CRCLEME
Cooperative Research Centre for
Landscape Environments
and Mineral Exploration

OPEN FILE REPORT SERIES

REGOLITH ARCHITECTURE AND GEOCHEMISTRY OF THE GIRILAMBONE REGION, NORTHWESTERN NEW SOUTH WALES - A SYNTHESIS REPORT

K.G. McQueen, R.A. Chan, K. Khider, R.S.B. Greene and K.M. Scott

CRC LEME OPEN FILE REPORT 215

December 2008

CRC LEME is an unincorporated joint venture between CSIRO-Exploration & Mining, and Land & Water, The Australian National University, Curtin University of Technology, University of Adelaide, Geoscience Australia, Primary Industries and Resources SA, NSW Department of Primary Industries and Minerals Council of Australia, established and supported under the Australian Government's Cooperative Research Centres Program.

REGOLITH ARCHITECTURE AND GEOCHEMISTRY OF THE GIRILAMBONE REGION, NORTHWESTERN NEW SOUTH WALES - A SYNTHESIS REPORT

K.G. McQueen, R.A. Chan, K. Khider,
R.S.B. Greene and K.M. Scott

CRC LEME OPEN FILE REPORT 215

December 2008

CRC LEME is an unincorporated joint venture between CSIRO-Exploration & Mining, and Land & Water, The Australian National University, Curtin University of Technology, University of Adelaide, Geoscience Australia, Primary Industries and Resources SA, NSW Department of Primary Industries and Minerals Council of Australia.

Headquarters: CRC LEME c/o CSIRO Exploration and Mining, PO Box 1130, Bentley WA 6102, Australia

Electronic copies of the publication in PDF format can be downloaded from the CRC LEME website: http://crcleme.org.au/Pubs/OFRSindex.html. Information on this or other LEME publications can be obtained from http://crcleme.org.au.
Hard copies will be retained in the Australian National Library, the J. S. Battye Library of West Australian History, and the CSIRO Library at the Australian Resources Research Centre, Kensington, Western Australia.

Reference:
McQueen, K.G., Chan, R.A., Khider, K., Greene, R.S.B. and Scott, K.M. 2008. Regolith architecture and geochemistry of the Girilambone Region, Northwestern New South Wales - a synthesis report. CRC LEME Open File Report 215, CRC LEME, Perth, 57 pp

Keywords: 1. Regolith - New South Wales 2. Transported materials 3. Exploration geochemistry 4. Girilambone

ISSN 1329-4768
ISBN 978 0 643 09674 5
Addresses and affiliations of Authors:

K.G. McQueen, K. Khider and RBS. Greene
CRC LEME
Australian National University
Canberra
ACT 0200

R.A. Chan
CRC LEME
Geoscience Australia
Division of Minerals and Geohazards
GPO Box 378
Canberra ACT 2601

K.M. Scott
CRC LEME
CSIRO Exploration and Mining
P.O. Box 136
North Ryde
NSW 1670

Published by: CRC LEME
c/o CSIRO Exploration and Mining
PO Box 1130, Bentley, Western Australia 6102.

ABSTRACT

The Girilambone region between Cobar, Nyngan, Bourke and Nymagee in western New South Wales has an extensive regolith composed of *in situ* and transported materials of greatly varying thickness (ca. 2-100 m). This regolith obscures the underlying bedrock and its contained ore deposits. It presents major challenges for mineral exploration in the region, particularly for surface techniques. The regolith geology and related surface processes also control soil types, landform features and landscape stability, important for agriculture and natural resource management.

The regolith composition, architecture and geochemistry of the region were investigated during a three year collaborative project between CRC LEME and the Geological Survey of the NSW Department of Primary Industries. This study combined data from regional regolith-landform-mapping and information obtained by air core drilling and sampling along a series of roadside traverses to produce an integrated three dimensional understanding of the regolith. Five 1:100 000 scale regolith-landform maps were produced (BYROCK, SUSSEX, COOLABAH, CANBELEGO and HERMIDALE). A total of 247 air core holes were drilled at depths ranging from 3 to 82 m, generally spaced between 1 and 4 km along 12 traverses mostly in an east to northeasterly orientation (7571 m of total drilling). Drill cuttings were logged visually and with the aid of a PIMA. Samples were collected for geochemical analysis and partial X-ray diffraction analysis from composites of 1 m intervals in the top 9 m and from larger interval composites below this. The project was conducted in three stages with detailed reports produced at the end of each stage.

Most of the Girilambone region is covered by colluvial and alluvial sediments with scattered areas of weathered bedrock rises (9-30 m relief). There is a significant component of wind blown dust in the soils. Palaeochannel systems are important and contain at least two major depositional sequences: an older clay-rich estuarine to marine and fluvio-lacustrine sediment sequence; and a younger colluvial-alluvial sequence of silts, sands and ferruginous gravels. Regolith-landform mapping and dating of key regolith materials has established the landscape history back to the Early Jurassic. This history reflects dominant subaerial exposure, with some marine incursion to the north, since the Mesozoic. There has been ongoing weathering, erosion and deposition controlled by bedrock composition, climate change, changes in base level and some neo-tectonic activity. A landscape evolution model has established the regional pathways for regolith transport and element dispersion.

Over 3360 samples collected by drilling were analysed using a multi-acid (hydrofluoric-perchloric-hydrochloric) digest followed by ICP OES and MS analysis (for Al, Ca, Fe, K, Mg, Mn, Na, P, Ti, Ag, As, Ba, Bi, Cd, Co, Cr, Cu, Mo, Ni, Pb, S, Sb, Sr, V, W, Zn, Zr). Sample splits were subjected to an aqua-regia digest and analysed for gold by solvent extraction and graphite furnace AAS. Bottom of the hole samples (mostly saprock) from each hole were also separately analysed by XRF for major elements (Al, Ca, Fe, K, Mg, Mn, Na, P, Si, Ti) and by ICP OES and MS following multi-acid digest of fused glass discs for some trace elements (Ag, As, Ba, Be, Bi, Cd, Ce, Cl, Cr, Cs, Cu, Dy, Er, Eu, F, Ga, Gd, Ge, Hf, Ho, La, Lu, Mo, Nb, Nd, Ni, Pb, Pr, Rb, S, Sb, Sc, Sm, Sn, Sr, Ta, Tb, Th, U, V, Y, Yb, Zn, Zr). Geochemical data have been used to characterise different regolith materials, establish parent rock types, estimate the degree of chemical weathering and identify important regolith-related element associations. It is clear that trace element dispersion has been controlled by the particular regolith processes operating under different and contrasting weathering regimes.

The project has established geochemical dispersion models for the Girilambone region. Areas worthy of further investigation by mineral explorers have been identified.

Table of Contents

List of Figures

List of Tables

REGOLITH ARCHITECTURE AND GEOCHEMISTRY OF THE GIRILAMBONE REGION, NORTHWESTERN NEW SOUTH WALES

1 INTRODUCTION

The Girilambone region lies between Cobar, Nyngan, Bourke and Nymagee in the Central Lachlan Orogen of eastern Australia. Between 2001 and 2004 a major study of this region was conducted by the Cooperative Research Centre for Landscape Environments and Mineral Exploration and the New South Wales Department of Mineral Resources (now N.S.W. Department of Primary Industries). The objective of the study was an improved knowledge and understanding of the regolith of this poorly known and relatively unexplored region. The area investigated covers 12,600 km^2 across the Hermidale, Sussex, Coolabah, Byrock and Glenariff 1:100 000 sheet areas (Figure 1).

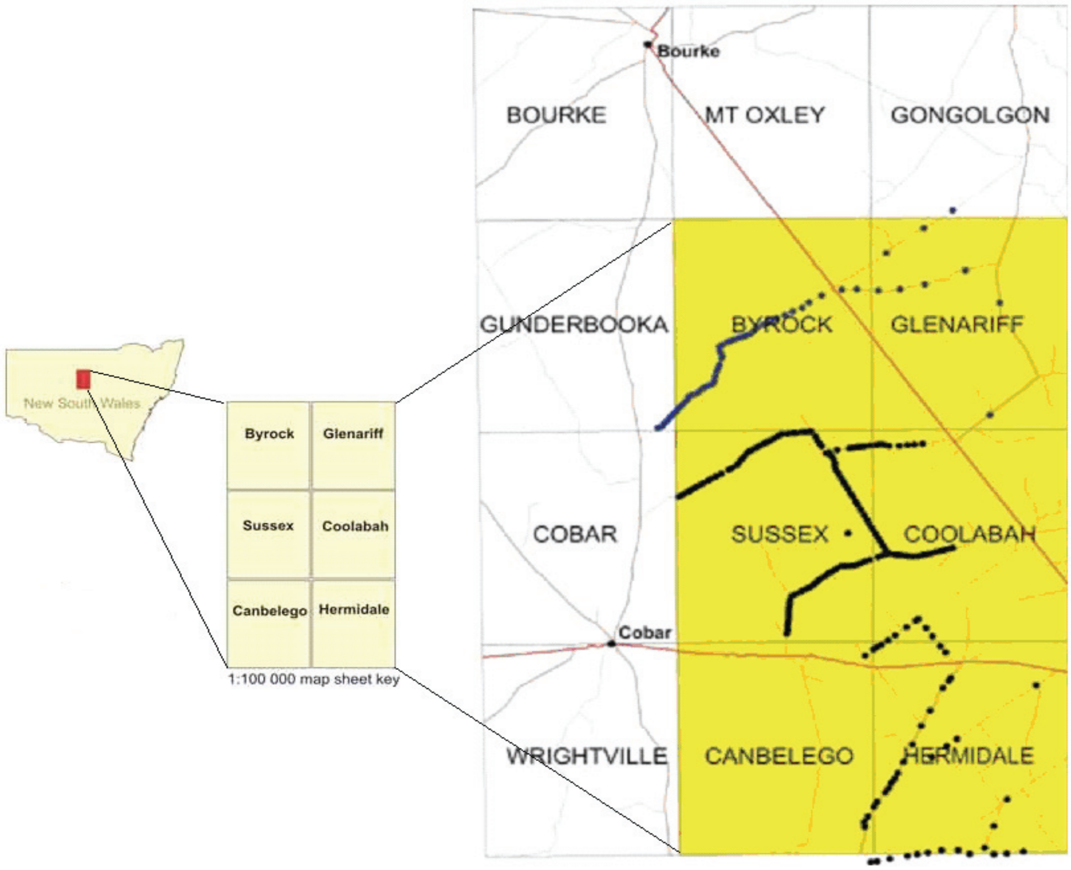


Figure 1. Location of the Girilambone region in western New South Wales. Large map shows the position of air core drilling traverses and the 1:100 000 sheet areas investigated.

The study aimed to stimulate and assist mineral exploration activities in this region through better knowledge of the regolith and the covered basement rocks. This involved:

- establishing the 3D nature of the regolith, including its material composition, structure, thickness and geochemical makeup;
- determining the major regolith controls on the dispersion of target and pathfinder elements used in geochemical exploration;
- interpreting the bedrock geology from *in situ* weathered and partly weathered rocks;

- constructing a landscape evolution model for the development and distribution of the different regolith types.

The work was conducted in three stages using an integrated, multi-disciplinary approach. The reader is referred to the three stage reports for additional details on the findings of the study (Chan *et al.*, 2003a;b; 2004). Four accompanying 1:100 000 regolith-landform maps were also produced: Hermidale (Maly 2004), Sussex (Maly *et al.*, 2004a), Coolabah (Maly *et al.*, 2004b), and Byrock (Buckley, 2004). Subsequently a regolith-landform map was also completed for the Canbelego 1:100 000 sheet (Roach, 2008).

A key feature of the project was the use of shallow air core drilling along a series of road traverses (Figure 1). Information and samples from these drill profiles were combined with data from regolith-landform mapping to provide the required 3D information on the regolith. Drilling also allowed sampling of less weathered saprock to help with bedrock mapping. A total of 247 holes were drilled and over 3360 samples analysed.

