
  4. Minor features
  5. Dominant vegetation community structure type and species

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ACah1

1. Subangular to rounded coarse lithic and quartzose sands, gravels and cobbles of quartz, quartzite and green slate.
2. Meandering to braided channels with rare elevated chutes outside small alluvial plains.
3. Ripples, dune-forms, channels.
4. RBFSS.
5. Riparian woodland dominated by River Red Gum (*Eucalyptus camaldulensis*) with understorey of Prickly Wattle (*A. Victoriae*), saltbushes (*Maireana sp.*), Emu Bush (*Eremophila sp.*), Lemon-scented Grass (*Cym-bopogon ambiguus*), other grasses and forbs.

CHep1

1. Dominant angular to subangular milky (vein) quartz lag.
2. Colluvial plain.
3. Minor ferruginised quartzite and highly ferruginised lithic fragments.
4. RBFSS.
5. Chenopod shrubland (*Maireana sp.*)
   Pearl Bluebush *(M. sedifolia),*
   Black Bluebush (*M. pyramid-
   ata*), Bladder Saltbush
   (*Atriplex vesicaria*),
   Copperburrs (*Sclerolaena sp.*),
   forbs and grasses.

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SMep1

1. Greenish slates, mostly outcropping, very thin colluvial mantle in places, little RCA.
2. Erosional plain.
3. Rare angular-subangular milky (vein) quartz, quartzite.
4. RBFSS.
5. Chenopod shrubland incl. Black Bluebush (*M. pyra-midata*), Pearl Bluebush (*M. sedifolia*), Bladder Saltbush (*Atriplex vesicaria*), forbs and grasses.

Aed1

1. Subangular to subrounded coarse lithic and quartzose sands, gravels and cobbles of quartz, quartzite, green slate and highly ferruginised bedrock, bedrock outcrop common in base.
2. Alluvial depression, < ca. 3 m deep.
3. Narrow channels often with undermined and collapsed banks.
4. RBFSS.
5. Dominated by Prickly Wattle (*A. victoriae.*), Black Bluebush (*Maireana pyramidata*), Lemon-Scented Grass (*Cymbopogon ambiguus*), Groundsel (*Senecio cunning-hamii*), Spiny Saltbush (*Rhag-odea spinecens*), forbs and grasses.

CHep2

1. Dominantly angular-subangular ferruginised quartzite lag with minor outcrop.
2. Colluvial plain.
3. Rare milky (vein) quartz and highly ferruginised lithic fragments.
4. RBFSS.
5. Sparse Belah (*C. pauper*), Rosewood (*Alectryon oleifolius*), Chenopods (*Maireana sp.*) Pearl Bluebush (*M. sedifolia*), Black Bluebush (*M. pyramidata*), Bladder Saltbush (*Atriplex vesicaria*), Copperburrs (*Sclerolaena sp.*), grasses and forbs.

CRCLEME

SSer1

1. Ferruginised quartzite outcrop and lag.
2. Erosional rise.
3. Rare milky (vein) quartz.
4. RBFSS.
5. Mulga (*Acacia aneura*), many dead, Pearl Bluebush (*M. sedifolia*), Ruby Saltbush (*Enchylaena tomentosa)*, Bladder Saltbush (*Atriplex vesicaria*), Copperburrs (*Sclerolaena sp*.), forbs and grasses.

CRCLEME

Cer1

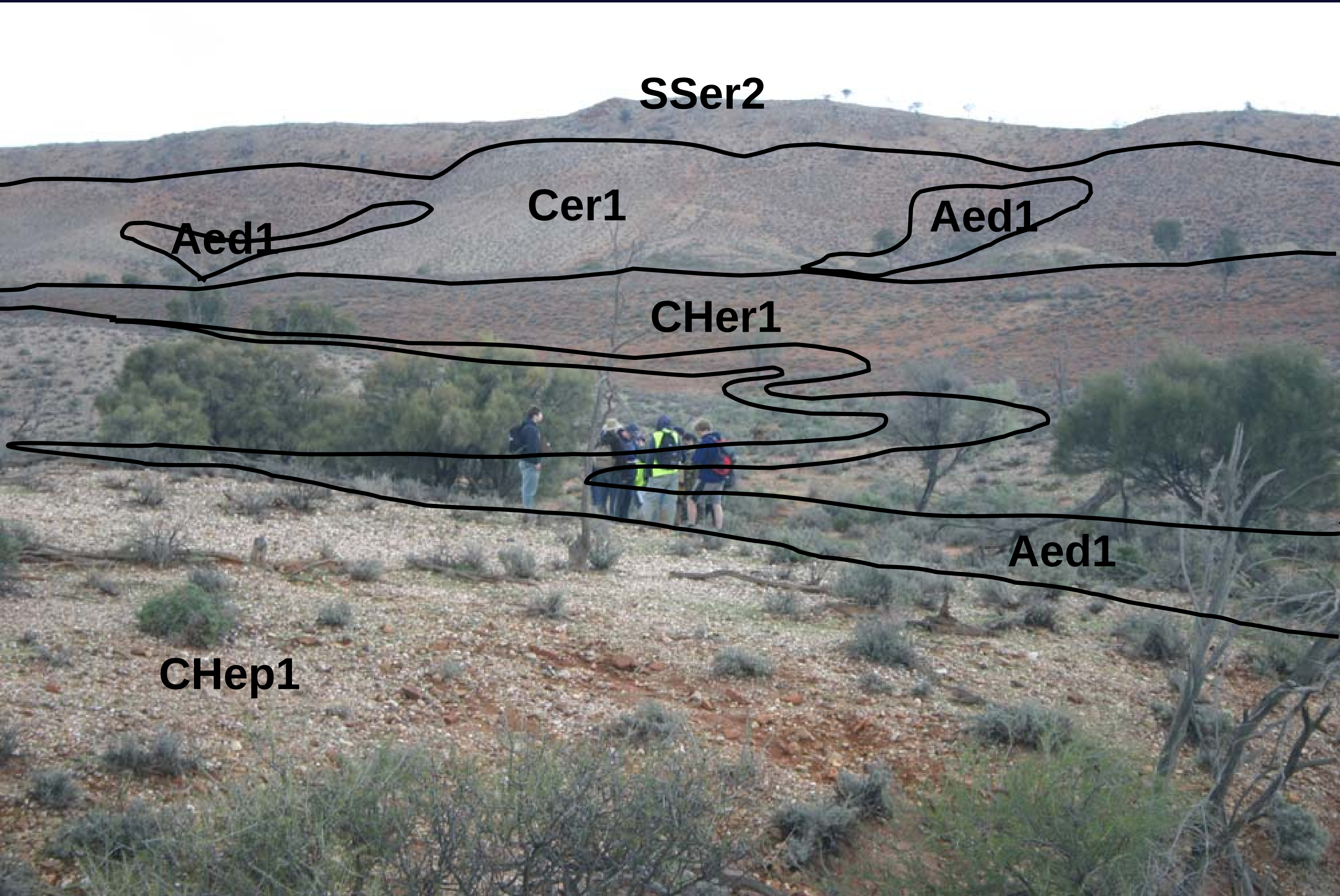
1. Angular ferruginised quartzite lag.
2. Colluvial erosional rise.
3. Rare milky (vein) quartz.
4. RBFSS.
5. Chenpods including *Maireana sp.* Pearl Bluebush (*M. sedifolia*), Mulga (*Acacia aneura*) and rare Ruby Saltbush (*Enchylaena tomentosa*) on upper slopes, Belah (*Casuarina pauper*) on lower slopes. Copperburrs (Sclerolaena sp.), Black Bluebush (*M. pyramidata*) and Bladder Saltbush (*Atriplex vesicaria*) are universal.

CRCLEME

SMep2

1. Greenish slates, mostly outcropping, very thin colluvial mantle in places.
2. Erosional plain.
3. Dominant angular green slate fragments, rare milky (vein) quartz.
4. RBFSS, clay, RCA coating fractures and sub-colluvial bedrock surfaces, surface dissected by numerous alluvial depressions.
5. Open woodland dominated by Curly Mallee (*Eucalyptus gillii*) and minor Pearl Bluebush (*Maireana sedifolia*), grasses, forbs.

CRCLEME


SSer2
Cer1
Aed1
Aed1
CHer1
Aed1
CHep1

Your task

- Complete your regolith-landform maps and extended legends using the available data, including:
  - Photomosaic basemap;
  - Sandstone and Sandstone Ridge Paddocks regolith-landform map;
  - Lake Paddock 2005 regolith-landform map;
  - Digital Elevation Model;
  - Airborne geophysics.

Legend Entries

- Legends should be as non-interpretive (i.e., as factual) as possible.
- Try to remember the 5 key ingredients:
  1. Dominant regolith lithology (including induration modification)
  2. Dominant landform
  3. Surficial features (e.g. lag)
  4. Minor features
  5. Dominant vegetation community structure type and species

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Sandstone 1:12,5k map

- ACah1 - (alluvial channel sediments/alluvial channel). Rounded and angular lithic and quartzose sands, gravels and minor silts, within sandy braided and meandering channels. Colonised by riparian woodlands dominated by *Eucalyptus camaldulensis* and minor *Grevillea striata* trees.
- ("ar" should be "ah" - it's a typo)

Sandstone 1:12,5k map

- Aed1 - (alluvial sediments/ drainage depression). Rounded to minor angular gravels, sands and silts composed of vein quartz, silicified sediment clasts, quartzose lithic fragments and minor lithic fragments and some weathered bedrock exposures. Incised channels and gullies and adjacent valley. Colonised by chenopod shrublands dominated by *Atriplex sp.*, *Maireana sp*. and *Xanthia ssp*., forbs with mixed shrublands dominated by *Acacia victoriae*, *Myoporum montanum* and minor *Hakea leucoptera*.

Sandstone 1:12,5k map

- CHep1 (sheetflow sediments/erosional plain). Angular lithic and quartzose gravels and red-brown quartzose sands on a low-relief (<9 m), low gradient landform with shallow bedrock subcrop that is locally shedding sediment. Colonised by open chenopod shrublands dominated by *Atriplex vesicaria*, *Maireana sp*. and grasses.

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Sandstone 1:12,5k map

- SSel1 (slightly weathered bedrock/erosional low hill). Quartzose bedrock (quartzite and quartz veins) exposure with minor opening of joint fractures, ferruginous staining and fragmentation of exposure surfaces. High-relief landform (30-90 m) associated with angular boulders and surface lags. Sparsely colonised chenopod shrublands typically dominated by *Atriplex sp*. And *Sclerolaena sp*. With occasional *Acacia aneura* trees.

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BROKEN HILL – FOWLERS GAP
REGOLITH & LANDSCAPE EVOLUTION FIELD GUIDE

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July, 2006

FOWLERS GAP TO BROKEN HILL AND THE BROKEN HILL LINE OF LODE

Introduction

This field trip passes from the northern Barrier Ranges at Fowlers Gap, through to the central Barrier Ranges at and near Broken Hill and then back to Fowlers Gap. This provides an introduction to a wide range of regolith materials and their associated landscape expression and significance.

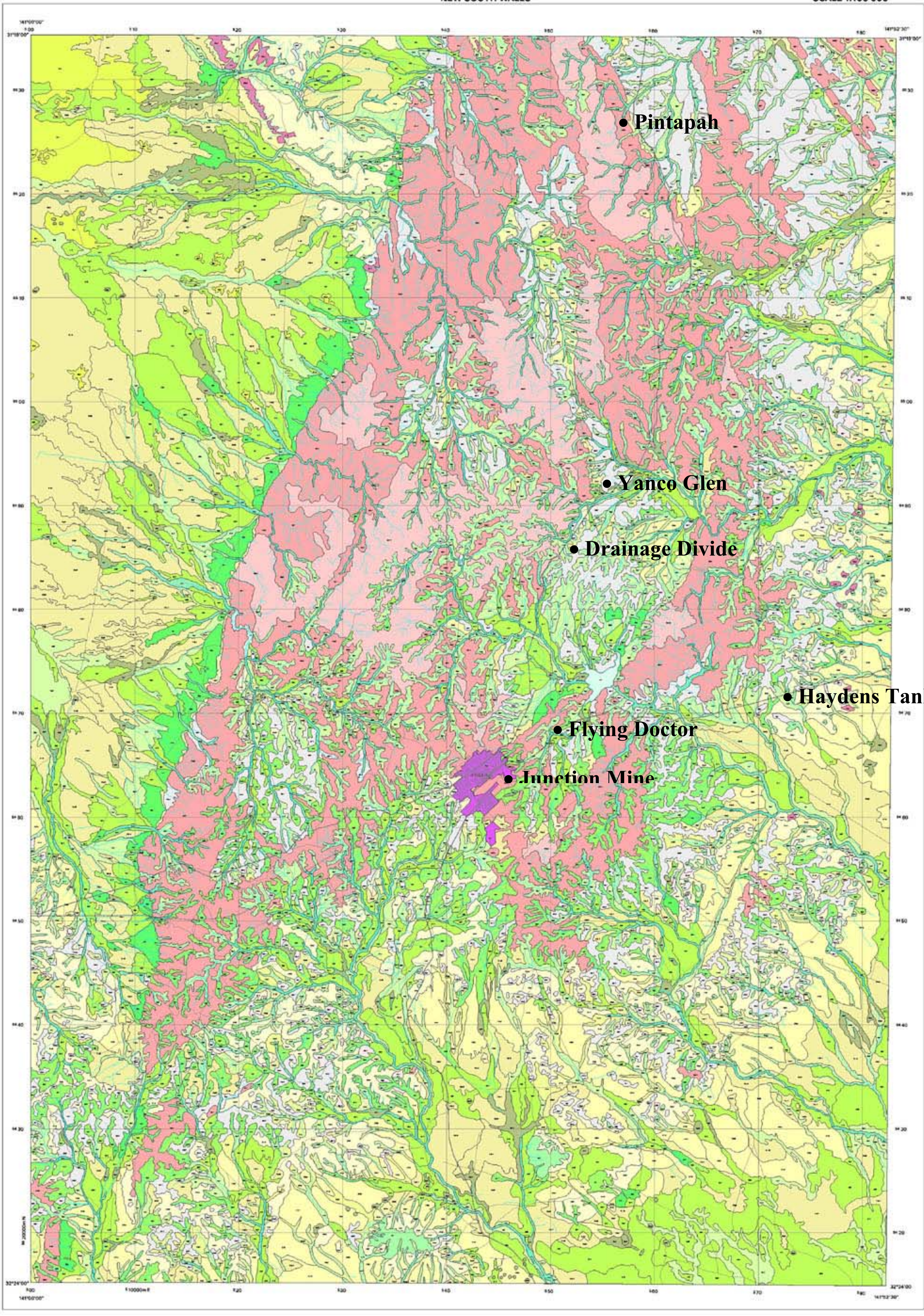
The focus for the morning is the regolith and landform expression of the Broken Hill Line of Lode and some of the exploration implications of this style of mineralisation within landscape settings with progressively greater regolith thickness and extent.

Lunch and last minute shopping can be taken at Broken Hill following the morning's activities.

The afternoon field sites occur occur between Broken Hill and westward to Silverton and the Mundi Mundi Plain. Time permitting, field sites may also be visited along the Silver City Highway between Broken Hill northwards to Fowlers Gap.

BROKEN HILL DOMAIN REGOLITH-LANDFORMS
(including part of Euriowie Domain and environs)
NEW SOUTH WALES

SCALE 1:100 000



Junction Mine, Broken Hill

The 'broken hill' was a well known topographical feature before mineralised was discovered there in 1883. It had a distinctive, black colour and steep irregular slopes, and was known to early pastoralists and miners as the 'hill of mullock' because of its highly weathered nature and surface samples that had low silver contents. Seven mining leases along the 'broken hill' ridge were pegged by Charles Rasp in September 1883. The Broken Hill orebody consists of silver-lead and lead-zonc lenses that have been deformed and structurally complicated resulting in zones of localised sulphide enrichment (Plimer, 2003).

At the Junction Mine we can see old mine working associated with Brownes Shaft, as well as some weathered exposure of the Broken Hill Line of Lode and surrounding rocks (Figure 1). Manganese oxides and hydroxides, goethite, kaolinite are the most prominent secondary minerals here. Looking at this exposure it is interesting to consider what would be some successful exploration strategies if it was covered by transported regolith?

A range of trees and shrubs have been sampled from this site for biogeochemical analysis (Table 1). The high contents of many of the metals within plant isuues at this site provides some indication of the potential for many of these shrubs to chemically express underlying mineralisation.

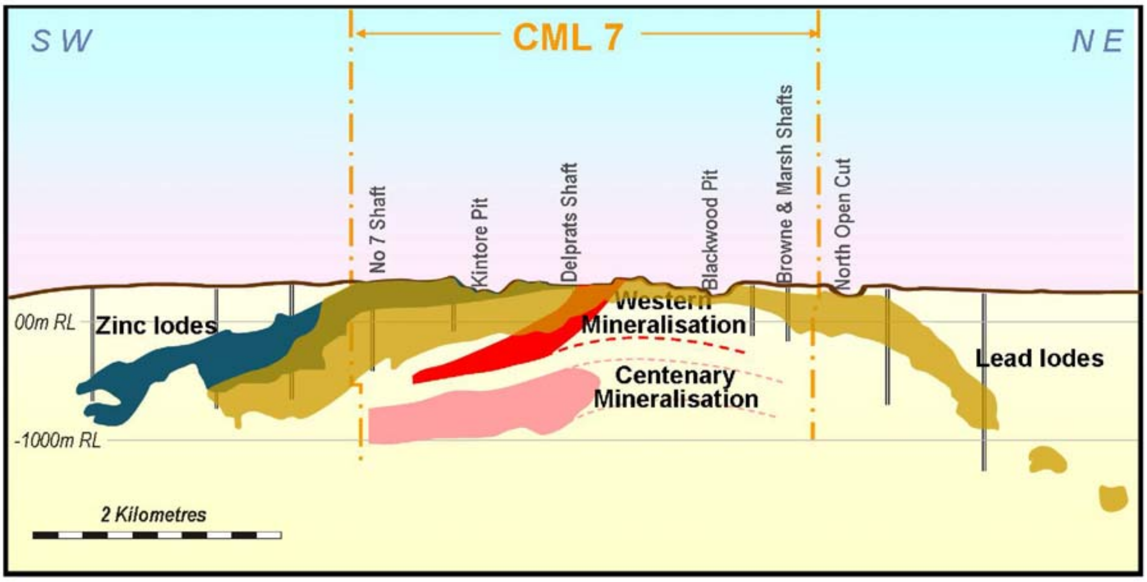


Figure 1: Pre-mining resources of the Broken Hill Main Lode (Plimer, 2003)

Species / organ (n = sample pop.)	**Elements**	**Assay Technique***	**Assay Range**
Eucalyptus camaldulensis Leaves (n=3)	Ag	INAA	<0.1 – 0.23 ppm
	Pb	ICP-MS[1]	18 – 29 ppm
	Zn	ICP-OES	108 – 256 ppm
	Cd	ICP-MS[1]	1.9 – 3.7 ppm
	Sb	INAA	0.05 – 0.07 ppm
Acacia aneura Phyllodes (n=4)	Ag	ICP-MS[2]	<0.01 – 0.02 ppm
	Pb	XRF	35 – 64 ppm
	Zn	XRF	190 – 445 ppm
	Cd	ICP-MS[2]	0.32 – 0.77 ppm
	Sb	ICP-MS[2]	0.2 – 0.4 ppm
Acacia victoriae Phyllodes (n=2)	Ag	ICP-MS[2]	0.01 ppm
	Pb	XRF	32 – 34 ppm
	Zn	XRF	331 – 349 ppm
	Cd	ICP-MS[2]	2.67 – 2.85 ppm
	Sb	ICP-MS[2]	0.3 – 0.4 ppm
Sida petrofila Twigs (n=2)	Ag	ICP-MS[2]	< 0.01 ppm
	Pb	XRF	47 – 152 ppm
	Zn	XRF	84 – 211 ppm
	Cd	ICP-MS[2]	0.83 – 4.34 ppm
	Sb	ICP-MS[2]	0.3 – 0.5 ppm

* Assay Laboratories: ICP-MS[1] (Bequerel Laboratories, Lucas Heights) ; ICP-MS[2] (Geoscience Australia); ICP-OES (Becquerel Laboratories, Lucas Heights); XRF (Geoscience Australia); and, INAA (Bequeral Laboratories, Lucas Heights).

Table 1: Biogeochemical assay ranges for various trees and shrubs sampled from over or adjacent to the Broken Hill Line of Lode, near Brownes Shaft, Junction Mine (from Hill, 2004).

Brownes Shaft headframe, Junction Mine, Broken Hill.

Flying Doctor

The Flying Doctor prospect occurs approximately 8 km E of Broken Hill, within an area referred to as 'the Northern Leases', which includes the NE continuation of the Broken Hill lode rocks and extends from the Broken Hill North Mine to the Stephens Creek Reservoir.

Physical Features And Environment

The prospect is in the central-E part of the Barrier Ranges, and includes a tributary of Willa Willyong Creek, which is a part of the Stephens Creek catchment within the Murray-Darling drainage basin. The drainage pattern of the prospect shows a well-developed trellis pattern reflecting a strong bedrock lithological and structural control. The vegetation of the area consists mostly of open woodlands dominated by *Acacia aneura* (mulga) on hills and rises, and *Acacia victoriae* (prickly wattle) in valleys. Shrubs occur most frequently within a chenopod shrubland dominated by *Mairiana pyramidata* (black bluebush) along valleys and *Sida petrofila* (rock sida) on rises and hills.

Geological Setting

The bedrock of the area is shown within the Mt Gipps 1:25,000 Geological Sheet (Bradley, 1984). Structurally the Globe Vauxhall Schist Zone extends across the central part of the area from W-E. Stratigraphically the rock units are part of the Early Proterozoic Willyama Supergroup, with most of the psammites and pelites interpreted as being part of the Sundown Group, and most of the other rocks as undifferentiated Purnamoota Subgroup within the Broken Hill Group (Bradley, 1984). Broken Hill type (Ag-Pb-Zn) mineralisation occurs along a NE-trending linear zone within two main lodes: the Main Lode Horizon; and, the Upper Lode Horizon (Burton, 1994). Examples of mineralisation in this area are the Barrier Main Lode, and the Flying Doctor mineralisation, which are both part of the Upper Lode Horizon.

Regolith

Slightly weathered bedrock is exposed within low hills and rises, and is buried by up to 3 m of transported regolith within valleys. Alluvial sediments consist of red-brown to brown-grey, quartzose and lithic silts, sands and gravels within depositional plains, alluvial channels, and drainage depressions. Colluvial sediments are widespread as lithic and quartzose sheetflow silts, sands and gravels within depositional plains and on erosional rises. Aeolian silts and fine sands are part of most regolith materials and may form sand sheets and hummocky dunes, particularly on the E slopes of rises and low hills. Mostly hardpan calcretes occur along the bedrock-regolith interface, and are best exposed in creeks. Detailed maps and accounts of the regolith here can be found in Thomas *et al.* (2002) and Lewis *et al.* (2002).

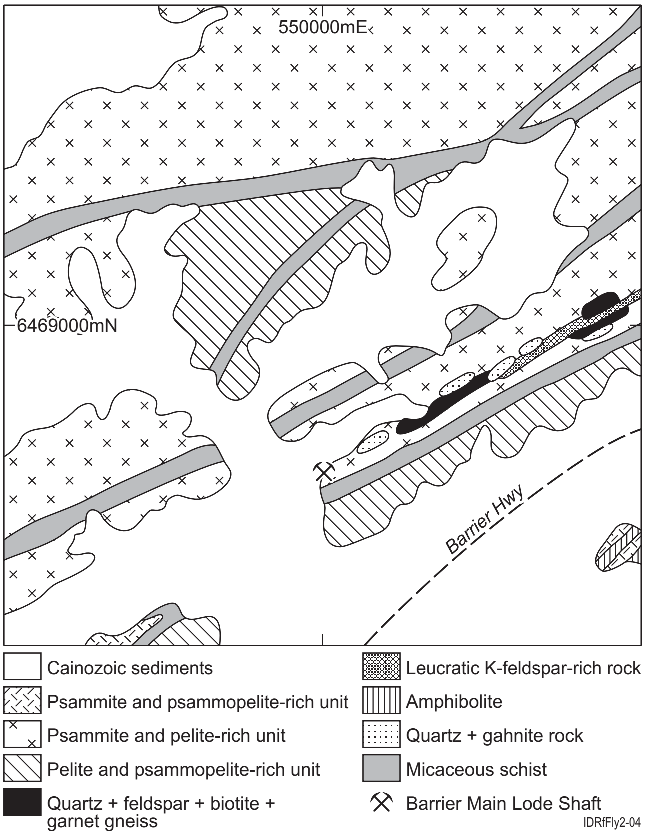
Regolith Expression Of Mineralisation

A combination of ICP-MS, ICP-OES, XRF and INAA were performed on regolith and biogeochemical samples, however only results for Cd, Cu, Pb, Zn are directly discussed here.

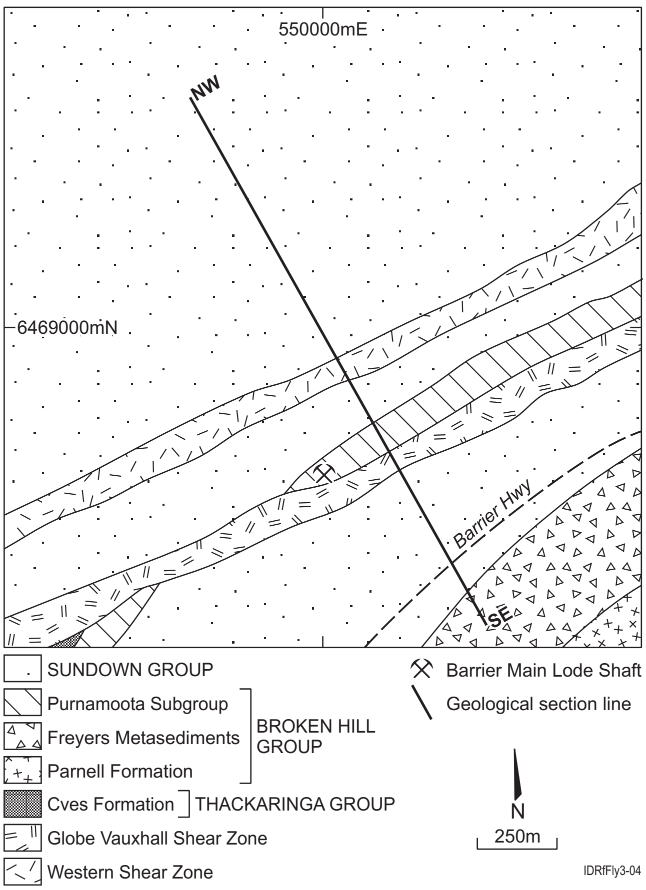
With the exception of *Sida petrophila* twigs, the assay results for all of the sampling media express the underlying mineralisation in varying degrees and for at least some elements. Two important aspects to consider when interpreting the results are: i) the regolith-landform setting and its relationship to local dispersion pathways (particularly for soil samples); and, ii) that strict comparison of equivalent sampling media is achieved. Dispersion distances mostly depend on the regolith-landform setting of samples (greater in alluvial and less in bedrock-dominated units).

Saprock samples show a large increase in Cd, Cu, Pb and Zn at the mineralisation lode. This sampling media however was not conveniently sampled across the whole area, particularly in alluvial settings where it was buried. Surface soil samples were available across the entire area and conveniently sampled. The two size fractions (<80um and 80-300um) show at least some aeolian and other transported components, largely accounting either for their relatively weak chemical expression of mineralisation or else the increase in metal contents (eg. Cd in both size fractions, and Cu, Pb and Zn in the 80-30 um fraction) in the alluvial depositional plain downslope from mineralisation. This demonstrates the importance of a regolith-landform context for interpreting soil chemistry results, and to distinguish between transported metal contents and those adjacent to mineralisation. A notable exception is that Pb contents in both soil fractions are greatest adjacent to mineralisation, suggesting that it is less mobile in soil fractions.

The biogeochemical results show variable expressions of mineralisation. *Sida petrophila* twigs did not express the presence of underlying mineralisation because it was not available for sampling at those sites. *Acacia victoriae* shrubs were widespread across the area (particularly in valleys) and the assay results for Cd, Cu, Pb and Zn were perhaps the most outstanding at expressing underlying mineralisation. The *Acacia victoriae* phyllode assay results down slope from mineralisation had low metal contents, suggesting that most of their metal contents are derived from the bedrock interface rather than the overlying transported regolith and associated soil. *Maireana pyramidata* leaves were widely available across the area and showed notable increases in Pb content over mineralisation. *Acacia aneura* phyllodes had greater Cu and Pb contents over the mineralisation zone, however Zn contents were relatively high both over mineralisation and within the alluvial depositional plain downslope of mineralisation. These results suggest that if carefully and consistently sampled (including precise species discrimination and systemised sampling techniques) biogeochemical methods may be better than some soil fractions for expressing mineralisation, particularly in areas of shallow transported regolith. The reason for this could be that the plant roots (such as for *Acacia victoriae*) penetrate the shallow transported regolith cover and are at least in part chemically connected to the underlying bedrock. Observations of *Acaia victoriae* root systems indicate that this species has a well developed tap-root, that would be suiable for facilitating this type of regolith penetration.



550000mE
6469000mN
Barrier Hwy
Cainozoic sediments
Psammite and psammopelite-rich unit
Psammite and pelite-rich unit
Pelite and psammopelite-rich unit
Quartz + feldspar + biotite + garnet gneiss
Leucratic K-feldspar-rich rock
Amphibolite
Quartz + gahnite rock
Micaceous schist
Barrier Main Lode Shaft
IDRfFly2-04



550000mE
6469000mN
NW
SE
Barrier Hwy
SUNDOWN GROUP
Purnamoota Subgroup
Freyers Metasediments
Parnell Formation
BROKEN HILL GROUP
Cves Formation
THACKARINGA GROUP
Globe Vauxhall Shear Zone
Western Shear Zone
Barrier Main Lode Shaft
Geological section line
N
250m
IDRfFly3-04

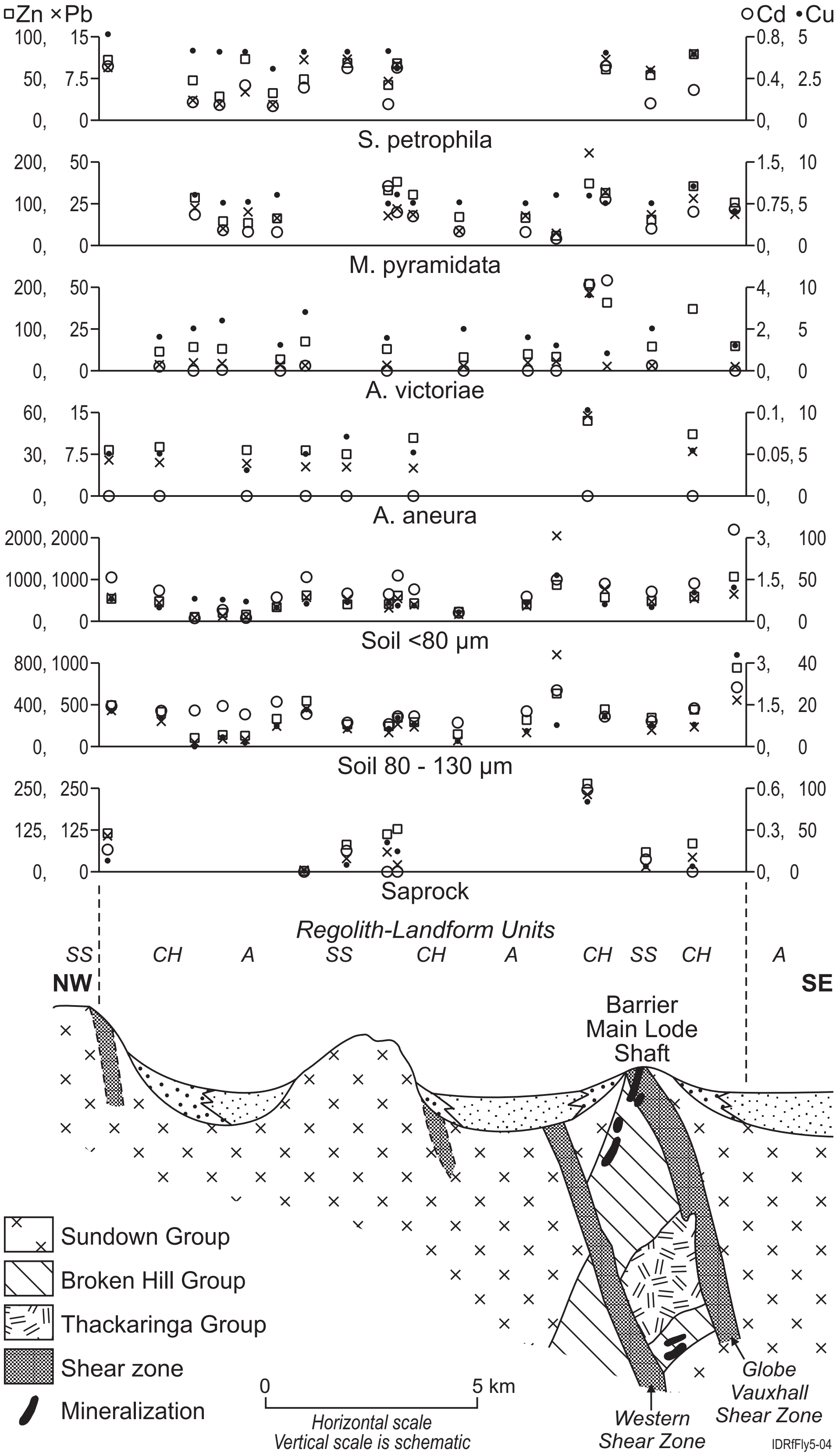


Figure 2: section across the Flying Dr prospect.

Haydens Tank (Wahratta 1:25 k mapsheet)

The regolith-landforms of this site are covered on the Wahratta 1:25k regolith-landform map (Foster *et al*., 2003). The landscape in this area consists of rises, which in most cases are capped by silicified palaeo-sediments or slightly weathered bedrock. The shallow transported regolith here is mostly derived from shallow overland flow (mostly sheetflow deposits) that includes clasts of weathered bedrock, indurated regolith and reworked aeolian deposits. The vegetation here is a chenopod shrubland dominated by bladder saltbush (*Atriplex vesicaria*), with some black bluebush (*Maireana pyramidata*).

Mapping of the palaeo-sediments here appears to define a quartzose, sandy, meandering palaeo-drainage system flowing towards the S, and therefore most likely a part of the Murray Basin (Hill *et al.*, 1994; Hill, 2000). The dam at Haydens Tank corresponds to the intersection of two approximately N-S trending elongate 'pods' of silicified sediment. The silica cement mostly consists of micro-crystalline quartz and minor micro-crystalline hematite and anatase. Framework grains mostly consist of a diversity of quartz types (Hill *et al.*, in press). In some places the silicification conforms to nodular and columnar morphologies that may be interpreted as ancient pedogenic structures. This interpretation is supported by micro-morphological examination which reveals illuviation-related structures and burrows. The silicification makes these sediments relatively resistant to erosion and as a result adjacent highly weathered materials are preferentially eroded and in turn the palaeo-sediments become topographically inverted. Charles Sturt in his expedition through this area in the 1840s first recorded the presence of rounded pebbles capping many of the rises near Stephens Creek, "*The surface was in many places covered with small fragments of white quartz, which together with a conglomerate rock cropped out of the ground where it was more elevated*" (Sturt, 1849, Vol.1, p.151).

Clasts of ferruginous regolith flank many of the rises and mostly include ferruginised saprolite (highly weathered bedrock indurated by Fe-oxides). In many cases the original bedrock fabrics are visible and can provide some indication of the original bedrock types. Although there is limited bedrock exposure at this site, weathered bedrock is typically less than 1 metre below the surface. Fresh bedrock however may be up to 30 m below the surface, however regional morphotectonics studies (Hill *et al.*, 2003) and recent regolith mapping of the Wahratta 1:25k sheet (Foster *et al*, 2003) has discovered large areas of previously unrecognised slightly weathered bedrock exposed near Mt Gipps Tank, to the SE of here.

Assays from several RCA samples from this area are included in the Table below. Although the trace metal contents are not as high as for many mineralised sites visited earlier in the field trip, Au contents of 5 and 6 ppb for two of the samples may be of some significance for this area of thicker regolith cover (further sampling is needed to resolve this). The relatively high Au and As contents for the sample from AMG66: 577350mE/6470750mN may be due to ferruginous contamination (2.98% Fe).

Table : RCA assay results for selected elements from near Haydens Tank.

AMG 66	Au (ppb)	Ca (%)	Cr (ppm)	Cu (ppm)	Fe (%)	Mg (%)	Ni (ppm)	Pb (ppm)	Zn (ppm)	Ag (ppm)	As (ppm)	Co (ppm)
0572888mE 6468611mN	<1	31.3	3	16	0.25	0.30	3	8	12	<0.1	2.5	2.5
0578285mE 6471804mN	5	22.8	15	30	0.14	0.56	8	32	33	<0.1	5	5
0577939mE 6471331mN	<1	31.5	5	16	0.05	0.39	4	10	16	<0.1	4.5	3.4
0577350mE 6470750mN	6	26.0	17	15.5	2.98	0.73	9	27	18	<0.1	14.5	6.5

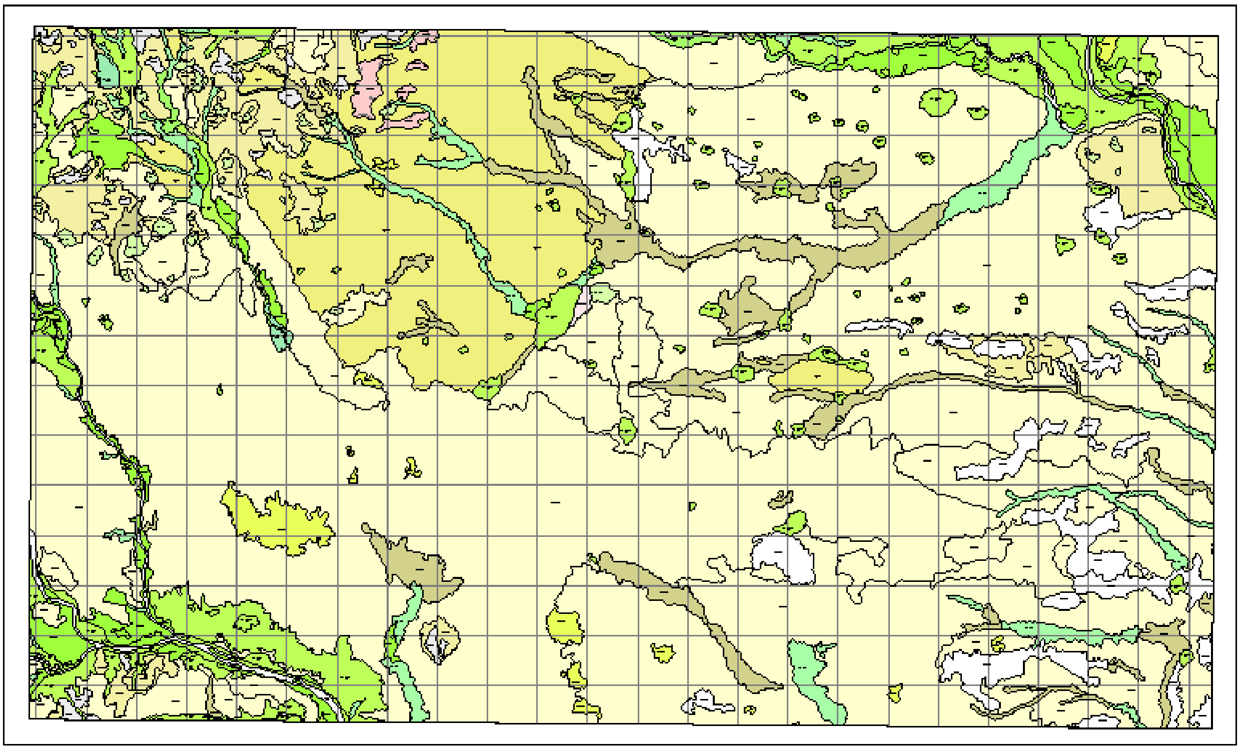


Figure: Draft of the Wahratta 1:25 k regolith-landform map (Foster *et al.*, 2003).

CENTRAL WESTERN BARRIER RANGES

Introduction

This is a half day field excursion is a field transect through the Umberumberka Creek drainage basin from the central Barrier Ranges, across the Mundi Mundi range-front and onto the Mndi Mundi Plain (we may end up doing this in reverse order depending upon time constraints). Either refreshments from the Silverton Pub or a sunset from the Mundi Mundi Lookout provide fitting finales to this trip.

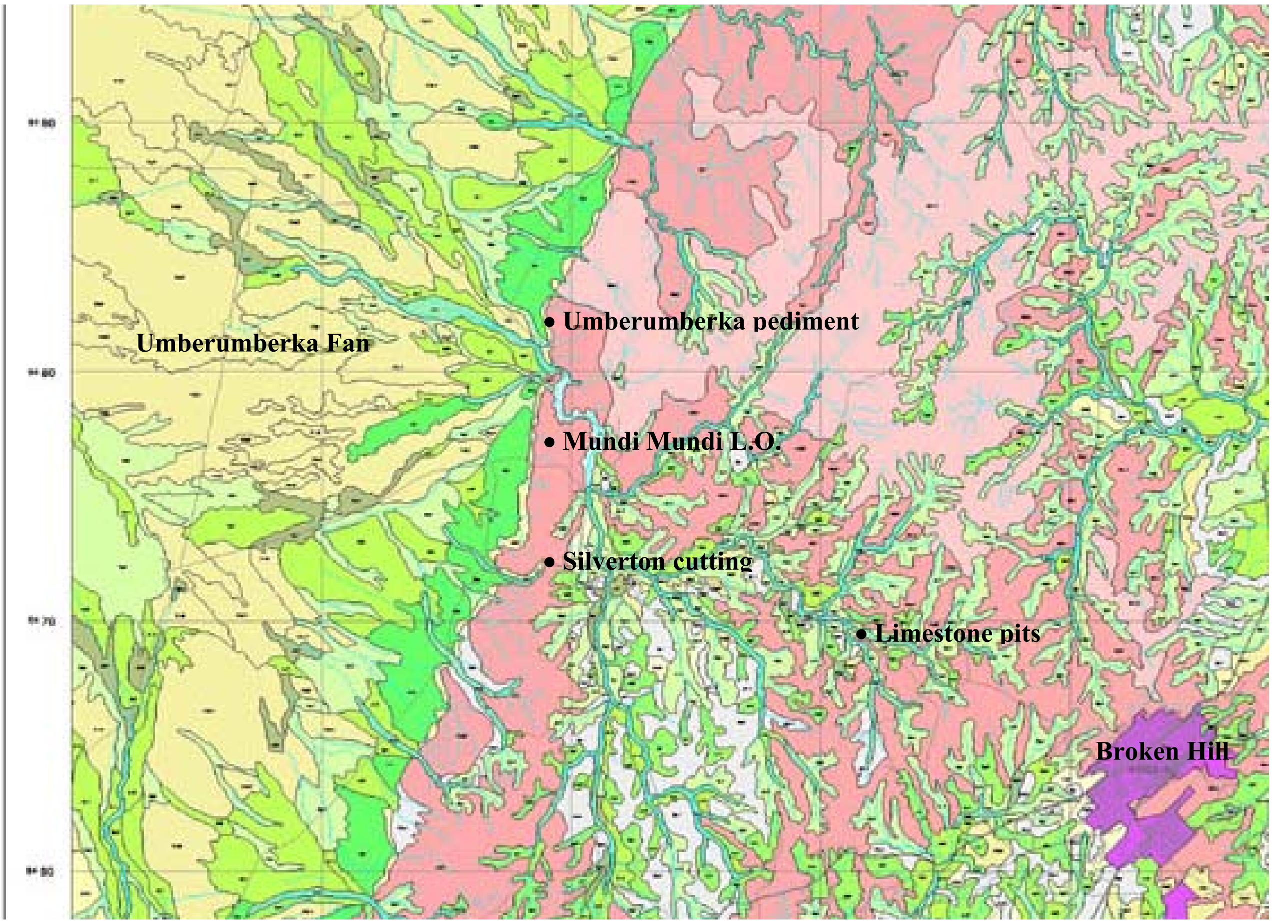


Figure : A portio of the 1:100 k regolith-landform map (Hill, 2001) showing the setting for this afternoon's field stops.

Limestone Station

West of Limestone homestead, in between the Silverton Road and Umberumberka Creek are a series of pits dug into the alluvium of the Umberumberka Creek system. These pits expose thick RCA profiles containing a range of RCA morphologies and changes in major and trace element chemistry and mineralogy.

Calcrete-dolocrete-dominated RCA profiles mostly contain Ca-carbonates as the main indurating carbonate in the upper part of the profile, mostly in the form of calcite. This grades downwards to more Mg-rich carbonates mostly in the form of dolomite. A wide range of morphologies can occur but most commonly include downwards in the profile nodular, hardpan (laminated and massive), powder, and massive tabular RCAs.

The 'Limestone' profile is exposed within a pit originally excavated to obtain flux for smelting at Broken Hill and later to obtain road base aggregate. The pit is dug into alluvial depositional plain sediments associated with Umberumberka Creek, with some mixed aeolian and sheetflow sediments. These sediments consist of quartzose and lithic sands, silts and gravels. The lower parts of the pit intersect an irregular bedrock interface consisting of slightly to moderately weathered micaceous schist. Bedrock in the area is very poorly exposed but mostly consists of micaceous schists, K-feldspar-rich pegmatite, amphibolite, and minor quartz-gahnite rock.

The profile here is up to 3 m deep. The uppermost parts consist of a zone of nodular RCAs with nodules up to 20 mm in diameter. This overlies several discontinuous laminar hardpans and then an underlying nodular zone with a weakly indurated matrix. The lowermost parts of the profile consist of friable powdery RCAs with 'pods' of massive, tabular RCAs in many places resting upon the bedrock interface and penetrating joints within the bedrock.

The carbonate mineralogy within the profile shows a systematic variation with depth from calcite-rich to dolomite-rich carbonates. This is also reflected in an increase in Mg content and a decrease in Ca:Mg with depth. The Au content in the profile shows a close association with Ca and calcite and is greatest in the upper high Ca:Mg nodular zone. The differences in Au content within the Limestone profile is typical of many others with a decreasing Ca:Mg and increasing Mg content with depth.

Within this single vertical profile there is enough variation in Au content for this site to be considered as having a Au content typically worthy of greater examination, while other parts of the profile may be considered as containing a "background" result. The way that samples from this profile may be expressed in regional sampling programs depends upon which part of the profile is considered and then compared with other samples from different parts of similar profiles. It suggests that the chemical, mineralogical and morphological facies changes observed with changes in depth of this profile may also be important to consider when comparing Au contents in a variety of RCA samples across an area.

As well as showing systematic changes in Ca and Mg contents with depth, the RCAs here show systematic catenary change across the landscape. From the valley margins towards the valley axis there is a gradual change from calcite to dolomite to gypsum to halite induration. Some of this lateral transition is shown in the following figure.

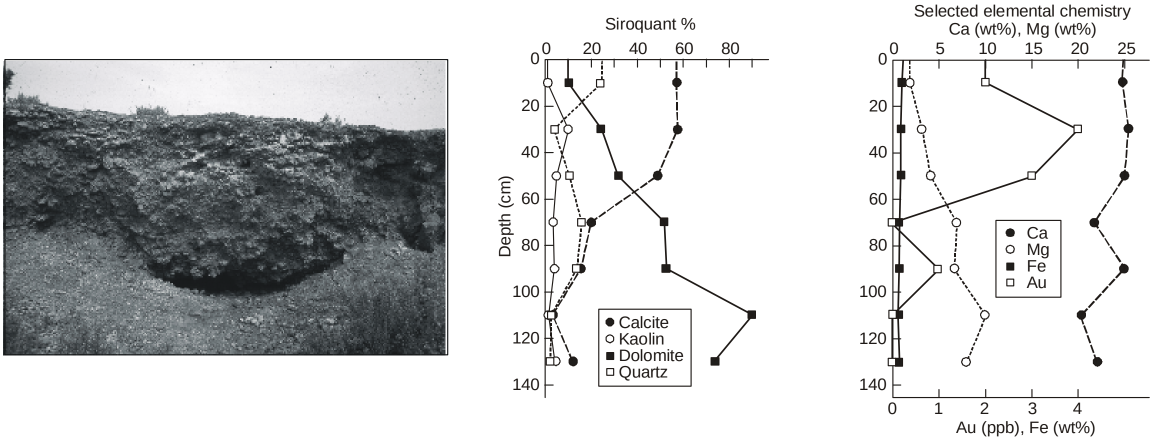


Figure: Limestone Station RCA profile selected element chemistry and mineralogy (Hill, 2000).

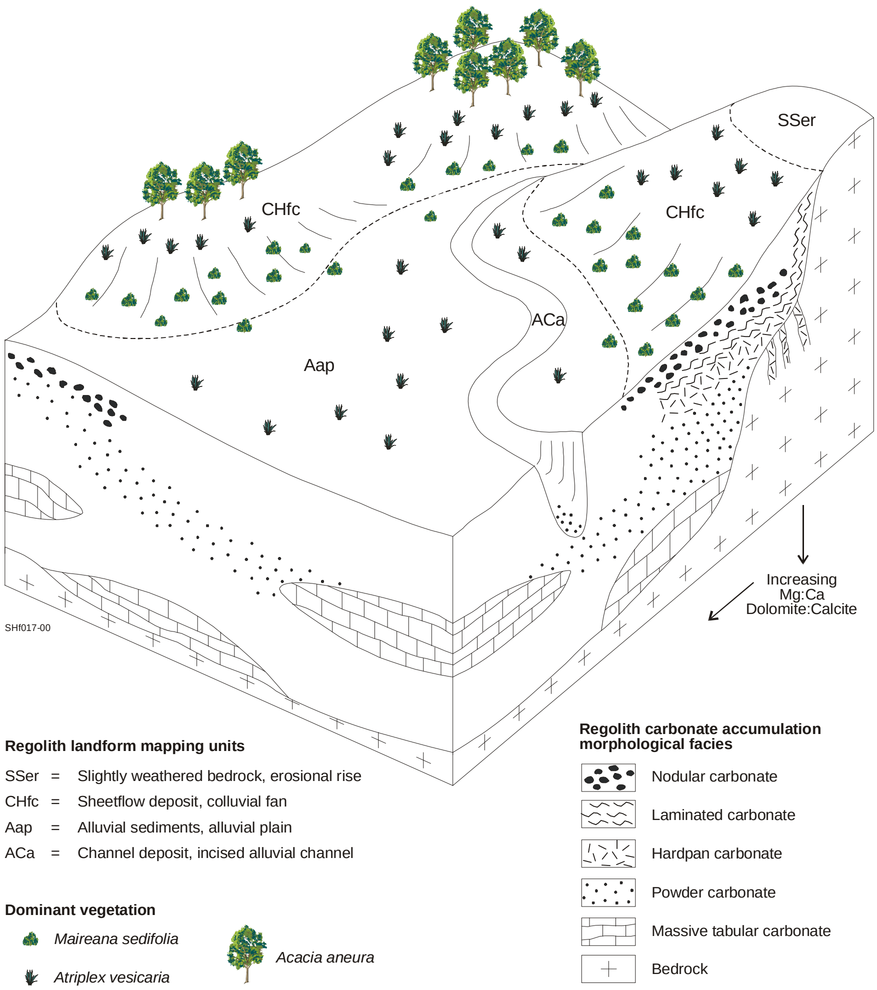


Figure: A 3D toposequence for RCAs in the Limestone Station area (Hill, 2000).

Silverton – Umberumberka Mine Railway Cutting
At this site a section of the regolith is exposed in the railway cutting between Silverton and the Umberumberka Mine. The cutting passes through moderately weathered, micaceous schists and granite of the Umberumberka Shear Zone.

Overlying the bedrock is a cover of sediment consisting of poorly-sorted and matrix-supported sediment, with angular bedrock boulders. This sediment is up to 10 m thick on the southern wall of the cutting, however it is less than 2 m thick on the north wall. This suggests that there were considerably greater slope gradients in this area at the time of sedimentation, compared with the contemporary landscape. These sediments have been interpreted as mostly of debris flow origins deposited within a palaeo-depression trending towards the southeast. The age of the sediments is not known with any certainty, however there poor surface landscape expression suggest some antiquity, although the slightly-moderately weathered natured of bedrock clasts and unconsolidated nature suggests that they are not extremely ancient.

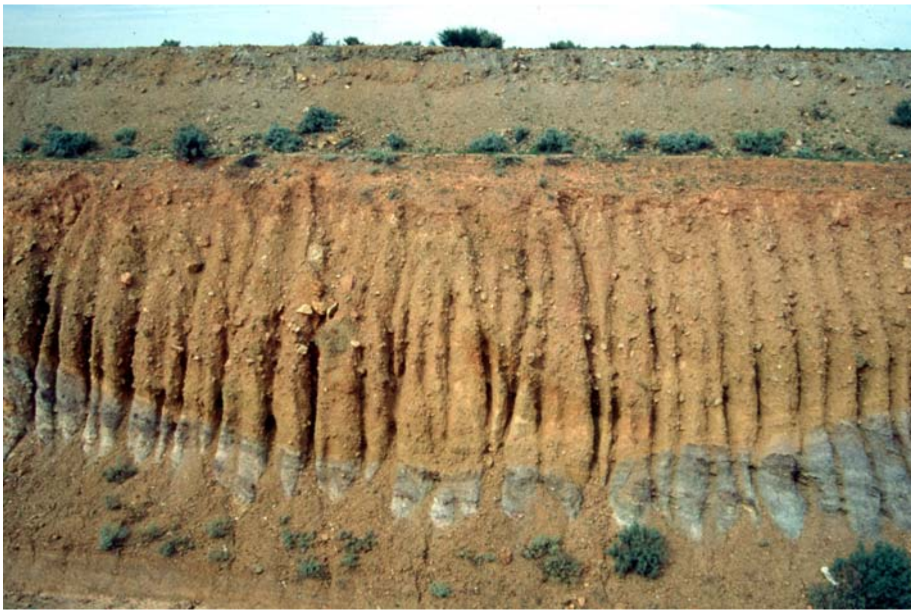


Figure: Southern face of the old railway cutting between Silverton and the Umberumberka Mine.

Mundi Mundi Lookout

From the hill crest there is an impressive view to the west across the Mundi Mundi Plain, while to the north and south there are views along the Mundi Mundi range-front. In this area the range-front is some 250 m east of the Mundi Mundi Fault. To the immediate west of the fault the sedimentary cover is over 200 m thick. In this area, where the range-front trends NE-SW, the range-front is of particularly low sinuousity (1.069).

To the northwest of here a line of river red gums defines the channel of Umberumberka Creek as it incises its way through the large Umberumberka fan. Our next stop will be just on the other side of this channel.

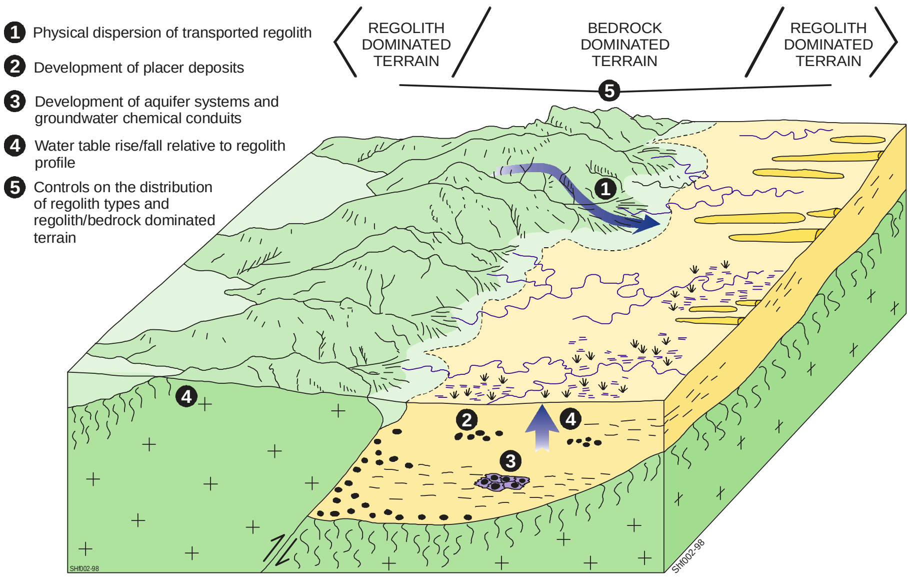


Figure: Some morphotectonic controls on regolith-landform processes associated with the Mundi Mundi range-front (Hill & Kohn, 1999).

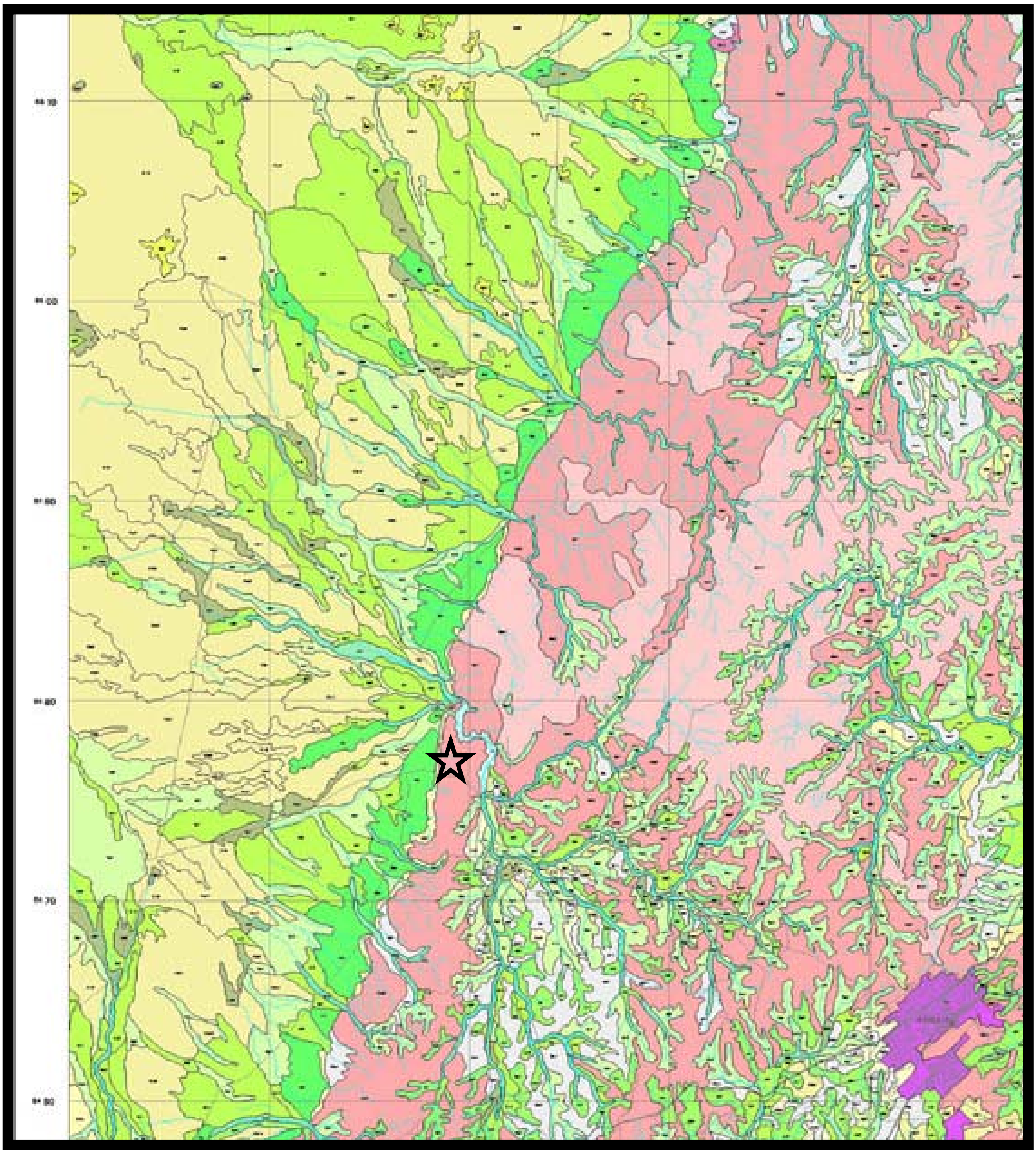


Figure: A portion of the Broken Hill Domain 1:100k regolith-landform map (Hill, 2001) showing the Umberumberka Creek catchment and large alluvial fan. Grid square interval is 10 km. The star denotes the location of the Mundi Mundi Lookout.

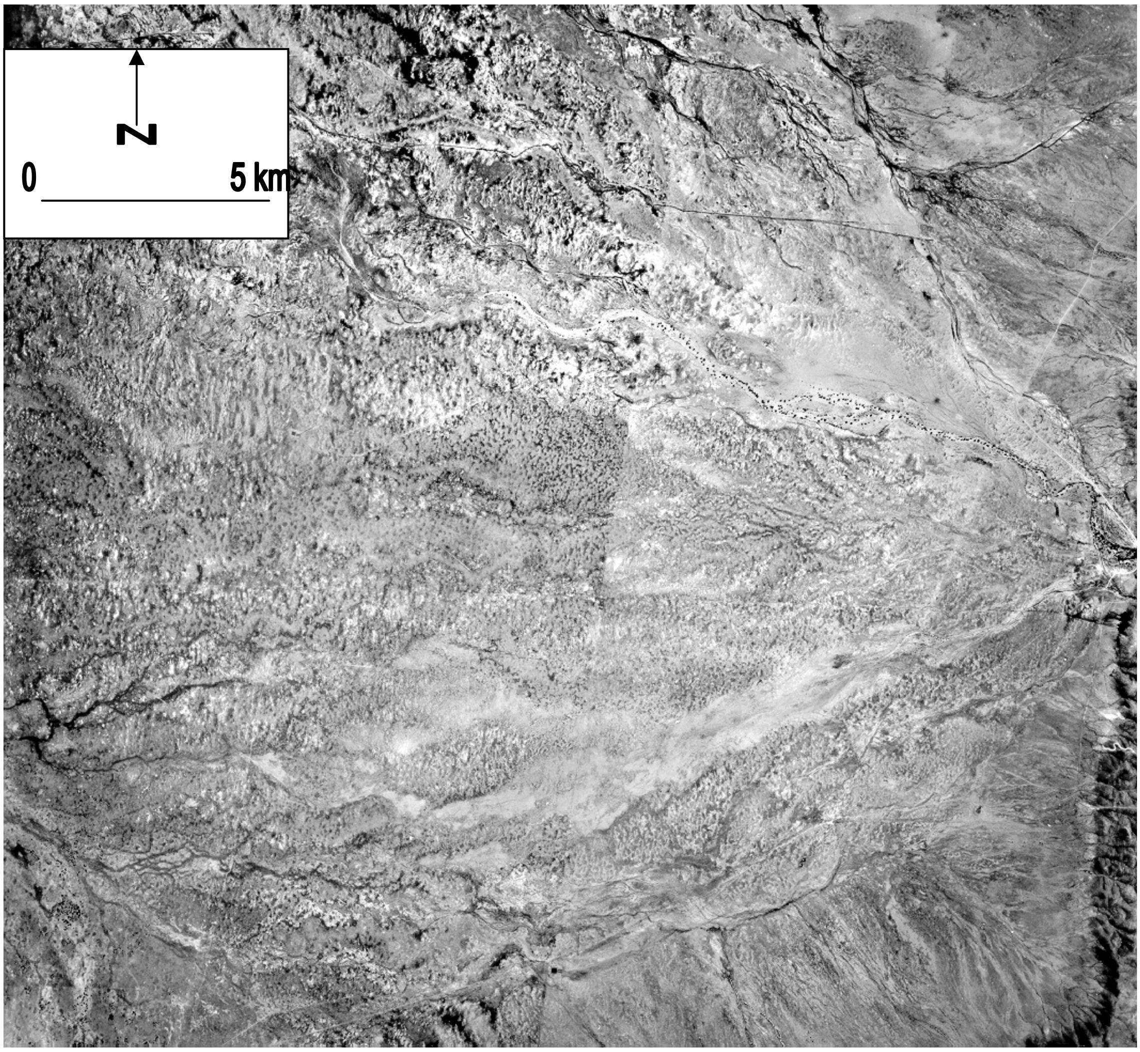


Figure: RC9 aerial photograph showing most of the Umberumberka Creek alluvial fan.

Umberumberka Fans – Mundi Mundi Range-front

Just north of where the road crosses Umberumberka Creek there are several flat-topped rises on the western side of the Mundi Mundi range-front. These rises are composed of alluvial fan sediment that are perched at a higher level than the fan sediments further west that make up fans such as that associated with Umberumberka Creek. The western margins of these high-level fans typically terminate some 250 m west of the range-front and very closely correspond with the position of the Mundi Mundi Fault. Further north, similar fan sediments rest upon a pediment of slightly to moderately weathered bedrock.

These higher-level fans are interpreted as having been uplifted by relatively young fault movement along the Mundi Mundi Fault. The upper surface of the high-level fans can be followed upstream in some of the smaller creeks where they coalesce with strath terraces. Approximately 4 alluvial fan surfaces between these high-level fans and the Umberumberka Creek channel can be seen in this area.

Wasson (1979), developed a Quaternary stratigraphic framework for the fan sediments, which was largely driven by episodic, climatically driven sedimentation, incision and pedogenesis. A more recent study by Hill (2000) suggests that instead, fan evolution is related to the intrinsic fan processes that have approximated continual operation throughout their development. This is supported by the irregular distribution of numerous palaeosols in the fan sequences, and the spatial mosaic of sedimentation, erosion and pedogenesis operating in the contemporary landscape.

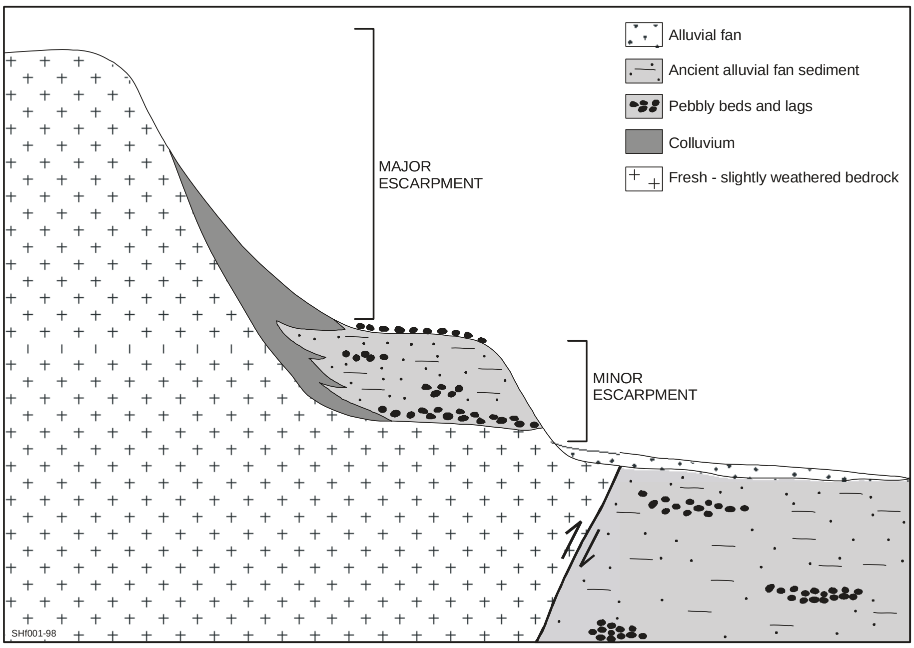


Figure: Generalised section across the Mundi Mundi range-front showing major and minor escarpments (Hill & Kohn, 1999).

Litho-stratigraphic Unit	**Age**	**Characteristics**	**Depositional Environment**
Modern channel sediments	500 BP to modern	Bedload of sand and gravel, small suspension load in floodouts	Entrenched channel flow and dispersed flow on floodouts
Thackaringa Unit	1000 to 500 BP	Coarse sands and fine gravels in terraces	Entrenched channel flow and presumed floodout flow
Mundi Mundi Unit	6000 to 3000 BP	Bedload sands and gravels; unsorted sands in matrix of clay and silt (typically 143 cm thick)	Braided streams and slurry flows
Korkora Unit	c. 13 000 BP	Slightly gravelly sandy loam with some sorted bedload sands and gravels (typically 50 cm thick)	Slurry flows and very shallow braided streams
Belmont Palaeosol	c. 16 000 to 13 000 BP	Angular polyhedral peds with pedogenic carbonate, manganese and gypsum accumulations. (typically 10 cm thick)	Pedogensis associated with a palaeosurface
Umberumberka Unit	15 000 BP	Gravelly loam, well sorted cosets of gravel and sand plus unsorted sands in matrix of clayed silt (>4 m thick)	Braided channels and slurry flows

Table: Late Quaternary stratigraphy of the Mundi Mundi Alluvial Fans (after Wasson, 1979; Wasson & Galloway, 1986).

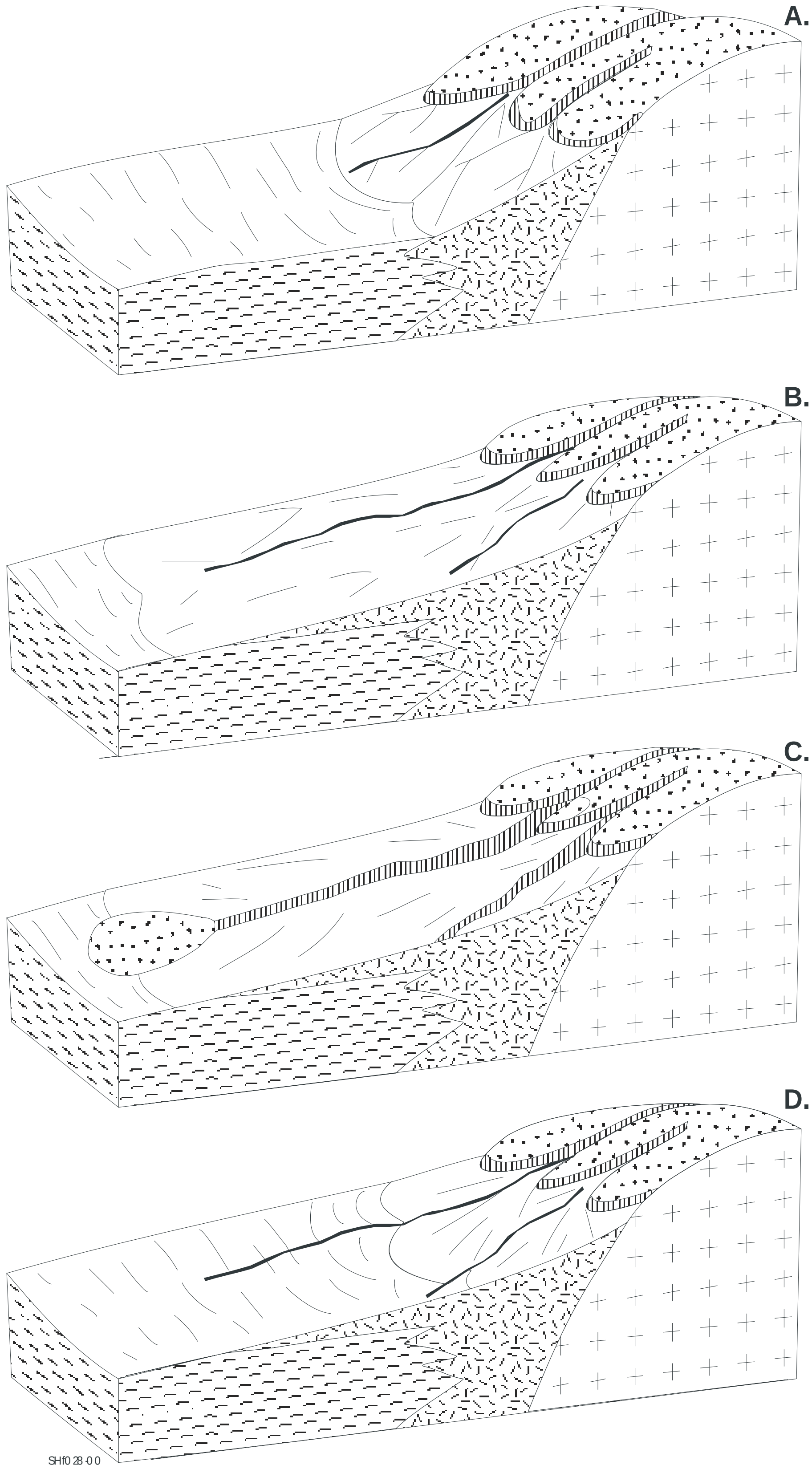


Figure: Evolution model for Mundi Mundi alluvial fans. A. Fan aggradation, B. Continued aggradation until a smooth concave profile develops, C. Reduced sediment flux and fanhead trenching with sediment bypassing upper fan and prograding lobes develop at lower fan, D. channel backfilling and reworking of fan surface (Hill, 2000).

BROKEN HILL TO FOWLERS GAP

We are unlikely to have time to visit all of these sites, although depending on how we are going, some of these may provide worthwhile breaks to the drive between Broken Hill and Fowlers Gap.

Yancowinna – Stephens Drainage Divide Instability

The influences of the headward migration of knickpoints and the mechanisms for drainage divide instability can be seen along many of the interfluves between some of the larger catchments in the region. An example is the interfluve between Yancowinna and Stephens Creeks, north of Broken Hill between Nine Mile station and Yanco Glen.

For the most part, rises and hills of slightly weathered bedrock define the divide between these catchments. Immediately to the east of where the Silver City Highway crosses the divide it is very poorly defined and corresponds with the alluvial plain of the headwaters of a tributary of Yancowinna Creek. The headwaters of the southerly flowing Stephens Creek system have incised into a northerly sloping alluvial plain surface that for the most part is more closely related to the northerly flowing Yancowinna Creek drainage system. This is further confirmed by the presence of trough cross-beds reflecting north to northwesterly flow directions exposed in the gully walls of southerly flowing channels of the Stephens Creek system in this area.