2 REGIONAL BEDROCK GEOLOGY AND MAJOR MINERALISATION STYLES

The Girilambone region is underlain by a hitherto poorly known basement composed of Ordovician Girilambone Group rocks with some in-faulted slices of probable Late Silurian to Early Devonian Cobar Supergroup rocks, intruding granites and some Late Devonian outliers or down-faulted blocks. In the east there are a number of Alaskan-type mafic-ultramafic complexes and mafic dykes. Recent mapping of the Sussex and Byrock 1; 100 000 sheet areas by the Geological Survey of New South Wales has provided a more detailed picture of part of the Girilambone block (Burton *et al.*, in press).

The Girilambone Group consists largely of turbidites with some intermediate to mafic igneous rocks. These rocks have been subjected to at least two phases of deformation and metamorphosed to variable grade (lower greenschist to lower amphibolite facies). Rock types include quartzites, arenaceous meta-sediments, slates, phyllites, cherts, meta-basalts and altered tuffs.

Cobar Supergroup rocks (mostly Kopyje Group) occur in narrow and elongate, faulted synclinal keels within the Girilambone Group rocks Burton *et al.* in press). Rock types include conglomerates, siltstones, quartzites (including the Coronga Peak Quartzite) and felsic volcanic rocks (Florida Volcanics).

Granites are known in the northern part of the region. These are poorly exposed, of felsic and I-type character and currently considered to be Siluro-Devonian in age (Blevin and Jones, 2004; Burton *et al.*, in press). There are several small granite bodies in the west, close to the eastern margin of the Cobar Basin (e.g. Nymagee Igneous Complex and the Tinderra, Wilgaroon, Wave Hill and Beanbah granites).

West and southwest of Nyngan there are outcropping and buried mafic-ultramafic bodies (e.g. at Rosedale, Miandetta, West Lynn, Honeybugle, Gilgai, Hermitage Plains). These consist of pyroxenites, gabbros and serpentinised rocks that can be grouped with the Alaskan-type zoned intrusions of the Fifield area to the south. These intrusions are considered Early Silurian in age and linked to subduction of an older basaltic back-arc basin (Barron *et al.*, 2004). These bodies contain variably elevated abundances of platinum group elements. Some have well developed ferruginous weathering profiles with concentrations of nickel and scandium.

The Girilambone-Cobar-Nymagee region is one of the richest mineral provinces in New South Wales. Major deposits occur in the Cobar Basin, around Girilambone and at Canbelego and Nymagee (Figure 2). However, much of the area remains to be explored in detail by modern exploration methods. Exploration has been hampered by the extensive regolith cover as well as poor knowledge of the underlying geology. Most discovered ore deposits and occurrences have been found at or close to the surface or as deeper extensions to known, smaller outcropping deposits (e.g. Perseverance near the Peak and QTS near the CSA deposit). A small number have been discovered beneath thin transported cover (e.g. Elura) or in areas of deeper, partly leached *in situ* regolith (e.g. Tritton). An elevation plot of the known deposits in the landscape (Figure 3) indicates that these largely lie within a relatively restricted zone (from 225-325 m a.s.l.). This zone reflects the range in exposure level of the mineralised rock units in the landscape. Large areas where mineralised crust is under cover or deeply weathered are prospective for further discoveries.

Known mineralisation styles in the region include:
- Structurally controlled hydrothermal base metal and gold deposits developed in dilational sites related to fault intersections or zones of competency contrast (Cobar-style);
- Stratigraphically controlled (stratabound) deposits with a structural control and/overprint. Some of these may be of low temperature hydrothermal origin (e.g. Wonawinta-style) or possibly volcanic-exhalative origin (e.g. Girilambone-style);
- Hydrothermal replacement deposits with epithermal characteristics, developed in faulted and brecciated meta-sedimentary rocks (e.g. the Mount Boppy gold deposit);
- Intrusion-related skarn and vein style deposits (e.g. Doradilla-style);
- Small structurally quartz-vein gold deposits (e.g. Muriel Tank and Restdown goldfields).

There is potential for other styles of mineralisation including:
- Volcanic-related massive sulfide deposits in felsic volcanic sequences (e.g. Florida and Babinda Volcanics);
- Hydrothermal gold and copper mineralisation associated with mafic volcanic complexes and dyke systems (e.g. Mt Dijou and Bald Hills);
- PGE mineralisation in Alaskan-type mafic-ultramafic intrusions;
- Residual and supergene deposits related to weathering (e.g. lateritic nickel deposits over weathered ultramafic rocks, supergene copper and silver deposits developed over weathered primary sulfide mineralisation);
- Placer deposits of gold, PGEs, heavy resistate minerals and pisolitic iron oxides in palaeochannels;
- Clays and refractory materials in the regolith and construction materials (gravels, sand and leucitite ‘blue metal’ aggregate).

Since completion of this study there has been increased exploration activity in the region including over most of the Girilambone region.

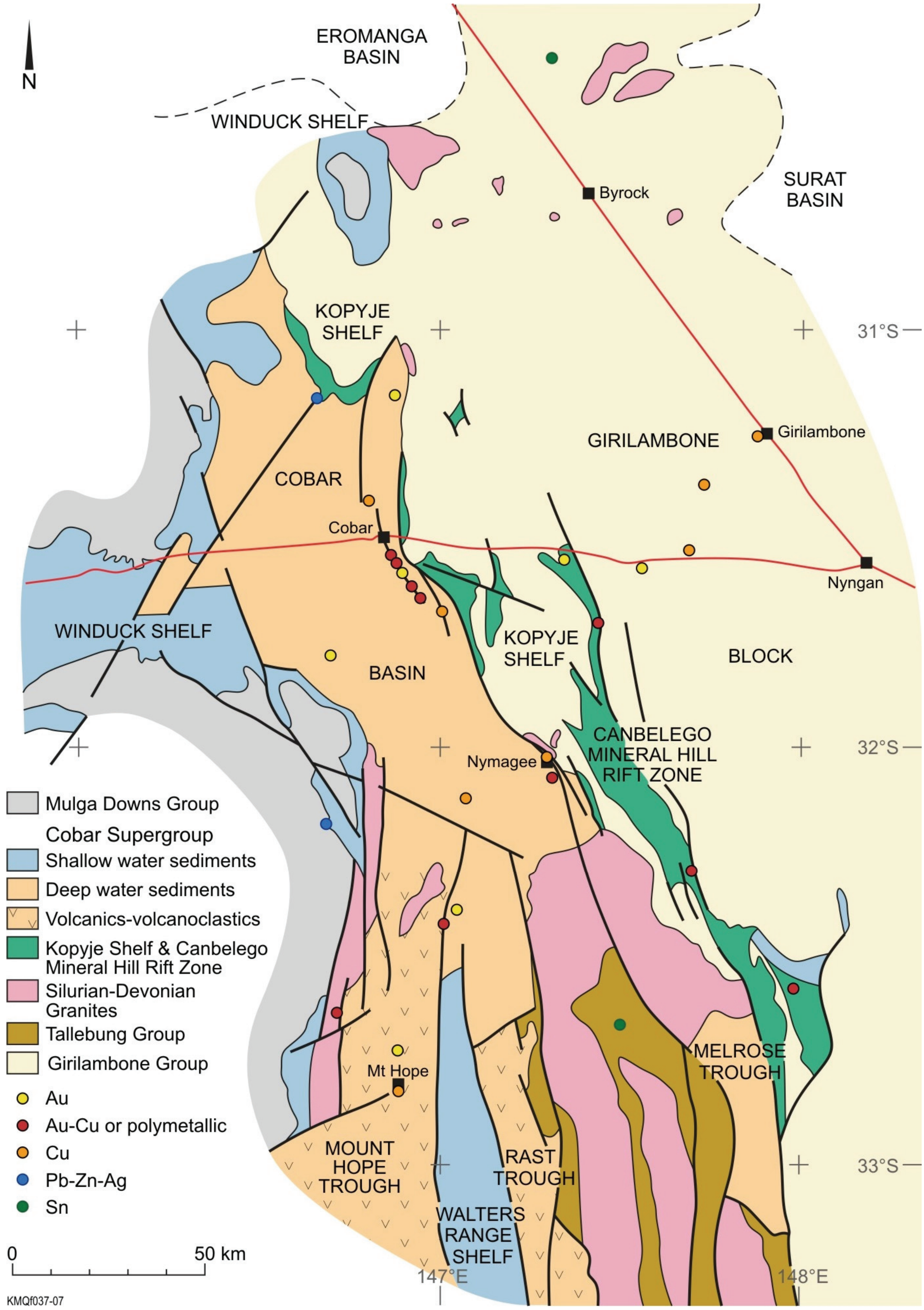
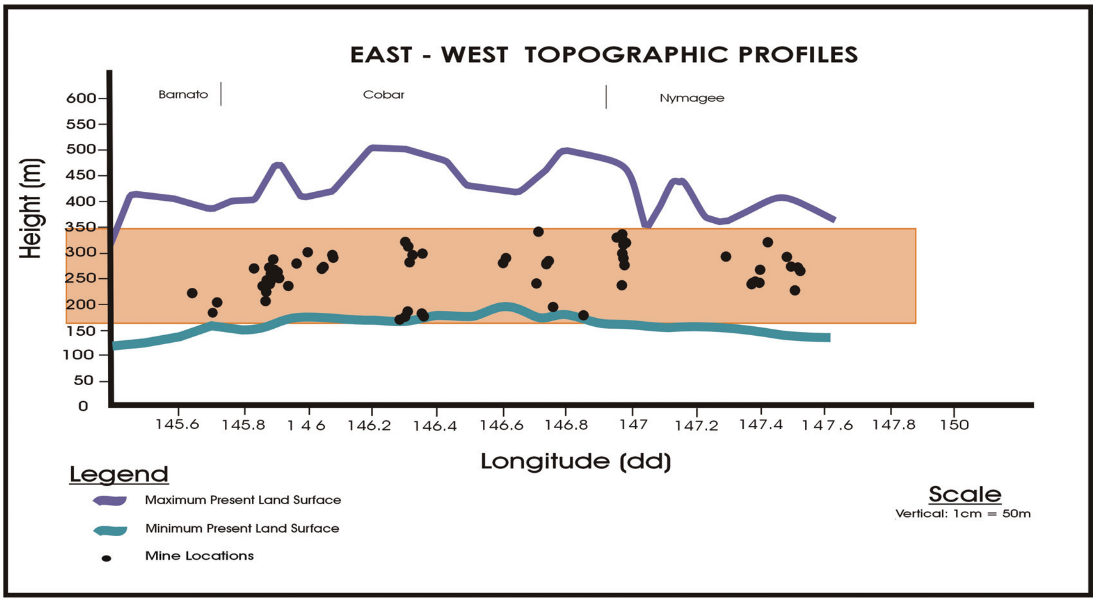
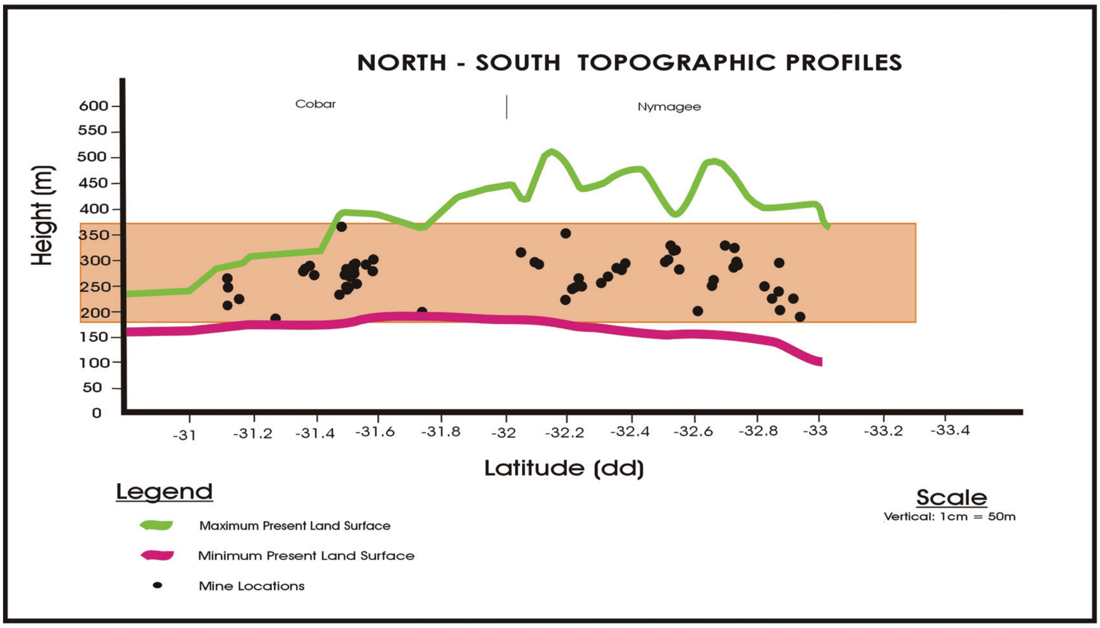


Figure 2. The geological framework of the Girilambone-Cobar-Nymagee-Mount Hope region and location of significant mineral deposits (adapted from David, 2005 and 1:250 000 metallogenic maps; Byrnes, 1993; Suppel and Gilligan, 1993; Gilligan and Byrnes, 1995).