During times of low stream discharge waters in the headwater channels of the Yancowinna Creek system are confined to the northerly flowing channel. When discharge exceeds channel capacity however, channel avulsion takes place, as low levees flanking the Yancowinna tributary channel are breached. After avulsion the waters flow across the alluvial plain surface and into the headwater channels of the Stephens Creek system which has incised into the alluvial plain. The channel patterns relating to this evolution can be traced across the sparsely vegetation alluvial plain surface.

This divide instability is an example of stream diversion in the sense of Bishop (1995). The rearrangement of stream pattern and drainage divide location is essentially driven by the top-down process of avulsion onto the incised alluvial plain. This incision is driven by erosion of an asymmetrical drainage divide with steeper channels in the Stephens Creek system graded to a lower local baselevel than within the Yancowinna Creek system. Further work is needed to more fully constrain the knickpoint evolution within the two adjacent catchments. The lower elevations of the local baselevels in the Stephens Creek catchment in this area, however appears to be closely related to the greater amount of headward retreat of knickpoints through that catchment compared with the Yancowinna Creek catchment.

Bishop (1995) recognised three forms of drainage rearrangement involving the encroachment of one catchment boundary into an adjoining catchment resulting in transfers of catchment area and drainage lines. These are:

- *capture*, due to greater headward erosion in the stream to which flow is diverted and the preservation of drainage lines (bottom-up processes);
- *diversion*, involving the redirection of drainage into an adjacent catchment with the preservation of drainage lines (top-down processes); and,
- *beheading*, where transfer of a stream's catchment to an adjacent catchment results in headward extension of a drainage system at the expense of another with the preservation of the appropriated catchment's drainage lines.

Stream capture ('piracy') has been a widely interpreted process in accounts of regional drainage evolution and landscape denudation (Davis, 1899; Taylor, 1911; Gardner & Sevon, 1989; Haworth & Ollier, 1992; Thomas & Shaw, 1991; Stanford, 1993). Despite its popularity and importance the precise processes of drainage rearrangement are usually poorly recognised, and typically interpreted from drainage pattern such as 'elbows of capture' or 'boathook bends' (Bishop, 1995). Alternatively many of these stream morphologies may be related to bedrock structural controls (e.g. Young, 1977; Nott, 1992), or stream diversion (Bishop, 1995).

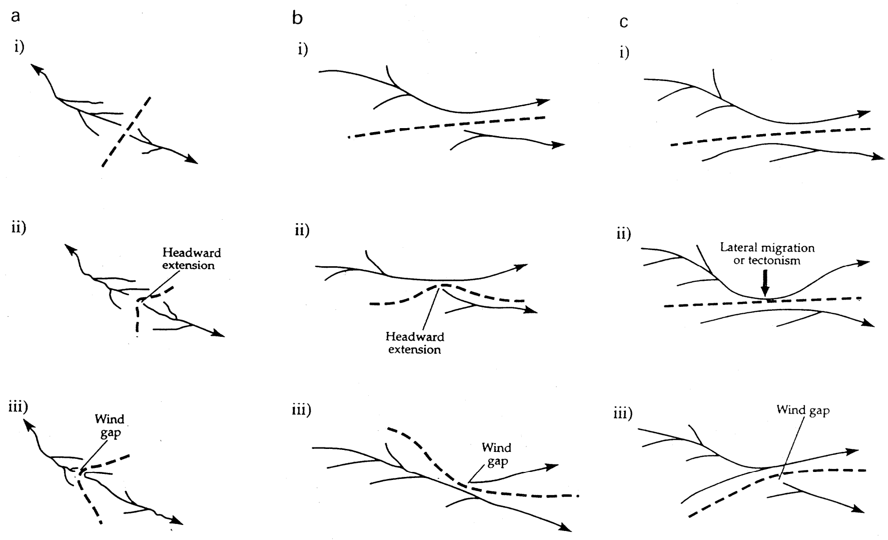


Figure: Mechanisms for rearrangement of planform patterns of drainage via stream piracy resulting in preservation of drainage lines and transfer of drainage area between catchments (Bishop, 1995).

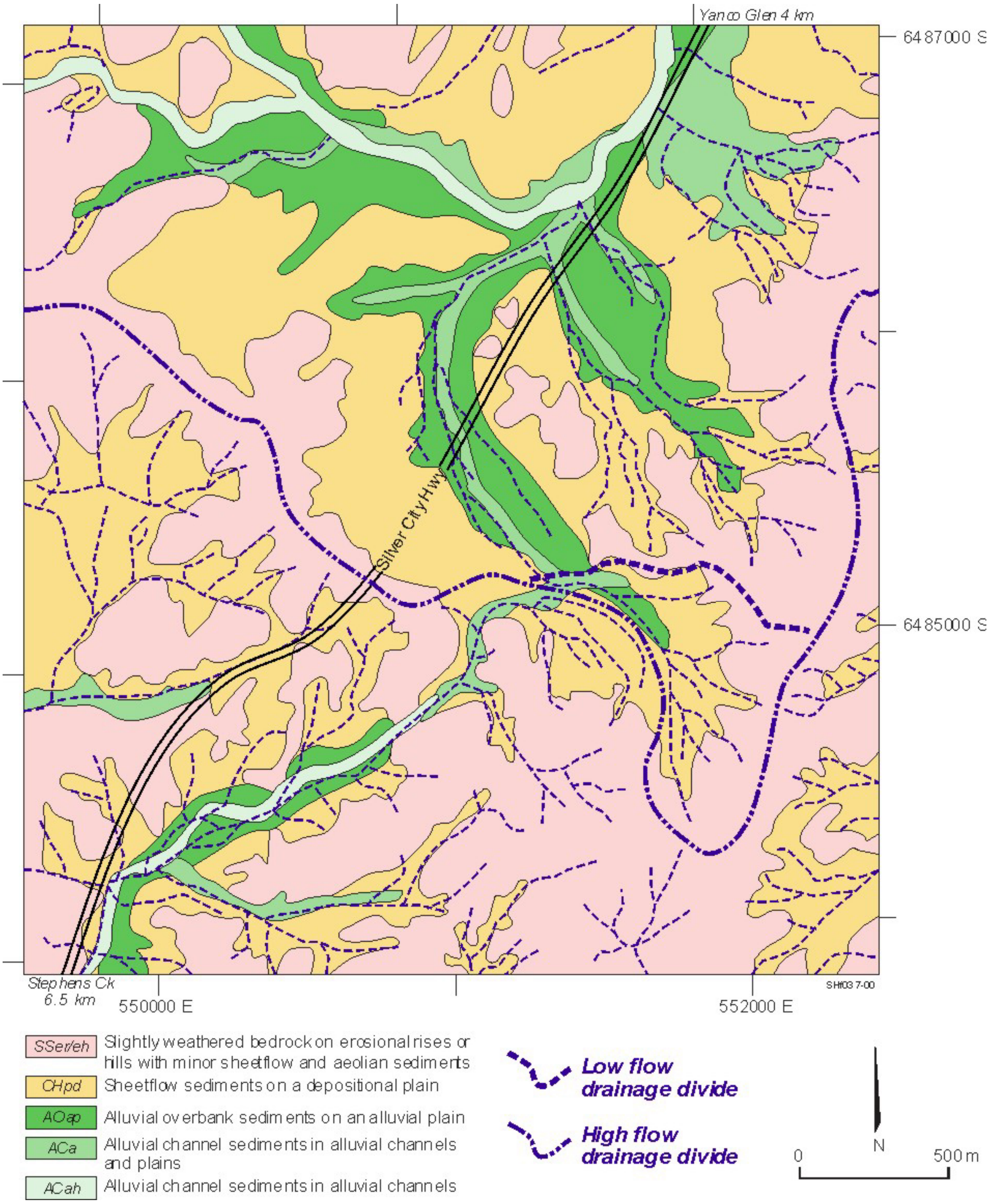


Figure : Location map showing the area of the drainage divide rearrangement between Yancowinna and Stephens creeks, north of Broken Hill (Hill, 2000).

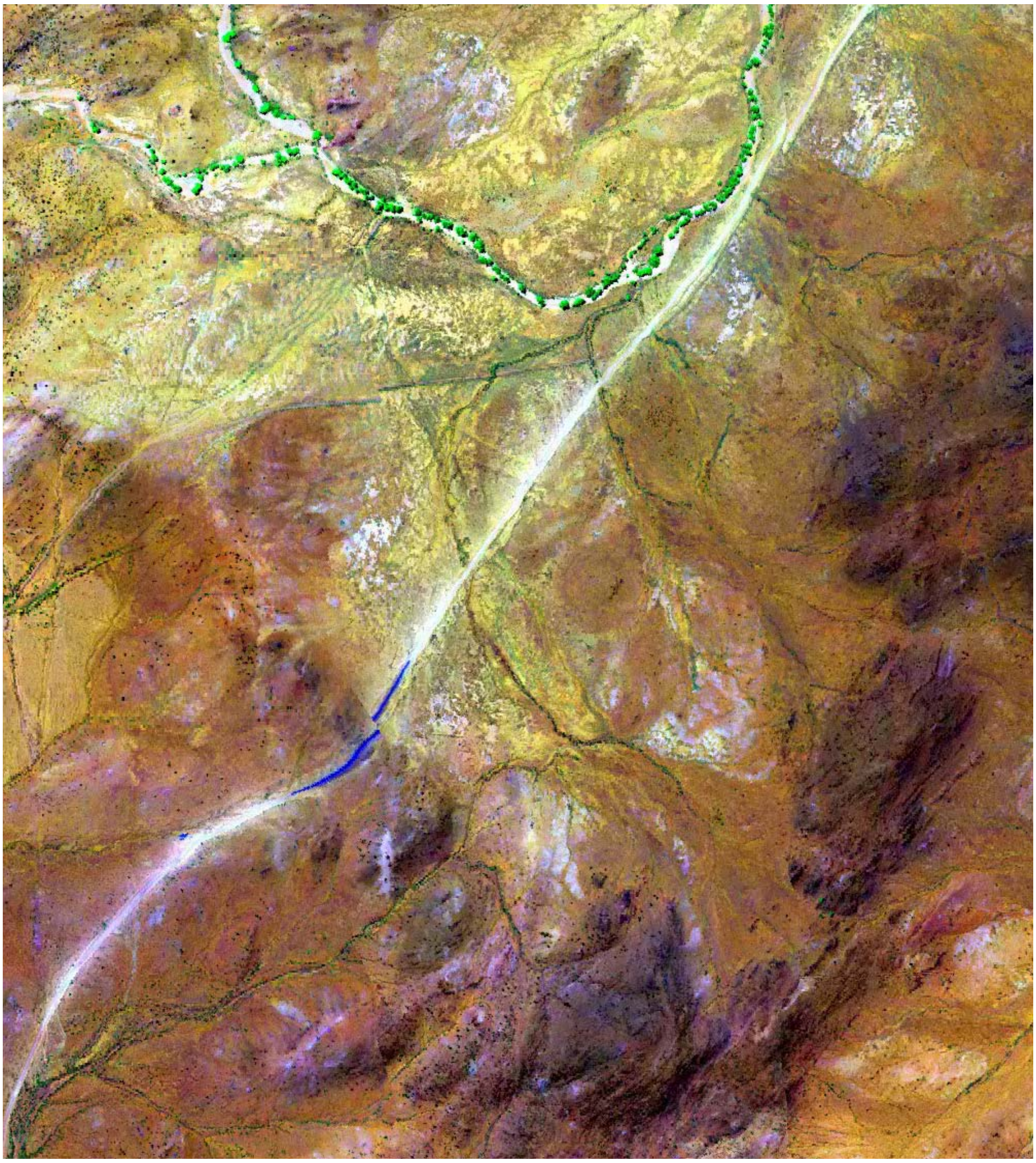


Figure: Hymap image of the drainage diversion site between the Yancowinna and Stephens creeks drainage divide (data courtesy of NSW DMR).

Yanco Glen

Just north of where the Silver City Highway crosses Yancowinna Creek, are famous exposures of the unconformity between the Palaeoproterozoic Willyama Supergroup and the Neoproterozoic Adelaidean metasediments. Near this site the undulating hills and rises that consist of variably weathered Willyama Supergroup rocks of the Broken Hill Block in the south, give way to broad lowlands consisting of variably weathered Adelaidean metasediments.

This unconformity can also be seen in bedrock exposures along Yancowinna Creek. There are also fascinating exposures of the extensive root systems of mature *Eucalyptus camaldulensis* (river red gum) trees.

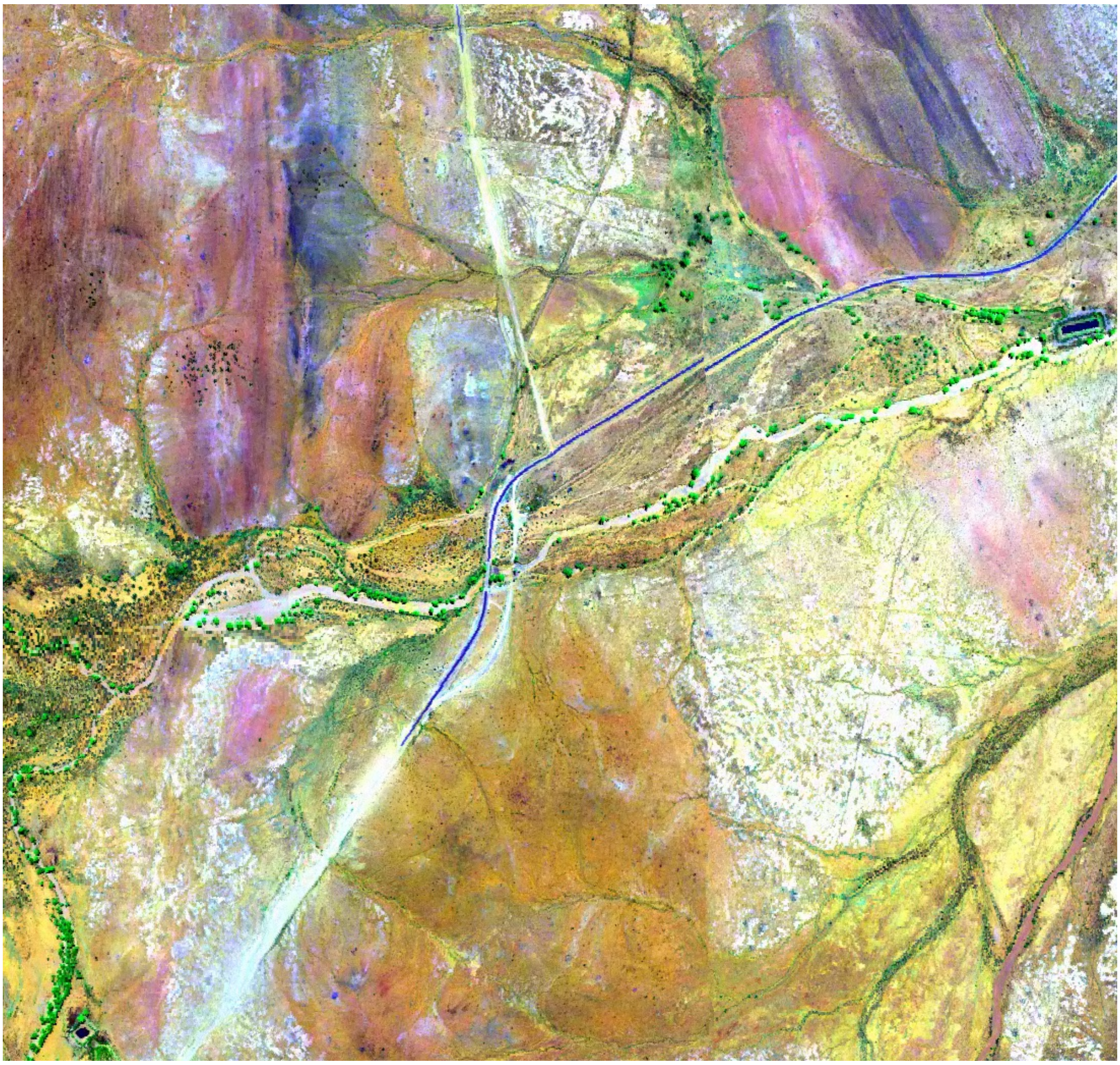


Figure: Hymap image of the Yanco Glen area (data courtesy of NSW DMR).

Son of Man
Crossing the Silver City Highway near the sign indicating the transition from Eastern to Central Australian time zones, is the ironstone hosted Cu-Au lode of the Son of Man mineralisation.

A summary of the geology and exploration history of the Son of Man mineralisation has been outlined in Burton (1999, pp.20-21), where much of the information below has been derived. The Son of Man prospect is an easterly to southeasterly trending zone about 3.25 km long consisting of a series of discrete quartz-iron sulphide layers, typically some tens of metres long. The system is hosted by retrogressed quartz-feldspar±sillimanite±biotite±porphyroblastic garnet gneiss and leucocratic quartz-feldspar-minor biotite gneiss.

Newmont Pty. Ltd. First studied the Son of Man area in 1975, finding elevated Cu, Pb and Au in lode samples. CRA Exploration Pty Ltd carried out IP and Sirotem surveys and RAB drilling on the Son Of Man prospect in 1980-1. Dominion Mining Limited carried out rock chip sampling of the Son of Man prospect in 1991 and found highly anomalous Cu, As and Au, and weakly anomalous Co, Pb and Zn. Soil geochemistry clearly defined the gossanous horizon but failed to locate other potentially mineralised areas. Dominion noted that the gossanous horizon continues, increasingly under cover, to the southeast.Regolith carbonate accumulation (RCA) samples were taken from the area in 2002 as part of a regional CRC LEME study, and the results are presented below.

Sample	Easting (AMG66)	Northing (AMG66)	Au (ppb)	Cu (ppm)	Pb (ppm)	As (ppm)	Co (ppm)	Zn (ppm)
SOM1	560333	6505665	6	105	10	11.5	8	31
SOM2	560306	6505677	5	42	12	4	5	28
SOM3	560254	6505658	4	72	34	4.5	7.5	105
SOM4	560256	6505677	5	210	12	16.5	7	31
SOM5	560216	6505695	4	340	16	17	56	33
SOM6	560211	6505717	4	58	30	10	7.5	72
SOM7	560196	6505704	19	240	12	8.5	6.5	30
SOM8	560163	6505730	4	900	18	94	26	31
SOM9	560125	6505751	4	135	18	21.5	8.5	41
SOM10	560101	6505742	3	130	24	10.5	8	50
SOM11	560062	6505715	8	28	14	3.5	3.5	35
SOM12	560050	6505766	4	34	30	6	5.5	36
SOM13	560018	6505746	38	1050	6	72	14	23
SOM14	559999	6505760	9	350	10	36	8.5	30
SOM15	559979	6505742	3	30	8	3	4.9	35
SOM16	559922	6505726	5	31	14	1.5	4.1	54
SOM17	559919	6505796	7	160	36	190	14	60
SOM18	559886	6505805	7	88	62	25	12	72
SOM19	559835	6505819	6	600	6	13	7	24
SOM20	559710	6505734	3	41	28	1	5	60
SOM21	559773	6505741	7	41	12	0.5	3.7	76
SOM22	559924	6505657	6	18	155	<0.5	2.6	47
SOM23	560044	6505672	11	20	32	1	3.4	45

Table: RCA assays for selected elements from Son of Man prospect.

Pintapah colluvial fans

On the western side of the Silver City Highway are some spectacular examples of Colluvial fans along lower slopes of Pintapah. The summit of Pintapah corresponds to the unconformity between the Willyama Supergroup rocks of the Euriowie Block and the Adeladean metasediments (in this case quartzite).

At the foot of the northern slopes of Pintapah are ruins associated with the old village of Euriowie.

Figure : Looking west from the Silver City Highway towards colluvium along the lower slopes of Pintapah (GR 561300mE/6520700mN).

Quarry in ferruginised Adelaidean metasediments

On the western side of the Silver City Highway is a quarry used to extract ferruginised weathered Adelaidean metasediments (mostly fine sandstone). The ferruginisation here is mostly related to hematite, with koalinitic and goethitic zones of the weathering profile also apparent. Minor hardpan RCAs can also be found at this site with some of the metal assays presented in the table below.

Samples of the ferruginised saprolite were taken from this site by Martin Smith as a part of his PhD study within CRC LEME based at the Research School of Earth Sciences, ANU. Preliminary results from this site provide a mid-Cainozoic (Miocene) age for the hematitic ferruginisation (Dr B. Pillans pers. comm., 2005).

AMG 66	Au (ppb)	Ca (%)	Cr (ppm)	Cu (ppm)	Fe (%)	Mg (%)	Ni (ppm)	Pb (ppm)	Zn (ppm)	Ag (ppm)	As (ppm)	Co (ppm)
0559115mE 6542671mN	2	30.8	6	16	0.26	0.40	4	12	22	<0.1	3	3

Southern Fowlers Gap Station Road Cuttings

A series of road cuttings along the Silver City Highway, near to southern boundary of Fowlers Gap Station provide some revealing sections through the regolith in the area. In particular they demonstrate the relationships between the evolution of surface pebble lags and the underlying weathered bedrock.

The lower parts of these cuttings consist of moderately to slightly weathered Adelaidean metasediments. Quartz veins are well developed in zones within the bedrock. Occassional concentrations of polycrystalline gypsum crystals occur along joints within the weathered bedrock and overlying the weathered bedrock interface. The upper parts of the cuttings reveal variable thickness (generally < 1 m) of red-brown clayey silt and fines sands. The uppermost landsurface is covered by angular and sub-angular pebbles of vein quartz.

Figure: Weathered Adelaidean metasediments with quartz veins, exposed in a road cutting along the Silver City Highway near the southern boundary of Fowlers Gap Station (Prof.M.Velbel for scale).

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REGOLITH AND LANDSCAPE EVOLUTION OF FAR WESTERN NEW SOUTH WALES

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INTRODUCTION

The western New South Wales landscape contains many of the elements that have been important to the study of Australian landscapes including ancient, indurated and weathered landscape remnants, as well as young and dynamic, erosive and sedimentary landforms. It includes a complex landscape history closely related to the weathering, sedimentation and denudation histories of major Mesozoic and Cainozoic sedimentary basins and their hinterlands, as well as the impacts of climate change, eustacy, tectonics, and anthropogenic activities. All this has taken place across a vast array of bedrock types, including regolith-dominated areas extremely prospective for mineral exploration.

PHYSICAL SETTINGS

Location

This region contains the landscape within New South Wales, west of the Darling River and north of Menindee Lakes, including the city of Broken Hill and the towns of Menindee, Wilcannia, White Cliffs and Tibooburra (Figure 1). It is included on the Menindee, Manara, Broken Hill, Wilcannia, Cobham Lake, White Cliffs, Milparinka and Urisino 1:250,000 map sheets in the NATMAP series.

Geology

Palaeoproterozoic metasediments and meta-igneous rocks of the Willyama Supergroup (Stevens, 1986; Stevens *et al.,*, 1988; Scheibner and Basden, 1998) are exposed as inliers of the Broken Hill Domain and Euriowie Domain and smaller inliers in the northern Barrier Range (e.g. Nardoo and Poolamacca Inliers) and Woowoolahra Range. These rocks are intruded by the Mesoproterozoic, Mundi Mundi Granites. Neoproterozoic to early Palaeozoic metasediments and minor metavolcanics from the Adelaidean sequence unconformably overlie or are in faulted contact with the Willyama Supergroup (Stevens, 1986; Scheibner and Basden, 1998). Palaeozoic metasediments, meta-igneous, and intrusive rocks of the Tasman Fold Belt occur in the eastern and northern part of the region (Mills, 1992; Scheibner and Basden, 1998).

Since the end of the Palaeozoic the region has hosted the development of major sedimentary basins. The northern part of the region is included within the Early Jurassic to Late Cretaceous, Eromanga Basin (Krieg *et al.*, 1995), while areas to the south may have been part of the Mesozoic, Berri Basin (Rogers, 1995). There is no major sedimentary record from the middle to late Cretaceous in the region, and this interval has been linked with a period of deep weathering and an erosional and sedimentary hiatus (Idnurm and Senior, 1978), or alternatively denudation and sedimentation outside of the region I areas such as the Ceduna Depocentre (O'Sullivan *et al*., 1998). Sedimentary basin development resumed in the Cainozoic with the formation of the Lake Eyre Basin in the north (Callen *et al.*, 1995) and the Murray Basin in the south (Brown and Stephenson, 1991; Rogers *et al.*, 1995). Mesozoic sediments in the area of the Bancannia Basin (Trough) have been traditionally considered as part of the Eromanga Basin, which may have been joined to the Berri Basin through this area. Cainozoic sediments in the Bancannia Basin have been previously described within the framework of the Lake Eyre Basin (Neef *et al.,* 1995; Gibson, this volume), but probably warrant a separate framework.

Geomorphology

The region mostly consists of undulating broad plains between 60 and 200 m above sea level, with a few areas of higher relief hills and mountains rising up to 473 m in the Barrier Ranges at Mt Robe.

The far west of NSW includes three main drainage basins (Figure 1):

1. The Murray-Darling Basin in the south and east of the region, including the Darling River, the Darling Anabranch and the Talyawalka Creek anabranch, and tributaries such as Pine Creek, Stephens Creek, Yancowinna Creek and Grassmere Creek. In the east of the region the Paroo Overflow and east flowing drainage such as Bunker Creek and Wannara Creek, occasionally flow into the Darling River (Thoms *et al.*, 2004).
2. The Lake Eyre Basin in the west of the region, with drainage mostly flowing towards the Lake Frome depocentre and mostly terminating in the Strzelecki Desert dunefields or on the Mundi Mundi Plain. Local stream systems such as Thackaringa Creek, Umberumberka Creek, Campbells Creek, Morphetts Creek, Teilta Creek, Floods Creek, Packsaddle Creek, Lake Wallace Creek, Yandama Creek, Stewarts Camp Creek and Fromes Creek are included in this basin.
3. The Bulloo – Bancannia Basin in the central north of the region, and including the Bulloo Overflow systems and the local depocentres of Bancannia Lake, Nuchea Lake, Cobham Lake, Salt Lake and Caryapundy Swamp, and locally fed by streams such as Gairdners Creek, Caloola

Creek, Noonthorangee Creek, Fowlers Creek, Yancannia Creek, Berawinnia Creek, and Twelve Mile Creek.

Most of the upland areas in the region broadly trend north-south. The Barrier Ranges in the far west of the region, are the area of greatest relief, and includes the Thackaringa Hills, Mt Darling Range, Mundi Mundi Range, Coonbaralba Range, Robe Range, Floods Range and Coko Range. The Woowoolahra Range forms a lower relief area to the west of the Barrier Ranges between Campbells Creek and Joulnie, rising to 204 m at Mt Woowoolahra. The southern Barrier Ranges includes the drainage divide between the Murray-Darling Basin and Lake Eyre Basin (an eastern continuation of the "Olary Spur", here called the Broken Hill - Olary Divide), and the northern Barrier Ranges includes the divide between the Bulloo – Bancannia Basin and Lake Eyre Basin (here named the Barrier – Grey Divide). Further north, the Grey Range includes Mt Arrowsmith (292 m), Mt Shannon (332 m), Mt Browne (332 m), and the Whittabrenah Ranges and Warratta Hills near Tibooburra, where the drainage divide between the Lake Eyre and Bulloo – Bancannia basins (Barrier – Grey Divide) continues to the north. Further east a group of ranges including the Scropes Range, Gap Range, Byngano Range, Turkaro Range, Koonenberry Mountain, Coturaundee Range and Yancannia Range form a broad north-south trending upland area that includes the drainage divide between the Bulloo – Bancannia Basin and the Murray – Darling Basin (here named the Koonenberry Divide). These regional drainage divides are shown in Figure 1.

Climate

The region presently experiences a semi-arid to arid climate. Daily temperatures in summer are frequently over 30°C and in winter may fall as low as -6 °C. The annual rainfall is about 250 mm at Broken Hill, with a high degree of yearly variability and no predictable seasonal pattern. Further north in the region the rainfall, whilst still highly variable, is slightly summer-dominated and it is slightly more arid (rainfall is about 170 mm per year at Tibooburra). Annual evaporation typically exceeds rainfall in the entire region. Prevailing wind directions are variable, although tend to be mostly from the south and south-west.

Vegetation

There are some strong associations between vegetation communities and regolith-landform settings. Mulga (*Acacia aneura*) woodlands, mostly occur in areas with bedrock exposure or subcrop, and in the north of the region it also occurs in stands on aeolian sandplains. Belah (*Casuarina pauper*) and rosewood (*Alectryon oleifolius*) occur near the margins of bedrock-dominated terrains especially where the regolith is calcareous. Major drainage lines and associated depositional areas host eucalypt-dominated woodlands, including the widespread river red gum (*Eucalyptus camaldulensis*), with black box (*Eucalyptus largiflorens*) in alluvial swamps and floodplains, and coolabah (*Eucalyptus microtheca*) along drainage lines and alluvial swamps in low lying areas mostly in the north of the area. Bloodwood (*Eucalyptus terminalis*) dominated open woodlands mostly occurs on weathered granite in the Tibooburra Inlier. Mallee (including *Eucalyptus oleosa,* and *E.dumosa*) occur on aeolian regolith in the Murray Basin that tend to be dominated by sandy soils with regolith carbonate accumulations. Isolated stands of curly mallee (*E.* gillii) occur in areas with abundant regolith regolith carbonate accumulations at Corona, Fowlers Gap, Thackaringa, and near K-Tank and Avondale. White Cypress Pine (*Callitris columellaris*) woodlands mostly colonise sandy aeolian deposits such as dune ridges in the Strzelecki Desert, sandy alluvial deposits, and on well drained rocky and colluvial slopes near Mutawintji.

Chenopod shrublands are the most widespread vegetation community in the region (Eldridge, 1988). Shrubs of *Atriplex spp*. and *Maireana spp*. are dominant. Bladder saltbush (*Atriplex vesicaria*) is abundant in areas with clay-rich regolith such as within alluvial plains and low rises and highly weathered rises, and *Maireana pyramidata* and *Maireana sedifolia* mostly occur in areas with friable and calcareous regolith. Grasslands mostly dominated by mitchell grass (*Astrebla spp.*) occur in some of the lowland areas, such as southeast of Broken Hill and north of Fowlers Gap.

Since the late 1800s the vegetation cover has been greatly modified due to herbivore grazing, including rabbits, kangaroos, sheep and cattle, as well as tree clearance for fuel and construction (Kenny, 1936; Fanning, 1999; Lord, 1999).

REGOLITH-LANDFORMS

Weathered Bedrock

The area contains a vast array of bedrock lithologies and structures which have variable responses to weathering, and therefore different weathering morphologies and landscape expressions. Bedrock lithologies such as micaceous schists tend to be moderately to highly weathered in surface exposures, largely as a result of their abundance of relatively labile mineral and their extensive fracturing and sheared fabrics that facilitate the access and throughflow of weathering solutions. These bedrock types tend to have a more subdued landscape expression. More resistant bedrock lithologies such as quartz veins, quartzite and quartz-magnetite rock (such as at the Pinnacles, the Tors, and the Sentinel) have a more prominent landscape expression. In many settings adjacent to sulphide mineralisation, such as the Broken Hill Line of Lode, there is a deep zone of highly weathered bedrock largely resulting from enhanced weathering and the production of acidic solutions and more porous and permeable materials. Although highly weathered, the Broken Hill Line of Lode was originally associated with a prominent ridge mainly because of ferruginisation and silicification of the weathered

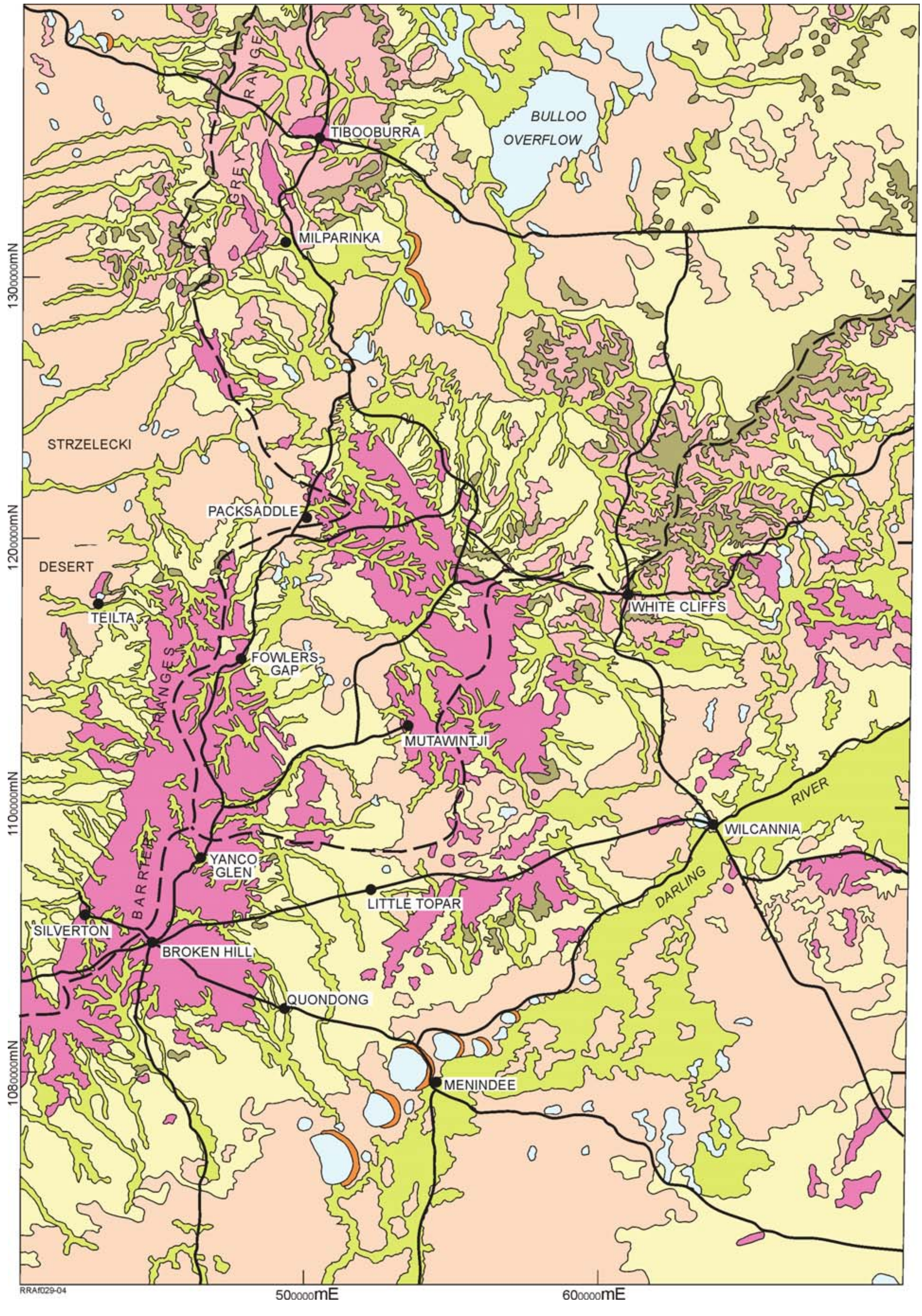
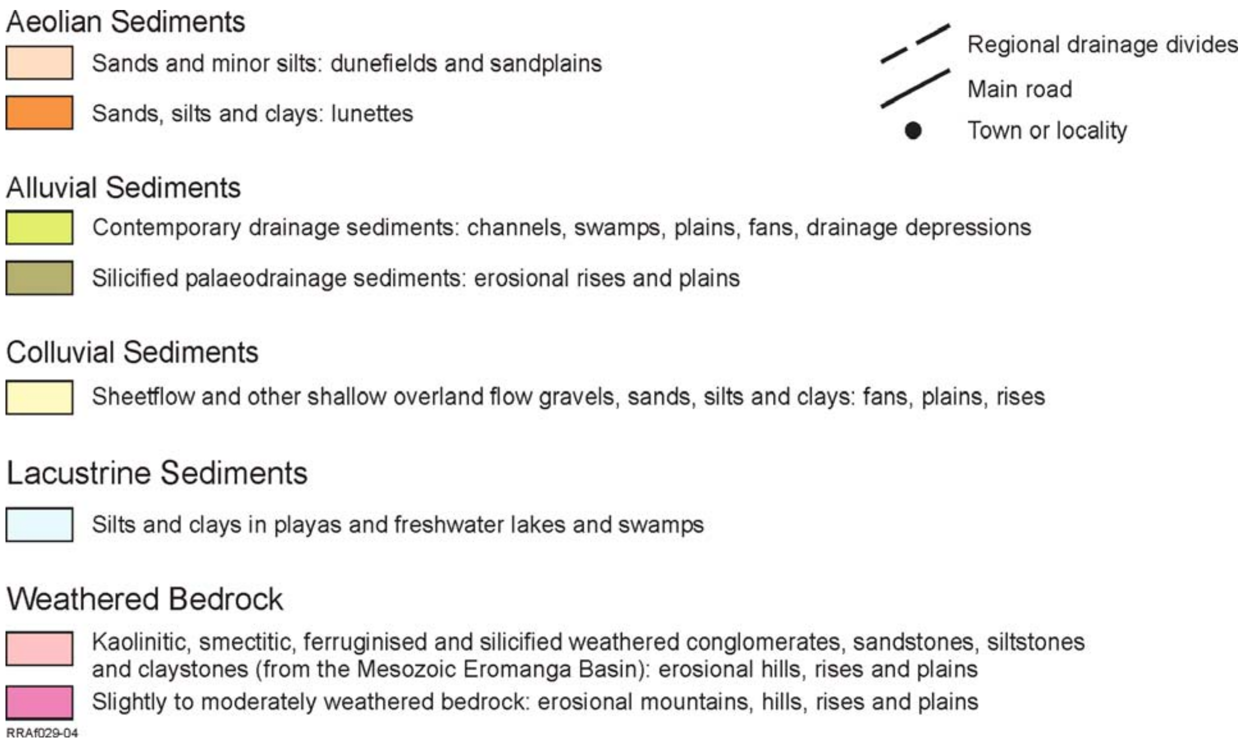


Figure 1. A regional regolith map of the study area also showing regional drainage divides.



bedrock (Plimer, 1984). Geological structures have also been important in controlling the extent of weathering and erosion, and the resulting landscape expression. Tectonic activity during landscape evolution has also had a major impact on the denudation and preservation of weathered materials, and their subsequent landscape expression. Range-fronts associated with the Mundi Mundi, Mulculca, Kantappa, Western Boundary, Koonenberry, Mt Browne and Warratta faults (Figure 2) show evidence of relatively young (at most post-Mesozoic) tectonism (Hill and Kohn, 1998; Gibson, 1997; Hill, 2000; Hill *et al.*, 2003; Anderson *et al.*, 2004).

Differences in landscape setting influence the formation and preservation of weathered bedrock. High relief areas, such as the central Barrier Ranges mostly consist of slightly weathered bedrock. Moderately to highly weathered bedrock is mostly exposed on the flanks of high relief areas, underlying plateaux capped by indurated regolith, or in low relief areas either with subdued landscape expression (such as low rises of erosional plains) or buried by transported regolith (such as underlying many valley systems).

Where weathered bedrock is well developed and preserved in the landscape it mostly consists of kaolinitic and siliceous saprolite with variable degrees and morphologies of ferruginous induration, including massive, slabby and mottled ferruginisations with well preserved saprolitic fabrics. In low lying areas such as south of Broken Hill and at the Mundi Mundi Plain west of Broken Hill, many weathering profiles underlying transported regolith may be over 50 m thick, although they are generally less than ten metres thick. The weathering front is typically highly irregular, largely relating to bedrock lithological and structural heterogeneities. In places (e.g. the southern margins of the Barrier Ranges), exposed, slightly weathered quartz veins may be adjacent to highly weathered bedrock extending for thickness up to 100 metres.

Alluvial Sediments

A wide range of alluvial sediments occur in the region, associated with both the modern and ancient drainage systems. They represent the preserved remnants of deposition associated with drainage systems from throughout the region's landscape history. The main alluvial sediment landform assemblages include channels, plains, swamps, outwash fans and drainage depressions, with more ancient sediments occupying erosional rises and erosional plains or are deeply buried (Figure 3).

The alluvial sediments contain a mixture of clays, silts, sands and gravels, with younger deposits mostly including a mixture of quartzose and lithic clasts, and more ancient deposits mostly dominated by quartzose clasts. Some of the younger sediments contain glass, wire and other anthropogenic derived materials indicating a significant post-settlement alluvial deposition (Fanning, 1999). Modern streams in the region are ephemeral. Larger streams mostly originate in bedrock-dominated uplands and flow towards flanking regolith-dominated terrains where they typically terminate as broad alluvial swamps, sheetflood fans, and lacustrine depressions. The dominant channel morphologies are

(a)

(b)

Figure 2. Range-fronts that have facilitated relatively recent tectonism in the region. a) Mundi Mundi range-front; b) Wahratta range-front.

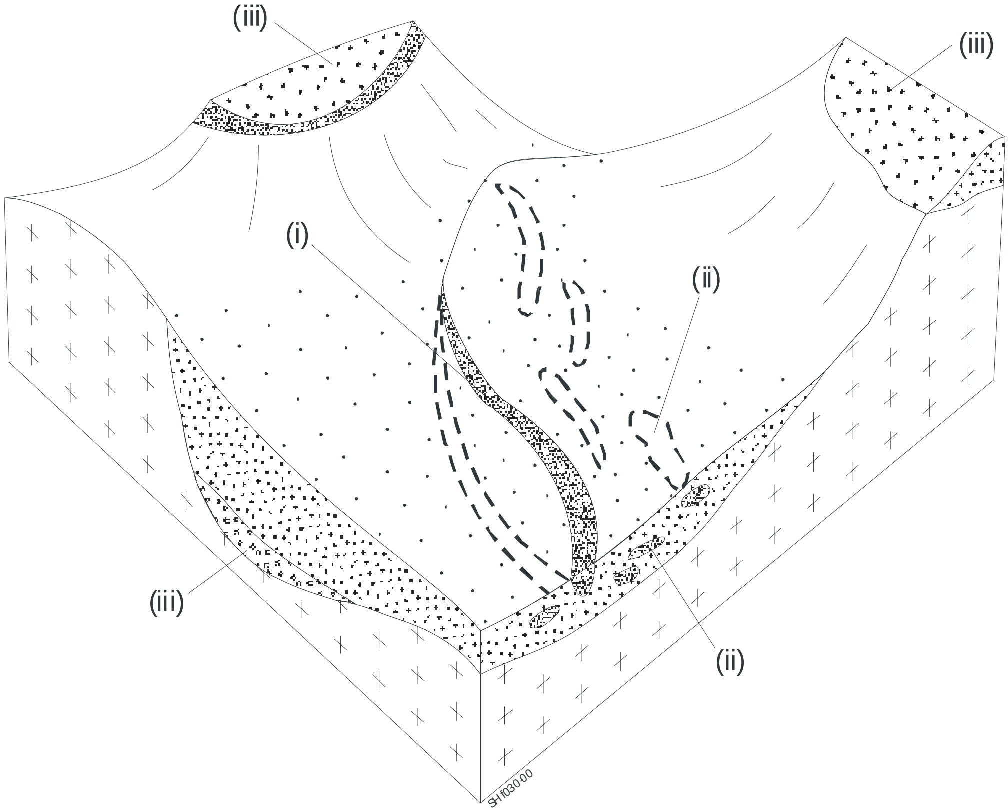


Figure 3. A diagrammatic representation of the landscape settings of major drainage systems from within the western NSW landscape. (i) Contemporary alluvial deposits associated with ephemeral stream systems; (ii) Alluvial sediments associated with contemporary valley systems that are either buried or slightly elevated so that they no longer carry stream flow; (iii) Channel deposits isolated from contemporary drainage systems through deep burial or elevation associated with inversion of relief (from Hill, 2000).

sandy meandering and braided channels. The middle reaches of many streams are entrenched within arroyos. Many of the ancient alluvial sediments are indurated by silica (e.g. silcretes) and occupy landscape settings isolated from modern drainage systems, either by burial or on erosional rises and erosional plains. These remnants were associated with sandy meandering to braided palaeovalley systems that were once linked to sedimentary basin depocentres such as in the Mesozoic Eromanga Basin and Berri Basin and the Cainozoic Murray Basin, Lake Eyre Basin and Bulloo-Bancannia Basin (Hill *et al.*, 1997; Hill, 2000).

Colluvial Sediments

Colluvial sediments in the region are derived from rockfalls, creep, slides, and debris flows, and sheetwash (Hill, 2000). Sheetwash sediments are extremely widespread across the region, typically extending from the upper slopes of rises down towards the axes of adjacent valley systems where they then typically contribute to alluvial sediments. Many of the features previously described as 'alluvial fans', largely consist of lobes of sheetwash deposits. They include a wide range of locally derived lithologies (clays, silts, sands and pebbles), and the composition of clasts is highly variable and depends on the nature of the local substrate. Vertical sections in many cases reveal alternating pebbly gravel and sand laminations, typically with pebbly gravel concentrated at the landsurface to form gravel surface lags. Most sheetwash deposits are contained within broad, low relief fans and lobes that mantle slopes over scales of 10s of metres to 10s of kilometres. Many have a prominent 'contour band' or 'tiger bush' surface pattern (Figure 4a), where surface lags conform to transverse bands of alternating sparsely vegetated pebbly bands and more densely vegetated bands of silty sand (Dunkerley and Brown, 1995; Wakelin-King, 1999).

Creep is a component of colluvial transport on most slopes in the region and is most apparent in surface exposures and cuttings into weathered pelitic schists, where steeply dipping cleavage planes are disrupted in accordance with the attitude of the landsurface. Rockfalls contribute to the development of talus deposits at the base of steep slopes, particularly adjacent to prominent exposures of slightly weathered bedrock, such as at the Pinnacles. Debris flows are rare in the region however they may have contributed to the development of many of the alluvial fans in the region, such as along the Mundi Mundi range-front, and debris flow deposits are also exposed in the railway cutting between Silverton and the Umberumberka Mine (Hill *et al.,* 1994; Hill, 2000).

(a)

(b)

Figure 4. a) 'Contour band' or 'tiger stripe' landsurface patterns defined by 'bands' of mitchell grass (*Astrebla spp.*) colonising fine red-brown sands and silts, alternating with sparsely vegetated pebble 'bands', Avondale Station, approximately 30 km southeast of Broken Hill; b) red-brown quartzose sands within linear dunes near Teilta on the southeastern margins of the Strzelecki Desert, northwest of Broken Hill.

Many hills and rises capped with silicified regolith are flanked by colluvial slopes with pebbly surface lags. These lags serve as an 'armour' to erosion of the underlying regolith and in many cases account for the development of 'ring-like' rises, surrounding and detached from a silica-capped hill or rise, such as at Peak Hill at Wonnaminta (Gibson and Wilford, 1996; Hill, 2000; Gibson, 2001), and Mt Wood northeast of Tibooburra.

Aeolian Sediments

Landforms dominated by aeolian sediments include longitudinal linear dunes, sand plains and lunettes. Aeolian sediments are widespread throughout the region and are at least a component of most surficial regolith materials. Linear dune fields consisting of low, WSW-ENE trending, elongate sand ridges are best developed in low lying areas such as the Strzelecki Desert in the northwest of the region (Figure 4b) (Wasson, 1983a; 1983b; Stevens, 1991), parts of the Mallee region in the south (Bowler and Magee, 1978), and across much of the Bulloo – Bancannia Basin. Sandplains and irregular, hummocky dunes are also typically developed on the margins of alluvial channel systems and lacustrine depressions. Aeolian materials are mostly composed of fine sand and silt size particles, typically consisting of clay mineral pellets, quartz and minor iron oxides, and calcium carbonate (Chartres, 1982; 1983; Hallsworth *et al.*, 1982). In most cases these sediments have a red to red-brown colour although these colours are lighter, tending towards white, nearer alluvial channels and lacustrine depressions. Lunettes (smooth, cresentic, transverse dunes) are well developed on the eastern shores of most ephemeral lakes in the region, such as the Menindee Lakes (Bowler and Magee, 1978; Chen, 1992), where they are typically extensively eroded with rills and gullies.

Lacustrine Sediments

Lacustrine basins are common in low-lying parts of the region, typically associated with the terminal or overflow systems of alluvial drainage. Water in most basins is ephemeral, although some of the Menindee Lakes system, Stephens Creek Reservoir and Umberumberka Reservoir are filled artificially for use as water storage basins. Lacustrine sediments are clays and silts, including clay minerals, quartz, salts (including halite and gypsum), and organic material.

Indurated Regolith

A range of regolith induration styles with different chemical compositions occur in the region within both *in situ* and transported regolith host materials. The main types include:

- Regolith Carbonate Accumulations (RCAs) respectively include 'calcrete', 'dolocrete', and 'magnecrete' for $CaCO_3$, (Ca, Mg)CO_3, and $MgCO_3$ end-members. They are extensively developed across the landscape in the south of the region and include nodular, hardpan, powder, rhizomorphic and tabular morphologies (Figure 5) (Hill *et al.*, 1998; McQueen *et al.*, 2000). Magnesite occurrences are restricted to sites with weathered serpentinites, such as at Thackaringa, Little Broken Hill and Macs Tank. In the north they mostly include hardpan morphologies restricted to bedrock-regolith and other hydromorphic interfaces, with powder and nodular facies in the swales of dunefields.
- Ferruginous regolith, also referred to as 'ferricrete' or 'laterite', is widespread in the region, but is mostly exposed on the margins of upland areas. This includes ferruginised saprolite, typically expressed as ferruginous surface lags derived from the exposure of mottled saprolite, as well as various morphological facies developed in transported regolith, such as ferruginised sediment, nodular ferruginisations consisting of detrital ferruginous clasts within a ferruginous matrix, and slabby ferruginisations (Figure 6) (Hill *et al.*, 1996; Hill, 2000; Hill *et al.*, 2003).
- Silica indurated regolith, has a wide range of morphological facies, such as silicified sediments with columnar, nodular, and tabular morphologies (Watts, 1978; Hill, 2000; Hill *et al.*, 2003), silicified hardpans (red-brown hardpans, Chartres, 1985), and silicified saprolite (Figure 7) (Hill *et al.,* 1996; 1997; Hill, 2000). The most abundant silica cement consists of micro-crystalline quartz, although opaline and chalcedonic varieties also occur in the region (Wopfner, 1978; Alexandre ***et al.*** 2004), and also include anatase and hematite in the cement.
- Gypseous regolith is a component of many regolith types, either as disseminated crystals or polycrystalline aggregates, particularly in low-lying landscape settings. Extensive zones of polycrystalline gypsum aggregates are well-developed in saprolite on erosional rises near Broken Hill at Balaclava (Figure 8a) and south of Cockburn and may relate to the weathering of sulphides (Shirtliff, 1998; Hill, 2000), while other polycrystalline gypsums aggregates are widely developed in low-lying sedimentary plains, such as near Teilta, Mulculca, and Yanco Glen and are probably mostly related to hydromorphic ponding of surface and groundwaters (Hill *et al.*, 2003). Gypsum is a major component of the regolith derived from the weathering of Mesozoic silts and clays, where it co-exists with kaolinitic and hematitic regolith. In this case the gypsum is probably derived from the weathering of pyrite originally within these marine sediments.
- Manganiferous regolith is limited in distribution in the region and mainly occurs adjacent to weathered Mn-rich bedrock lithologies including spessartine garnets and rhodonite (e.g. Line of Lode gossan (Figure 8b), and Melbourne Rockwell Mine). Morphologies include laminated, coralline, and botryoidal types (Hill, 2000), and desert varnish surface coatings (Dragovich, 1988).

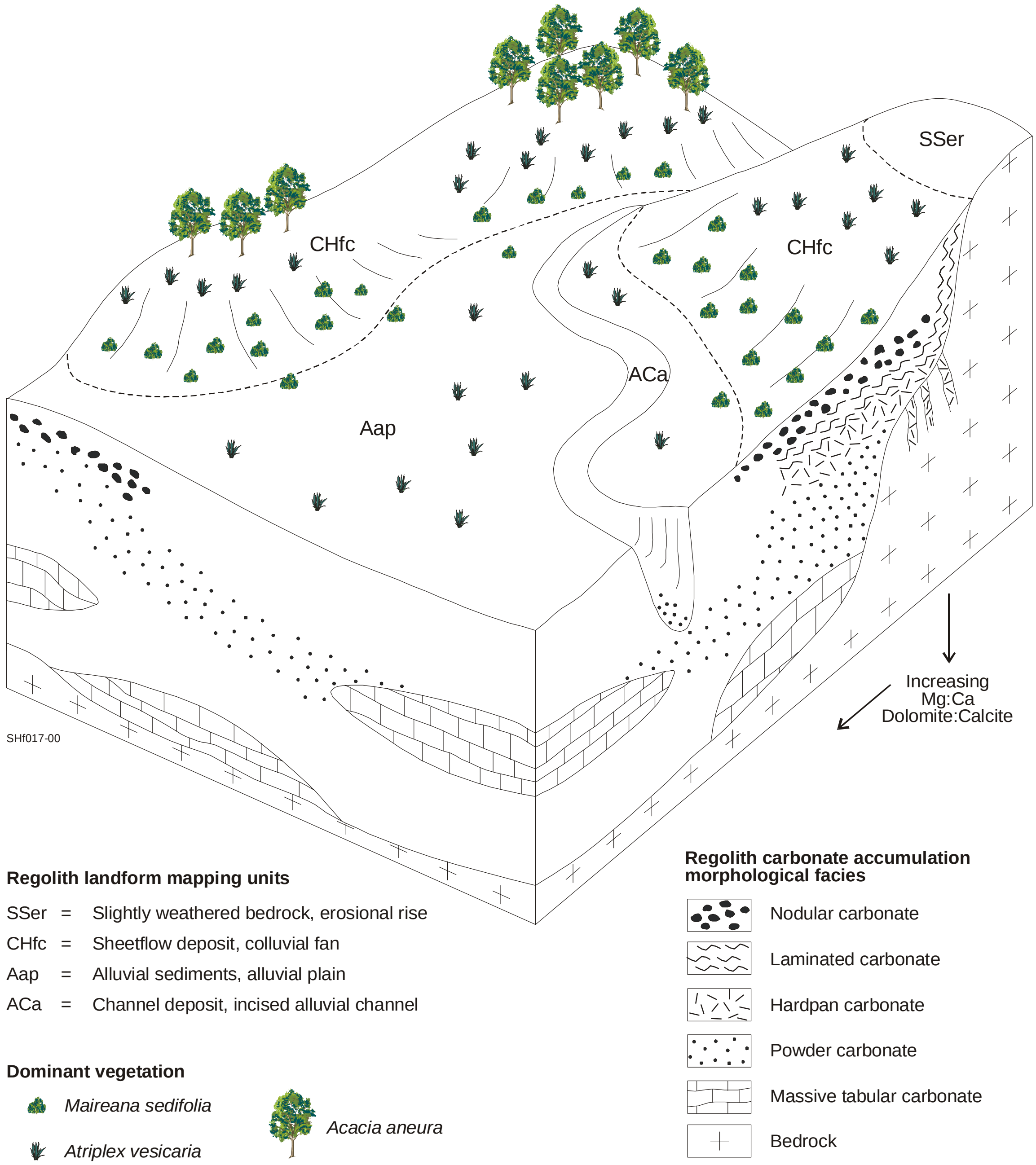


Figure 5. Landscape settings of major regolith carbonate accumulation (RCA) morphological facies, based on the upper Umberumberka Creek catchment, Limestone Station (from Hill, 2000).

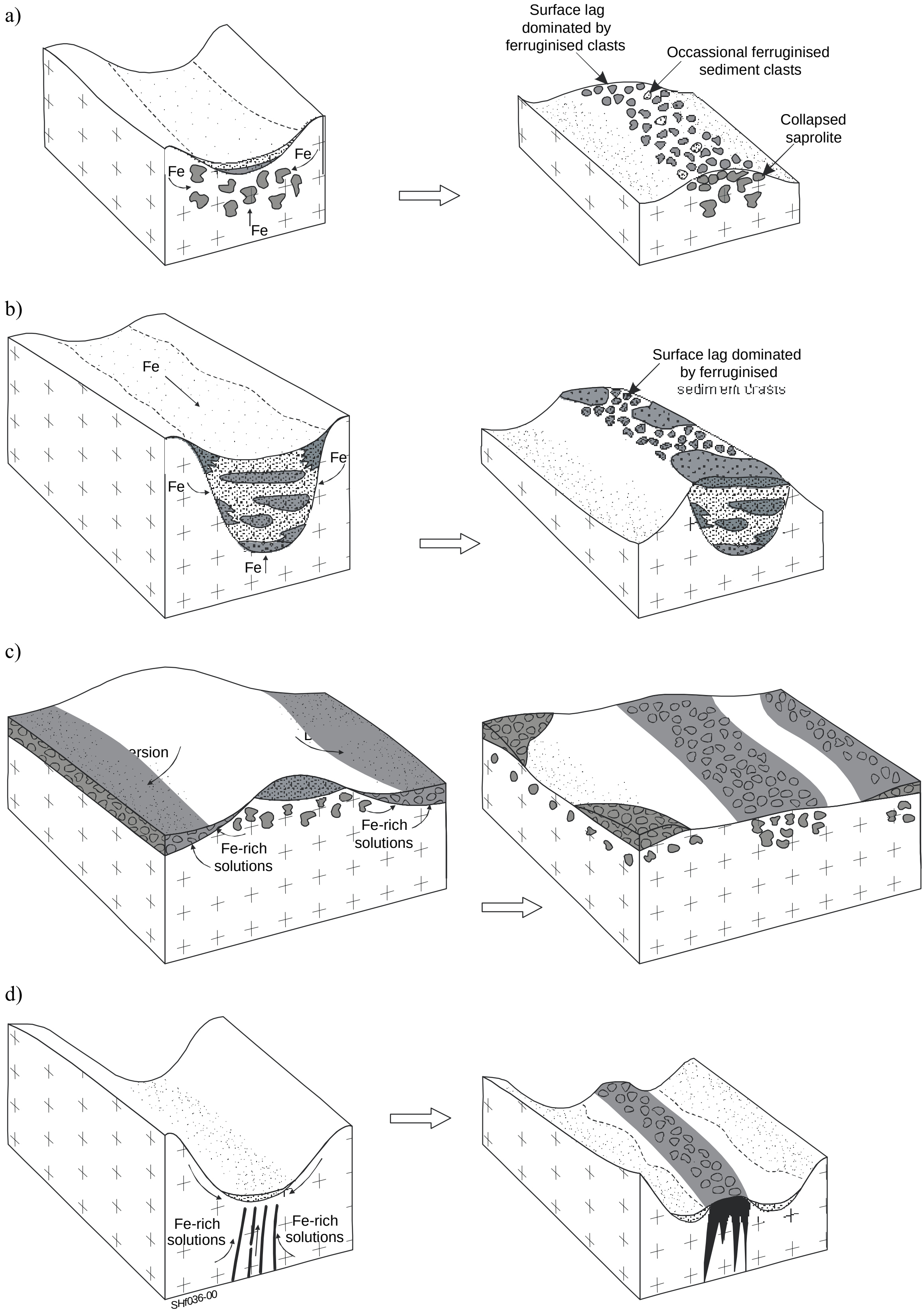


Figure 6. Landscape settings for the development and contemporary surface expression of ferruginised regolith in western NSW (from Hill, 2000).

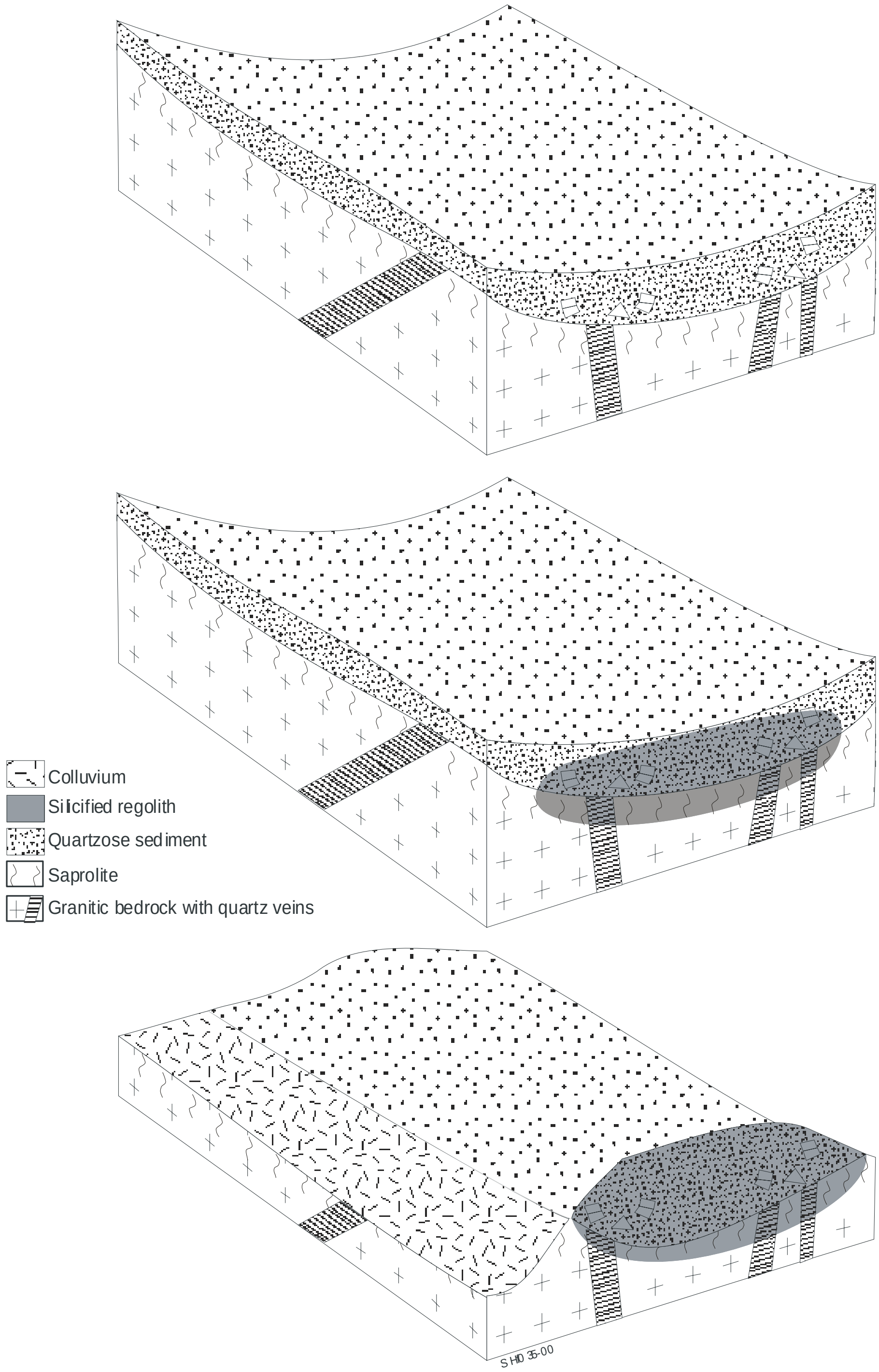


Figure 7. Landscape settings for the development and the contemporary surface expression of silicified sediments and underlying silicified saprolite near Boulder Tank, McDougalls Well station, northwest of Broken Hill (from Hill, 2000).

(a)

(b)

Figure 8. a) Polycrystalline gypseous regolith at Balaclava station, south of Broken Hill; b) Manganese oxide and hydroxide indurated regolith along the Broken Hill Line of Lode, near the Junction Mine.

REGOLITH AND LANDSCAPE EVOLUTION

Many of the controls on regolith and landscape evolution are shown diagrammatically in Figure 9.

Weathering and Induration

The bedrock of the region has continued to weather during its exposure to surface and near-surface processes and conditions.

Pre-Mesozoic weathering profiles and palaeosurfaces have been partly exhumed from beneath Mesozoic sediments along the margins of the Eromanga Basin, such as at Wonnaminta (Gibson, this volume) and Tibooburra (Hill *et al.*, this volume). The quartzose with very minor lithic composition of many of the basal Mesozoic sediments, support the interpretation that the landscape was highly weathered immediately prior to much of the Mesozoic sedimentation. Remnants of weathering profiles associated with the late Cretaceous 'Mornay Profile' (Idnurm and Senior, 1978) are also likely to occur in the region, and is also supported by the deposition of quartz and kaolin-rich sediments (e.g. Eyre Formation and other equivalent sediments) derived from the erosion of a highly weathered landscape that had developed by Palaeogene times.

Previous interpretations of weathering and induration during the Cainozoic mostly highlight a mid-Cainozoic event (e.g. Wopfner and Twidale, 1967; Idnurm and Senior, 1978; Callen, 1983; Alley, 1998). For example, this has been associated with the development of the Late Eocene to Oligocene 'Cordillo Silcrete' and 'Cordillo Surface' in parts of the Lake Eyre Basin (Wopfner and Twidale, 1967; Alley, 1998), and probably also the Late Oligocene Canaway Profile in western Queensland (Idnurm and Senior, 1978). A silicified Eocene flora assemblage within partially topographically inverted palaeovalley sediments at Fowlers Gap (Greenwood *et al.,* 1997; Hill and Roach, 2003) are consistent with Eocene silicification in at least this part of the landscape in western NSW. It is not clear whether this period represents a time of enhanced weathering and induration in the region, or instead an extensively developed and preserved weathering feature (Hill, 2000). Landscape settings hosting sediment accumulation and induration (such as the 'Cordillo Silcrete' overprinting the Eyre Formation) have a relatively high preservation potential, and therefore have a tendency towards its emphasis within the landscape and stratigraphic record. The Lake Eyre Basin sediments also provide some of the few stratigraphic benchmarks used for determining the age of induration, and as such they are an incomplete stratigraphic context for induration, especially considering that in some circumstances the presence of silicification has been used to establish a stratigraphic context. Later Cainozoic weathering and induration events have also been interpreted, such as Plio-Pleistocene silicification associated with gypsum development (e.g. Wopfner, 1978).

Previous interpretations of the weathering and induration histories derived from the stratigraphy of the sedimentary fill in the Lake Eyre Basin propose an episodic framework. This includes weathering and induration immediately preceding the Cainozoic, and again in the mid-Cainozoic and the later Cainozoic (e.g. Firman, 1994; Alley, 1998). Further work is needed to better constrain weathering and induration development in the Lake Eyre Basin in western NSW. Recent interpretations, suggest that the evolution of weathered and indurated materials has been more complex than many of the previous region models suggest, with weathering and many types of induration having taken place throughout much of the history of landscape development (Hill, 2000). By comparison, interpretations of the landscape history of western NSW derived from the study of the sedimentary fill of the Murray Basin have been poorly developed, and instead this basin has been mostly considered in the context of landscape evolution in the Eastern Highlands. The sedimentary fill of the Bancannia Basin has received no attention in this respect.

The development of regolith carbonate accumulations (RCAs) has occurred in the later part of landscape evolution in the region. This is reflected by its development within relatively young regolith host materials (e.g. aeolian, alluvial and colluvial materials closely related to the contemporary landscape) and its overprinting (such as hardpan coatings) of ancient regolith materials. This development is partly related to reduced leaching associated with increasing aridity during the Cainozoic, but also the increased input of marine derived dust and dissolved components in rainfall, particularly in the south of the region (Hill, 2000; L. Hill, 2004; Dart *et al*., 2004).

Denudation

The sedimentary record of the sedimentary basins in western NSW has been very broadly used to develop denudation histories of the region. One of the major limitations here is the poorly constrained Mesozoic and Cainozoic stratigraphy of the region, plus the very general mapping and irregularity of the three-dimensional information needed to determine sediment volumes and palaeogeographic context. The sedimentary fill of the Murray Basin in the south of the region has been mostly considered in relation to the evolution and denudation of the Eastern Highlands. Recent studies in the Broken Hill region however suggest that the erosion of the Barrier Ranges have also been supplying sediment into this basin since at least the early Cainozoic (possible Renmark Group and younger equivalents) (Hill *et al.,* 2003). Landscape evolution and more specifically denudation histories of the region in relation to the sedimentary fill of the Lake Eyre Basin propose episodic models of denudation and landscape evolution. For example, the Palaeogene sediments of the Eyre Formation are widely interpreted to be derived from the stripping of highly weathered regolith in hinterland areas, such as the Barrier Ranges, with subsequent development of a low relief, indurated landsurface in the mid-Cainozoic (e.g. Wopfner *et al.*, 1974; Alley, 1998).

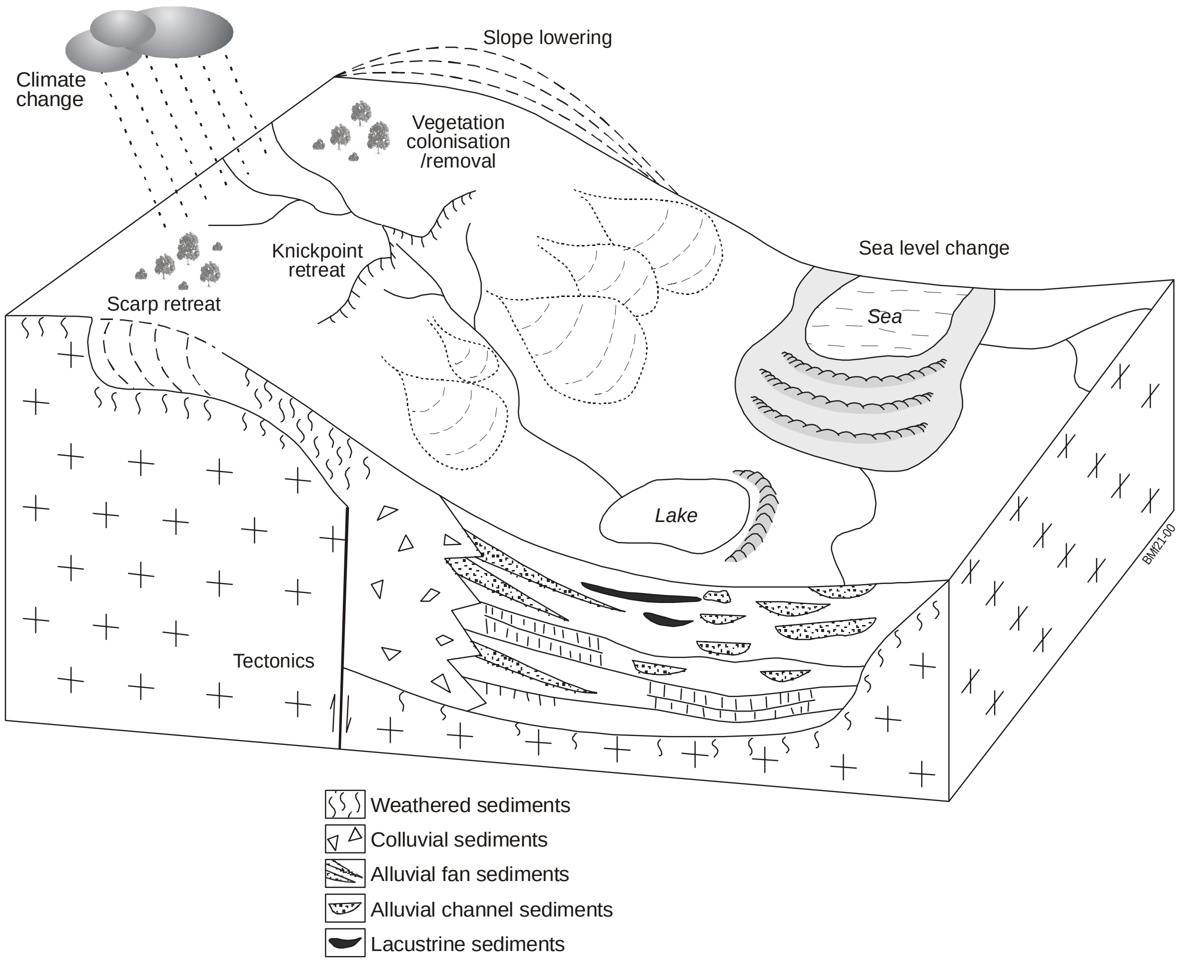


Figure 9: Diagrammatic representation of some of the major controls on regolith and landscape evolution in western NSW.

An Apatite Fission Track Thermochronology (AFTT) study of the Mundi Mundi range-front by Hill and Kohn (1999) shows a period of Late Palaeozoic cooling perhaps due to denudational cooling associated with the Lachlan Orogeny. Mesozoic and Cainozoic denudation has also been proposed from AFTT studies, with the Darling Lineament appearing to be an important structure controlling the denudation (e.g. O'Sullivan *et al.*, 1998), although further sampling across the region is needed to better constrain this in time and space.

Tectonism

Tectonic processes have had a major expression in the landscapes and the development of regolith materials in western NSW (Gibson, 1996; this volume; Hill and Kohn, 1999; Hill, 2000; Hill *et al.*, 2003; Hill, this volume; Hill *et al.*, this volume). Many of the range-fronts in the region reflect ongoing tectonic processes, such as along the Mundi Mundi, Kantappa, Mulculca, Warratta and many other faults near Tibooburra. Much of this tectonic activity is related to the evolution of Mesozoic and Cainozoic sedimentary basins in the region, and reflects the evolution of continental-scale stress regimes within this region. The younger (mid to late Cainozoic) tectonism appears to be associated with reverse-faulting, which is consistent with the contemporary compressive stress field. It is likely that older (early Cainozoic and Mesozoic) tectonism was associated with extensional tectonism associated with sedimentary basin evolution. Importantly, the expression of tectonism within the regional long-term landscape evolution model is in contrast to many previous suggestions of the region's, and much of Australia's, long-term, intraplate, tectonic stability.

Climate

Morphoclimatic models for regolith and landscape development have been widely cited for the region. The development of ferruginous regolith materials has been widely attributed to wetter and more 'tropical' conditions in the past (Stephens, 1971; Langford-Smith and Watts, 1978). Ferruginous materials however appear to have developed at many times throughout the landscape evolution of the region, and may still be forming in the present conditions (Hill *et al.*, 1996; Hill, 2000). Silcretes have been both attributed to either wetter conditions than present (e.g. Alley, 1998) as well as to aridity, such as presently experienced in the region (e.g. Langford-Smith and Watts, 1978), or to both climatic extremes (e.g. Wopfner, 1978). The development of silcretes is poorly understood, largely because of the lack of recognised modern analogues for their development. Hill (2000) suggests that there development could be due to acidic weathering conditions associated with organic acids and pyrite weathering within Mesozoic and Cainozoic sedimentary sequences. This would lead to de-alumification of the regolith, leading to local redistribution of silica-rich byproducts. Regolith Carbonate Accumulations (RCAs) have been previously interpreted as an indicator of climatic aridity and as such reduced leaching of their chemical constituents. Although this is partly true, it is an over-simplification and overlooks the importance of variations in the supply of chemical constituents for their initial development. Simply attributing RCA development to climatic aridity does not account for the present distribution of RCAs in this region, which are less widespread towards the more arid northwest of the region. Chemical inputs associated with atmospheric contributions (rain and dust) have instead been suggested as an important control on the widespread development of RCAs in the winter-rainfall dominated areas to the south that are more proximal to marine Ca and Mg sources that the summer-dominated rainfall areas to the north that are more distal to marine Ca and Mg sources (Hill *et al.*, 1998; McQueen *et al.*, 1999; Hill, 2000; L .Hill, 2004).