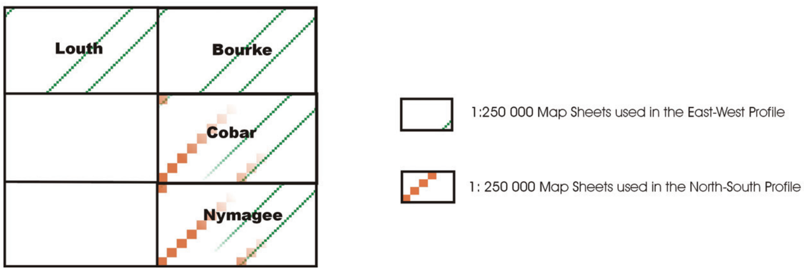


Figure 3. Elevations of known ore deposits in the present landscape. Deposit positions are projected onto north-south and east-west oriented sections showing the maximum and minimum land surface elevations. Ore deposit positions reflect the exposure levels of the mineralised horizons in the most prospective host rock sequences of the region.

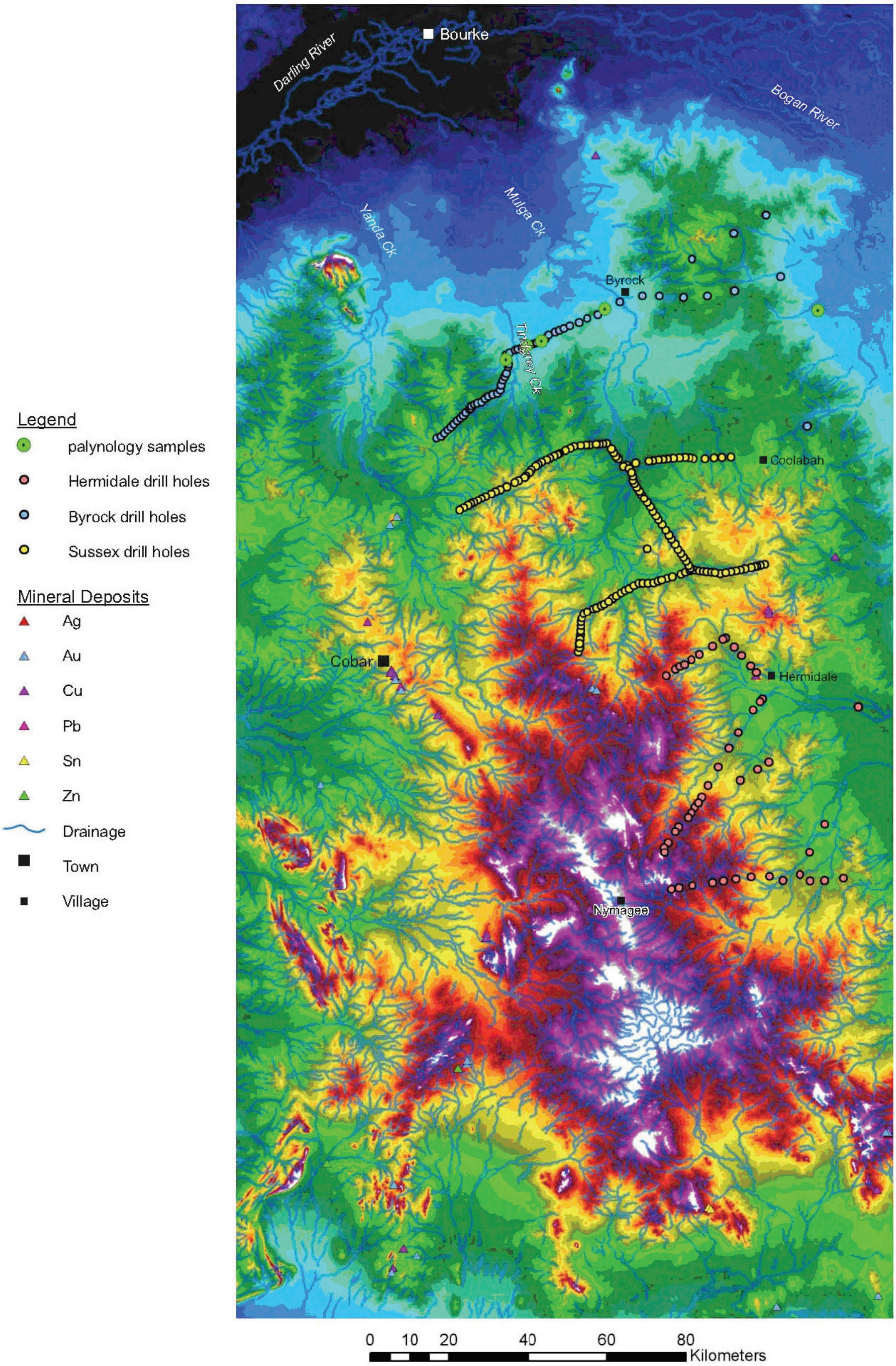


Figure 4. Relative elevation image (hot colours higher) of the Girilambone-Cobar-Nymagee region with present drainage, drill hole and palynology sample sites for this study, and some mineral deposit locations (source of image: Discovery 2000 Initiative, NSW DPI).

3 REGOLITH ARCHITECTURE AND MATERIALS

3.1 Regolith-landforms

Most of the Girilambone region is covered by colluvial and alluvial sediments with small scattered areas of weathered bedrock rises (9-30 m relief). In the Sussex, Coolabah and Hermidale 1:100 000 sheet areas there are some low hills (30-90m relief), and in the Byrock 1:100 000 area more extensive highly weathered bedrock rises. A few small volcanic plateaux of slightly weathered leucitite occur in the Sussex and Byrock areas. Colluvial sediments are generally more widespread than alluvial sediments, although there are extensive areas of stagnant alluvial plains in the Byrock sheet area and along the mid-reaches of Mulga Creek in the Sussex area. Colluvial sheetwash sediments on rises dominate in the Sussex and Coolabah sheet areas, whereas colluvial sheetwash sediments on erosional plains and depositional plains dominate in the Hermidale sheet area. Alluvial plains are dominant along major east-draining creeks in the Hermidale and Coolabah areas. Alluvial fans occur along the upper to mid reaches of Mulga Creek in the Coolabah and Sussex areas, and a large fan occurs at the confluence of Whitbarrow and Pangee Creeks in the Hermidale area. Many small head-water tributary valleys are eroded depressions with alluvial sediments in valley channels and colluvial sheetwash on valley sides. Quartzose sediments form an area of inverted relief (low rises) in the vicinity of Coolabah village and these sediments also occur on erosional plains immediately to the west.

3.2 Regolith Materials

The Girilambone region contains a wide variety of regolith materials. These can be conveniently divided into: *in situ* regolith; transported regolith and soils. These different regolith materials can also show varying degrees of induration by silica, iron oxides/oxyhydroxides and carbonates.

A series of summary regolith sections have been constructed from drill hole information (Figures 5 to 13). These display the regolith architecture in toposequences.

In situ regolith
Saprolite and saprock components of *in situ* regolith are distinguished according to the degree of weathering of weatherable minerals (see Appendix 1). Depth of weathering is highly variable (Figures 5-13), and relates to the weatherability of bedrock (e.g. chert less weatherable than shale), water supply and proximity to palaeovalleys. The depth and degree of bedrock weathering are generally greater beneath and adjacent to palaeovalley sediments due to the basal clays, which have acted as aquitards and forced palaeo groundwaters into the underlying bedrock. Elements thus mobilized were leached laterally and vertically as palaeo-groundwaters fluctuated, forming zones of pallid saprolite (Figures 5 and 6). Some of these pallid saprolite zones may indicate where older clay palaeosediments have been completely eroded away (e.g. CBAC41 and CBAC124; Figures 8 and 6 respectively).

Major bedrock lithologies (identified from petrographic, mineralogical and geochemical analysis) are: sandstone-siltstone-claystone and their low grade metamorphic equivalents, quartzite-micaceous quartzite-slate, schist, felsic volcanics, and granitoids. Minor lithologies are chert, breccias, mafic igneous rocks, and altered sedimentary rocks. Quartz veins, ferruginous induration, and to a lesser extent, silicification are widespread in the drill hole regolith profiles. Carbonate induration is dominant at and just below the transported/*in situ* unconformity. Details of the various *in situ* regolith characteristics are in Chan *et al.* (2003a;b; 2004).

Transported regolith

The transported regolith of the region can be broadly subdivided into two major depositional sequences: an older estuarine to marine and fluvio-lacustrine sediment sequence; and a younger colluvial-alluvial sediment sequence. These two sequences constitute the preserved sediments in two palaeovalley systems, one superimposed on the other (see Section 4 below).

The older sequence consists of clay, and minor quartz silt-sand-gravel sediments, and is more widespread at depth and thicker in the Byrock area (Figure 5), though remnants are preserved in higher terrain in the Sussex-Coolabah and Hermidale areas (Figures 8 and 11). This sequence generally underlies lower elevation areas, though this is not always the case, as at CBAC96, where the sediments are inverted in relief.

The younger sequence is more widespread and buries some palaeohighs (e.g. at CBAC104). It consists of ferruginous pisoliths, lithic fragments (which may be ferruginised), quartz pebbles and granules, sand, and minor silt and clay. Recent sediments have been included in this sequence. The younger sequence also has a grey/white clay component which is interpreted as redeposited clays eroded from the older sequence (see Section 4 below). This clay component only occurs in the Sussex-Coolabah and Hermidale areas, where the elevation is higher than in the Byrock area. The ferruginous pisoliths contain varying amounts of maghemite so this sequence is evident on airborne magnetics imagery, defining a widespread drainage network (Discovery 2000 Initiative, NSW Dept. DPI; Chan *et al*., 2003a;b; 2004). This network co-locates with some present-day head-water tributaries, but commonly deviates from the present drainage, thus indicating palaeodrainage lines. These palaeodrainage lines underlie a variety of regolith-landforms, from the lower parts of erosional rises to alluvial plains (see magnetic maps in Chan *et al*., 2003a;b; 2004).

These sediments show some ferruginous, siliceous, carbonate, and minor manganese oxide induration. This is mainly in the younger sequence, with minor occurrences in the older sequence. Details of the various transported regolith characteristics are in Chan *et al.* (2003a;b; 2004).

Colluvium is widespread in thin, bedrock-masking deposits on depositional plains, slopes and rises and less commonly in fans adjacent to range-fronts and higher relief landforms. The colluvium is generally dominated by lithic and vein quartz clasts in a silty to fine-sand matrix. Clasts are typically coarse and angular on upper slopes and decreases in grainsize downslope.

Aeolian silt and clay are significant components in the red silty-loam soils of the region. Well-rounded and sorted sands and silts occur in stabilised longitudinal dunes on the western edge of the area and in some source-bordering dunes adjacent to lakes and the modern drainage system.