Quaternary climate changes have been an important control on the development of regolith and landforms, particularly associated with the surficial alluvial, colluvial, aeolian and lacustrine sediments (Chen, 1992; Bowler and Magee, 1978; Wasson, 1979). Wasson's (1979) morphoclimatic model for alluvial fan development along the Mundi Mundi range-front however is in need of further refinement. Recent tectonism along the range-front and its potential contribution to fan development (Hill and Kohn, 1998; Hill, 2000) was not recognised by Wasson. The sedimentary architecture of the fans also consists of irregular and laterally discontinuous fan lobes (Hill, 2000), rather than the broad "layered" alluvial fan architecture proposed by Wasson (1979). This not only has implications for better understanding the evolution and dispersion processes with the fans, but also in developing models for pre-1800s erosion and sedimentation within the landscape.

Eustacy

For an inland area like western NSW it may seem surprising that eustacy could be considered in models of landscape evolution, however because the development of this landscape extends at least beyond the Mesozoic, implications for marine transgressions with the Eromanga Basin and the Murray Basin may be significant. Many of the landscape changes outlined by Gibson (this volume) in the Wonnaminta area, and similarly by Hill *et al.* (this volume) in the Tibooburra region, are driven by the initial deposition and later stripping of marine sediments since the Mesozoic. The influence of the mid-Cainozoic marine transgression into the Murray Basin is not clear for this region. A similar transgression did not occur within the continental Lake Eyre Basin.

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NORTHERN BARRIER RANGES REGION, NEW SOUTH WALES

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INTRODUCTION

This case study encompasses the area of the northern Barrier Ranges between latitude 30°45' and 31°5'S, and longitude 141°35' and 141°55'E, and is based on the investigations of Gibson (1997, 1998, 1999, 2000). The area falls within the COBHAM LAKE (SH54-11) and BROKEN HILL (SH54-15) 1:250 000 map sheets, immediately north of the Fowlers Gap Arid Zone Research Station (Macdonald, 2000) and about 100 km north of Broken Hill in northwestern NSW (Figure 1). A northerly trending range dominates the central part of the area, with depositional plains to the east, and undulating rises and low hills to the west.

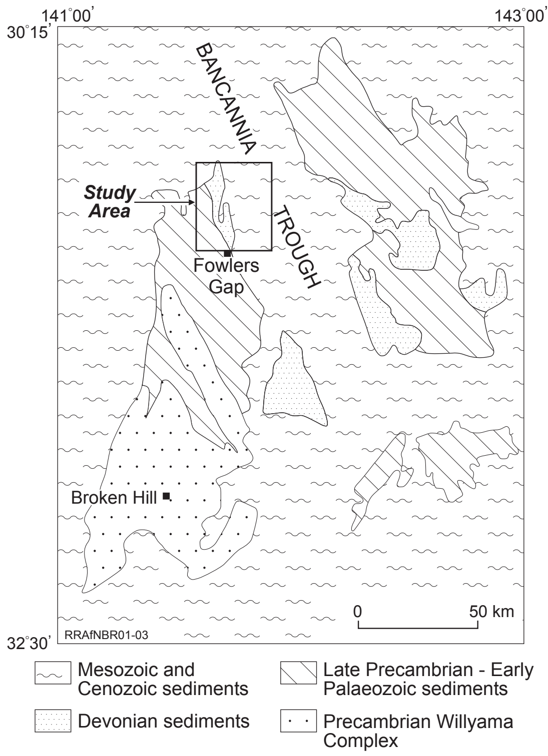

Figure 1. Location of study area and regional geology.

PHYSICAL SETTING

Geology

Ward *et al*. (1969), Cooper *et al*. (1978), Beavis and Beavis (1984), and Neef *et al*. (1995) have described the bedrock geology of the area. Dipping Neoproterozoic low-grade metasediments (shale, quartzite and dolomite) with open fold structures are present in the west of the area, and are unconformably overlain by, and faulted against, easterly dipping Devonian sandstones (Figures 2, 3). The dip of the Devonian sandstones increases towards the east (Figure 3). Middle and Late Devonian sequences are separated by the major north-trending Nundooka Fault (Figure 2). Sediments of the Telephone Creek Formation, traditionally thought to be Tertiary but more recently determined to be of Early Cretaceous or possibly Late Jurassic age on the basis of plant macrofossil and microfossil evidence (Gibson, 2000), unconformably overlie the Neoproterozoic and Devonian rocks (Figure 3). The Mesozoic sediments are flat-lying in the east and west of the area, but have an easterly dip of up to 30° close to the eastern margin of the ranges. A small area of strongly silicified sediment containing Tertiary plant fossils is present in the southwest of the area. Quaternary sediments in the form of a depositional plain characterise the eastern part of the area (Figure 2). The Quaternary sediments are underlain by the NNW-trending Bancannia Trough; a graben containing more than 5 km of Devonian sediments and overlain by a thin cover of Mesozoic and younger sediments. Minor aeolian sand is locally present.

Geomorphology

Mabbutt (1973) described the geomorphology of part of the area, and Mabbutt *et al*. (1973) produced a map of the geomorphic units. The Neoproterozoic rocks form an undulating topography, with persistent strike ridges underlain by the more resistant rock types. The Devonian sandstones form low ranges with

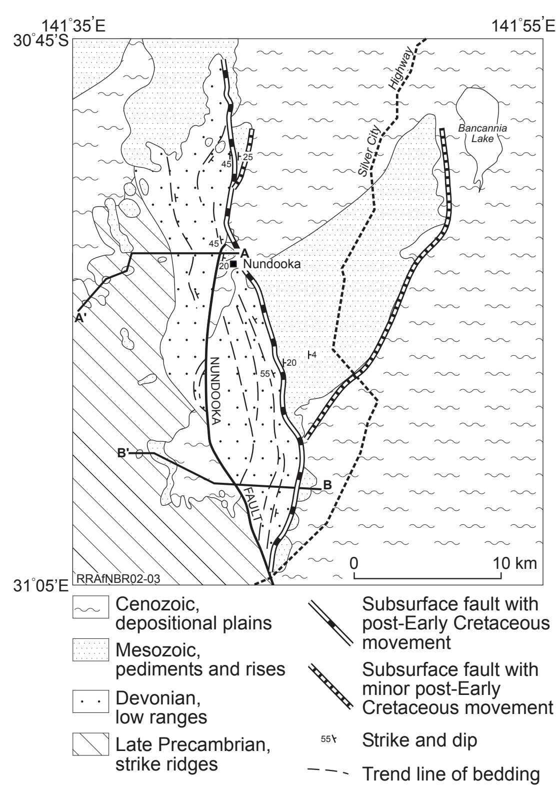

Figure 2. Generalised geology of study area. Sections A–A' and B–B' are shown in Figure 3.

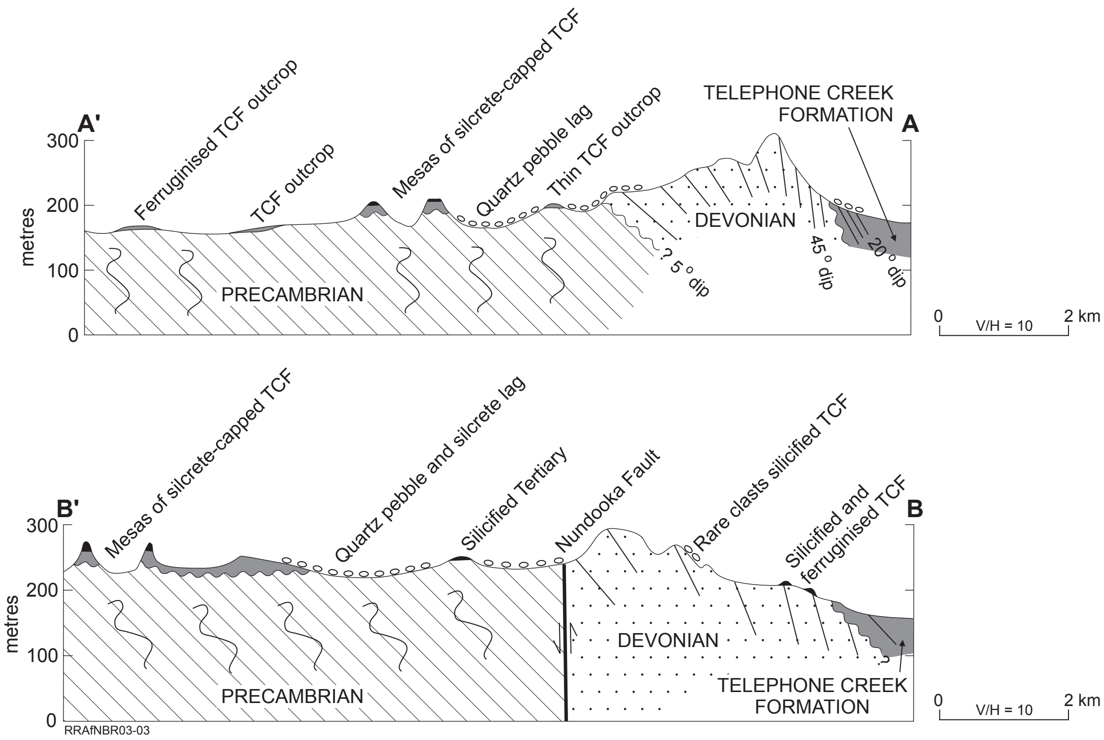

Figure 3. Sections across the ranges with geological data. Locations are shown in Figure 2. TCF = Telephone Creek Formation.

asymmetric strike ridges (cuestas) producing a sawtooth topography. Stony pediments and rises underlain by Mesozoic sediments fringe the east and north margins of the ranges (Figure 2), and there is a distinct break of slope at the range/pediment boundary which coincides with the surface trace of the Palaeozoic–Mesozoic unconformity (Figure 3). Low relief strike-parallel ridges of silicified[1] and more rarely ferruginised Mesozoic sediment are locally present on the pediments. The pediments merge downslope with depositional plains associated with the modern drainage. Scattered silcrete-capped mesas and undulating areas of Mesozoic sediments are present in the west of the area (Figure 3).

Climate and vegetation

The climate is hot and dry, with much of the highly variable rainfall falling during summer and winter storms (Bell, 1972; Macdonald, 2000). Vegetation (Milthorpe, 1972a,b; Walker, 1991) consists mainly of saltbush and bluebush with grasses, forbs and copperburrs. Some mulga (*Acacia aneura)* and other small trees occur on the erosional plains and rises, and Mitchell Grass, saltbush and bluebush occur on the depositional plains. River gums (*Eucalyptus camaldulensis*) are locally present along larger drainage lines. All of the area is used for low intensity grazing on pastoral leases. The natural vegetation has been significantly affected by the introduction of domestic animals and rabbits (Bailey, 1972).

[1] Silicification of the Mesozoic sediments has been intense leading to the formation of silcrete.

REGOLITH–LANDFORM RELATIONSHIPS

The Neoproterozoic rocks are variably weathered, depending on lithology. There is minor weathering of resistant quartzite, which forms steep strike ridges. Dolomite, which has undergone some weathering, forms lower strike ridges. Shales have been deeply weathered possibly to 100 m (Beavis and Beavis, 1984), and form strike valleys. Loamy calcareous soils predominate, except on the quartzite ridges. A colluvial mantle of locally-derived rock fragments dominated by angular fragments of quartz vein and locally quartzite occurs on lower relief areas (Figure 3). Locally, the mantle includes, or is dominated by, fragments of silicified sediments and rounded quartz clasts. These materials are interpreted to be the remnants of a former cover of Mesozoic sediment (Telephone Creek Formation).

The Devonian sandstones are mostly fairly fresh, with a few weathered interbeds. They form low ranges with cuestas of more resistant beds. Soils are mostly skeletal, with abundant fragments of Devonian sandstone. Pockets of aeolian sand are locally present at the foot of west-facing bluffs. A stony mantle over the Devonian sandstones locally includes fragments of silicified sediment and rounded quartz clasts that are also interpreted to be the remnants of a former cover of the Telephone Creek Formation (Figure 3).

The Mesozoic sediments of the Telephone Creek Formation are highly weathered forming pediments and erosional rises in the east of the study area (Figure 3). Relatively fresh exposures of the Mesozoic sediments, with preserved easterly dips, occur in eroded gullies. Resistant beds cemented by silica (silcrete)

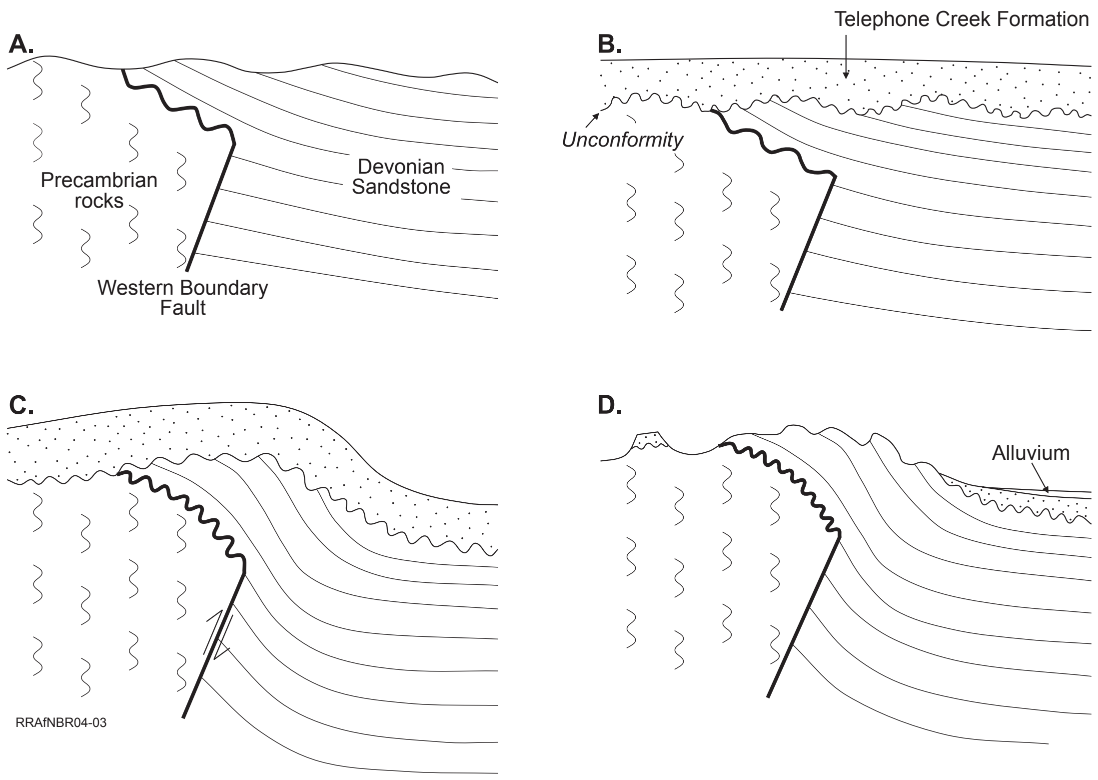

Figure 4. Interpreted stages of development of ranges north of Fowlers Gap by post-Early Cretaceous deformation and erosion. **A** Relatively uniformly dipping Devonian sandstone with little relief. **B** Deposition of Telephone Creek Formation during shallow marine incursion. **C** Monoclinal folding and uplift due to reverse faulting at depth. **D** Differential erosion of the uplifted areas imparts present day features to the ranges.

and/or iron oxides form low strike ridges on the pediments. In the west of the study area, the sediments are flat lying and form mesas capped by discontinuous *in situ* silicified beds of sediment and ubiquitous loose silcrete fragments (Figure 3). Undulating areas with a mantle of silcrete fragments, ferruginised sediment, and rounded quartz clasts from eroded conglomerates are also present.

The Tertiary sediment with plant fossils in the southwestern part of the area has been silicified and has a mantle of silcrete fragments. Unsilicified Tertiary sediment is not exposed. Alluvium is locally present along watercourses. The alluvial tracts widen in the east of the area to form a broad alluvial plain dominated by coalescing low angle fans. Some of the plain is subject to severe wind erosion, and the lower lying part of the Bancannia Trough to the east of the area is dominated by sand dunes derived from sediment deposited over the trough. Many soils in the area are carbonate-rich, and soil on lower slope erosional areas display a contour-parallel banding of micro-topography, vegetation and soil properties (Mabbutt, 1972, 1977; Macdonald 2000; Macdonald and Melville 1999, 2000; Macdonald *et al*., 1999). The finer material in many soils is interpreted to be at least in part aeolian-derived (Macdonald, 2000). Gypsum is locally abundant in soils and near-surface deposits.

Some scree slopes beneath silcrete outcrops have been partly cemented to form a hardpan with a red earthy matrix enclosing clasts. The hardpan protects the slope from erosion. However, where it has been breached, the underlying highly weathered materials are easily eroded.

REGOLITH AND LANDSCAPE EVOLUTION

Along the eastern margin of the ranges, the Mesozoic sediments of the Telephone Creek Formation typically dip to the east at about 20°–30°, but further to the east and in the west of the area the Mesozoic sediments are near flat-lying. The base of the Mesozoic sediments lies at a higher elevation in the west of the area than in the east (Figure 3). The easterly dip of the Devonian rocks increases to the east, reaching a maximum of about 50°–70° at the eastern margin of the ranges. The eastern slope of much of the ranges approximates the dipping Palaeozoic–Mesozoic unconformity, and lags interpreted to have been derived from the Mesozoic sediments overlie the more steeply dipping Devonian sandstone at varying elevations on the eastern slope of the ranges (Figure 3).

Reconstruction of the palaeogeology of the area immediately before deposition of the Telephone Creek Formation suggests that the Devonian sandstones dipped towards the east at up to about 30° and formed an undulating area (Figure 4a). The Mesozoic sediments were subsequently deposited, burying the older Precambrian and Devonian rocks (Figure 4b). Studies of cross-bedding show that palaeocurrents were from the south (Neef *et al*., 1995), indicating a north-flowing drainage.

At some time after Mesozoic sedimentation, reverse movements along the northwest-dipping fault system at the northwest margin of the Bancannia Trough resulted in monoclinal folding of the Devonian and Mesozoic rocks (Figure 4c). This steepened dips in the Devonian sediments nearby to the fault system, and deformed the previously flat lying Mesozoic sediments to form a topographic high west of the fault. The presence of dipping silcrete beds within the Mesozoic sediment, some with inclined columnar structures oriented normal to bedding, suggest that some beds in the sediment had been silicified at depth prior to deformation. A new drainage system developed normal to the uplifted zone, and differential erosion of the mostly poorly cemented Mesozoic sediment resulted in exhumation of the Devonian rocks along the uplifted area, forming the modern range (Figure 4d). Further erosion of less well-cemented rocks in the Devonian sequence has resulted in the present day cuesta strike ridges of the range. Minor movements along north- to northeast-trending faults emanating from bends in the main fault planes appear to have influenced the distribution of alluvial plains over part of the Bancannia Trough (Figure 2).

During erosion of the Mesozoic sediments in the early Tertiary, the valley of a palaeodrainage line eroded down onto Neoproterozoic bedrock and was then partially filled with sediment, which included leaves of the local flora. This sediment was subsequently silicified, and is now preserved as a single silcrete body with plant fossils, west of the ranges. More recent development of regolith includes the deposition of coalescing low-angle alluvial fans over the Bancannia Trough, the formation of the hardpans on slopes below silcrete, limited deposition of aeolian sand, widespread deposition of aeolian dust, and the development of partitioned soils with regolith carbonate, which may be in part aeolian-derived. The top silty layer of alluvium exposed in gully banks, sometimes attributed to deposition since European settlement, has been shown to be up to 5 000 years old (Wakelin-King, 2000).

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TEILTA, WESTERN NEW SOUTH WALES

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INTRODUCTION

The Teilta area contains regolith and landforms typical of many of the low relief and transported regolith-dominated landscapes of south-eastern central Australia. Although knowledge of the underlying bedrock is limited, it is interpreted to include highly prospective Palaeo-Proterozoic Willyama Supergroup lithologies associated with a possible northwestern extension of the Broken Hill and Euriowie blocks (Cameron, 1993a and b). The knowledge of the regolith materials and their landscape evolution context are therefore very important for mineral exploration programs here, and for understanding mineral exploration approaches in areas with transported regolith types.

PHYSICAL SETTINGS

Location

The Teilta area conforms to the area of the Teilta 1:100 k scale mapsheet. Teilta is named after an abandoned homestead now incorporated into Avenel Station, approximately 120 kilometres north-northwest of Broken Hill. The area extends from the western margins of the Barrier Range and flanking sheetwash-dominated gibber plains, through to the Strzelecki Desert dunefields as far west as the NSW-SA border.

Geology

Mineral exploration drilling and geophysics have interpreted the underlying bedrock to include the Palaeo-Proterozoic Willyama Supergroup and Neo-Proterozoic Adelaidean metasediments and metavolcanics (Cameron, 1993a and b). Relatively little is known about the bedrock geology here because transported regolith materials extend across most of the landscape. To the east, Neoproterozoic Adelaidean bedrock is extensively exposed within the northwestern parts of Barrier Ranges. Quartzite exposures further west at Bull Hill, and previously undescribed exposures near Teilta and Joulnie homesteads are probably Adelaidean metasediments. Pelitic metasediments (phyllites) occur in some creek exposures in the central south (e.g. south of Teilta homestead), and are possibly from the Paragon Group of the Palaeo-Proterozoic Willyama Supergroup (Richard Barrett, NSW DMR, pers. comm., 2004).

The main structural feature of the area is the northern end of the N-S trending Mundi Mundi Fault. This structure subdivides the bedrock-dominated terrain to the east, from sheetwash and aeolian regolith-dominated landscapes to the west. Other structural lineaments can be detected from subdued range-fronts, rises and linear drainage patterns within the regolith-dominated terrain in the west, particularly along the western margins of the Woowoolahra Range, west and southwest of Teilta homestead (Figure 1). The western margins of the Woowoolahra Range are associated with a northerly continuation of the Kantappa Fault (Hill and Kohn, 1999). Between the Mundi Mundi Fault and the Woowoolahra Range regolith depths have been drilled up to 60 m, whereas west of the Woowoolahra Range they have been drilled to up to 178 m (Cameron 1993a and b).

BHP Minerals conducted the most detailed mineral exploration in the area for Cu-Au and Ag-Pb-Zn mineralisation during the early 1990s (Cameron, 1993a and b). Their approach was to initially define regional aeromagnetic targets from regional Bureau of Mineral Resources data and then conduct more detailed, low level aeromagnetic and radiometric surveys and grided ground surveys. Limited drilling (including RC and diamond drilling) tested some of the magnetic targets. Assays of basement and the basement-'overburden' interface had low base metal contents over moderate to wide intervals (Cameron 1993a and b).

The area is within the southeastern parts of the Mesozoic Eromanga Basin (Krieg and Rogers, 1995) and the Cainozoic Lake Eyre Basin (Alley, 1998). The Mesozoic Eromanga Basin sediments in this area mostly include marginal and shallow marine sediments. Although extensive towards the northwest of the area, their surface expression is poor due to aeolian dunefield cover or shallow gibber surface lags associated with surficial sheetwash sediments. In the northeast near Floods Creek and near Tarango Tank in the south, silicified fossil wood fragments derived from Mesozoic sediments are a component of surface gibber lags. The Lake Eyre Basin sediments in the area include the transported regolith materials described here. The most prominent of the older sediments from this basin are silicified, rounded and polished quartzose gravels and sands equivalent to the Palaeogene Eyre Formation.

Geomorphology

The area contains a variety of landscape types representative of large parts of western NSW. The western margins of the Barrier Ranges form the most prominent landscape feature in the east of the area. The highest point here is at Mt Westwood and adjacent peaks, which rise to about 240 m above sea level. A lower, N-S trending ridge of rises and low hills of the northern part of the Woowoolahra Range extend through the central-southern parts of the area south of Joulnie homestead (Kenny, 1934). The central parts of the area are dominated by alluvial and sheetwash sediment plains covered with gibber. These plains extend westwards from the Barrier Ranges and east and west from the

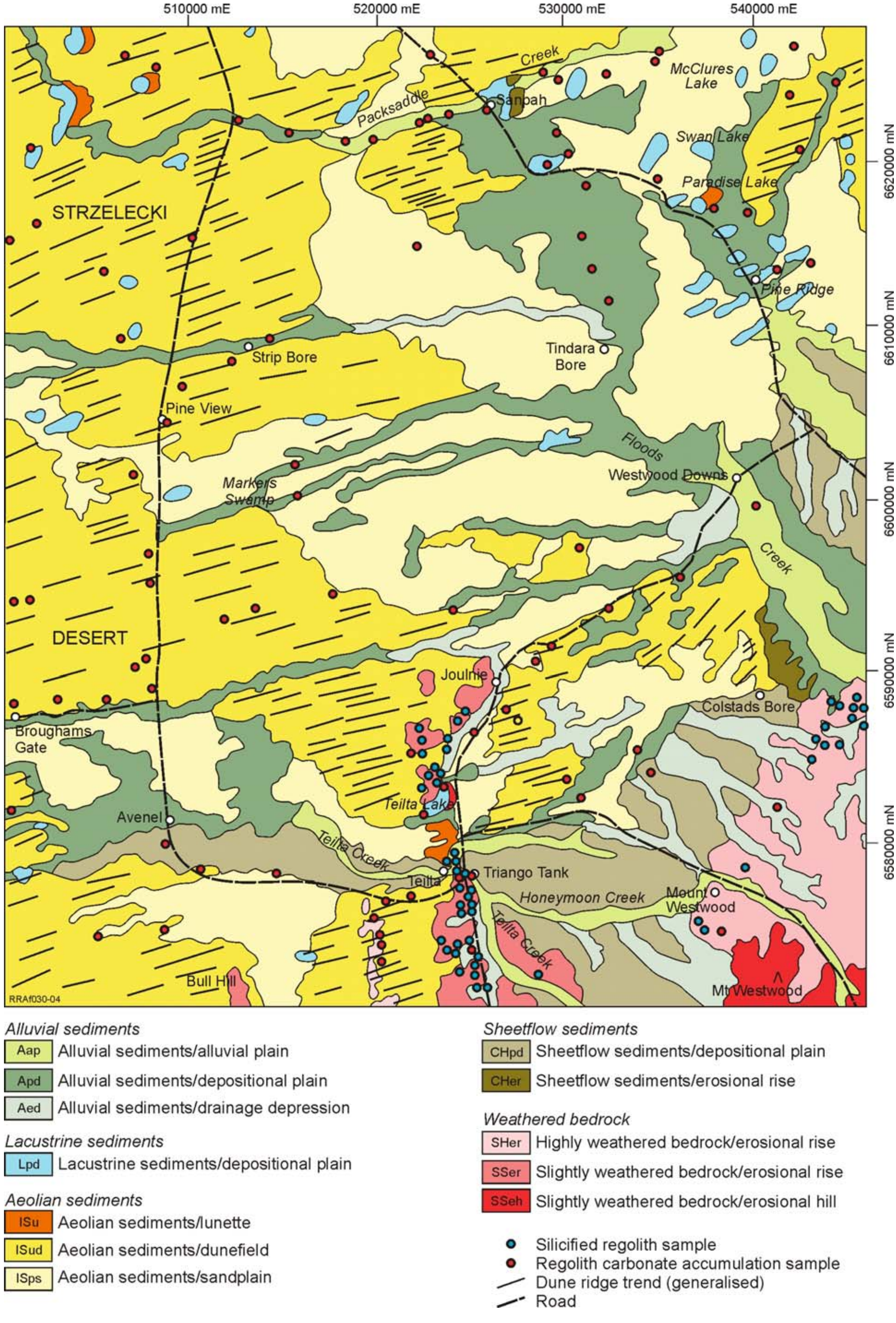

Figure 1. Simplified regolith-landform map of Teilta 1:100,000 sheet area.

margins of the Woowoolahra Range. A linear dunefield, with minor alluvial outwash swamps and lakes, and playas, of the Strzelecki Desert occurs the west. Bull Hill forms a bedrock-dominated, low hill rising above the dunefield in the southwest. The lowest parts of the study area are within playa depressions in the northwest, at approximately 50 m above sea level.

Drainage systems mostly extend from the western margins of the Barrier Ranges and flow west, terminating in alluvial swamps and lacustrine depressions within the Strzelecki Desert dunefield. Major drainage systems include Packsaddle Creek in the north of the area; Floods Creek in the central parts of the area; and, Honeymoon and Teilta creeks in the south (Figure 1).

Climate

The nearest meteorological station is at Broken Hill. The region has a semi-arid climate, with warm to hot summers and cool winters, and an erratic and generally low, annual rainfall. The average annual rainfall for Stephens Creek Reservoir is 220 mm, with average maximum and minimum temperatures of 32.7^o C and 18.1^o C in summer (January) and 15.5^o C and 3.8^o C in winter (July) (Bureau of Meteorology, 2003). Teilta occurs close to the transition between winter-dominated seasonal rainfall to the south and summer-dominated seasonal rainfall to the north. Rainfall is expected to be slightly lower than that of Broken Hill and maximum temperatures slightly higher. In summer, winds are mostly from the S and SE. South and SE winds also prevail in autumn but tend to be of moderate velocity, with stronger winds originating from the N and W. Strong winds predominate in winter and mostly come from the N and S. Generally moderate to strong winds originate from all directions in spring.

Vegetation

The vegetation communities are very closely associated with the major landform settings. The general characteristics include:

- Barrier Ranges hills and rises are mostly colonised by chenopod shrublands dominated by saltbush (*Atriplex spp.*) and bluebush (*Maireana spp.*), with some areas of open woodland with mulga (*Acacia aneura*), belah (*Casuarina pauper*) and rosewood (*Alectryon oleofolius*) trees. Major drainage channels host a river red gum (*Eucalyptus camaldulensis*) riparian woodland, and smaller streams are colonised by small trees of prickly wattle (*Acacia victoriae*).
- Colluvial and alluvial outwash plains are mostly colonised by barley mitchell grass (*Astrebla pectinata*) grasslands and chenpod shrublands dominated by saltbush (*Atriplex spp.*) and bluebush (*Maireana spp.*). Major drainage channels host river red gum (*Eucalyptus camaldulensis*) riparian woodlands in the south (e.g. Honeymoon Creek), while to the north (e.g. Floods Creek) they also include coolabah (*Eucalyptus microtheca*), beefwood (*Grevillea striata*) and river coobah (*Acacia stenophylla*) trees.
- Aeolian dunefields include open woodlands dominated by white cypress pine (*Callitris columellaris*) and belah (*Casuarina pauper*), with some mulga (*Acacia aneura*) and rosewood (*Alectryon oleofolius*) trees. Aeolian sandplains are mostly colonised by shrublands dominated by hopbush (*Dodonaea spp.*). Drainage channels and alluvial swamps within the dunefields host riparian woodlands dominated by black box (*Eucalyptus largiflorens*) and occasional river red gum (*Eucalyptus camaldulensis*) and beefwood (*Grevillea striata*) trees. Playas within the dunes are sparsely vegetated with their fringes hosting chenopod shrublands typically dominated by samphire (*Arthrocnemum halocnemoides*).

REGOLITH-LANDFORM RELATIONSHIPS

Weathered Bedrock

Weathered bedrock is mostly buried by transported regolith within the area. The main exposures are associated with hills, rises and erosional plains of the Barrier Ranges in the southeast. Minor weathered bedrock exposures occur on the flanks of rises and within drainage depressions in the Woowoolahra Range (Figure 2), and at Bull Hill. Bedrock lithologies more resistant to weathering and erosion (such as quartzites) are most prominently expressed in the landscape as hills and rises, whereas more labile lithologies are buried or exposed within deeply incised drainage depressions.

Alluvial Sediments

Alluvial sediments associated with contemporary drainage systems include channels, swamps, depositional plains, and drainage depressions. Most of the drainage systems flow from east to west, terminating in alluvial swamps and lacustrine depressions within the Strzelecki Desert.

Silicified, quartzose alluvial sediments cap the crests of erosional rises in the central and northeastern parts of the area (Figure 3). Most exposures of these sediments are topographically inverted from their original low-lying valley settings to now occur on rise crests. Palaeocurrent direction indicators are poorly preserved in these sediments, however some cross-bedding measurements, as well as the field context of the sediments and the gradient of basal unconformities, suggest that they were mostly part of drainage systems that generally flowed towards the west and northwest.

Colluvial Sediments

The most dominant colluvial sediment type forms broad plains with shallow overland flow, including sheetwash. These extend westward from the Barrier Ranges as well as eastwards and westwards from the Woowoolahra Range. A large, multi-lobed, sheetflow fan extends westward for about 15 km from near Mount Westward homestead to Triango Tank, east of Teilta Homestead. The sheetflow fans have a distinctive 'contour band' surface pattern defined by pebbly bands with sparse vegetation cover

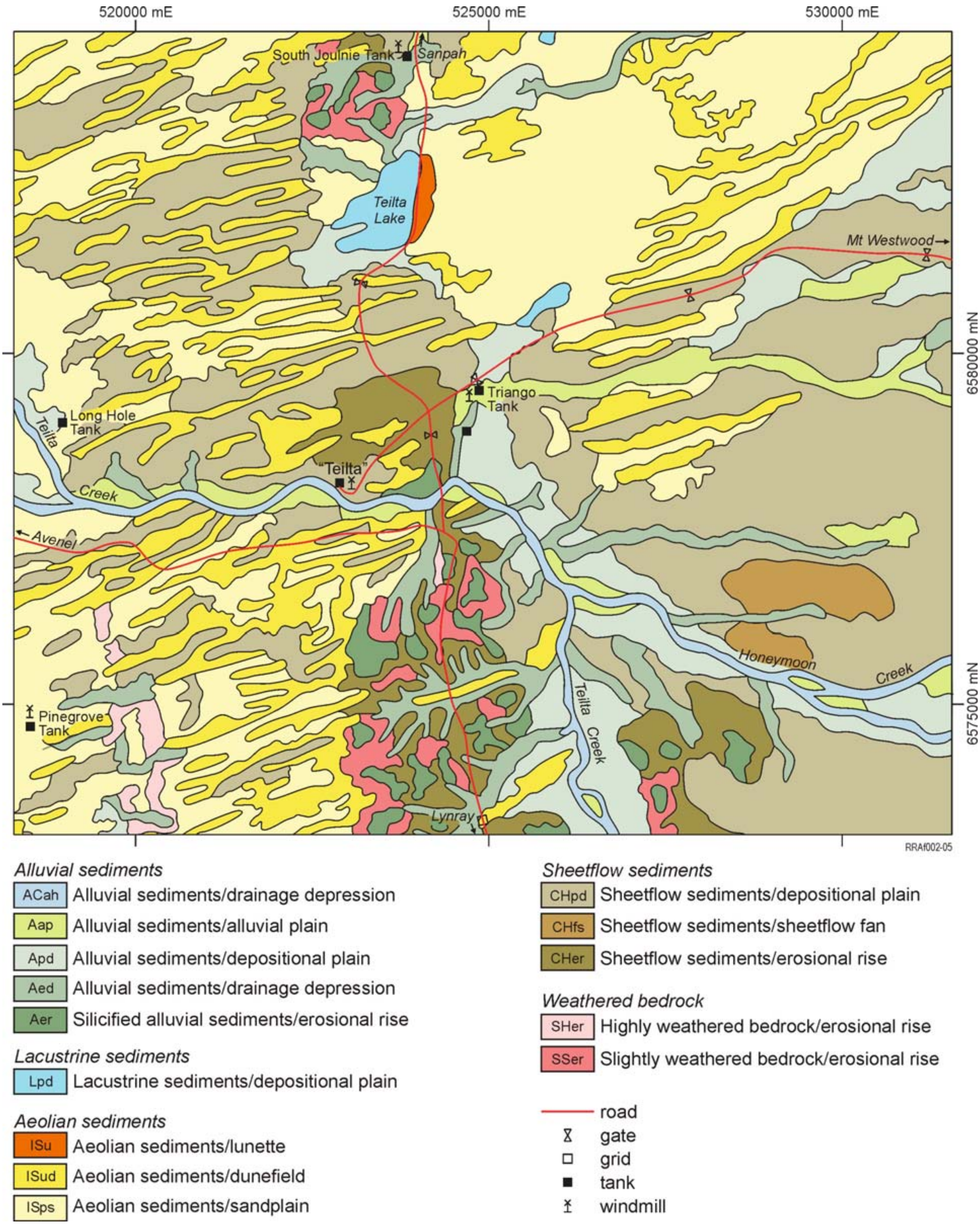

Figure 2. Detailed regolith-landform map of the Teilta homestead area.

a)

d)

b)

e)

c)

f)

Figure 3. Photographs of regolith-landform features of the Teilta area. **a)** slightly weathered bedrock exposure on erosional rise otherwise dominated by sheetflow sediments (AMG66: 526924mE / 6574424mN); **b)** lake shore and depositional plain of Paradise Lake (AMG66: 538618mE / 6615276mN); **c)** gibber plain with pebbles of silicified sediments. Gibber clasts are deposited by sheetflow within a depositional plain (AMG66: 544939mE / 6600427mN); **d)** topographically inverted silicified sediments exposed on an erosional rise (AMG66: 544007mE / 6584840mN); **e)** alluvial sediments associated with the Floods Creek depositional plain colonised by coolabah woodland near Tindara Bore (AMG66: 531679mE / 6607872mN); **f)** red brown sands within linear dunes of the Strzelecki Desert (AMG66: 509386mE / 6575775mN).

interspersed with more densely vegetated bands composed of red-brown sands and silts. Rises and low hills flanking the plains host more localised but steeper gradient sheetflow sediment transport. Minor creep and rockfall talus deposits flank erosional rises and hills, particularly in the southeast of the area.

Aeolian Sediments

Aeolian sediments are at least a minor component of surficial regolith, as well as dominating many landforms. Linear dunes within the Strzelecki Desert dunefield trend ENE-WSW across the western and northern parts of the area. Most dunes range from several metres to up to 10 – 20 m high, with most aeolian cover being less than 10 –20 m thick (with underlying materials exposed in many dune swales). The eastern margins of the dunefield and some areas flanking drainage channels consist of aeolian sandplains. These represent former extensions of the dunefield that have been reworked by overbank flow, such as along the outwash margins of Teilta Creek west of the Woowoolahra Range. Lunettes are crescentic, transverse dunes that have mostly formed on the eastern margins of lacustrine depressions, in particular near Sanpah homestead and at Paradise Lake.

Lacustrine Sediments

Numerous playas and lakes occur mostly within the north and west. The two main types include: 1) irregular-shaped and sparsely-vegetated playas, mostly isolated from drainage channels, particularly in the far northwest; and, 2) round, circular and oval-shaped swamps and lacustrine depressions typically flanked by black box (*Eucalyptus largiflorens*) trees, and associated with alluvial channels and outwash swamps. The playas receive only localised surface water inputs as well as groundwater discharge, whereas the swamps and lacustrine depressions mostly receive surface water inputs associated with major drainage channels. The underlying bedrock structure and lithology influences the development of some lacustrine depressions, such as at Teilta Lake which is largely constrained by exposures of resistant quartzites on its western margins. Lakes in the northeast, such as McClures Lake, Swan Lake and Paradise Lake occur along a northern extrapolation of the Mundi Mundi Fault, suggesting the possibility of underlying structural controls.

Silicified Regolith

Silicified regolith occurs as small pods up to several 10s of metres wide, capping erosional rises and erosional plains composed of ancient alluvial sediments. The most prominent exposures occur along the Woowoolahra Range and within rises in the southeast between Mount Westwood homestead and the channel of Floods Creek to the north. As discussed earlier, these materials had a former landscape expression associated with palaeovalley systems that have since been topographically inverted.

Ferruginous Regolith

Ferruginous regolith is mostly associated with ferruginised saprolite exposed on the flanks of erosional rises typically consisting of shale units within the Adelaidean metasediments. It is not widespread in the area, but is most typically exposed in the southeast within the Barrier Ranges. Ferruginised Mesozoic sediments also occur along the margins of rises in the Woowoolahra Range.

Regolith Carbonate Accumulations (RCAs)

Nodular and powder RCAs occur within linear dunefields and sandplains in the west, especially where they have been incised by major alluvial channels and drainage depressions. These RCAs are interpreted as pedogenic RCAs. Minor hardpan coatings are associated with weathered bedrock and silicified regolith interfaces on erosional rises in the southeast of the area and within the Woowoolahra Range. These RCAs form from soil water ponding along hydromorphic boundaries. Low mounds of massive, tabular accumulations are associated with some lacustrine depositional plains, particularly in the northeast of the area, such as at McClures Lake and east of Sanpah homestead. This type of RCA is interpreted as forming from palaeo-groundwater discharge and evaporation within lakes.

Gypseous Regolith

Gypseous regolith typically underlies alluvial depositional plains, particularly overlying weathered bedrock near drainage constrictions such as near Teilta, and exposed in drainage depressions and excavated station tanks (e.g. Tarango Tank). Near Teilta homestead, polycrystalline gypsum aggregates have indurated up to 3 m of alluvial sediments overlying weathered bedrock. Minor gypsum aggregates are also typically associated with many exposures of ferruginised Mesozoic siltstone, suggesting that the weathering of sulphides (such as pyrite) is at least a local chemical source for gypsum in some cases. Silt-size gypsum crystals are also associated with playa floors and flanking lunettes (kopi) in the northwest.

Halite-Rich Regolith

Halite is mostly associated with irregularly shaped playas in the northwest, and as efflorescence along the banks of many channels and drainage depressions. This is most notable along the banks of Honeymoon Creek upstream of Mount Westwood homestead. In this case, saline waters have ponded upstream of the stream knickpoint defined by a locally resistant Adelaidean quartzite unit trending transverse to the drainage channels and the alluvial plain. Patches of dead river red gums at this site suggest that this saline ponding is a relatively recent development.

REGOLITH CHARACTERISATION

Weathered Bedrock

Highly weathered bedrock in this area consists of kaolin and quartz in many cases with ferruginous (hematite and goethite) induration. The preservation of primary bedrock fabrics such as quartz veins and schistosity are diagnostic features. Moderately weathered bedrock typically has some iron-oxide staining and kaolin. This is mostly associated with Adelaidean pellites in the southeast. Slightly weathered bedrock (saprock) is typically associated with quartzite and quartz vein exposures, where very few of their primary minerals are weathered, although joints and fractures may be slightly opened.

Alluvial Sediments

Alluvial sediments associated with contemporary alluvial systems include gravels, sands, silts and clays, with both lithic and quartzose clasts. More ancient alluvial sediments are composed of silicifed quartzose gravels and sands. The quartz clasts in these sediments consists of rounded milky vein quartz and clear metamorphic and igneous quartz.

Colluvial Sediments

Sheetwash sediments consist of red-brown quartzose sands and silts with either quartz-rich (vein quartz and silicified clasts) gravels, or a mixture of quartzose (mostly vein quartz) and lithic gravels. The mixed lithic gravel deposits mostly occur within the sheetflow fans extending westward from the Barrier Ranges. Gravel clasts are mostly angular to sub-rounded, although rounded clasts become more significant to the west, probably because of increased contributions from palaeo-sediments in the Woowoolahra Range, as well as increased transport distances from source areas, which are mostly to the east.

Aeolian Sediments

The aeolian sediments consist of a range of materials, largely depending upon their landscape setting. The linear dunefields and sandplains mostly consist of red-brown quartzose sands. The sands typically have a paler red-brown colour on sandplains, largely because of alluvial and sheetwash reworking which removes the ferruginous component. Lunnetes flanking playas mostly consist of gypsum and clays, whereas lunettes flanking round and oval-shaped lacustrine depressions mostly consist of white quartzose sand.

Lacustrine Sediments

The composition of lacustrine sediments relates to the type of lacustrine depression. Playas are mostly composed of halite, gypsum, kaolin, smectite, organic materials and quartz, whereas the lacustrine depressions associated with surface drainage systems consist of quartz and minor kaolin and organic materials.

Silicified Regolith

Silicified regolith mostly occurs within quartzose sands and gravels. The cementing material is dominated by micro-crystalline quartz and minor anatase and hematite. Silicification is mostly massive, although nodular and ‘glerp’ morphologies also occur. They are mostly a light grey colour, although near Teilta homestead, some are distinctively bluish. Assays of some of the bluish silicified sediments show Cu contents up to 60 ppm.

Ferruginous Regolith

Minor occurrences of ferruginous regolith include ferruginised saprolite composed of variable amounts of primary bedrock minerals with hematite and goethite. Many of these materials have variable base metal contents that may be relatively high compared with other regolith types in the area, largely reflecting the ability of these materials to act as trace metal repositories.

Regolith Carbonate Accumulations

These include calcite-rich nodules, powder and minor hardpan and tabular accumulations. Trace element contents are variable, and include Au contents up to 8 ppb.

Gypseous Regolith

Gypseous regolith mostly consists of polycrystalline accumulations in some cases up to 2.5 m thick. Inclusions of detrital clasts are rare, suggesting that rapid displacement is associated with their development.

DATING

There has not been any systematic regolith dating research undertaken in this area other than the determination of relative ages derived from field relationships.

REGOLITH EVOLUTION

Some of the key components of the regolith and landscape evolution of this area include:

- *Weathering of bedrock*: Likely to have a long history of formation with weathering profiles developed in bedrock underlying Mesozoic sediments, and the quartzose composition of Palaeogene sediments suggest a highly weathered landscape existed at least by the Mesozoic.
- *Mesozoic marine incursion*: This was likely to have been important for both drainage baselevels and climatic controls on landscape evolution. The deposition of Mesozoic sediments appears to have been locally controlled by the bedrock ridge of the Woowoolahra Range, with a local depocentre forming immediately to the east of the range. Many of these sediments were pyrite-rich, influencing the materials involved in later weathering reactions, where acid-sulphate conditions associated with the weathering of pyritic sediments may be important in the development of silicified

regolith materials facilitating Al removal and local concentration of silica (Hill, 2000).

- *Cainozoic tectonics*: This is linked with sedimentary basin and hinterland upland evolution. Importantly, even in areas with widespread transported regolith, some underlying basement structures have a landscape expression (such as linear lacustrine depressions and swamps and subdued range-fronts). Topographically inverted, Eyre Formation sediments covered most of the Woowoolahra Range in the Palaeogene, and tectonism along the Kantappa Fault is likely to facilitated subsequent base-level change and erosion.
- *The predominance of aeolian and sheetflow sediments in the contemporary landscape.* Interactions between these processes in the past means that the margins of dune fields where sandplains now occur have had a complex history of regolith development. This has included dune development and reworking by sheetwash processes. Although the cover from these two sediment types is widespread, it is not very deep (typically < 10 m), suggesting that buried bedrock may have some expression in the surficial landscape.

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SOME ISSUES AND CHALLENGES FOR REGOLITH-LANDFORM MAPPING WITH PARTICULAR REFERENCE TO THE BROKEN HILL REGION

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INTRODUCTION

Although a relatively new field of geoscience, regolith-landform mapping is beginning to be recognised and adopted as a valuable way of representing regolith materials and associated landforms. It is flexible and robust, and as such is able to combine a range of regolith and landscape attributes in multi-purpose maps but also provide a framework for special purpose maps and applications. The wide range of applications of these maps makes them especially valuable and popular, particularly for providing a framework and as a tool for mineral exploration, and landscape and environmental management and research.

A range of regolith and closely related maps are now being produced, in a wide range of landscapes, by an increasing range of geoscientists. As a result there is increasing scope for considerable variations, and in some cases inconsistencies, to occur between these maps. Some of the reasons for this may be that many regolith geoscientists have had little training or equivalent experience in this field, plus there are relatively few detailed and specific guidelines for regolith mapping that have been widely available. Although there are many exciting achievements and potential for regolith-landform mapping, some of its aspects typically challenge new regolith-landform geoscientists and users of these maps. Some of these challenges and issues are presented and discussed here, with particular reference to the regolith-landform mapping program that has evolved in the Broken Hill region within CRC LEME.

REGOLITH-LANDFORM MAPPING APPROACH

The regolith-landform mapping program in the Broken Hill region has used the Geoscience Australia Regolith-Landform Unit (RLU) approach (Pain *et al.* in prep.). This primarily represents units based on: (i) regolith materials; and (ii) landform expression. A standard set of alpha-numeric codes (using upper-case letters to represent regolith material, lower-case letters to represent landforms and subscript numbers to further subdivide RLUs) and polygon colours are used to represent the various RLUs on the map face (Pain *et al.* in prep.).

Further detailed unit and site-specific information is recorded in compilation notes and presented in reports or theses that accompany the maps, and in a distilled version within the text of the map's legend. The minimum amount of detailed information recorded for each field site and for each mapping unit includes descriptions of:

1. dominant regolith material;
2. dominant landform assemblage;
3. minor regolith and landform attributes (attributes too small to represent as distinct map units);
4. materials expressed at the landsurface (e.g. surface lags, soils, etc.)
5. the dominant vegetation community type and dominant species;
6. geohazards (such as erosion, anthropogenic land disturbance, rabbit warrens, etc.); and,
7. other attributes (such as photograph and sample numbers and any attributes not covered above).

Further details of this mapping approach at Broken Hill can be found in Hill (2002), Senior & Hill (2002) and Thomas *et al.* (2002).

MAPPING OBJECTIVES

It is important to have a clear appreciation of the objectives of the mapping program before regolith-landform mapping is commenced. Typical objectives may include multi-purpose or special purpose mapping and broad regional coverage or detailed local coverage. Mapping scale is discussed further below, and is closely linked with the overall objectives of the mapping.

Although interest and support for the regolith-landform mapping program in the Broken Hill region has so far mostly come from mineral exploration applications, the maps released are designed to not only meet these requirements but also to provide multi-purpose information. The multi-purpose mapping includes

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information that is of general interest to mineral explorers, and the range of data collected can also be used to produce special purpose maps specific to the needs of mineral explorers. Some special purpose applications of the regolith-landform maps relating to mineral exploration include: highlighting the distribution of specific sampling media such as regolith carbonate accumulations (RCAs); showing geochemical dispersion vectors; or presenting maps of regolith geochemistry. Similarly, for land management applications, these maps can be used to broadly delineate the nature of soil erosion, or local sedimentary depocentres that may be characterised by weed infestations and sediment burial, and are related to the distribution of rabbit burrows, or affect potential stocking rates, amongst many other things.

MAPPING SCALE CONSIDERATIONS

The scale of regolith-landform mapping mostly relates to the objectives of the mapping program. Regional scale maps best show broad patterns of regolith-landform assemblages that could be used to plan regional exploration programs, or decide upon the general approach of exploration programs (e.g. showing regolith- versus bedrock-dominated terrains; areas where drilling may be needed as opposed to surficial sampling, etc.). Detailed scale maps (at 1:25,000 scale or larger) are best able to show information relating to local dispersion pathways and the distribution of specific sampling media, and are ideal for use on the scale of most mineral exploration tenements in the Broken Hill region. Time and financial constrains are also a consideration for the choice of a suitable mapping scale. For example, although an extremely detailed map of a large area may be desirable, it would take considerable time and expense compared with regional scale mapping.

By influencing the detail that can be shown on a map face, the scale of the map also relates to the amount of heterogeneity or homogeneity of RLUs. Regional scale RLUs have greater heterogeneity and typical include an assemblage of several regolith and landform types, such as a particular toposequence. The compilation of maps at different scales therefore requires different approaches and ways of 'reading' the landscape. Table 1 shows the influence of mapping scale on the minimum size of mapping units and the resolution of polygon boundaries. For detailed scale maps, the density of polygons and field description sites across the landscape is generally greater than for regional scale maps. As a general guide, in the Broken Hill region field sites are taken along mapping traverses at intervals < 1 km for the production of 1:25,000 maps, whereas for 1:100,000 maps they are generally taken at intervals of < 5 km. This density of field sites also depends on the objectives and time constraints of the mapping, as well as the complexity and heterogeneity of regolith-landforms in particular areas. Ultimately however, all maps can only present a finite selection of an infinite number of possible observations. The challenge for the mapper is to best select the observation sites within the context of the objectives and constraints of the mapping program.

Table 1: Minimum recommended width of mapping polygons and cartographic precision of map unit boundaries at various scales.

Map Scale	Minimum width of mapping units if greater than 3 mm on map sheet	Line thickness at 0.3mm on the map sheet
1 : 500,000	1500 m	150 m
1 : 250,000	750 m	75 m
1 : 100,000	300 m	30 m
1 : 50,000	150 m	15 m
1 : 25,000	75 m	7.5 m
1 : 10,000	30 m	3 m

DESCRIPTIVE AND INTERPRETIVE MAPS

All regolith-landform maps are a constructed representation of the spatial pattern of regolith materials and associated landforms. Some mapping schemes however are strongly driven by interpretations. Typically, these interpretations are based on stratigraphical and chronological frameworks (e.g. Grimes 1984) and landscape evolution models (e.g. Anand *et al.* 1998). The validity of these approaches depends on the validity and reliability of the underlying interpretations.

The RLU approach has a degree of interpretation in its presentation. This is largely based on genetic interpretations for regolith materials and associated landforms. The potential problems with the interpretive basis for presentation have been greatly minimised in the more recent regolith-landform mapping in the Broken Hill region. This has been done by ensuring that the detailed legend descriptions keep interpretation to a minimum, therefore only using the interpretive presentation framework as a convenient and easy to read means of presentation. In particular, the legend descriptions should be free of repetition and direct translation of RLU codes, therefore making them somewhat independent of the interpretative label given. For example the regolith lithology of an IS unit should not be given in the legend as 'aeolian sands' but instead should describe the sediment lithology (e.g. colour, grain size and range, grain shape, composition. etc.). This also helps resolve the problem of units where the origin is uncertain, or if units include an even mixture of materials from different sources and a dominant material is not easily decided upon. If at a later date the interpreted polygon label is found to be incorrect then at least the RLU polygon and legend description should still stand.

Although standard definitions of regolith are widely cited (e.g. Taylor & Eggleton 2001, Eggleton 2001), putting them into practice is not always easy. For example, the exposures of the sediments associated with the Mesozoic sedimentary basins, particularly the marginal marine sediments of the Eromanga Basin, and to a lesser extent the Cainozoic sedimentary basins in western NSW, could be considered to be either bedrock or regolith. In the Tibooburra region these sediments have been mapped as 'saprolite' (S), with an unspecified weathering grade (Chamberlain & Hill 2002). Equivalent uncertainties also exist for Cainozoic volcanics in eastern Australia. Cainozoic basalts are considered as weathered bedrock and therefore could be mapped as saprolite or saprock with varying degrees of weathering (i.e. SS, SM or SH). They are also inherently a landscape feature and form in relation to the landscape. In many cases they are underlain by regolith units such as sub-basaltic gravels and weathering profiles. They could therefore be mapped as volcanic (V) regolith materials. Recent mapping in the upper Shoalhaven valley of southeastern NSW (Lewis *et al.* 2002), and student mapping exercises in the Cooma region of NSW, have shown Cainozoic basalt flows as Ver and Vep units with modifier numbers reflecting the degree of weathering.

Mappers and map readers need to also be aware of regolith mapping surrogates used both in their mapping and as the basis for later interpretations drawn from maps (Hill 1995). There is a risk of becoming entrenched in circular arguments if distribution patterns of landscape attributes are compared with regolith-landform map polygons. An example of this can be seen in some of the maps of Anand *et al.* (1997) where the underlying bedrock lithology was used as a basis for subdividing regolith units, yet this work uses mapping to support conclusions about the relationships between regolith materials and bedrock. Comparing regolith maps with vegetation, soil and remote sensing responses could have similar problems. As a general rule, surrogates can be a powerful tool and a great assistance to regolith mapping, but if not tested, acknowledged, or recognised they can limit the value of the mapping.

3D AND 4D REPRESENTATION

The traditional regolith-landform map is a graphical representation of observations and interpretations on a horizontal plane (a sheet of paper or a computer screen). In reality, however, regolith materials vary in at least three dimensions (4 if you consider temporal variations). It is a major challenge of regolith maps, and even geological maps, to present information beyond two-dimensions.

Regolith-landform maps have previously been able to show some three dimensional information by using cross sections, and presenting compilations of accessory data sets (such as drilling information, geophysics, 3D graphics of the regolith architecture), either on the map sheet or as derivative maps. Regolith-landform mapping representing the timeframe of the evolution of regolith and landscapes (4-dimensional mapping) has had little previous consideration. Recent work within CRC LEME at the University of Canberra has produced regolith-landform maps from over a 50 year period in the area of the Shoalhaven River Delta, south-eastern NSW (Christian & Hill 2002). The major limitation on being able to map 3D and 4D regolith information, however, is only in small part related to the possible methods of presentation. Instead, the difficulties in obtaining reliable data, in both the vertical scale and over the time scale of regolith and landscape evolution, are major limitations. The most reliable and useful maps are initially based on what can be directly described rather than what can be imagined or interpreted.

The subject of regolith mapping deals with material that extends from the fresh bedrock interface up to the landsurface. This may range from thicknesses of millimetres to 100's of metres. Two possible approaches for dealing with this material are therefore either from the 'top down' or the 'bottom up'. Many traditionally trained geologists are most interested and comfortable with a 'bottom up' approach to understanding and accounting for regolith. In this case the regolith is considered in the context of what is in many cases deeply buried bedrock and structures. The challenge for applying this approach to mapping the regolith across a map sheet area is the reliability and availability of information to compile the map. In contrast the RLU mapping approach is mostly a 'top down', where landforms are a strong basis for considering regolith materials. Some 3D information is gained by the topographic relief and cross-sections (typically in gullies, pits, drill holes or geophysics). The RLU approach is also flexible enough to show deeply buried regolith and bedrock geology information on derivative maps. The advantage of this approach is that:

- landform information required to define RLUs extends in infinite detail across the landscape;
- RLUs can be readily observed in the field and using remote sensing techniques; and,
- the presentation and understanding of landsurface and near surface settings can have important connections to more deeply buried features.

MAPPING REGOLITH IN BEDROCK-DOMINATED TERRAINS

Many people become confused about the concept of being to map regolith-landforms in areas that appear to be dominated by bedrock. In some cases they are at a loss to know what to do, while others may believe that regolith mapping need only show information from areas where bedrock is not exposed (i.e. just add detail to the sea of yellow around the islands of outcrop). The problems with showing regolith-related features on the same map sheet as detailed bedrock geology presentations include:

- the map sheet may be presenting too much information for clear presentation;
- the detail and nature of stratigraphic information traditionally used on bedrock geology maps may not be available for the regolith-dominated parts of the map sheet; and,
- the mapping representation may be inconsistent and in conflict across the map sheet.

In the Broken Hill region separate bedrock geology and regolith-landform maps have been produced for equivalent sheet areas. On the regolith-landform maps, bedrock-dominated terrains are represented by the weathering grade of the weathered bedrock (typically slightly weathered, moderately weathered or highly weathered) and the landform expression (typically erosional rises, hills, mountains and plains). The division of RLUs based on landform expression, and in some cases slope facets, is a successful way to further subdivide these units, especially if detailed topographical information is available. By viewing the bedrock geology and regolith-landform maps together, this provides flexible information that can form the basis for significant interpretations, such as bedrock lithological controls on regolith and landscape expression, and geochemical analyses of bedrock samples can be evaluated based on the weathering grade of bedrock exposures.

PERSONAL MAPPING STYLES

The presentation on a regolith-landform map sheet ultimately depends on how different people read, describe and interpret the regolith and its associated landscape. This will depend on many of the factors discussed above, although personal mapping style is also significant. Standard mapping schemes and mapping consistency, however, are ideal objectives. In reality there may be as many different styles of regolith mapping as there are regolith geoscientists. As the techniques and approaches evolve and become more standardised these differences may be minimised. Some of the main style differences that occur between regolith-landform geoscientists are outlined in Table 2.

CONCLUSIONS

Regolith-landform mapping has a lot to offer geoscience research and its applications, largely because of its ability and flexibility to represent regolith materials that are otherwise difficult to represent on more traditional geological maps. The approach to this mapping is an evolving process that will need to resolve the challenges of trying to represent regolith materials and associated landforms effectively and consistently.

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Table 2: Some typically encountered personal mapping styles

Mapping Style	Description	Advantages	Disadvantages
'complex wriggles'	Regolith polygon boundaries and shapes show great detail and irregularities	• may reflect true irregular nature of landscape • can appear detailed and thorough	• may extend beyond the detail of primary information and therefore become 'artistic'; • slow to compile and draft; • can reflect poor drafting technique
'sausage and donuts'	Regolith polygon boundaries and shapes are simple and smooth	• clear and simple presentation; • may show fundamental framework; • quick to compile and draft	• does not represent true inter-relationships and complexity of polygons
'lumpers'	Regolith heterogeneity grouped into single units	• clearly distilled representation of the landscape	• neglects important details and regolith complexity • may be too simple for scale of presentation
'splitters'	Regolith heterogeneity subdivided into multiple units	• represents detail and complexity of the landscape	• presentation may be difficult to read; • may be too detailed for scale of presentation
'idea driven explorer'	Organises mapping program to test ideas and hypotheses	• planned use of observations and descriptions; • May quickly develop an interpretive understanding	• may have closed mind and miss out on new discoveries
'blank minded explorer'	Enters mapping program with few pre-conceived ideas	• open mind for new discoveries	• may be more time consuming • may not develop any ideas

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THE REGOLITH-LANDFORMS OF SANDSTONE PADDOCK, FOWLERS GAP, WESTERN NSW

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INTRODUCTION

The Fowlers Gap Arid Zone Research Station is host to a wide range of regolith materials and associated landforms that have been developing since at least the Mesozoic (Gibson 1996, 2000, Jansen 2001). Many of these features are clearly expressed in the contemporary arid landscape and therefore provide an excellent venue for teaching the fundamentals of regolith-landform mapping and for developing models for regolith and landscape evolution.

Previous regolith-landform mapping of the area has only been conducted at 1:500,000 scale (Gibson & Wilford 1996). This provides a general representation of the area but does not intend to show the local-scale heterogeneity and complexity of many of its regolith and landforms. Beginning with Sandstone Paddock, the regolith-landforms of this area are being mapped at 1:25,000 scale. This mapping will provide more detail than the previous Land Systems maps over the station (Mabbutt 1972, 1973, Walker 1991) and the 1:500,000 regolith-landform map (Gibson & Wilford 1996, 1998). This will provide a useful landscape context for the many multi-disciplinary environmental and land management studies undertaken in the area, as well as providing a fundamental framework for developing regional regolith and landscape evolution models, both for academic objectives and for the development of regional mineral exploration models. The first results from this more detailed regolith-landform mapping program, presented here at 1:10,000 scale (Figure 1), have been completed during the course of Honours- and Masters-level regolith-landform mapping courses conducted during April and August 2003 by CRC LEME for the Minerals Council of Australia's Minerals Tertiary Education Council (MTEC). This is part of an ongoing and integrated regolith mapping teaching (Hill & Roach 2003, Roach 2003) and research program (when time permits).

SETTING

The Fowlers Gap Arid Zone Research Station is located in southeastern central Australia, 100 km NNE of Broken Hill. It extends across the northern Barrier Ranges and the margins of the Bancannia Basin to the east and the Lake Eyre Basin to the northwest. Sandstone Paddock is located in the northwest of the station, and extends across the uplands of the Barrier Ranges, mostly including the headwaters and gorge of Sandy Creek.

The oldest bedrock in the study area consists of Neoproterozoic Adelaidean metasediments of the Farnell Group (Cooper *et al*. 1978) that are mostly exposed in a N-S trending zone extending across the central parts of the paddock. These include moderately deformed, low-grade metamorphosed marine sediments including quartzite, phyllite, limestone and dolomite. Late Devonian Nundooka Sandstone of the Mulga Downs Group occurs in the east of the paddock and consists mostly of quartzose arenite with some kaolinitic finer-grained units (Beavis & Beavis 1984, Neef *et al*. 1995). Unconsolidated to weakly lithified Early Cretaceous fine sandstones and siltstones (Ward & Sullivan 1973) of the Telephone Creek Formation (Fisher 1997) have been identified in the west of the paddock (Gibson 1996, 1997, 2000) and to the east of the study area (Beavis & Beavis 1984, Fisher 1997) and are extrapolated to have extended across the entire area (Gibson 1997). Although there has been some confusion regarding either the Mesozoic or Tertiary stratigraphic context of many of the sediments in the area, a small area of silicified Tertiary fine sands are exposed south of Sandstone Tank (Ward *et al*. 1969, Greenwood *et al*. 1997). A mixture of Quaternary alluvial, colluvial and aeolian sediments have also accumulated within the area, particularly associated with broad valley systems (Mabbutt 1972, Chartres 1982a, b, 1985, Akpokodje 1987, Jansen 2001). The Adelaidean and Late Devonian bedrock are juxtaposed by the Nundooka Creek Fault, which forms a major SSE-NNW trending zone through the area. Another major N-S trending structure extends across the western parts of the paddock, and appears on the 1VD aeromagnetics.

The climate is predominantly dry with hot summers and mild winters (Bell 1972). A mean annual rainfall of 231 mm was recorded between 1966-1996, however, longer-term determinations including unofficial station records suggest that the mean annual rainfall since the 1880s is closer to 200 mm (Jansen 2001). Rainfall patterns are extremely variable and the station lies in the transitional zone between summer and winter rainfall dominance.

In: Roach I.C. ed. 2003. *Advances in Regolith*, pp. 193-200. CRC LEME.

The vegetation of the area mostly consistes of chenopod shrublands dominated by bladder salt-bush (*Atriplex vesicaria*) and copper-burrs (*Sclerolaena* spp.) across plains and rises, particularly in the west of the area, and mulga (*Acacia aneura*) and belah (*Casuarina pauper*) open woodland with a chenopod understorey across rises and hills in the east of the area. Riparian woodlands of river red gum (*Eucalyptus camaldulensis*) occur along the lower stretches of Sandy Creek Gorge. Tree cover has markedly declined over the post-settlement period for use in fences, firewood and drought-fodder (Jansen 2001).

The area has hosted pastoral grazing since the 1860s. Until 1949 it was part of the Corona Run, and since 1966 the University of NSW has run the area as an Arid Zone Research Station that includes some sheep, goat, and cattle grazing. Rabbits arrived in the region in 1885 and have been a very significant herbivore grazer since that time.

REGOLITH-LANDFORM UNITS

Regolith-landform units (RLUs) for mapping are assigned codes according to Pain *et al.* (in prep.). The main attributes recorded at individual field sites and within RLU descriptions include: regolith lithology; landform expression; surface material; minor attributes; vegetation community and dominant species; and, land management hazards (Hill 2002).

IN SITU REGOLITH

Slightly Weathered Bedrock (SS)

The slightly weathered bedrock of the area has developed from two main rock types: 1. Adelaidean metasediments; and, 2. Devonian sedimentary rocks. The slightly weathered bedrock is still relatively hard, and shows slight surficial ferruginous staining, cryptogam colonisation, and opening of fracture sets. The main landform assemblages, and resulting RLUs, are:

- erosional plains with less than 9 m topographic relief developed on both the weathered Adelaidean ($SSep_1$) and weathered Devonian ($SSep_2$) bedrock;
- erosional rises with 9 – 30 m topographic relief developed on the weathered Adelaidean ($SSer_1$) and weathered Devonian ($SSer_2$) bedrock;
- erosional low hills with 30-70 m topographic relief, developed on both the weathered Adelaidean ($SSel_1$) and weathered Devonian ($SSel_2$) bedrock.

Minor regolith materials associated with these RLUs include red-brown fine sand and silt, typically derived from aeolian additions or their local reworking by shallow overland flow. Minor hardpan and powdery regolith carbonate accumulations (RCAs) are locally developed, particularly associated with Devonian sandstones with minor calcareous components. These RLUs mostly support open woodlands dominated by mulga (*Acacia aneura*) and belah (*Casuarina pauper*) with a mixed understorey locally dominated by chenopods including bladder salt-bush (*Atriplex vesicaria*) and blue-bushes (*Maireana* spp.). Gully erosion is locally developed within these RLUs.

Moderately Weathered Bedrock (SM)

Moderately weathered bedrock has a limited landscape expression in the area, and is mostly confined to areas of relatively recent erosion in gullies or sheet eroded areas. Within Sandstone Paddock, areas of moderately weathered bedrock large enough to be mapped as RLUs at 1:25,000 scale are limited to materials derived from the weathering of Adelaidean bedrock in the far south and northwest of the area, and weathered Cretaceous sediments in the west of the paddock. The moderately weathered material is highly friable, and easily falls apart when kicked. Most of the weathered bedrock types were slates, where the slatey cleavage has now opened up, accounting for the weakness of this material. Many of the primary aluminosilicate minerals have been replaced by kaolin clays and may have a weak ferruginous staining and in many cases there is a well-developed cryptogam cover. More calcareous and dolomitic bedrock types show well-developed rillen-karren and surface dissolution features and powdery and minor hardpan regolith carbonate accumulations (Hill *et al.* 1999).

The landscape expression is typically quite subdued, and mostly forms erosional rises with 9–30 m topographic relief ($SMer_1$). Minor regolith materials associated with this RLU include red-brown fine sand and silt, typically derived from aeolian additions or their local reworking by shallow overland flow. This is colonised by open woodland dominated by mulga (*Acacia aneura*) and belah (*Casuarina pauper*) with a mixed understorey locally dominated by chenopods including bladder salt-bush (*Atriplex vesicaria*) and blue-bushes (*Maireana* spp.). Gully erosion is typically widely developed with this RLU.

TRANSPORTED REGOLITH

Alluvial Sediments (A)

Alluvial sediments are mostly associated with the channel and tributaries of Sandy Creek. The main landform assemblages and their associated materials include:

- Aap_1: red-brown, subrounded to subangular quartzose and lithic sands, gravels and silts, associated with a low relief landsurface containing a mixture of incised channels and smooth depositional surfaces. Vegetation cover is an open chenopod shrubland dominated by bladder salt-bush (*Atriplex vesicaria*) and blue-bushes (*Maireana* spp.), with minor prickly wattle (*Acacia victoriae*) and needlewood (*Hakea leucoptera*) trees.
- Apd_1: red-brown, subrounded to subangular quartzose and lithic sands, gravels and silts, associated with a smooth, low relief landsurface, typically associated with the depositional floodout of channels and drainage depressions. Vegetation cover is a chenopod shrubland dominated by blue-bushes (*Maireana* spp.).
- Aed_1: red-brown, subrounded to subangular quartzose and lithic sands, gravels and silts, with locally exposed slightly weathered bedrock, associated with incised channels and the immediately flanking gully slopes. Vegetation is typically a chenopod shrubland dominated by blue-bushes (*Maireana* spp.) and bladder saltbush (*Atriplex vesicaria*).
- Aep_1: rounded and minor angular quartzose sands and pebbles, with local concentrations of leaf, fruit and wood impressions, indurated by microcrystalline quartz and minor microcrystalline anatase and hematite, associated with exposures with low topographic relief locally shedding material into flanking sediments. Vegetation is a very sparse chenopod shrubland mostly dominated by bladder saltbush (*Atriplex vesicaria*).
- Aer_1: rounded and minor angular quartzose sands and pebbles, with local concentrations of leaf, fruit and wood impressions, indurated by microcrystalline quartz and minor microcrystalline anatase and hematite, associated with exposures with slight topographic relief, locally shedding material into flanking sediments. Vegetation is a very sparse chenopod shrubland mostly dominated by bladder saltbush (*Atriplex vesicaria*).

Aeolian Sediments

Aeolian sediments are a component of RLUs across the study area, however, in some cases the aeolian accumulations are extensive enough to be mappable in their own right at 1:25,000 scale. In these cases they typically consist of well-rounded and well-sorted, red-brown quartzose fine sand. The largest accumulations of these materials occur within sand plains ($ISps_1$) along the west-facing footslopes of erosional rises and low hills. These areas are typically colonised by an open woodland dominated by mulga (*Acacia aneura*) with a mixed understorey typically with an abundance of blue-bushes (*Maireana* spp.).

Colluvial Sediments (C and CH)

Colluvial sediments are a component of most RLUs in the area, however, for much of the area they are significant enough to form RLUs in their own right. Colluvial sediments, where the dominant sediment transport mechanism is by way of slope creep and rock fall, flank most prominent bedrock and indurated regolith exposures. They include:

- Cer_1: angular lithic (mostly quartzite) and quartzose gravels with minor red-brown quartzose sands, associated with areas of slight topographic relief. Vegetation is a chenopod shrubland dominated by bladder salt-bush (*Atriplex vesicaria*).
- Cer_2: angular gravels of silicified sediment clasts and angular to rounded quartzose gravels with minor red-brown quartzose sands, associated with areas of slight topographic relief. Vegetation is a chenopod shrubland dominated by bladder salt-bush (*Atriplex vesicaria*).

Shallow overland flow, dominated by sheetflow, is very prevalent across the area. This is responsible for the erosion and transport of sediment from the upper parts of the landscapes, such as erosional rises and plains, and their deposition in local depositional 'sinks' associated with depositional plains. The main erosional settings for these materials include:

- $CHer_1$: angular lithic (mostly quartzite) and quartzose gravels with minor red-brown quartzose sands, associated with areas of slight topographic relief, with prominent 'contour band' surface patterns, and locally shedding material into flanking sediments. Vegetation is a chenopod shrubland dominated by bladder salt-bush (*Atriplex vesicaria*).
- $CHer_2$: rounded quartzose gravels and angular silicified sediment gravels with minor red-brown quartzose sands, associated with areas of slight topographic relief, with prominent 'contour band'

surface patterns, and locally shedding material into flanking sediments. Vegetation is a chenopod shrubland dominated by bladder salt-bush (*Atriplex vesicaria*).