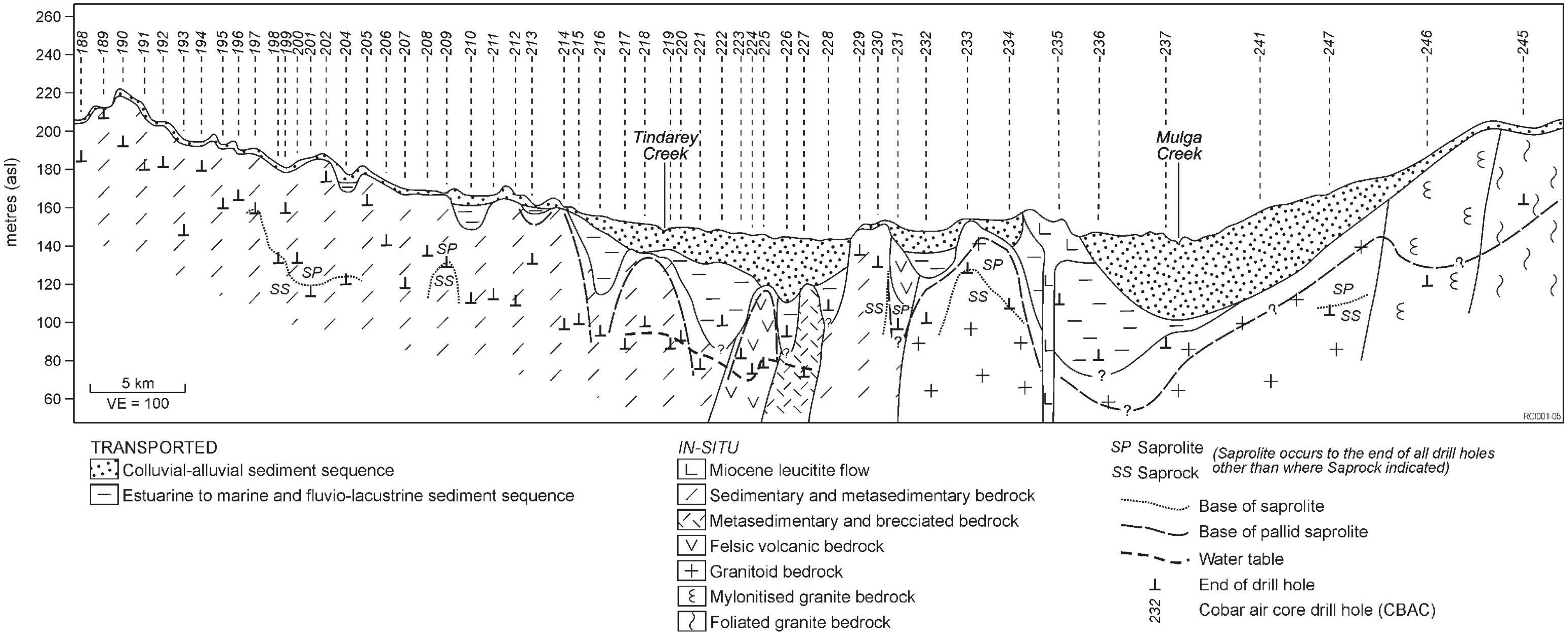


Figure 5. Regolith section along Byrock Road air core drill hole traverse.

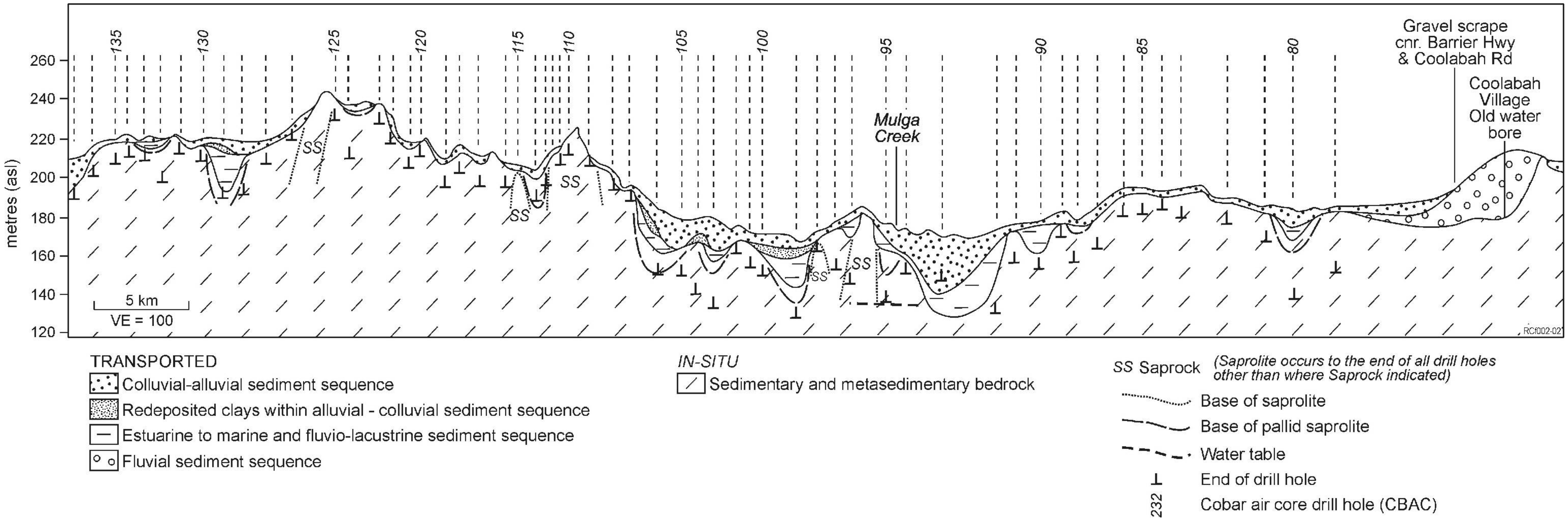


Figure 6. Regolith section along Coolabah Road air core drill hole traverse

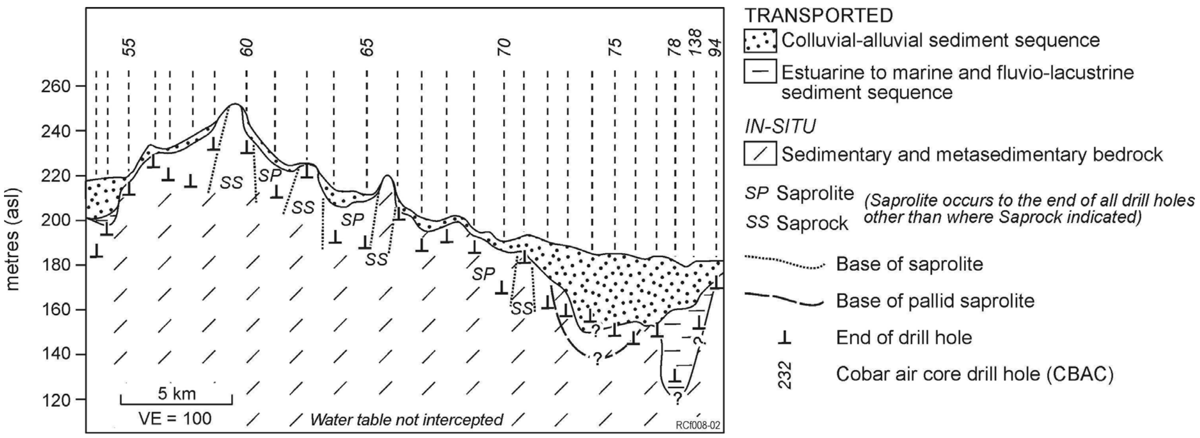


Figure 7. Regolith section along Elmore Road air core drill hole traverse.

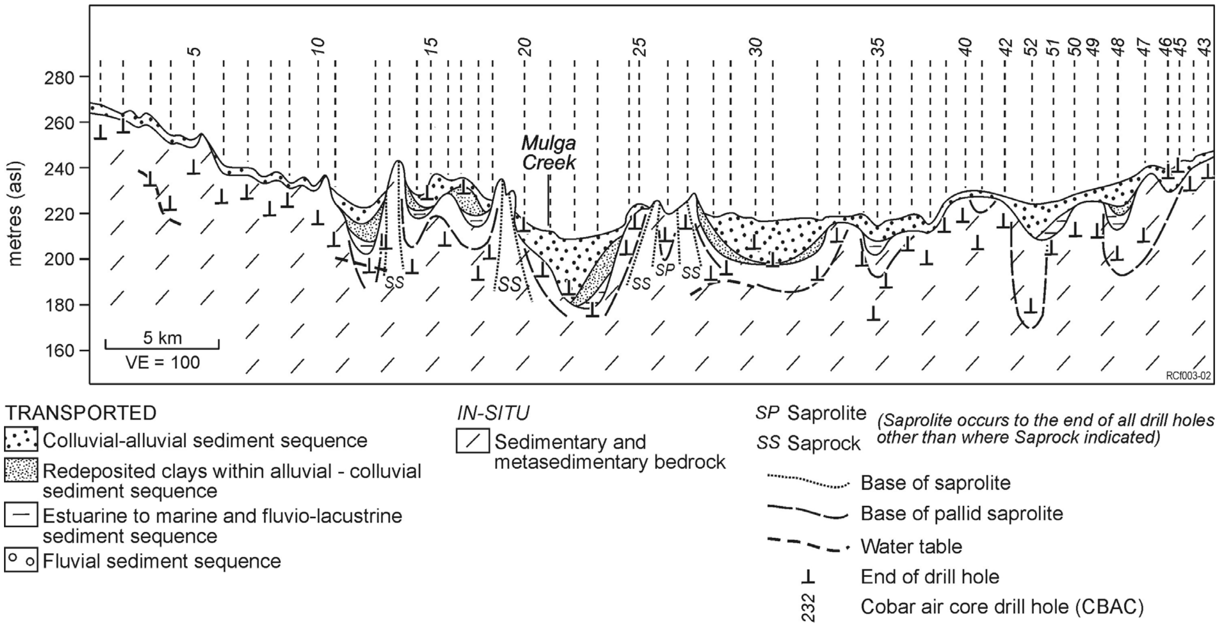


Figure 8. Regolith section along Booroomugga Road air core drill hole traverse.

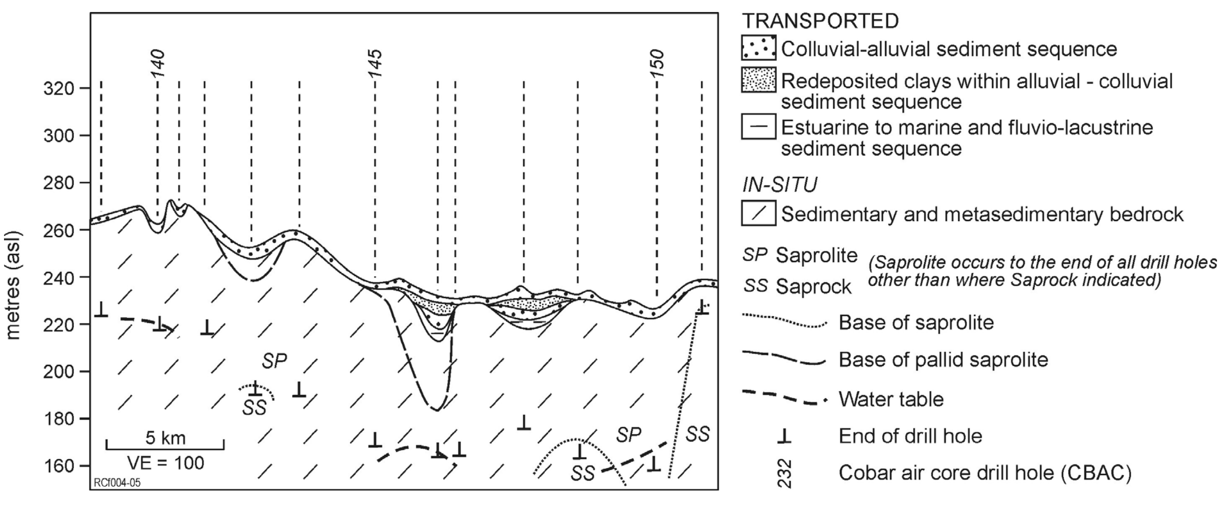


Figure 9. Regolith section along White Rock Road air core drill hole traverse.