- $CHep_1$: rounded quartzose gravels and angular silicified sediment gravels with minor red-brown quartzose sands, associated with areas of low topographic relief, with prominent 'contour band' surface patterns, and locally shedding material into flanking sediments. Vegetation is a chenopod shrubland dominated by bladder salt-bush (*Atriplex vesicaria*).
- $CHep_2$: rounded quartzose gravels and angular silicified sediment gravels with minor red-brown quartzose sands, associated with areas of low topographic relief, with irregular 'contour band' and circular depressions typically about 10 m diameter, and locally shedding material into flanking sediments. Vegetation is a chenopod shrubland dominated by bladder salt-bush (*Atriplex vesicaria*).
- $CHed_1$: red-brown, subrounded to subangular, quartzose and lithic sands, gravels and silts, associated with elongate depressions, with irregular 'contour banding' surface patterns and numerous circular depressions typically of about 10 m diameter. Vegetation is typically a chenopod shrubland dominated by blue-bushes (*Maireana* spp.) and bladder saltbush (*Atriplex vesicaria*).

The main depositional settings include:

- $CHpd_1$: angular lithic (mostly quartzite) and quartzose gravels with minor red-brown quartzose sands, associated with areas of low topographic relief, with prominent 'contour band' surface patterns. Vegetation is a chenopod shrubland dominated by bladder salt-bush (*Atriplex vesicaria*) and minor blue-bushes (*Maireana* spp.).
- $CHpd_2$: rounded quartzose gravels and silicified sediment gravels with minor red-brown quartzose sands, associated with areas of low topographic relief, with prominent 'contour band' surface patterns. Vegetation is a chenopod shrubland dominated by bladder salt-bush (*Atriplex vesicaria*) and minor blue-bushes (*Maireana* spp.).
- $CHpd_3$: angular, mixed lithic, silicified sediments and quartzose gravels with minor red-brown quartzose sands, associated with areas of low topographic relief, with irregular 'contour band' surface patterns. Vegetation is a chenopod shrubland dominated by blue-bushes (*Maireana* spp.) and minor bladder salt-bush (*Atriplex vesicaria*).

INDURATED REGOLITH

Silicified Regolith

Massive, tabular pods of sediment mostly indurated by microcrystalline quartz. Aep_1 and Aer1 RLUs are indurated by microcrystalline quartz with minor ferruginisation and microcrystalline anatase induration. Minor silicification is also hosted by the moderately weathered Cretaceous sediments ($SMer_1$), with silicification being more complex and extensively exposed in the region outside of this mapping area (such as within the mesas immediately west of this area). The main morphological facies of silicified regolith include massive, tabular pods, preserving leaf, wood and seed impressions and sedimentary structures in the host material, such as graded and trough cross bedding. Minor columnar and nodular silicification morphologies also occur in the area.

Ferruginised Regolith

Ferruginisation is relatively restricted in this area. The main occurrences are associated with ferruginised saprolite, including a NNW-SSE trending zone of ferruginised weathered Adelaidean metasediments in the central west of the paddock, and ferruginised zones and beds within the weathered Cretaceous sediments. Variable hematite cement contents occur with the silicified sediments, particularly along the SW margins of the Aer1 RLU that hosts abundant plant fossils.

Regolith Carbonate Accumulations (RCAs)

Nodular, hardpan and powder RCA morphologies (Hill *et al.* 1999) are locally associated with Devonian sandstones ($SSel_1$, $SSer_1$, $SSep_1$), but are most extensive near areas of moderately weathered Adelaidean limestone and dolomite ($SMer_1$).

DISCUSSION: REGOLITH AND LANDSCAPE EVOLUTION MODEL

Previous studies have indicated several key components of the area's long-term regolith and landscape evolution that this study further illuminates.

Extrapolation and significance of sedimentary and indurated palaeo-landsurfaces

Regionally extensive palaeo-surfaces, indurated regolith ('duricrusts') and sedimentary units have been a major feature of previous long-term landscape evolution studies in the region. This study finds little to support many of the previous extrapolations across this area by previous workers, more specifically:

- Silicified regolith (duricrusts and silcretes) has been widely extrapolated and interpreted to be part of former low relief landsurfaces, such as mid-Tertiary landsurfaces including the Cordillo Surface (e.g., Mabbutt 1972, 1973, Neef *et al.* 1995). In contrast, the silicified regolith mapped in this area is associated with localised silicification within palaeo-valley systems that flowed between ridges of relatively resistant bedrock (discussed below);
- Extrapolation of Cretaceous sediments overtopping the northern Barrier Ranges, and thereby formerly extending across this area (Gibson 1996, 1997, 2000), is not supported by positive evidence in the area. Remnants of Cretaceous sediments occur in the western half and further to the west and to the east of the area. Although it may be argued that they have since been eroded away from across the entire area, the coarse-grained basal Early Cretaceous sediments described by Gibson (2000) suggest that uplands existed in this area during the Early Cretaceous, and may not have allowed for Cretaceous deposition across the entire ranges. Based on drilling logs and sedimentary sections, Jansen (2001) suggests that the Early Cretaceous depositional sequence thins from 201 m thick within the Bancannia Basin depocentre to < 70 m thick towards the Barrier Ranges. This continues to thin farther west, leaving the higher parts of the ranges (including the higher parts of Sandstone Paddock) exposed. As such, the presently higher parts of the northern Barrier Ranges may have formed part of a subaerial land-mass, perhaps a peninsula or archipelago, flanked by two structurally controlled, submerged sedimentary depocentres to the west and east.
- Early Tertiary Eyre Formation correlations in the area (e.g., Neef *et al.* 1995) cannot be substantiated. This is not only due to the major shortfallings in areas of proven Mesozoic sediments (particularly outside of this mapping area, as shown by Gibson 1996, 1997, 2000) but also within the mapping area where there are major lithological differences between the Early Tertiary Eyre Formation. This includes an abundance of well-rounded, well-sorted and highly polished pebbles at its basal beds (Alley 1998), and the Early Tertiary alluvial sediments from Sandstone Paddock that include a mixture of angular and rounded, and in parts, poorly-sorted pebbles. Chronologically these sediments may be equivalent, with the palaeosediments here possibly representing more proximal feeder channels into the Eyre Formation alluvial sediments of Lake Eyre Basin, constrained to the east and west by resistant sandstone and quartzite ridges.

Palaeodrainage and sedimentary history

From the palaeobotanical (Greenwood *et al.* 1997) and sedimentological descriptions, and mapping results presented, it is suggested that the Aer_1 and Aep_1 RLUs are associated with an Early Tertiary palaeo-drainage system. Trough cross-bedding indicates that palaeo-flow was towards the NNW. The western margins of these palaeo-valley sediments have been topographically inverted by erosion along the southern tributaries of Sandy Creek, upstream of Sandstone Tank, however, some exposures of similar fossiliferous, silicified sediments occur lower in the landscape further east. Many of these less elevated exposures of silicified sediments are partially covered by sheetflow sediments dominated by rounded quartzose pebbles, which are most likely derived from equivalent palaeo-valley sediments. This suggests that a major NNW flowing palaeo-drainage system extended through this area, across the present course of the main Sandy Creek channel. In the south of the paddock this closely corresponds with the position of the Nundooka Creek Fault Zone, suggesting that the Early Tertiary palaeo-drainage was strongly controlled by bedrock structure and locally constrained by strike ridges composed of relatively resistant bedrock. This entire interpretation is significant because it suggests that the E-W trending, transverse drainage system of Sandy Creek was initiated after the Early Tertiary, rather than during the Early Tertiary as suggested by Jansen (2001). It also suggests that much of the topographic relief and the strong bedrock lithological and structural controls were in place at least by the Early Tertiary.

The chronological and palaeo-environmental context for induration

The silicified palaeovalley sediments contain relatively intact Early Tertiary plant remains. The silicification must therefore post-date the Early Tertiary deposition. The preservation of delicate leaf remains suggests that silicification may have closely followed deposition. This is consistent with silicification having taken place in the Early to Mid-Tertiary. Although this may be chronologically equivalent to the ‘Cordillo Silcretes’ of the Lake Eyre Basin, as discussed earlier the silicification here is more closely associated with a palaeo-valley system rather than a regional extensive low-relief landsurface (i.e., the ‘Cordillo Surface’). The Eocene plant assemblage reflected in the fossil remains suggests that the climate at the time of sedimentation was wetter than the contemporary climate. The abundance of water and organic remains in the sediments may have had a significant influence on silicification, such as providing acidic conditions suitable for the leaching and subsequent removal of Al, the local mobilisation of Ti to form the microcrystalline anatase, and the precipitation of Si-compounds.

Bedrock and structural controls on landscape development

The relief and drainage evolution of the area strongly reflects local bedrock lithologies and structural trends, such as that shown by the trellis drainage pattern in the Sandy Creek gorge area. The thickly bedded coarse-grained Devonian sandstones are very resistant to weathering and erosion in the area of the gorge, and further west the Adelaidean quartzites similarly form elongate ridges of low hills and rises. Jansen (2001) suggests that the nature of the cement is important in explaining the landscape expression of the Devonian sedimentary rocks, with rocks with siliceous cement being more resistant to weathering and erosion than those with kaolinitic cements. The Nundooka Creek Fault is also an important structural control, with differential weathering and erosion having outweighed any possible post-Early Cretaceous vertical tectonic displacement (Gibson 2000, Jansen 2001).

CONCLUSIONS

It is hoped that a continuation of this teaching and mapping program will allow some of these research findings to be further developed. This program has already promoted the skills and importance of regolith-landform mapping to course participants, and it is intended that it will also make important contributions to the knowledge of regolith and landscape evolution in this area and be of use to other researchers and land users in the area.

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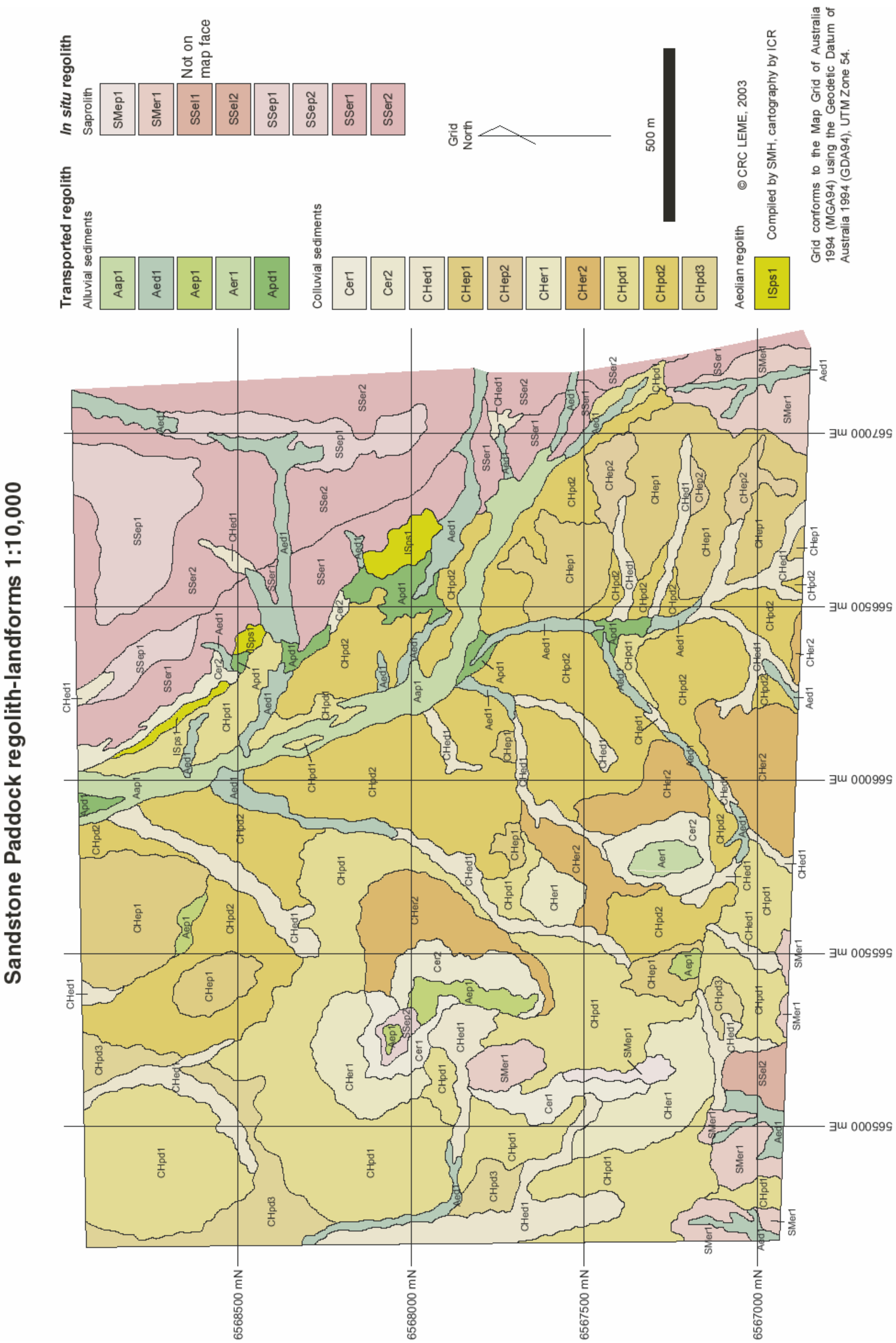

Figure 1: 1:10,000 Regolith-landform map of part of Sandstone Paddock, Fowlers Gap (not to scale).

REGOLITH-LANDFORMS OF NORTHERN LAKE PADDOCK, FOWLERS GAP ARID ZONE RESEARCH STATION, WESTERN NSW

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INTRODUCTION

The northern part of the Lake Paddock at the University of New South Wales' Fowlers Gap Arid Zone Research Station (Fowlers Gap) (Figure 1) contains a diversity of regolith materials and associated landforms that represent some of the significant processes in the regolith and landscape evolution of this part of the Barrier Ranges, western NSW. This landscape is the culmination of the interaction between many different landscape controls such as bedrock lithology and structure, Cainozoic tectonism, climate change and Mesozoic eustacy. This manuscript provides an account of the regolith and landforms of the northern Lake Paddock area, as well as outlining some of the aspects of the broader northern Barrier Ranges regolith and landscape evolution that can be determined from this area.

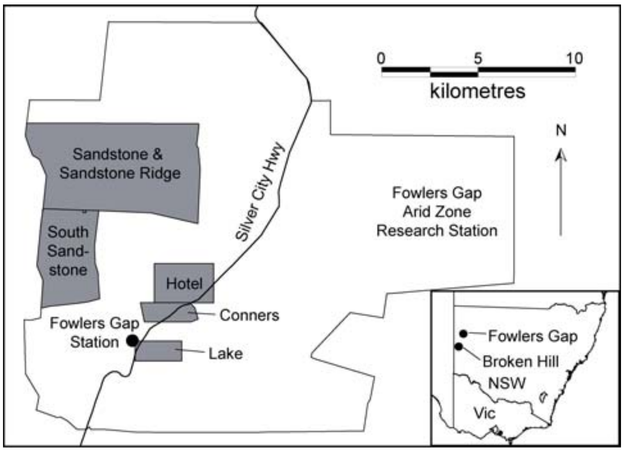

Figure 1: Location map of the Fowlers Gap Arid Zone Research Station. Boundaries of the Station and paddocks mapped to date (greyed-out) are shown. Lake Paddock is indicated in the south of the Station.

SETTING

The study area is approximately 2.3 km x 1 km, along the northern edge of Lake Paddock (Figure 1, 3). The homestead buildings of Fowlers Gap Station are just beyond the northwestern corner of the study area, which makes access to the study site within easy walking distance. The study area includes part of the channel of Fowlers Creek in its northwestern corner. The remainder of the area is dominated by rises and low hills of the Barrier Range (culminating in the 'Lake Ridge' in the east), with minor erosional and depositional plains, particularly in the west of the area. The Silver City Highway passes through the western edge of the area and station tracks traverse other parts, mostly along the NNW-SSE trending ridge crests.

Geology

The bedrock geology of the area was mapped by Cooper *et al.* (1975) and is dominated by Adelaidean metasediments including quartzite, shales, dolomitic shales and minor dolomite of the Caloola Synclinorial Zone. These have been included within the Fowlers Gap Formation, which includes thick beds of massive quartzite, underlain by the Faraway Hills Quartzite and the Sturts Meadows Siltstone. The Devonian Coco Range Sandstone (Neef *et al.* 1995) occurs in the far east of the area. The Adelaidean and Devonian are separated by the Nundooka Creek Fault, which trends NNW-SSE in the east of the area. Mesozoic fluvial and marginal marine gravels are interpreted as capping many of the rises in the far east of the area and are part of the basal units of the Telephone Creek Formation (Beavis & Beavis 1984), which is equivalent to sediments of the Eromanga Basin (possibly equivalent to parts of the Cadna-owie Formation and the Bulldog Shale). These include clasts of local bedrock (Adelaidean, Devonian) plus medium-high grade metamorphic rocks (schists, gneisses) that are presumed to be derived from the Palaeoproterozoic, transported from the Euriowie Inlier or possibly parts of the Broken Hill Inlier further south. The Cainozoic geology units are described as a part of the transported regolith-landform units of this manuscript.

Vegetation

Chenopod shrublands dominated by bluebushes (*Maireana spp.*) and saltbushes (*Atriplex spp.)* extend across much of the study area through most of the regolith-landform units. Riparian woodlands are dominated by river red gums (*Eucalyptus camaldulensis*) along Fowlers Creek and the tributary flowing from the "Lake" reservoir—Gum Creek. Smaller streams (mapped here as drainage depressions) are mostly colonised by prickly wattle (*Acacia victoriae*) shrubs. A mallee shrubland-woodland dominated by curly mallee

(*Eucalyptus gillii*) occurs in the east of the study area. Slopes and upper drainage depressions are mostly colonised by belah (*Casuarina cristata*), dead finish (*Acacia tetragonophylla*) and rosewoods (*Alectryon oleifolium*) and quartzite ridges are dominated by mulga (*Acacia aneura*).

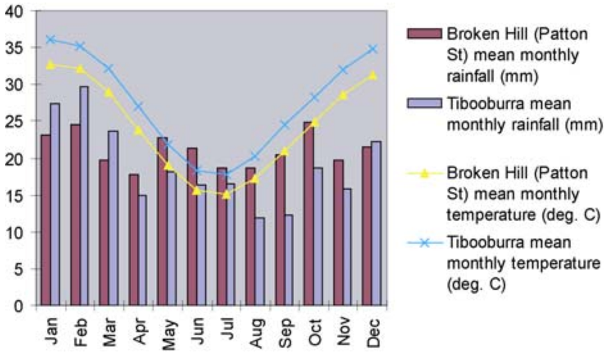

Figure 2: Climate averages for Broken Hill (Patton St) and Tibooburra. BOM (2005).

Climate
The climate at Fowlers Gap is semi-arid with average rainfall is ca. 220 mm, occurring principally as low frequency, high magnitude falls.

Landuse
The area has hosted pastoral grazing since the 1860s. Until 1949 it was a part of the 'Corona' run, and since 1966 the university of New South Wales has managed the area as an arid zone research station that includes some sheep, goat and cattle grazing. Rabbits arrived in the region in 1885 and have been a very significant herbivore grazer since that time.

MAPPING METHODS
The field mapping of this area was conducted as a part of an undergraduate regolith geology field trip jointly run within CRC LEME between the Australian National University and the University of Adelaide. This included two days of field mapping with one half day dedicated to biogeochemistry and soil sampling in the mapping area. To assist with the mapping a range of remote sensing data were used, including:

- A georectified aerial photo mosaic (Qascophoto 1981 1:10,000 colour infra-red aerial photos) (Figure 3);
- Landsat 5 TM;
- Radiometrics (NSW DPI Koonenberry version 1 dataset);
- First Vertical Derivative (1VD) aeromagnetics (NSW DPI Koonenberry version 1 dataset);
- Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) bands 3N21 image;
- Topographic map (Fowlers Gap 1:25,000) and Digital Elevation Model (DEM, developed from 5 m contours of the Fowlers Gap 1:25,000 topographic sheet and Shuttle Radar Topography mission—SRTM—90 m pixels); and,
- Torowangee-Fowlers Gap 1:100,000 geology sheet (Cooper *et al.* 1975).

Students mapped onto the aerial photo mosaic basemap and used the geophysical and remotely-sensed images to compare and contrast different regolith materials in their different landscape settings. Students worked in groups, each also being issued with a GPS receiver to more accurately record their observations for each regolith-landform unit (RLU).

RESULTS: REGOLITH-LANDFORMS
A total of 24 RLUs have been mapped and described from the area (Figure 4). The polygon codes and presentation style is compatible with the Geoscience Australia RTMAP scheme (Pain *et al.* in press), as this provides a universally applicable mapping standard for regolith materials and landforms and has been shown to be adaptable to a range of applications including landscape research, mineral exploration frameworks and land management. The RLU nomenclature scheme applied to this area is based on the scheme developed for the Sandstone and Sandstone Ridge Paddocks 1:25,000 regolith-landform map (Hill & Roach 2005), based on earlier work by Hill & Roach (2003). Note that not all of the same RLUs appear on this map, therefore RLUs may not be numbered sequentially.

TRANSPORTED REGOLITH

Alluvial Sediments
Alluvial sediments are mostly associated with the channel and tributaries of Fowlers Creek and Gum Creek, with minor occurrences in small pools and levees along alluvial depressions.

Aap1: Red-brown clays and silts and sub-rounded to sub-angular quartzose and lithic sands, granules, pebbles and cobbles associated with a low-relief, relatively smooth land surface with some minor incised channels. Vegetation consists of a chenopod shrubland dominated by bladder saltbush (*Atriplex vesicaria*), bluebushes (*Maireana* spp., principally *M. pyramidata*), prickly wattle (*Acacia* *victoriae*), belah (*Casuarina cristata*) on the east, forbs and grasses. River red gum (*Eucalyptus camaldulensis*) also occurs adjacent to Aap1 on Gum Creek.

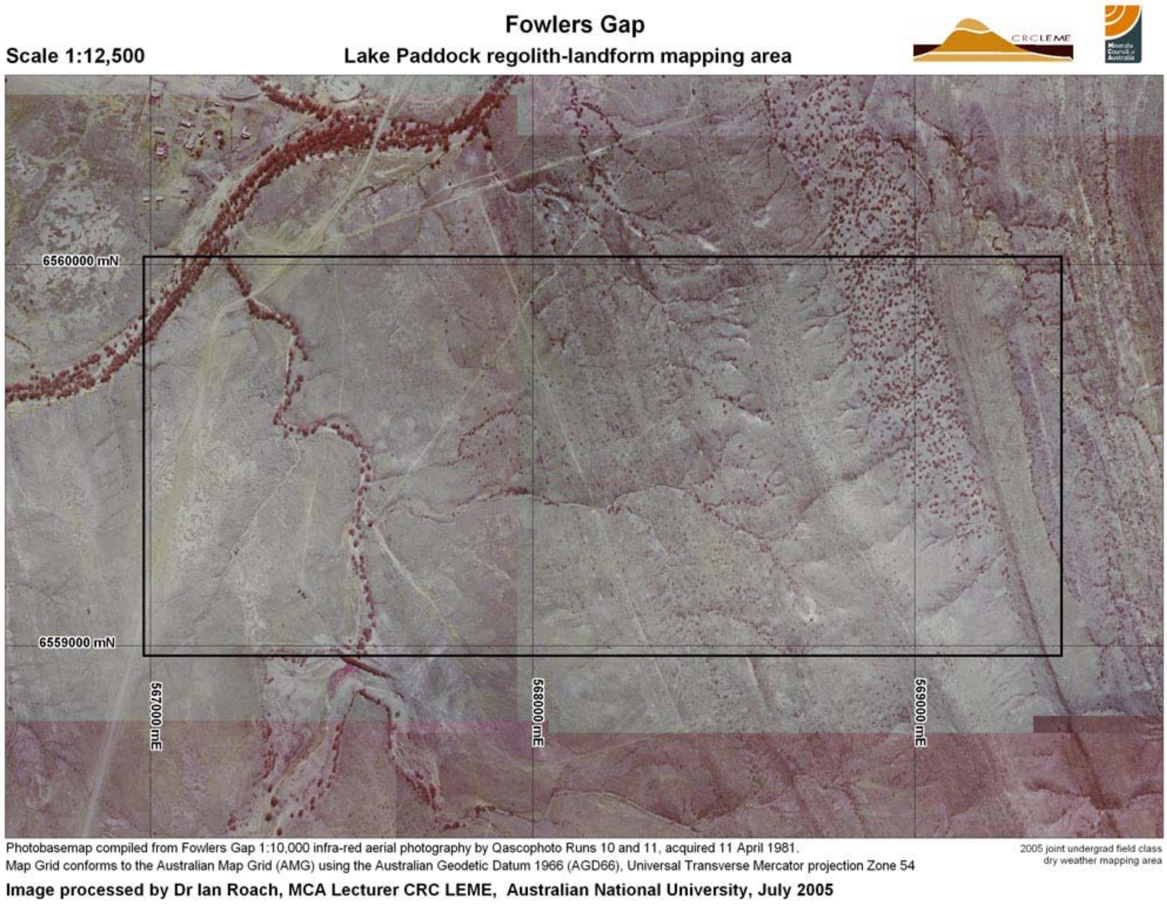

Figure 3: photo mosaic basemap.

Aaw2: Red-brown clayey and silty sediments associated with "The Lake". Fringed by a riparian woodland of river red gum (*Eucalyptus camaldulensis*), with an understorey consisting of chenopods, predominantly bladder saltbush (*Atriplex vesicaria*) and bluebushes (*Maireana* spp., principally *M. pyramidata*), forbs and grasses.

ACah1: Red-brown silts and sub-rounded to sub-angular quartzose and lithic sands, granules, pebbles and cobbles in channels and chutes incised < 3 m into the surrounding land surface. Vegetation in the channel of Fowlers Creek and Gum Creek is dominated by a riparian woodland consisting of river red gum (*Eucalyptus camaldulensis*), prickly wattle (*Acacia victoriae*) and some boobiala (*Myoporum montanum*) with an understorey consisting of chenopods including bladder saltbush (*Atriplex vesicaria*), bluebushes (*Maireana* spp., principally *M. pyramidata* and *M. astrotricha* but also some *M. sedifolia*), thorny saltbush (*Rhagodia spinescens*), emubushes (*Eremophila ssp.*), forbs and grasses.

Aed1: Red-brown silts and sub-rounded to sub-angular quartzose and lithic sands, gravels, pebbles and cobbles with locally exposed weathered bedrock in incised channels and gullies. Vegetation consists of rare river red gum (*Eucalyptus camaldulensis*) in the lower reaches, prickly wattle (*Acacia victoriae*) and dead finish (*Acacia tetragonophylla*) in the central to upper reaches and belah (*Casuarina cristata*) and rosewood (*Alectryon oleifolius*) in the upper reaches. A ubiquitous chenopod shrubland includes bladder saltbush (*Atriplex vesicaria*), black bluebush (*Maireana pyramidata*), southern bluebush (*M. astrotricha*), pearl bluebush (*M. sedifolia*) and rare old man saltbush (*Atriplex nummularia*). Lemon-scented grass (*Cymbopogon ambiguus*) and groundsel (*Senecio sp.*) are common within and immediately adjacent to channels, plus forbs and grasses.

Apd1: Red-brown, subrounded to subangular quartzose and lithic sands, granules and silts associated with smooth, low relief landforms (< 9 m), typically associated with intersection point floodouts of alluvial channels and drainage depressions. Colonised by chenopod shrublands dominated by *Maireana spp*., *Atriplex spp.,* and *Sclerolaena spp*., with *Xanthum spp.*

Colluvial Sediments

Cel1: Weakly ferruginised angular, blocky quartzite rubble of coarse sand to cobble size with minor red-brown fines sand and silt associated with the edges of a high relief quartzite ridge. Vegetation consists of scattered belah (*Casuarina cristata*) on the lower slope and mulga (*Acacia aneura*) on the upper slope, chenopod shrubland (principally pearl bluebush *Maireana sedifolia*), forbs and grasses.

Cep1: Angular lithic (mostly quartzite) and quartzose granules with minor red-brown quartzose sands, associated with areas of low topographic relief (< 9 m). Colonised by chenopod shrublands dominated by *Atriplex vesicaria*.

Cer1: Angular lithic (mostly quartzite) and quartzose gravels with minor red-brown quartzose sands, associated with areas of slight topographic relief (9-30 m). Colonised by chenopod shrublands dominated by *Atriplex vesicaria*.

Sheetwash Sediments

CHep1: Angular lithic and quartzose gravels and red-brown quartzose sands on a low-relief (< 9 m), low gradient landform with shallow bedrock sub-crop that is locally shedding sediment. Colonised by open chenopod shrublands dominated by *Atriplex vesicaria, Maireana spp.* and grasses.

CHep2: Rounded and minor sub-angular quartzose and silicified sediment clast gravels and red-brown quartzose sands on a low-relief (< 9 m), low gradient landform that is locally shedding sediment. Colonised by open chenopod shrublands dominated by *Atriplex vesicaria*.

CHep4: Rounded to minor sub-angular quartzose, silicified sediment clast gravels and red-brown quartzose sands on a low-relief (< 9 m), low gradient landform with shallow bedrock sub-crop that is locally shedding sediment. Colonised by open chenopod shrublands dominated by *Atriplex vesicaria,* and *Maireana spp.* and occasional *Casuarina pauper* trees.

CHer1: Angular lithic and quartzose gravels and red-brown quartzose sands on a moderate-relief (9-30 m), moderate gradient landform with shallow bedrock sub-crop that is locally shedding sediment. Colonised by open chenopod shrublands dominated by *Atriplex vesicaria* and *Maireana spp*.

CHer4: Rounded to minor sub-angular quartzose, silicified sediment clast gravels and red-brown quartzose sands on a moderate-relief (9-30 m), moderate gradient landform with shallow bedrock sub-crop that is locally shedding sediment. Colonised by open chenopod shrublands dominated by *Atriplex vesicaria* and *Maireana spp.* and occasional *Casuarina pauper* trees.

CHpd1: Angular lithic (mostly quartzite) and quartzose gravels with minor red-brown quartzose sands associated with areas of low topographic relief (< 9 m) with prominent 'contour band' surface lag patterns. Colonised by chenopod shrublands dominated by *Atriplex vesicaria* and *Maireana spp.*

IN SITU REGOLITH

Slightly Weathered Bedrock

SSel1: Outcrop and angular float of weakly ferruginised Adelaidean quartzite, clasts ranging from coarse sand to boulder size, with minor red-brown fine sand and silt in a high relief landform. Dominant vegetation consists of mulga (*Acacia aneura*), chenopod shrubland, dominated by pearl bluebush (*Marieana sedifolia*) and minor ruby saltbush (*Enchylaena tomemtosa*) plus forbs and grasses.

SSep1: Outcrop and angular float of weakly ferruginised quartzite, clasts ranging from coarse sand to boulders, with minor red-brown fine sand and silt in a low relief landform. Vegetation consists of belah (*Casuarina cristata*) and rosewood (*Alectryon oleifolium*) with chenopod shrubland, forbs and grasses.

SSer1: Blocky, weakly ferruginised Adelaidean quartzite outcrop with angular lithic lag up to cobble size and minor red-brown fine sand and silt on a moderate relief landform. Vegetation consists of western boobialla (*Pittosporum spp.*), prickly wattle (*Acacia victoriae*), chenopods, forbs and grasses.

SSer2: Weakly ferruginised Adelaidean quartzite and interbedded green dolomitic shale outcrop with angular lithic lag up to pebble size and minor red-brown fine sand and silt on a moderate relief landform. Hardpan RCA is associated with the shale, coating joint surfaces and the soil-saprolite interface. Dominant vegetation consists of mulga (*Acacia aneura*) and chenopod shrubland, principally bluebush (*Maireana spp.*), grasses and forbs.

Moderately Weathered Bedrock

SMep1: Kaolinitic, ferruginous quartzose and micaceous shales with minor quartz veins, sandstones and dolomite. Low-relief landform (< 9 m) associated with angular gravel surface lags. Sparsely colonised chenopod shrublands typically dominated by *Atriplex vesicaria* and *Sclerolaena spp.* with occasional *Casuarina pauper* trees.

SMep3: Kaolinitic and dolomitic shales with minor quartz veins and dolomite. Abundant powder and hardpan (fracture fill and bedrock interface) regolith carbonates. Low-relief landform (< 9 m) associated with angular gravel surface lags. Sparsely colonised chenopod shrublands typically dominated by *Eucalyptus gillii*, *Maireana spp.* and *Sclerolaena spp.* with occasional *Casuarina pauper* trees.

SMer1: Kaolinitic, ferruginous quartzose and micaceous shales with minor quartz veins, sandstones and dolomite. Moderate-relief landform (9-30 m) associated with angular gravel surface lags. Sparsely colonised chenopod shrublands typically dominated by *Atriplex vesicaria* and *Sclerolaena spp.* with occasional *Casuarina pauper* trees.

Highly Weathered Bedrock

SHer1: Kaolinitic, highly ferruginous sandstones and micaceous shales with minor quartz veins, sandstones and dolomite. Moderate-relief landform (9-30 m) associated with angular pebbly and granule surface lags. Sparsely colonised chenopod shrublands typically dominated by *Atriplex vesicaria* and *Sclerolaena spp.* with *Casuarina pauper* trees.

INDURATED REGOLITH

Ferruginised regolith

The occurrences of ferruginised regolith in the area are mostly restricted to ferruginised saprolite exposures along the eastern footslope of 'Lake Ridge'. Hematitic saprolite derived from the weathering of a fine sandstone and adjacent shales conforms with the strike of the weathered metasediments. This suggests that there is a strong lithological control on the occurrences of these materials, probably due to the weathering of sulphides in the original sedimentary rocks. Minor, rounded maghemite pebbles occur within the CHep2 RLUs flanking Fowlers Creek in the east of the area.

Regolith carbonate accumulations (RCAs)

Hardpan and powdery RCA morphologies are associated with the Adelaidean dolomitic shales (SSer1, SSer2, Aed1) and Devonian sandstones (SSer2) in the mapping area. Hardpan carbonates also occur as bedrock fracture fill and coating the hydromorphic boundary along the bedrock/transported regolith interface.

DISCUSSION: REGOLITH AND LANDSCAPE EVOLUTION

Lithological Controls

Bedrock lithology and structure has a major influence on the expression of regolith and landforms in the area. The positive relief along strike ridges associated with Adelaidean quartzite is most prominent in the area. The structural-grain (mostly N-S trending) of the area also has a major influence on the drainage pattern of lower order stream tributaries in the area. In contrast, larger streams, such as Fowlers Creek, appear to cut across this structural grain and may reflect the inherited pattern of these streams derived from palaeodrainage. The mineralogy and chemical characteristics of bedrock lithologies also strongly influences the nature of regolith materials derived from different bedrock types. The ferruginous saprolite occurrences are likely to be mostly related to the presence of bedrock lithologies that previously contain sulphides, while regolith carbonates are most abundant overlying calcareous and dolomitic Adelaidean rocks.

Tectonic Controls

The Western Boundary Fault, and possibly the Nundooka Creek Fault, have facilitated active tectonism during the landscape evolution of the area. This is demonstrated along the range front associated with the Western Boundary Fault to the north of the area, where Mesozoic sediments have been tilted, and a series of stream terraces are closely associated with this fault system. This tectonism is related to the relative uplift of the Barrier Ranges and subsidence of the Lake Bancannia Basin area. Other than confidently ascribing this tectonism to post-Mesozoic times, further resolution of its timing is poorly constrained from this area. Strath terraces (here mapped as $CHep_2$ RLUs) flanking Fowlers Creek in the area represent a graded valley profile associated with relative drainage stability in the area. The incision that subsequently elevated these terraces extends upstream from the location of the Western Boundary Fault and therefore most likely reflects tectonic influences on drainage evolution in the area. The discovery of rare, rounded silcrete clasts that are lithologically similar to the Sandstone Tank silcretes (Hill & Roach 2003) suggest that these terraces post-date the late Eocene.

Climatic Controls

The area has experienced considerable climatic change since the Mesozoic. A detailed synthesis and study of this has so far not been undertaken in this study. Generally, one of the greatest climatic influences on the landscape evolution would be the increasing climatic aridity that developed towards the later part of the Cainozoic.

Eustatic Controls

For an intra-continental setting such as Fowlers Gap, it may at first seem surprising that changes in sea-level could have a significant influence of the region's regolith and landscape evolution. A major marine transgression and regression in the Cretaceous had a major influence on the regolith and landscape evolution of the area. The marine transgression towards shallow marine conditions in the east of the area is best expressed in the deposition and micro-fossil content of the Telephone Creek Beds, exposed along the Western Boundary Fault range front (Beavis & Beavis 1984, Gibson 2005). Rounded pebbles and boulders expressed on erosional plains capping rises (mapped here as $CHep_4$) underlie Telephone Creek Beds to the east and northeast of the area. These gravels contain a mixture of locally derived Adelaidean quartzite and Devonian sandstone, but also amphibolite and gneiss typical of Willyama Supergroup rocks, suggesting derivation from the south (Nundoo Inlier, Euriowie Block and possibly Broken Hill Block source). These gravels maybe basal fluvial and most probably cobble beach deposits associated with basin subsidence and marine transgression.

CONCLUSION

This relatively small area contains an important variety of easily accessible regolith-landform features that express some of the important regional features in the regolith and landscape evolution of the northern Barrier Ranges near Fowlers Gap.