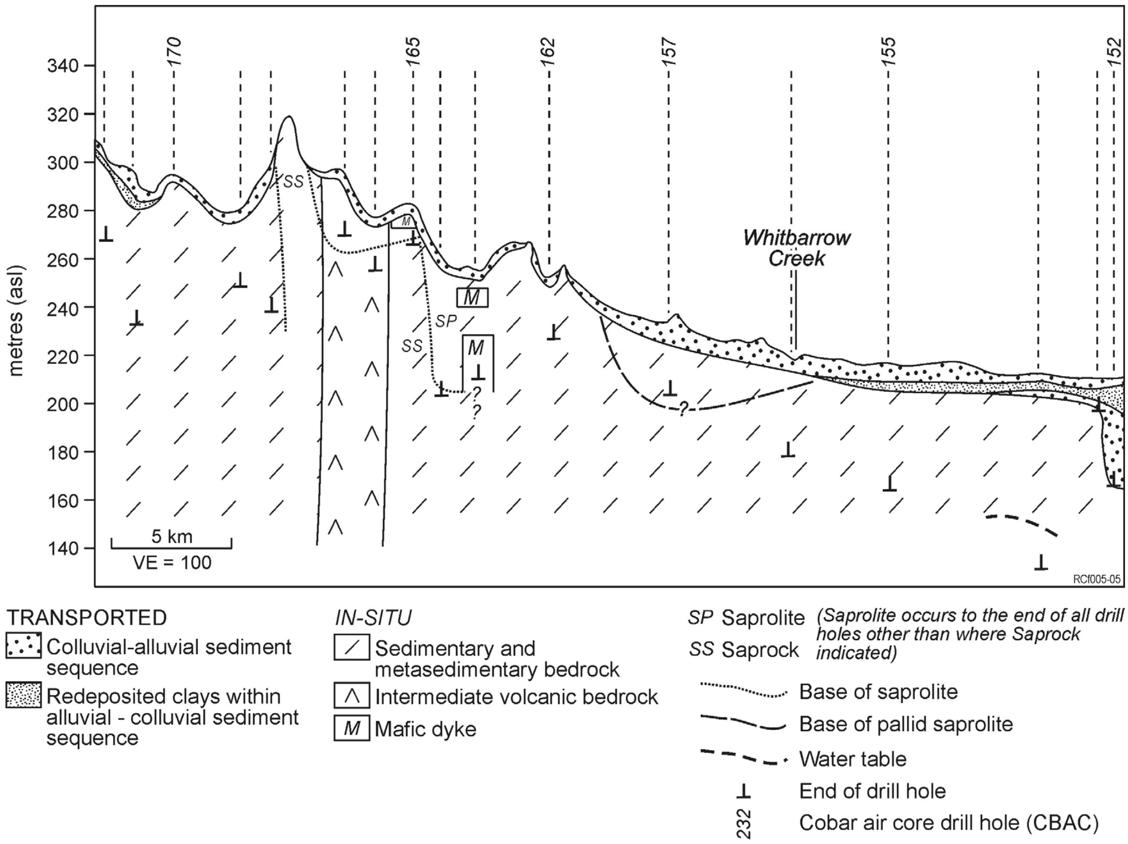


Figure 10. Regolith section along Nymagee-Hermidale Road air core drill hole traverse.

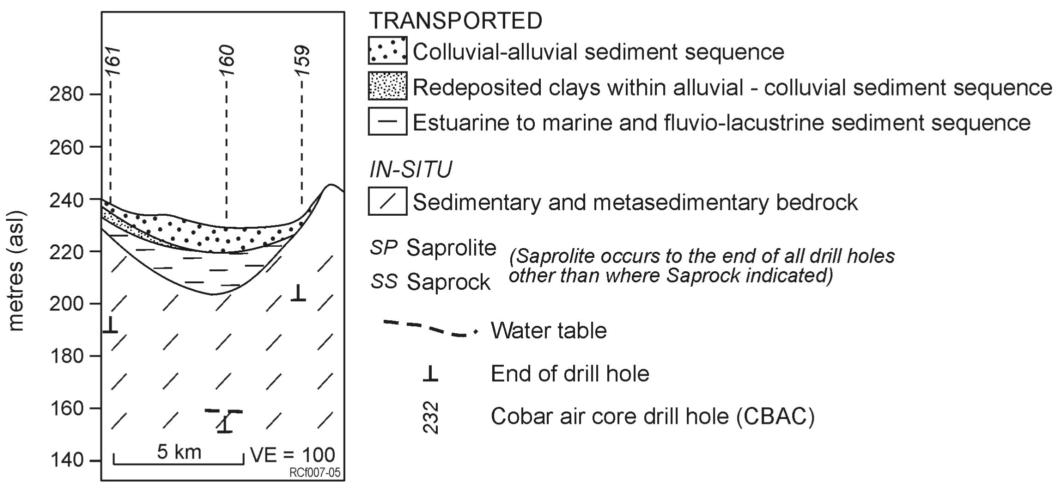


Figure 11. Regolith section along Gilgai Road air core drill hole traverse.

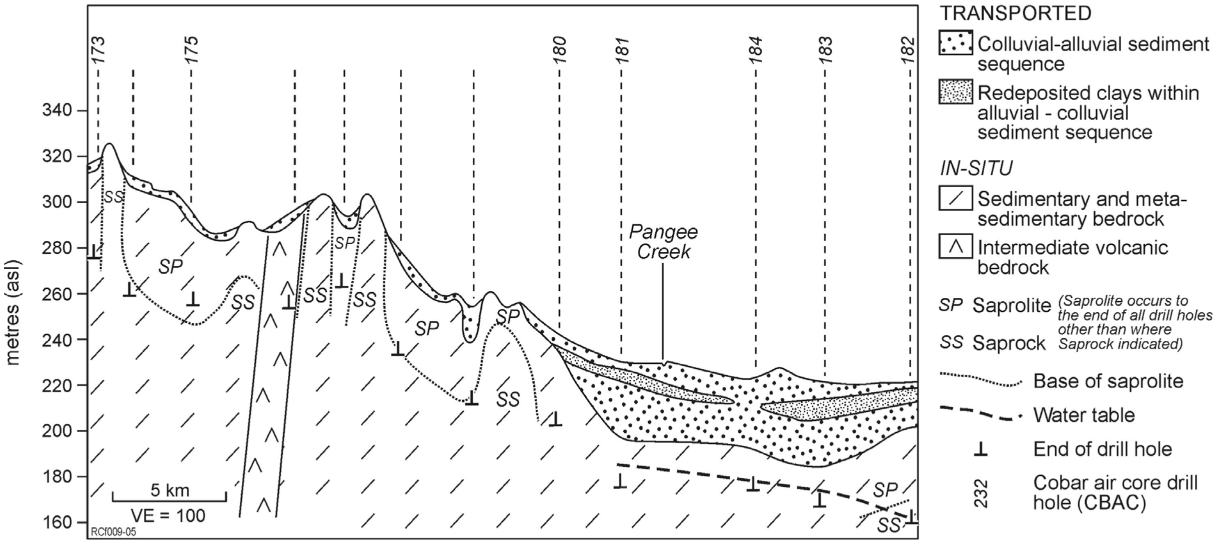


Figure 12. Regolith section along Peisley Road air core drill hole traverse.

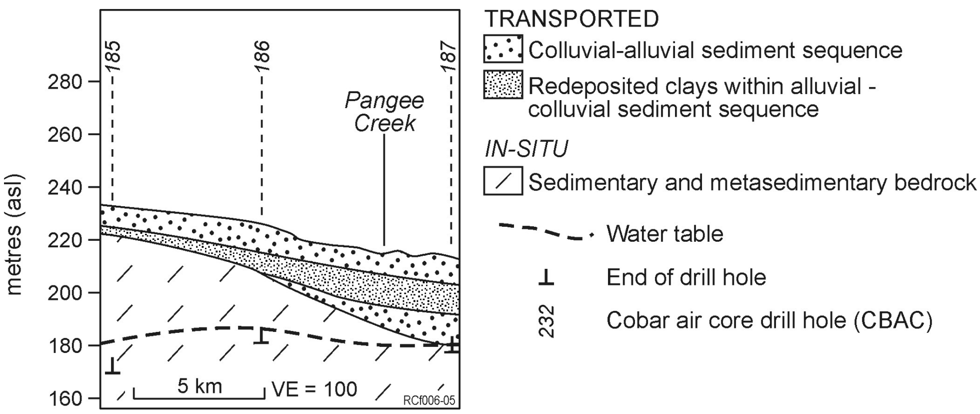


Figure 13. Regolith section along Pangee Road air core drill hole traverse.

Soils

The Girrilambone region is mantled by red-brown silty loam soils, which contain a significant aeolian (wind blown) component (up to 45 wt%; Tate *et al.*, 2007). These soils can be broadly divided into soft and hard red types and according to the Great Soil Group (GSG) the dominant types are classified as calcareous red earths and normal red earths (Stace *et al.*, 1968). The soft red soils are generally red and red-brown sands to clay loams with very little change in texture with depth apart from a slight increase in clay content. They occur on plains, sand dunes, and in major creek beds. The hard red soils are red and red-brown sandy loams to clay loams with little change in texture with depth apart from a slight increase in clay content. They occur on the upper ridges, lower slopes and in drainage lines.

Figure 14 is a typical toposequence showing the distribution of the dominant soil types (according to the GSG classification) in relation to major regolith-landform units. Calcareous red earths are common on level and slightly undulating plains. They are slightly acid to neutral near surface, with alkaline pH and free carbonate at depth. Normal red earths are common on undulating areas of residual regolith. They show an acid trend with no free carbonate at depth, but they may have hardpans.

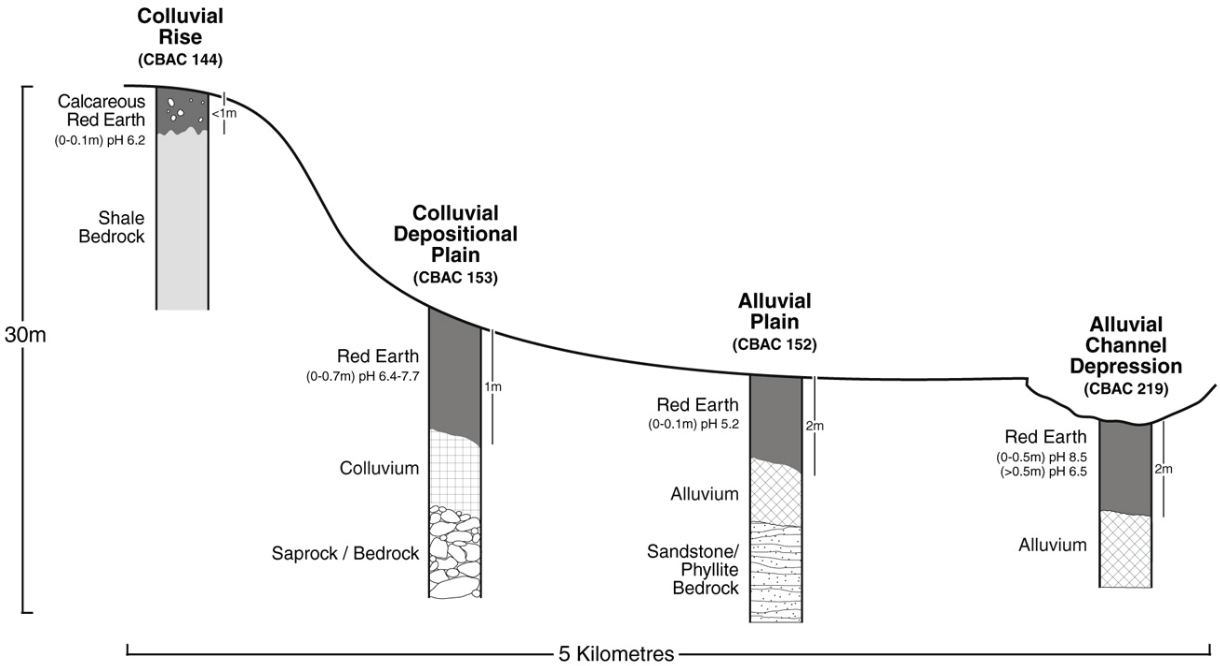


Figure 14. Regolith-landform soil type toposequence models for the Girilambone region.

A more detailed analysis of the relationship between soils types and key regolith-landform units was undertaken at four drill hole sites. Information for these sites was also obtained from the existing Land Systems maps (Walker, 1991). The results are presented in Table 1.

Table 1. Relationship between regolith landform unit, soil type and land system classification at four key sites.

Regolith unit (drill hole site)	Soil Type	Land system classification
Colluvial Rise Erosional Plain (CBAC 144)	Calcareous red earth	*Cobar Land System* Slightly undulating rounded ridges and higher residuals, and drainage lines
Colluvial Depositional Plain grading to Alluvial Depositional Plain (CBAC 153)	Normal red earth	*Pangee Land System* Broad plains, relief to 3 m
Alluvial Depositional Plain (CBAC 152)	Normal red earth	*Pangee Land System*
Alluvial Channel Depression (CBAC 219)	Normal red earth	*Kenilworth Land System* Plains of quaternary alluvium (with drainage sinks and lines)

Detailed particle size, morphological and mineralogical analysis of soils from key landscape settings, including natural dust trap sites and the four localities described above, indicates that the aeolian component has a dominant particle size in the 63-75 μm range and is composed largely of quartz with clay coatings (Tate *et al*., 2007). This material is mainly concentrated in the upper 0.3 m of the soil profile, particularly on colluvial and alluvial plains. Profiles on alluvial depositional plains show signs of this material to a depth of at least 5 m. In this case it is likely that the aeolian materials have been redistributed to depth by bioturbation, as well as colluvial and alluvial processes.

4 REGOLITH GEOCHEMISTRY

Multi-element analysis of samples collected during drilling has provided a large data base of major, minor and trace element compositions for the regolith of the Girilambone region (see Appendix 3 for an introduction to this data and the analytical methods and Appendix 4 for the geochemical data and site information). Geochemical data can be used to:

- understand the general geochemical characteristics and compositional variability of the regolith;
- determine parent rock compositions for *in situ* regolith and the degree of chemical weathering;
- assess the level of background variation in key target and pathfinder elements; and
- establish element associations related to normal regolith-forming processes, as distinct from dispersion around mineralisation.

Knowledge of host sites for target and pathfinder elements in the regolith can be used to interpret the dispersion processes and construct dispersion models.

4.1 Geochemical characteristics of regolith material

Different regolith materials across the Girilambone region have broadly definable geochemical characteristics. These can assist in identifying particular regolith-landform units. The most useful major element parameters are K/Al (reflecting relative proportions of kaolinite and muscovite), Mg/Al (reflecting relative proportions of kaolinite and smectite/chlorite clays or presence of Mg-bearing carbonate) and Fe content (reflecting the proportion of ferruginous concentrations). Using these parameters it is possible to model the dominant mineralogy of the weathered materials and provide a general basis for regolith typing (e.g. Figure 15). Whole rock analysis by XRF, by fusion and acid digest or by ICP-OES following multi-acid total digest, is required to give total contents of the major elements for this type of discrimination.

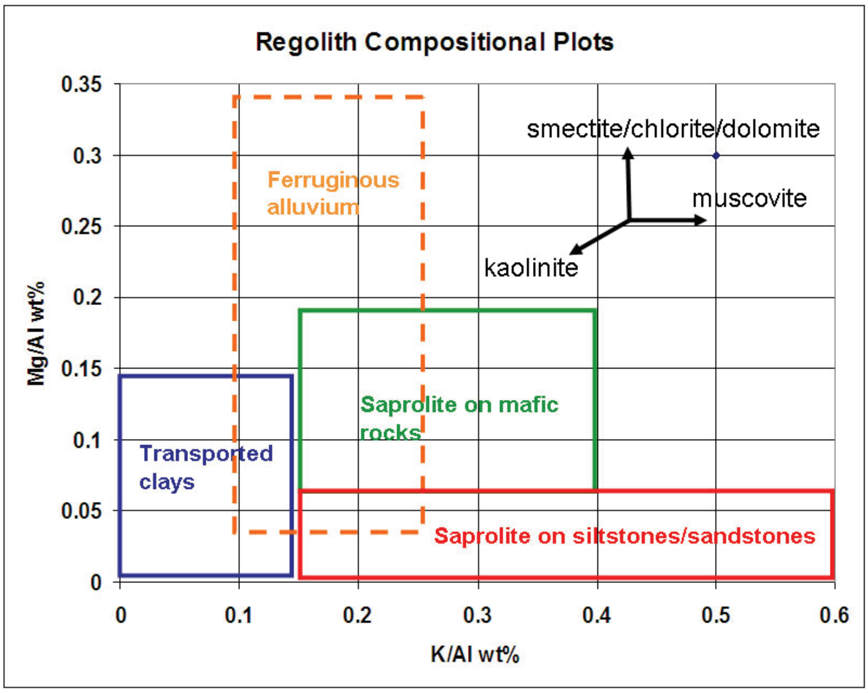


Figure 15. Geochemical template showing the typical range in K/Al and Mg/Al for different regolith materials in the Girilambone region.

This approach is particularly helpful in distinguishing the transported lake clays, which have very low K/Al ratios (<0.15) from clay-rich saprolite (Figure 16). These can be difficult to distinguish in drill cuttings. The younger, ferruginous sediments can also be distinguished.

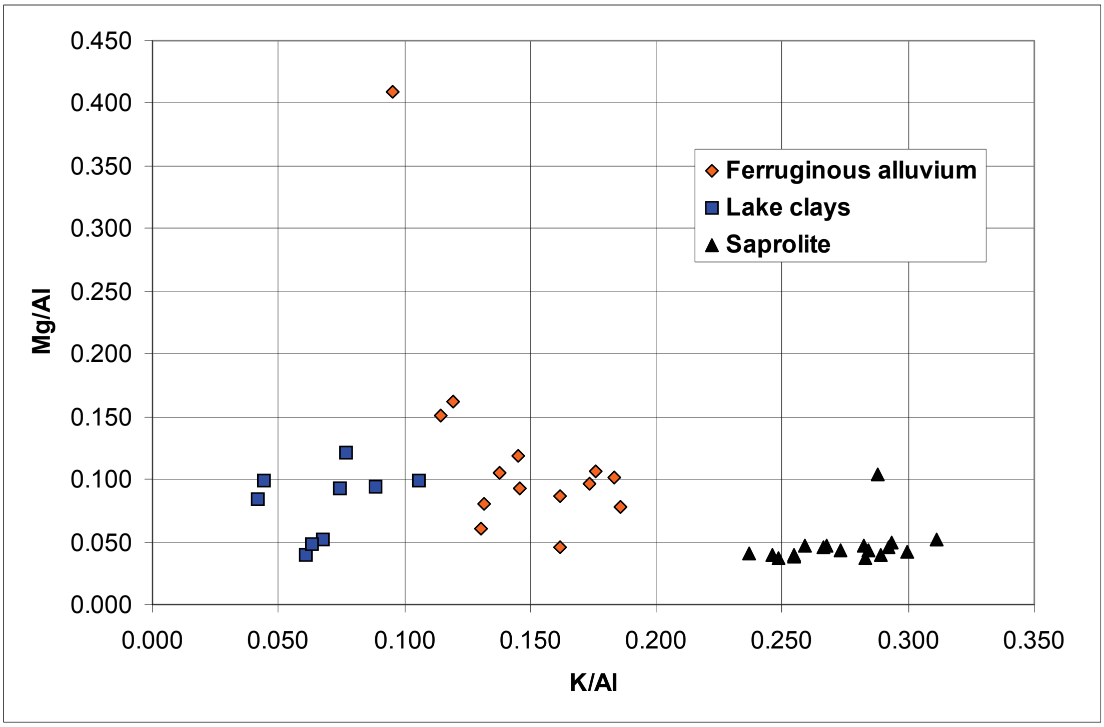


Figure 16. Plot of Mg/Al and K/Al ratios (wt% basis) for different well characterised regolith materials. Samples are from drill holes BRAC1, CBAC215 and CBAC217 (analysis by XRF).

The different mineralogical and chemical compositions of these materials reflect their different regolith history. The lacustrine clays were deposited in the Late Mesozoic to Early Cenozoic and were derived from a deeply weathered landscape. They were well sorted during erosion and transport to produce a kaolinite-smectite-quartz dominant sediment. The saprolite/saprock contains significant muscovite and illite, which have been variably weathered to kaolinite, depending on degree of *in situ* weathering and depth in the profile. The younger alluvium/colluvium was deposited in the later Cenozoic, when the climate was significantly drier and chemical weathering less intense. Erosion of less weathered profiles, more limited sorting and low levels of post-depositional weathering produced material that retained significant amounts of weakly weathered phyllosilicates. These sediments can also contain local concentrations of dolomitic calcrete, which is then apparent in their Mg/Al ratio. There is some compositional overlap between the three materials and the clearest distinction is between saprolite and transported clays.

The distribution of iron oxide/oxyhydroxides in the regolith reflects zones where soluble ferrous iron has been oxidised and fixed as ferric iron in the profile. This generally occurs above the water table, but the resulting goethite and hematite concentrations may survive periods of higher water table level. The distribution of total Fe in the regolith of the Girilambone region shows that high Fe contents (>10%) are restricted to the top 30 m of the profiles, including ferruginous concentrations in transported regolith (Figure 17). Regolith profiles with high Fe concentration are more common on the Byrock, Sussex, and Coolabah sheet areas, whereas profiles in the southern Hermidale sheet area are typically not as Fe-enriched. This probably reflects variations in bedrock lithology (more abundant Fe-bearing mafic rocks in the north) and greater concentration of ferruginous pisoliths in transported regolith in the central and northern parts of the terrain.

Manganese shows similar redox behaviour to Fe but is stable in solution over a wider Eh-pH range. This can allow Mn to remain in solution and separate from Fe that has precipitated as goethite and hematite under oxidising conditions. A further increase in Eh or pH can then cause formation of stable Mn oxides and oxyhydroxides or carbonates. This could occur at water table positions, particularly if conditions at or above the water table were moderately alkaline. The broad distribution pattern of Mn in regolith profiles across the Girilambone region shows that Mn enrichments (Mn>2000 ppm) occur below 10 m depth in the Byrock and Hermidale sheet areas and in the top 20 m in the central Sussex-Coolabah area (Figure 17). These zones of Mn enrichment are more common in the Byrock area and appear to represent paleo-water table positions. The uppermost concentrations possibly mark stillstands in the water table at a time when groundwaters were becoming increasingly alkaline (e.g. from the Late Miocene).