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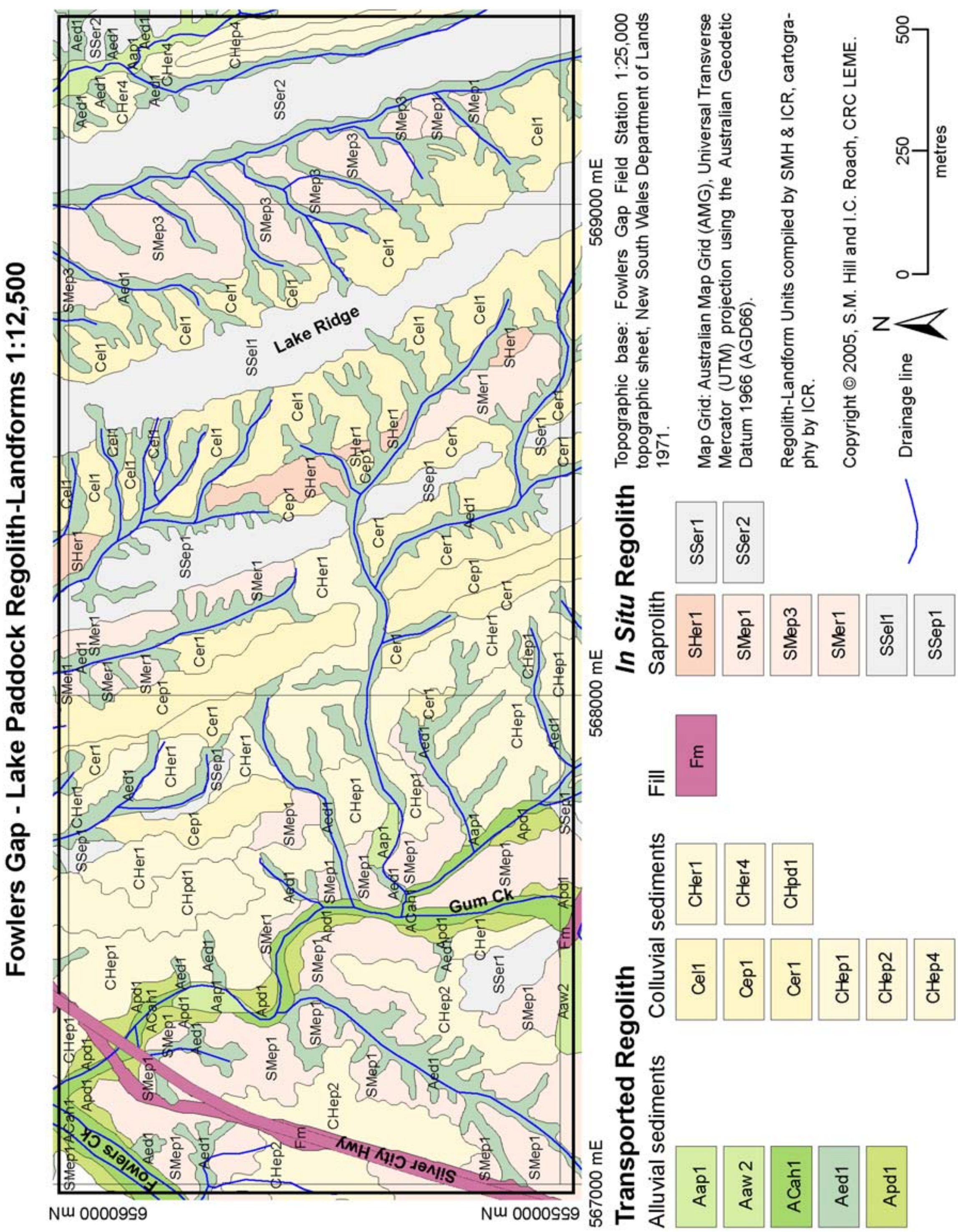

Figure 4: Lake Paddock regolith-landform map.

BRANCHING OUT INTO BIOGEOCHEMICAL SURVEYS: A GUIDE TO VEGETATION SAMPLING

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Biogeochemical surveys can provide a valuable insight into the dispersion pathways between regolith and vegetation within the landscape. Geochemical sampling surveys may involve the sampling of vegetative material, regolith and bedrock with the sampling process dependent on what the results are to be used for, and constraints on time and resources. This paper provides a guide to sampling vegetation and discusses some of the issues associated with it including contamination and developing a survey design. A robust and relatively easy method of vegetation sampling has also been included.

SURVEY DESIGN

Designing a sampling program will depend on the aims of the survey and the abundance of selected species. Sampling may be conducted along transects, within a grid, where target species are present (depending on vegetation density) or as a stratified random survey. As a guide, areas liable to contamination should be noted or avoided. Potential contaminants may include metallic objects, buildings, fences, power lines and roadways. Prior to sampling, a detailed geobotanical survey should be conducted. This will include recording vegetation cover, regolith material, landforms, geology and climatic conditions. Depending on the area to be sampled and the complexity of the surface expression, regolith-landform mapping along with detailed vegetation surveys may help to select suitable sampling media and sampling sites. Detailed vegetation surveys may include identifying taxon and recording its cover within a quadrat. As a guide, cover abundance can easily be recorded using the modified Braun-Blanquet scale (Table 1) where an abundance rating is allocated according to a subjective estimation of the percentage cover in the quadrat. The size of quadrats will depend on vegetation density (Cain 1938).

Table 1: Modified Braun-Banquet abundance ratings for geobotanical surveys, from Causton (1988).

Abundance	Braun-Blanquet rating
<1%	+
1 – 5%	1
5 – 25%	2
25 – 50%	3
50 – 75%	4
75 – 100%	5

WHAT TO SAMPLE

Selection of plants should be limited to species that are easy to identify, dominant and widespread. Plant uptake can vary according to a number of internal and external factors and so selected plant individuals must be of similar size, age and health so that results are comparable. As every species has different chemical compositions, nutrient requirements and tolerances, comparisons should only be made at the species level unless adequate knowledge of the plant's uptake strategies is known. In addition, each plant organ has a different capacity to store metals and, therefore, comparing the same plant tissue may be the only way to draw valid conclusions. Many researchers have found that above-ground vegetative material provides results that adequately reflect the elemental levels of the entire plant. Moreover, aerial tissues have the advantage of being easy to sample and less handling is required to tackle soil contamination issues. However, certain plants will store trace elements in root material that may be used effectively as an indicator of metalliferous ground.

Regardless of which plant tissues are targeted for sampling, care must be taken to ensure that selected plant organs have no obvious deformities (including presence of faunal products) or desiccation. Moreover, most nutrient concentrations are highest in younger tissues (Allen 1989, Ernst 1995) and so samples for the survey should be restricted to those of similar age and size. Some researchers have separated petioles and blades before analysis (Allen 1989), however, to keep sampling procedures simple bulk leaf samples may be taken. Certainly problems arise when sampling leaves; nutrient levels are reported to vary between sun and shade leaves and the crown position (Allen 1989, Salisbury & Ross 1992). Therefore, it is necessary to sample around the circumference of the plant to gain an estimate of the entire plant chemistry.

In: Roach I.C. ed. 2002. *Regolith and Landscapes in Eastern Australia*, pp. 50-53. CRC LEME.

HOW TO SAMPLE: A SUGGESTED METHOD

When sampling tree species, samples should be taken at a similar height (chest height is perhaps the easiest) and, along with shrubs, sampled at various points around the circumference of the plant to ensure a representative sample for the entire individual. The amount of sample taken needs to be enough for chemical analyses and also to be representative of the individual's chemistry. The optimum sample size is still debated between researchers but as a guide should be no less than 20 g.

The most important issue for sampling procedures is one of contamination. Plant material is especially open to contamination from a variety of sources and particular care is needed when sampling. Non-powdered latex gloves should be worn at all times when sampling and all jewellery (especially rings) must be removed during the sampling program. Teflon-coated pruning clippers are best used for sampling but should be cleaned regularly with distilled water. Where necessary, a clear or white plastic paint scraper can be used to help remove bark from tree trunks (Dunn *et al*. 1995). It is recommended that, if sampling aerial vegetation, samples be collected as whole branches. Twigs and leaves can be separated with greater ease after drying.

Once collected samples need to be stored. Plant material is likely to sweat and decompose if stored for a reasonably long period of time and this may cause some change in mineral composition. Storage of fresh material in polyethene bags in warm conditions for long periods of time has been known to encourage enzymic reactions which may lead to the breakdown of organic material (Allen 1989) and also volatilisation due to microbial activity. Therefore, it is suggested that samples be stored in brown paper bags. This allows the sample to air and keeps the sample out of direct light, avoiding mould development. Bags also need to be sealed. There are a number of different methods that may be used to seal the bags—folding the top of the bags twice for example. If needed, folds may be secured with staples although extra care needs to be taken to ensure that staples do not come into contact with sample material.

WHEN TO SAMPLE

Plants have different nutrient requirements depending on physiological activity. Therefore, their chemical composition will vary throughout the year and from year to year. This affects all living tissue within the plant (excludes bark and older tissues such as wood) and needs to be considered when sampling. For biogeochemical studies in the northern hemisphere sampling in springtime, when plants are most physiologically active, is often recommended (Allen 1989, MacNaeidhe 1995). However, in semi-arid and arid regions of Australia there is no distinct growing season. An optimum season for sampling has yet to be determined for these regions but care should be taken to ensure that sampling programs are conducted in as short a time as possible (over no more than 2-3 weeks depending on conditions and plant material). Some researchers have reported slight diurnal variations in elemental concentrations and recommend sampling during the mid-day period (Allen 1989). This is of course quite an uncomfortable proposition in semi-arid and arid environments. Instead it is important to ensure that the weather conditions are relatively constant throughout the entire time of sampling. Variations due to changes in weather have been noted in some studies (Markert 1995, Brooks 1998).

PRE-DIGESTION PROCEDURE AND STORAGE

The pre-digestion procedure may involve the washing, drying and grinding of samples depending on the method of digestion and chemical analysis. Washing of samples for biogeochemical analyses has been used to reduce the effects of locally- and distally-sourced soil contamination on vegetative materials. However, there are no defined rules for cleaning vegetative material and a great variety of cleaning methods have been reported in the literature. Washing with water (tap, deionised, distilled or ultrasonic washing), detergents and diluted acids are the most commonly used methods of cleaning. The efficiency of washing and its effect on plant tissues is difficult to assess and is likely to vary between plant species and tissues (Bargagli 1998, Markert 1995). The effect of washing is also effected by particle-size (i.e. submicron particles are difficult to wash off and may contribute significantly to trace metals levels, while larger particles (> 1 µm) are easily removed). Moreover aerosols from washing water may be absorbed or embedded in waxy outer layers, thus making washing ineffective. Washing may not be applied to some vegetative materials as it causes significant elemental loss from tissues (Bargagli 1998, Brooks 1998, MacNaeidhe 1995, Markert 1995). Clearly this is an area of sample preparation that requires more consideration, particularly its effect on Australian plant species.

Vegetation samples need to be dried to discourage the decomposition of material. Air-dried ground plant material can be stored for long periods of time at room temperature in well-ventilated conditions (Allen 1989). However, the effect of drying on the chemical composition of material needs to be considered. Drying the samples prior to digestion will lead to a significant loss of moisture that will almost certainly be accompanied by a slight loss of volatile constituents by chemical changes within the sample (Allen 1989). Although this is probably not significant for most species, it is suggested that samples not be dried for more than 48 hours. High temperature drying (above 80°C) for long periods is to be avoided because it causes significant loses in total weight, in volatiles or in charring. Elements that are readily oxidised, such as sulphur, boron and selenium, may be more susceptible to loss. Conversely, temperatures below 40°C won't halt metabolic activity and mould development that can alter elemental levels particularly if the samples are initially damp (Allen 1989, Bargagli 1998, MacNaeidhe 1995). It is suggested here that samples be dried in an oven for 48 hours at 60°C.

When dry, vegetation samples can be more easily separated into leaves and twigs and then, if a wet ashing digestion method is to be applied, ground to a fine (5 mm–63 µm) powder. The risk of contamination during grinding can be quite high, therefore, selecting the right pulveriser is crucial to the success of the survey. The chemical composition of the mill must taken into account. If a broad suite of trace elements is to be analysed then a zirconia mill may prove to be one of the best options for grinding. A Rocklabs™ Nilcra Poly-Stabilised Zirconia (PSZ) 100 g ring mill has been used successfully for biogeochemical surveys (Jones 1999, Senior 2000, Debenham 2000, Dann 2001, Hill *in prep*., Thomas *et al*. 2002) for rapid, fine grinding of material, particularly for moderately hard and brittle material such as twigs and bark. The PSZ mill represents a good trade-off between wear resistance and contamination, as it contains principally Zr, Mg and Hf but is quite wear-resistant. The optimum relation between particle size and sample weight is still debated between researchers but most agree that a particle size of 0.5 mm or less is acceptable (Allen 1989). Sample homogenisation is important to ensure that the sample used in analysis has the same mean chemistry as the sample collected in the field (Markert 1995). As such, care should be taken to ensure that the entire sample, including the final residue, is obtained from the mill. Samples should then be stored in well-sealed containers in the absence of light to reduce the intake of water vapour and avoid fungal infection.

ROOTING OUT POTENTIAL CONTAMINATION PROBLEMS

There is a broad range of contamination sources that may effect biogeochemical surveys. Some of those sources have already been mentioned: field equipment, skin and jewellery. Vegetative material may also be contaminated from the substrate either from aeolian particles or soil splash. Soil particles can become lodged in plant tissue and can be extremely difficult to remove. Interestingly, Allen (1989) notes that if a sample is contaminated by soil, potassium from plant tissues will readily bind to soil minerals, decreasing potassium levels in the vegetative sample. Identification of the presence of soil contamination (using chemical markers such as Ti) and its possible source can help deduce the effects of contamination on biogeochemical results. Other sources of contamination may include: animal droppings; films of insect products; wind blown fertilisers; smelting practices; metal contamination from nearby structures; and corroded sampling tools. Many of these contaminants can be avoided through careful sampling procedures and careful selection of sampling sites.

CONCLUSION

To obtain meaningful and comparable results it is important that sampling procedures and analyses are accurate, precise and representative. The sampling method described in this paper is by no means the only possible method of sampling vegetation and may simply be used as a guide to develop sampling procedures. It is important that sampling programs incorporate some attempt to constrain environmental factors such as regolith cover and climatic conditions, and that the sampling process is consistent.

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SOME IMPORTANT PLANT CHARACTERISTICS AND ASSAY OVERVIEWS FOR BIOGEOCHEMICAL SURVEYS IN WESTERN NEW SOUTH WALES

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INTRODUCTION

Plants are a significant component of regolith and landscapes across most terrestrial settings. Their use as mineral exploration and environmental chemistry sampling media has previously gained mixed support in Australian regolith studies, however they have numerous advantages for use due to:

- Widespread cover across the landscape;
- Easy access to samples that in many cases are easy to take;
- An ability to construct chemical pathways that penetrate regolith (especially transported cover) to the underlying bedrock;
- An ability to selectively extract and concentrate some elements;
- An ability to amalgamate a chemical signature from an enlarged sampling area (potentially achieving greater site representation and reducing potential problems with heterogeneous sample media, leading to 'nugget effects')
- Minimal site disturbance and remediation costs associated with sampling; and,
- Some proven exploration success for a wide range of elements, regolith-landform settings and mineralisation styles.

In recent years a small and emerging biogeochemistry research program has been undertaken in Western NSW. This data are now being compiled, and some preliminary results and background information are presented here. The research approach has been to target trees and shrubs that are widespread across the region, or else are locally significant to areas hosting regolith geochemistry case and pilot studies (Hill, 2003). Honours and PhD student research projects have been one of the main ways of accommodating this research, when greater funding and support has not been particularly forth-coming at the larger project level.

Unless otherwise stated, sampling and sample preparation are according to Hill (2002). Names and botanical descriptions are after Cunningham *et al.* (1992) and Ross (1996). Analytical suites and techniques are described in Appendix 1 at the end of this manuscript.

SPECIES INFORMATION - TREES

Mulga (*Acacia aneura* var. *aneura*)

Mulga is abundant and widespread, particularly in the northern half of the region. It is most abundant in well drained sites with neutral-acidic regolith, particularly associated with bedrock exposures on erosional hills and rises and aeolian sand plains. It is estimated to be 100-200 years old at maturity (Slatyer 1961). Juvenile trees are rare in the district, with most trees at maturity or senescence. Evidence from over-turned dead trees suggests that the root system is mostly shallow and branching. Two main habit forms occur in the region: a bushy; and, an elongate form, however both have ascending to near horizontal branches. Flowering and phyllode generation is generally determined by proximity to variable rainfall events.

A total of 59 mulga trees have been sampled from the region. Nine of these have included samples of phyllodes, twigs and bark analysed by ICP-MS[1] and INAA for Au from near Tibooburra (Hill in prep.). Near Broken Hill phyllode samples were taken from 17 trees in areas of ultramafic bedrock and adjacent Willyama Supergroup rocks (Hill & Barratt 2003) and from 33 trees from the Flying Doctor prospect (Thomas *et al.* 2002, Hill *et al.* 2003), and analysed by XRF and ICP-MS[2]. Phyllodes are generally easy to sample and detach from twigs relatively easily, although some trees without low branches can be difficult to reach. In general, the chemistry of the phyllodes and twigs is not significantly different. Biogeochemistry results typically provide a strong bedrock signature when growing on erosional rises and hills. Near Broken Hill, in sites where transported cover is thicker (e.g., up to 2 m of aeolian sediments), the phyllode chemistry tended to represent bedrock chemistry when growing near ultramafic rocks, rather than the overlying sediments (Barratt & Hill 2003).

In: Roach I.C. ed. *Advances in Regolith*, pp. 187-192. CRC LEME.

Prickly Wattle (*Acacia victoriae*)
The prickly wattle is one of the most widespread small trees – large bushes in the region, where it mostly grows in areas closely associated with alluvial regolith, such as along small channels and drainage depressions and across alluvial plains and floodout fans. It has a large tap-root that penetrates the regolith for depths of at least 3 metres (observed in gully sections), and it is generally short-lived (10-15 years, Cunningham *et al.* 1992). Although samples are generally easy to access, the spiny branches can make sampling very uncomfortable. Sampling by closing fingers around stems and running fingers down the stem avoids most prickles, although can tear sampling gloves.

62 prickly wattle phyllode samples were taken from the Flying Doctor prospect near Broken Hill, and assayed by XRF and ICP-MS[2] (Thomas *et al.* 2002, Hill *et al.* 2003). The results from this program were extremely exciting, suggesting that the trace metal biogeochemistry was more closely related to bedrock buried by shallow transported regolith, rather than to surface soils.

Bastard Mulga (*Acacia clivicola*)
Bastard Mulga is limited to the far north-west of the region. It is abundant on aeolian sand plains, but is also associated with bedrock exposures on erosional hills and rises, particularly those with silicified regolith. Flowering and phyllode generation is typically in spring-early summer. No information has been able to be obtained on the longevity of this species, although it is likely to be equivalent to the mulga.

24 individuals have been sampled at Tibooburra, with leaves and twigs analysed by ICP-MS[1] and INAA for Au (Hill in prep.). Twigs and phyllodes are generally easy to detach from the branches, however, they can be sticky and covered in ants. Although similarly named, the concentrations of trace metals in bastard mulga are generally lower than the mulga. The exceptions are Ni and Zn, which accumulate in relatively high concentrations in this plant. As with mulga, their restricted distribution on thick transported regolith makes it difficult to assess their ability to provide a bedrock signature from beneath the cover.

Cabbage Tree Wattle (*Acacia cana*)
The cabbage tree wattle is widespread in the northern half of the region, in particularly in the White Cliffs-Milparinka area, where it mostly grows across sheetwash plains and alluvial plains, and in some cases across erosional rises of weathered bedrock. They grow to 4 m high and have distinctive silvery-grey phyllodes and a gnarled, stunted habit which makes them easy to identify in the field. Phyllodes and twigs are difficult to detach from the branches without clippers, however, they can be removed by pulling branchlets upwards, towards the tree trunk. The tip of the phyllodes are sharp and care is needed to ensure that gloves and bags are not torn during the sampling process. A strong, festering 'cabbage-like' smell is produced from the leaves when they are drying, and can become quite unpleasant.

52 samples of phyllodes have been collected from the Milparinka-Kayrunnera region, and analysed by INAA (Au+31). These samples were taken to test a reported associated between these trees and elevated Se contents giving stock the staggers (McBarron 1977). Only one sample contained detectable Se (and also detectable Au), and this came from the vicinity of the Williams Peak Au-field.

Western Rosewood (*Alectryon oleifolius***)**
Western Rosewood is widespread and abundant throughout the region, most typically occurring in association with belah. It is generally associated with sandy soils containing regolith carbonates, but is rare on mid-slope settings. Leaves are olive-grey with a prominent vein and the habit is characteristically gnarled. Root systems appear to be very deep, exceeding 5 m in gully sections. Flowering and leaf generation is mostly in late spring-summer, with a high rate of leaf shedding in summer. Cyanogenetic foliage production is suspected in some instances following summer rains (Cunningham *et al.* 1992).

15 samples of leaves have been taken at Thackaringa, near Broken Hill (Hill 1998). Leaves were analysed by AAS and Flame Photometer. Leaves are generally easy to sample, however, individuals may be heavily infested with mistletoe and care is needed to ensure that only host material is collected. Biogeochemical results typically provide a strong bedrock signature, however, concentrations are relatively low for most trace elements including Cu, Fe, Zn, Mn and Pb when compared to mulga.

White Cypress Pine (*Callitris columellaris*)
White Cyress Pine is abundant in southern and eastern parts of the region, although it becomes less abundant in the Broken Hill region and the far north-west, although this is possibly due to timber harvesting. It is

typically associated with aeolian sand plains and dune fields and colluvial hills and rises, with rare occurrences on slightly weathered bedrock rises (e.g., Pyrite Hill, Thackaringa Station). Branchlets are typically aromatic and have a scaly texture. Flowering and leaf generation is generally in spring-early summer. It is a long-lived tree, although longevity data was not able to be obtained. Sampling is relatively easy, with branchlets and shoots easily ripped off by hand, although they appear to hold a considerable amount of dust and variable amounts of pollen in some cases.

Approximately 70 branchlet - shoot tip samples have been obtained from the dunefields of the Teilta 1:100k mapsheet area, and assayed using INAA (Au+31), ICP-MS[3] and ICP-OES. Results are yet to have been fully investigated.

Belah (*Casuarina pauper*)
Belah is common throughout the region, occurring as relatively dense woodlands in association with other tree species such as western rosewood to the south and as isolated clumps or individuals to the north. It is found in association with a variety of regolith materials and landscape settings, however, appears to be strongly controlled by hydromorphic characteristics of substrates sometimes growing over saprolite or bedrock, or sometimes lacustrine sediments, typically with an associated hardpan regolith carbonate coating. Reported to live for up to 100 years (Irons & Quinlan 1988). The leaves are small pointed scales sheathing the joints between sections of branchlets. Flowering and foliage generation typically occurs in summer-autumn, but has been observed in other seasons after suitable rains. This species of belah is smaller, more gaunt and more widespread than *Casuarina cristata* which may also be referred to as belah. Branchlets are relatively easily sampled.

Branchlets from 20 trees have been collected from Thackaringa, near Broken Hill (Hill 1998) and analysed using AAS and Flame Photometer. Biogeochemical results provide a strong bedrock signature for individuals on serpentinites, in particular exhibiting a markedly higher concentration of Cu compared to individuals on an adjacent pegmatite.

River Red Gum (*Eucalyptus camaldulensis*)
River red gums are widespread in the region, mostly confined to the riparian fringes of large alluvial channels, particularly within and flanking upland areas. They are generally large (15-30 m high) gnarled trees with a spreading canopy. Flowering periods are variable due to the variable availability of water, however it generally takes place in spring. River red gums have an extensive and deep taproot system that may extend over 100 m horizontally and at least 20 m deep (Hulme & Hill 2003a & b). They are reported to live for at least 400 years (Ogden 1978). Leaf samples tear off branches relatively easily, however some specimens without low branches can be difficult to sample. Twigs and bark are more time consuming to sample however can be readily obtained, roots are variably exposed, and fruits are susceptible to seasonal variations in availability and maturity.

Dann (2001) conducted a pilot study of river red gum organ chemistry and sampling along Stephens Ck. He found that leaves and twigs tended to accumulate higher concentrations of most trace metals than fruit, roots, wood and bark, and recommended leaves as the better regional sampling media for most trace elements. Leaf samples from 37 trees along Stephens Creek were analysed by ICP-MS[1] and showed that Pb contents were greater nearer Pb mineralisation such as at the Parnell Mine, although most other trace metals gave variable results. Barratt & Hill (2003) showed extremely elevated Pb contents (over 300 ppm) from near the Pinnacles Mine for leaves from 51 trees in Pine Creek that were analysed by INAA (Au+31), ICP-MS[3] and ICP-OES. Ongoing research is further characterising the biogeochemistry of these trees in the region (Hulme & Hill 2003a & b).

Curly Mallee (*Eucalptus gillii*)
Curly Mallee has a very restricted distribution, with only a few isolated stands along the Barrier Range. It has been previously described from Corona and Fowlers Gap districts (Cunningham *et al.* 1992), but also recently found at the Thackaringa Serpentinite (Hill 1998, Hill 2000), and in the Mt Darling Ranges (Avondale, Rupee and K-Tank stations). Typically associated with calcareous and carbonate-rich regolith, in particular more Mg-rich substrates. It is a multi-stemmed, small to medium-sized tree (2-6 m high) with crooked stems giving a gnarled or 'curly' habit. Flowering and leaf generation is typically in late winter-early spring.

Leaves were collected from 10 trees by Hill (1998) at the Thackaringa serpentinite and analysed by AAS and Flame Photometer. Leaves are easily collected from trees, although many exhibit microbial infestation and care is required to avoid these. Biogeochemical results suggest that curly mallee has developed chemical tolerances which limit its ability to provide a strong bedrock signature, although more work is needed on this species.

SPECIES INFORMATION - SHRUBS

Bladder Salt-bush (*Atriplex vesicaria*)
This perennial is widespread throughout the region. Although found in association with most regolith types and landscape settings, bladder saltbush is most typically associated with clay-rich alluvial and sheetwash plains, particularly with distinctive 'contour-band' micro-topography. It is reported to live for 20 to 30 years (Cunningham *et al*. 1992). The root system is shallow, mostly penetrating to 30 cm depth (Eldridge 1988), although it may extend up to about 1 m. Flowering and leaf generation generally occurs in spring and summer, but it may also flower at other times following adequate rainfall. Its recently observed susceptibility to drought mortality, plus the high and variable salt content of leaves, have favoured twig sampling for biogeochemical surveys (Brown in prep.).

Leaf and twig samples from 28 individuals from near Tibooburra have been sampled and analysed by ICP-MS[1] and INAA for Au (Hill in prep.). The results showed higher Na, Cl and Zn contents in bladder salt-bush leaves and twigs than other chenopods in the area, however most other elements are in significantly lower abundance than in blue-bushes. A comparison of the biogeochemical characteristics of leaves and twigs suggest that most trace elements are accumulated in the leaves, except for Pb which was below detection limit in the leaves. Leaves from 26 bladder salt-bush individuals on Thackaringa station were sampled and assayed by ICP-MS[1] (Debenham 2000). The assay results in this low-order stream catchment study suggest that bladder salt-bush leaf chemistry is influenced by landscape setting, and regolith substrate chemistry. Notable here was that all leaf samples had Pb contents below detection limit, even though adjacent black blue-bush and soil samples had detectable Pb contents and that Zn contents in bladder salt-bush were greater than in black blue-bush. A nearby study at the White Dam prospect (Brown in prep.) has sampled about 100 bladder salt-bush dead twig samples, for assays by INAA (Au+31), ICP-MS and ICP-OES which are soon to be completed.

Black Blue-bush (*Maireana pyramidata*)
Black bluebush is a widespread perennial throughout the region, where it is generally associated with friable substrates, typically with regolith carbonate accumulations. A tap-root system may penetrate to >3 m observed from creek sections and costeans in the region. Flowering and leaf generation is generally in spring. It is reported to be a long-lived shrub (Cunningham *et al.* 1992). It is relatively easy to sample, with the aid of clippers, although when heavily grazed care is needed to ensure that twigs do not tear sampling bags and gloves. These shrubs also appear to trap large amounts of dust.

23 individuals have been sampled, with the leaves and twigs analysed by ICP-MS[1] and Neutron Activation for Au (Hill in prep.). The assay results show an ability of the shrub to accumulate high concentrations of trace metals (particularly in leaf tissues) compared to other chenopods growing in the sampling areas. Leaves collected from 20 individuals near the Thackaringa serpentinite (Hill 1998) were analysed using AAS and Flame Photometer. In general, these results suggest that there is an ability for these shrubs to process or exclude many trace elements when on ultramafic bedrock, however, Cu was significantly higher in the leaves of individuals on serpentinite compared to adjacent substrates. Senior (2000) and Senior & Hill (2002) found that Cu, Pb and Zn contents from a data set of 34 samples of black blue-bush leaves from near North Tank were able to detect a partially buried mineralised quartz-gahnite lode. Debenham (2000) compared the assays of leaf samples from 15 black blue-bush shrubs with leaf samples from adjacent bladder salt-bush shrubs and found that the black blue-bush samples generally had greater Cu, Fe, Mn and Pb contents and lower Bi and Zn contents. Leaves from 71 shrubs at the Flying Doctor prospect were analysed by ICP-MS[2] and XRF and showed a notable increase in Pb over mineralisation (Thomas *et al*. 2002, Hill *et al*. 2003).

Pearl Blue-bush (*Maireana sedifolia*)
Pearl bluebush is a common perennial throughout the region. It is associated with friable regolith substrates that allow great root penetration, such as fractured bedrock or most typically sites with regolith carbonate accumulations within 60 cm depth (Cunningham *et al*. 1992). Reported to live at least 150-300 years (Irons & Quinlan 1988). They have a relatively deep tap-root system (up to 3 m) with shallow deciduous feeding roots (Cunningham *et al*. 1992). Flowering and leaf generation is generally in summer. Leaf sampling is relatively simple, especially with the aid of clippers, where mixed leaf and twig samples can be further

separated after they fall apart during drying. Care needs to be taken not to confuse this species with *M.astrotricha*, which has stalked leaves (*M. sedifolia* leaves are stalkless).

Leaves and twigs from 32 individuals were analysed by ICP-MS[1] and Neutron Activation for Au (Hill in prep.). Assays showed similar biochemical patterns to black blue-bush, however, trace element concentrations were generally lower except for Cl and Zn. A few specimens were sampled from near the Great Goulburn mineralisation Jones (1999), however the sample number was not great enough to make any significant conclusions.

Rock Sida (*Sida petrophila*)
Rock sida, is typically abundant in the region where bedrock is close to the surface (subcropping), where it typically grows across erosional rises and along drainage depressions, particularly on south- and east-facing slopes. It is an erect and twiggy, perennial forb, mostly up to about 1 m high. Following rains it has greyish-green felty leaves and its yellow flowers may form at most times of the year. Twigs are relatively easily sampled, either by breaking by hand or else with clippers. The availability of abundant foliage limits the application of leaf sampling.

38 living twig samples were collected from the Flying Doctor prospect area (Thomas *et al*. 2002, Hill *et al*. 2003), and assayed by XRF and ICP-MS[2]. The results did not show a strong reflection of mineralisation mainly because samples were scarce in mineralised sites.

Velvet Potato Bush (*Solanum ellipticum*)
Velvet Potato-bush is widespread throughout the region in a wide range of regolith and landscape settings, particularly within drainage depressions, channels and alluvial outwash areas, and at the base of trees within aeolian sand plains. This perennial forb has blue or purple flowers followed by globular berries up to 20 mm, at most times of the year. Leaves are easy to access, however, their fine surface hairs makes them very susceptible to detrital contamination. Avoiding the slender prickles on branches and along the stems of many leaves can also be challenging.

The leaves from 14 specimens were sampled near Tibooburra and analysed using ICP-MS[1] and Neutron Activation for Au (Hill in prep.), and from 20 specimens near the Thackaringa serpentinite (Hill 1998) and assayed using AAS. The later results showed significantly higher Zn, Pb and Ni concentrations in the leaves for individuals growing over serpentinite compared to those over adjacent rock types.

CONCLUSIONS

Preliminary results are very promising however, particularly for the ability of many of these plants to 'penetrate' transported cover. Some of the data sets are now becoming significant enough for preliminary results to be presented and compiled. So far there has been a lot of scepticism and unfounded negativity towards developing these approaches, specifically in this region. It must be remembered that it is difficult to present supportive results for a new technique before the research has ever been conducted in a region! Hopefully this abstracts shows the development of some of the potential of this research.

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APPENDIX 1: Laboratories and analytical suites

ICP-MS[1]: Ecochemistry Laboratory, University of Canberra: Al, As, B, Ba, Br, Ca, Cd, Ce, Cl, Co, Cr, Cu, Fe, Ga, K, La, Li, Mg, Mn, Mo, Na, Nd, Ni, P, Pb, Rb, S, Sc, Se, Si, Sr, Ti, V, Y, Yb and Zn.

ICP-MS[2]: Geoscience Australia Laboratories, Canberra: Ag, As, Be, Bi, Cd, Ce, Cs, Dy, Er, Eu, Ga, Gd, Ge, Hf, Ho, La, Lu, Mo, Nb, Nd, Pr, Sb, Sm, Sn, Ta, Tb, Th, U, Y, and Yb.

ICP-MS[3]: Becquerel Laboratories, Lucas Heights: Be, Bi, Cd, Ga, In, Nb, Nd, Pb, Sn, and Sr.

ICP-OES: Becquerel Laboratories, Lucas Heights: Al, Cu, Mg, Mn, Ni, P, S, Ti, and V.

XRF: Geoscience Australia Laboratories, Canberra: Al, Ba, Ca, Cl, Cu, Fe, K, Mg, Mn, Na, Ni, P, Pb, Rb, S, Si, Sr, Zn, and Zr.

INAA Au: Becquerel Laboratories, Lucas Heights: Au.

INAA Au + 31: Becquerel Laboratories, Lucas Heights: Ag, As, Au, Ba, Br, Ca, Ce, Co, Cr, Cs, Eu, Fe, Hf, Ir, K, La, Lu, Mo, Na, Rb, Sb, Sc, Se, Sm, Ta, Te, Th, W, U, Yb, Zn, and Zr.

AAS: Melbourne University Geography Department, Atomic Absorption Spectrometry: Ca, Cu, Fe, Mg, Mn, Ni, Pb and Zn; and, Flame Photometer: K and Na.

National Undergraduate Regolith Geology school (NURGS)

Further reading

A series of copyright readings were also provided to students on an individual basis, copied under the fair dealing clause of the Australian Copyright Act.

Photocopies were provided of:

B.W. Murphy 1992. Chapter 5: The Soil Profile. In: P.E.V. Charman and B.W. Murphy eds. Soils their properties and management. Soil Conservation Commission of New South Wales. Printed by Sydney University Press.

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Regolith-landform Unit (RLU) mapping codes from Pain *et al.* (2007)*.

REGOLITH TYPES		LANDFORMS	
TRANSPORTED REGOLITH		a	alluvial landforms
		ap	alluvial plain
A	Alluvial sediments	ah	alluvial channel
AC	Channel deposits	af	flood plain
AO	Overbank deposits	aa	anastomatic plain
		ab	bar plain
I	Aeolian sediments	ac	covered plain
IS	Aeolian sand	am	meander plain
IL	Loess	ao	floodout
IP	Parna	at	alluvial terrace
		as	stagnant alluvial plain
C	Colluvial sediments	al	terraced land
CM	Mass movement	aw	alluvial swamp
CH	Sheet flow deposit		
CF	Fanglomerate	u	dunefield
		ul	longitudinal dunefield
E	Evaporite		
EH	Halite	f	fan
EG	Gypsum	fa	alluvial fan
		fc	colluvial fan
L	Lacustrine sediments	fs	sheet-flood fan
G	Glacial sediments	p	plain
		pd	depositional plain
V	Volcanic sediments	pl	lacustrine plain
VT	Tephra	pp	playa plain
		ps	sandplain
F	Fill		
		g	glacial landforms
O	Coastal sediments	gd	depositional glacial landforms
OB	Beach sediments	ge	erosional glacial landforms
OE	Estuarine sediments		
OC	Coral	d	delta
OM	Marine sediments		
		c	coastal lands
***IN-SITU* REGOLITH**		cb	beach ridge plain
		cc	chenier plain
W	Weathered bedrock	cr	coral reef
		cm	marine plain
R	Residual material	ct	tidal flat
		cd	coastal dunes
S	Saprolite	cp	coastal plain
SC	Completely weathered bedrock	cc	beach
SV	Very highly weathered bedrock		
SH	Highly weathered bedrock	e	erosional landforms
SM	Moderately weathered bedrock	ep	erosional plain
SS	Slightly weathered bedrock	ei	pediment
		ea	pediplain
		en	peneplain
		ec	etchplain
		er	rise
		eu	residual rise
		el	low hill
		eh	hill
		em	mountain
		ee	escarpment
		eb	badlands
		ed	drainage depression
		k	karst
		l	plateau
		v	volcanic landform
		vc	caldera
		vv	cone
		vl	lava plain
		va	ash plain
		vf	lava flow
		vp	lava plateau
		m	made land
		t	meteor crater

*Pain C.F., Chan R., Craig M., Gibson D., Kilgour P., Wilford J. 2007. RTMAP Regolith Database Field Book and Users Guide. CRC LEME OFR 231.