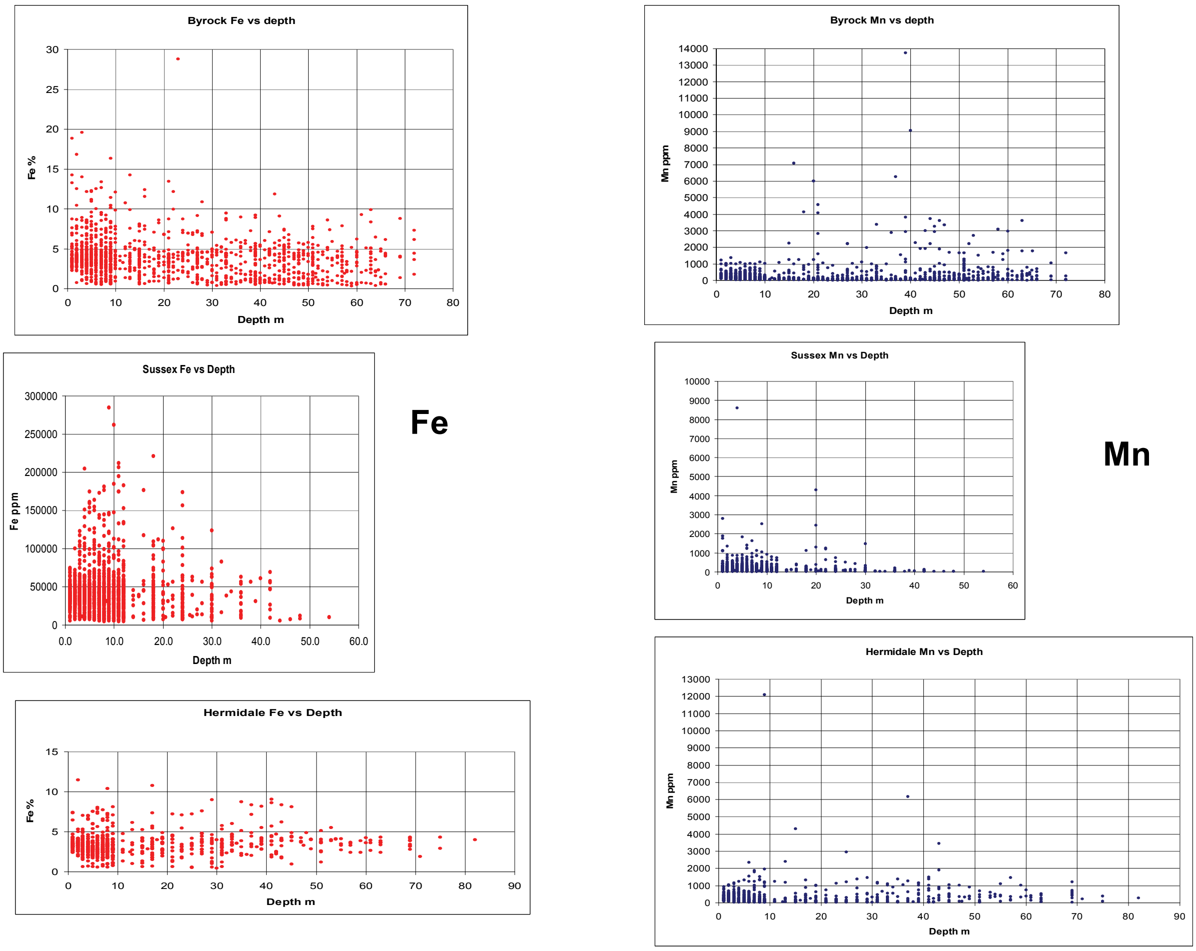


Figure 17. Plots of Fe and Mn content versus depth for all analysed regolith samples from the Byrock, Sussex-Coolabah and Hermidale areas of the Girilambone region. Most samples analysed by ICP OES following multi-acid digest. Bottom of hole samples analysed by XRF.

4.2 Regolith element associations

Specific regolith processes have generated a number of element associations and concentrations in regolith materials of the Girilambone region. Some of these give rise to highly variable background levels for ore and pathfinder elements in different parts of the regolith, which may be confused with ore-related anomalies. The main associations are:

- an "evaporative" association of Ca-Mg±Au, in some cases with Ba-Sr, related to regolith carbonate and barite accumulation in the near-surface regolith and at the base of palaeochannels and transported regolith;
- an association of Mn-Co-Zn±Ni-Cu±Au developed in redox boundary accumulations of manganese oxides/oxyhydroxides (particularly lithiophorite), commonly at around 20-30 m and at the present, deeper water table;
- an association of Fe-Cu-Zn with goethitic accumulations in the regolith;
- an association of Fe-As-Pb±Sb±Bi with hematite, particularly in ferruginous lag, palaeochannel sediments containing ferruginous lag and in hematite rich mottles in the upper saprolite.

These and other regolith-controlled element associations can account for some of the background variation encountered when sampling the regolith of the region. They need to be taken into account when determining threshold levels for anomaly definition. Using case studies from areas of known mineralisation, it is possible to construct geochemical templates for different regolith materials that identify trends in multi-element relationships reflecting mineralised environments as distinct from normal background regolith concentrations and variations. This information can also help in selection of the most appropriate sampling media for a given area and allow appropriate normalisation procedures to be applied to the data.

4.3 Primary rock indicators

Certain "immobile" elements (including Zr and Ti) have been widely used to help determine parent rock compositions or affinities in chemically leached *in situ* regolith (e.g. Hallberg, 1984). Zirconium and Ti are considered the least mobile elements during chemical weathering as they are typically fixed in resistate minerals such as zircon, rutile and ilmenite. Figure 18 shows a Ti vs Zr plot for some bottom of hole drill samples from the Girilambone region.

These plots are useful for grouping or subdividing saprolite compositions of variably weathered parent rocks and aiding identification of parent rocks for saprolite formed from igneous rock types. As most of the parent rocks in the Girilambone region are metasedimentary this plot will not identify these rock types but will reflect the composition of the original sedimentary provenance and any subsequent fractionation of Ti and Zr related to sedimentary processes. Ratios for granites from around Byrock plot in the dacite (granodiorite) field. A small number of samples plot in the field of mafic compositions and probably indicate mafic dykes intersected in the drilling program. High quality total rock analyses are required (XRF or INAA). Analyses based on multi-acid digest are not sufficient as resistate minerals such as zircon (containing most of the Zr) and rutile/ilmenite (containing significant Ti) will not be dissolved.

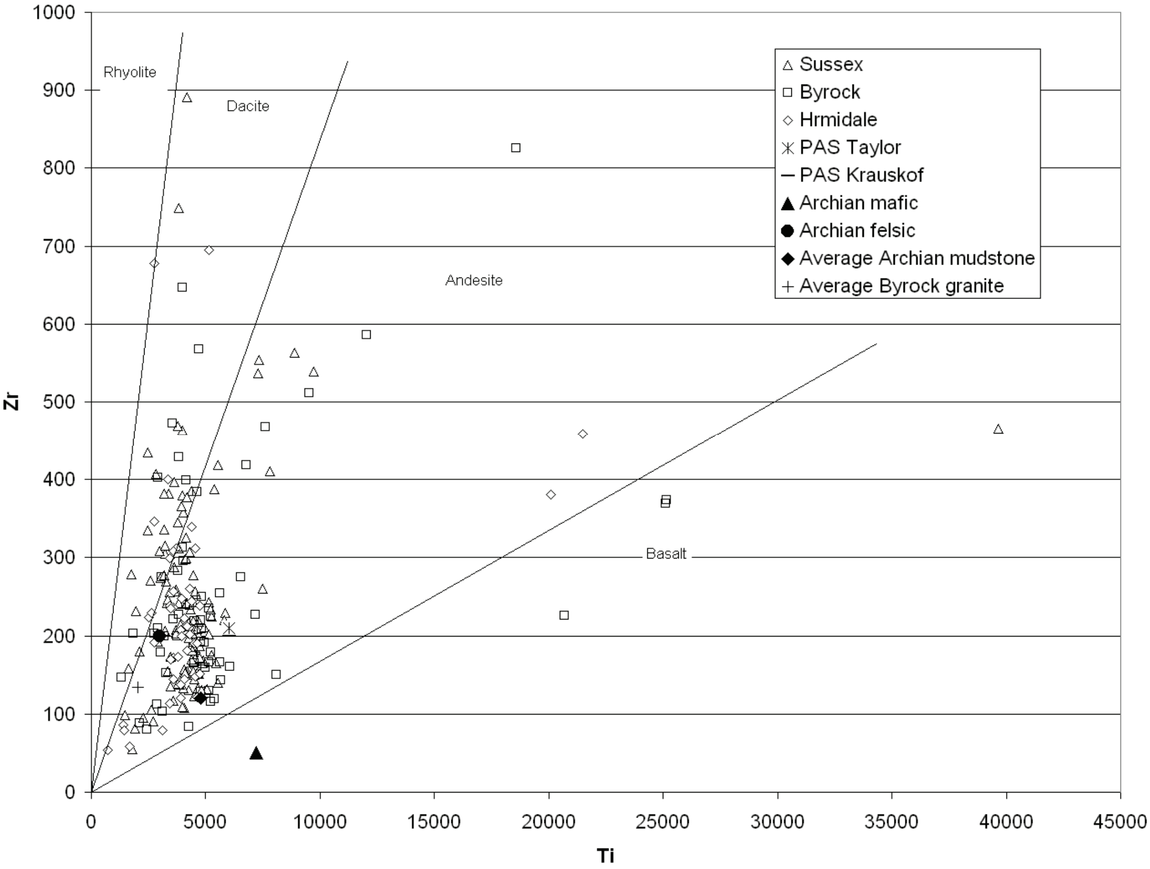


Figure 18. Ratios of Ti/Zr (wt%) for saprolite samples from the Hermidale-Byrock region. Fields for different igneous rock compositions are after Hallberg (1984) and values for post-Archaean Australian shale (PAS), Archean mafic, felsic and sedimentary rocks after Taylor and McLennan (1985). Ratio for average Byrock granites is from Blevin and Jones (2004a). Most saprolite compositions are after metasedimentary rocks and fall within the intermediate to felsic compositional range, reflecting original provenance composition. Analyses by XRF.

This approach to parent rock discrimination can be extended by including aluminium, which is generally the least mobile of the major elements. Inclusion of Al, for example in an Al_2O_3-TiO_2-Zr plot, allows characterisation of a wider range of parent rock compositions, including sedimentary and metamorphic rocks. Interpretation of compositional variation on this diagram is based on the premise that sedimentation involves weathering, transport, mixing from different sources and sorting. In the first three processes, the contents of insoluble elements such as Al, Ti and Zr may vary in response to the degree of leaching of the soluble elements. However, their relative proportions are transferred from the source area into the bulk sediment or regolith with little modification. This material is then sorted according to the hydraulic properties of its mineral components and the chemical fractionations between complementary shales and sandstone are generated. Other rock types such as felsic and mafic igneous rocks or immature volcanic-derived sediments plot in specific fields on the diagram.

Figure 19a shows the typical range of a variety of different rock types in terms of these parameters. Figure 19b is a plot of least weathered bedrock samples from the Girilambone region together with siltstones and shales from the CSA Siltstone unit of the Cobar Supergroup and known granites from the Byrock area. Most of the bedrock samples plot on the sandstone-shale fractionation trend with a wide range of TiO_2/Zr variation. Some samples plot in the granite compositional field (partly weathered granites) and some in the mafic igneous rock field (weathered mafic dykes). This approach can both characterise *in situ* regolith materials (saprock and saprolite) and identify the likely parent lithology, but requires total analyses for the three elements involved (XRF analysis or INAA).

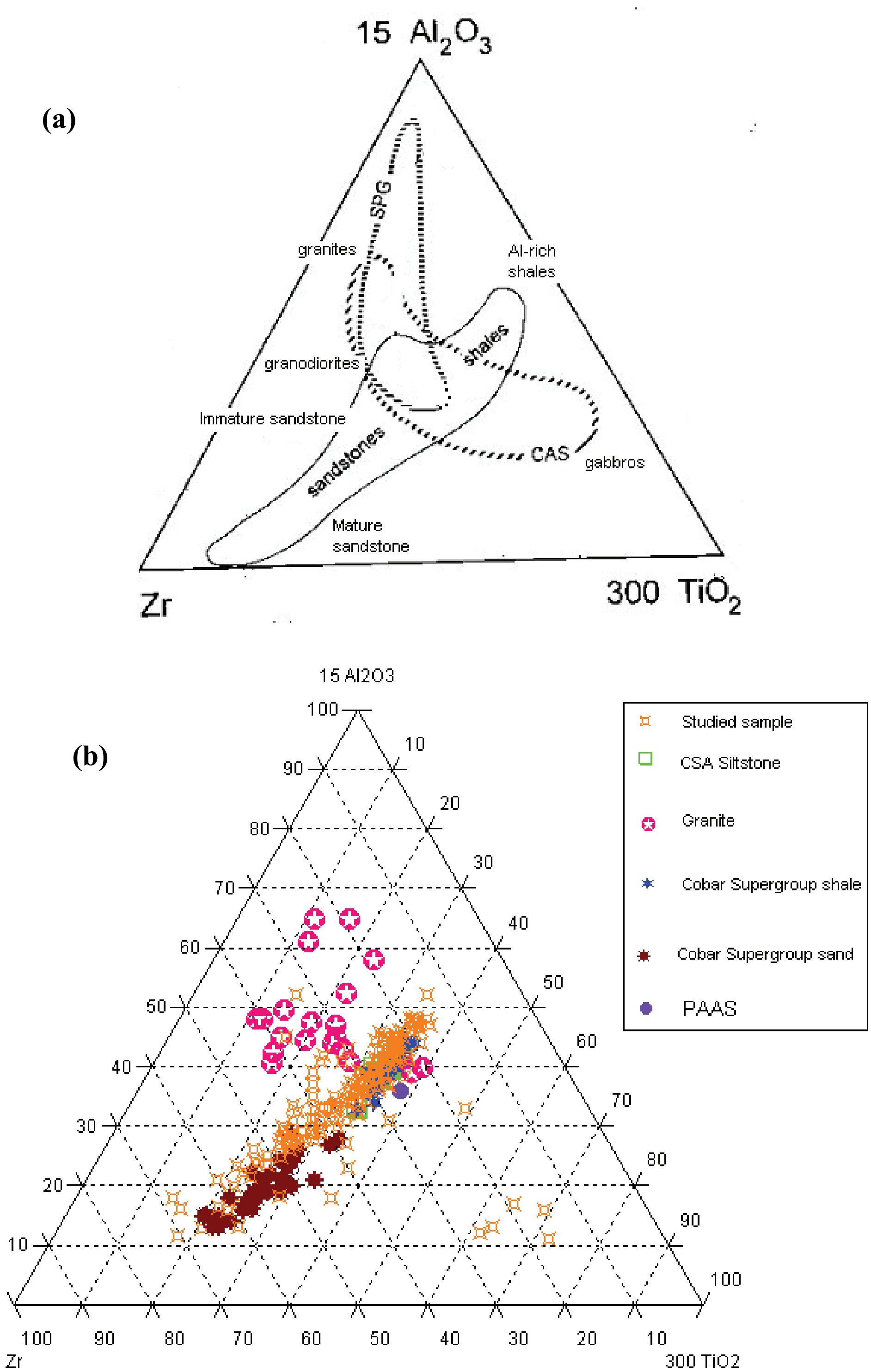


Figure 19. Al_2O_3-TiO_2-Zr diagram. (a) Compositional fields after Garcia *et al*, (1994) (SPG strongly peraluminous granite, CAS calc-alkaline suite). (b) Plot of studied bottom of hole samples from Hermidale-Byrock region and unweathered samples of shales and sandstones from the CSA Siltstone (Cobar Supergroup: Whitbread, 2004), granites from the Byrock area (Blevin and Jones, 2004a) and post-Archaean Australian Shale (Taylor and McLennan, 1985).

4.4 Provenance features of parent rock types

As part of the drilling program, bottom of hole (mostly saprock) samples were collected from each drill hole and subjected to whole rock XRF analysis for major elements and ICP OES/MS analysis of dissolved fusion disks for trace element (analyses performed at Geoscience Australia). Major element variations for these least weathered rocks were examined using the discriminant functions of Roser and Korsch (1988) to determine information about the provenance for the dominantly metasedimentary bedrocks (assuming minimal compositional changes to the sediments during metamorphism). The bulk data should reflect the average composition of rocks exposed to erosion at the time of deposition. The majority of samples plot in the intermediate igneous and quartzose sedimentary provenance compositional ranges with some in the felsic and mafic fields (Figure 20). This is broadly consistent with the Ti-Zr rations (Figure 18). There are some interesting differences in detail. Samples from the northern and central Byrock-Sussex-Coolabah sheet areas cluster towards the intermediate igneous provenance field with some samples falling in the mafic igneous provenance field (some of these samples are probably from mafic dykes or volcanic units). Samples from the Hermidale sheet area in the south appear to have a different provenance and are clustered in the top end of the quartzose sedimentary field. The reference Cobar Supergroup samples show a distinct compositional range within the quartzose sedimentary provenance and group most closely with the Hermidale samples. Reference granites from the Byrock area plot in the felsic igneous compositional range as expected. Some extreme outliers in the data probably represent altered/weathered samples.

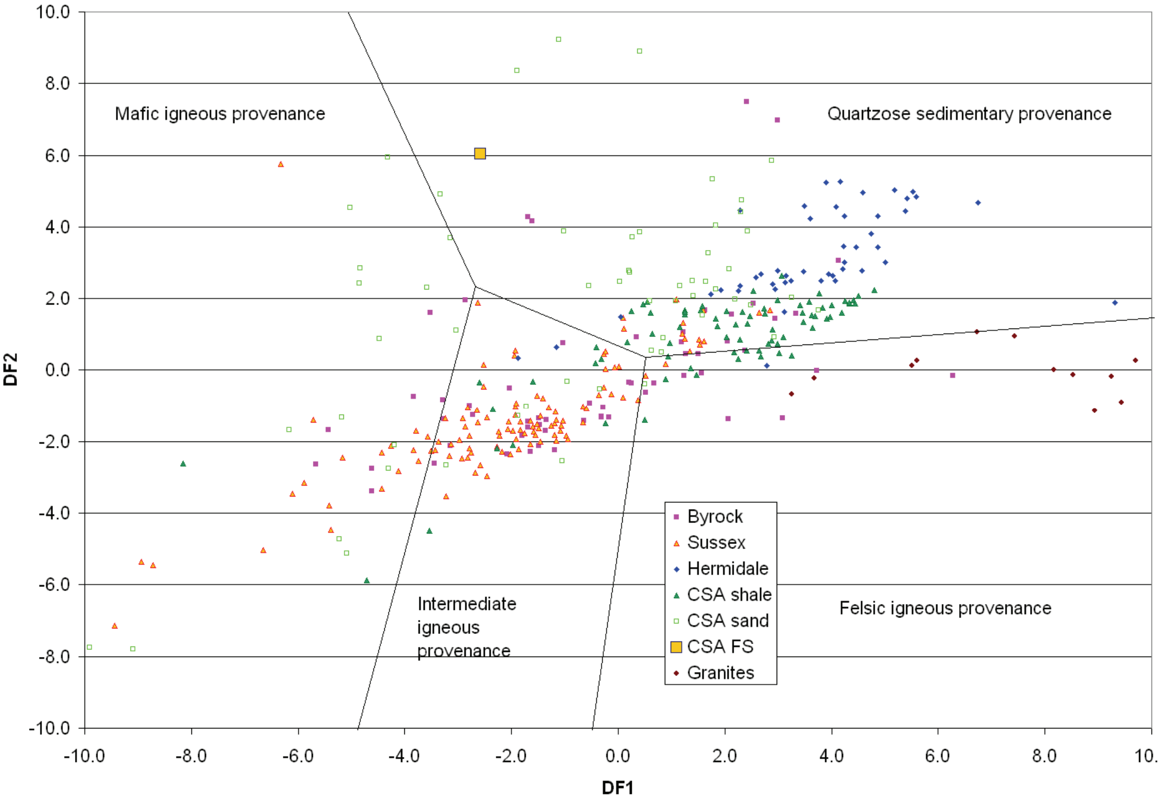


Figure 20. Major element provenance discriminant diagram for bottom of hole saprolith samples from the Girilambone region. Also included are some known bedrock types from the region. Discriminant functions and fields are after Roser and Korsch (1988). Granite data are from Blevin and Jones (2004a;b). Data for CSA shales and sandstones are from Whitbread (2004). CSA footwall siltstone (CSA FS) data are from Binns and Appleyard (1986).

$DF1=30.6038TiO_2/Al_2O_3-12.541Fe_2O_{3(total)}/Al_2O_3+7.329MgO/Al_2O_3+12.031Na_2O/Al_2O_3+35.42K_2O/Al_2O_3-6.382$.

$DF2=56.500TiO_2/Al_2O_3-10.879Fe_2O_{3(total)}/Al_2O_3+30.875MgO/Al_2O_3-5.40Na_2O/Al_2O_3+11.112K_2O/Al_2O_3-3.89$.

4.5 Degree of weathering and the chemical index of alteration

The trace element and mobile element content of regolith materials is affected by the degree of weathering and chemical leaching. This can be estimated from the relative proportion of alteration (weathering) minerals, the physical coherence of the weathered material and other signs of weathering processes such as bleaching and iron staining. The degree of chemical weathering can be calculated using the Chemical Index of Alteration (CIA: Nesbitt and Young, 1982). This index, CIA = 100 x $Al_2O_3/(Al_2O_3 + CaO + Na_2O + K_2O)$, reflects the breakdown of feldspars and mica to kaolinite, but it has a major drawback in that it estimates the total history of weathering from the primary source rock, i.e. including that already present in sedimentary rocks prior to further weathering. It is thus difficult to apply this index as a direct measure of the *in situ* weathering of a particular regolith sample. However, it is useful for comparing samples within profiles developed on a variably weathered common rock type. Figure 21 shows a plot of CIA values for variably weathered siltstone-sandstone bedrock down four combined profiles from the Byrock area. The plot shows that for these profiles the most intensely weathered material is in the top 10 m, with the least chemically weathered samples below 50 m.

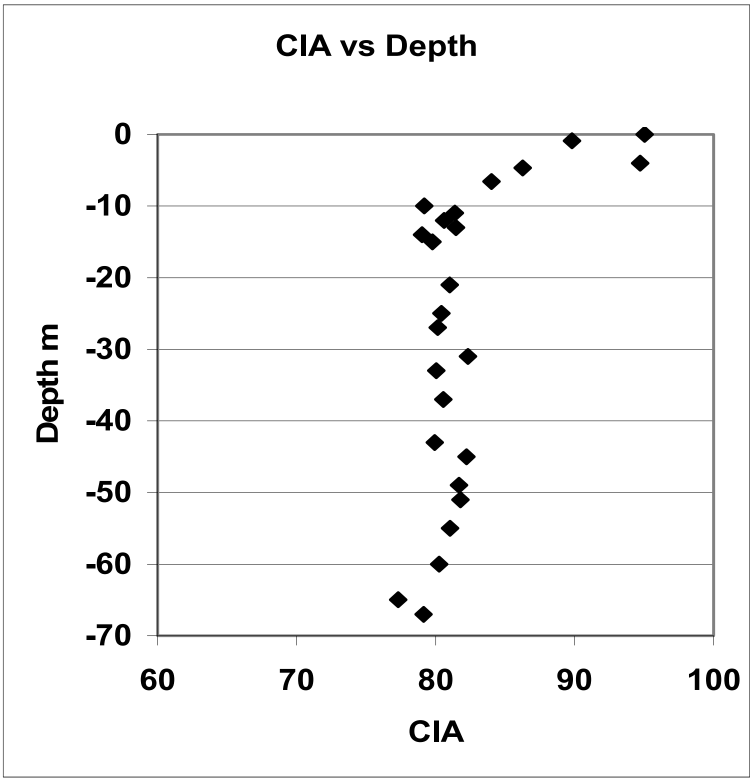


Figure 21. Chemical Index of Alteration (CIA) vs sample depth (below surface or unconformity with transported regolith) for variably weathered *in situ* saprolite samples from 4 profiles on siltstone-sandstone from the Girilambone region. Analyses by XRF.

The total history of chemical alteration (i.e. prior to sedimentary deposition and during subsequent weathering) can be explored diagrammatically on an Al-Ca+Na-K plot (Figure 22). This can highlight some of the mineralogical features of source materials and controls on final sediment and regolith compositions. The least weathered rocks from the Hermidale sheet area generally show much lower degrees of total chemical alteration (CIA<60) compared with those from the Sussex-Coolabah and Byrock sheet areas (CIA>60). This probably reflects different parent rock compositions and provenance for the metasedimentary rocks from the different areas. The sediments making up the Girilambone Group in the central and northern parts of the region appear to have been derived from an original mafic to intermediate compositional provenance (see section 4.4) but have undergone significant chemical recycling and now have a very chemically mature character (mostly within the muscovite kaolinite-gibbsite-chlorite-illite field). Their composition is not inconsistent with sediments derived by weathering of feldspar-rich material (i.e. along the ideal feldspar weathering line). The sediments from the Hermidale sheet area show a trend along the muscovite line indicating that they contain a significant muscovite component. They are most similar in composition to the sandstones of the Cobar Supergroup. The reference samples of unweathered Cobar Supergroup sediments (CSA shales and sandstones) show a strong trend towards muscovite, particularly in the finer shale fraction, consistent with a major muscovite component. They depart from the ideal feldspar weathering line. It is possible that some of the Byrock-Sussex saprolith samples are more weathered than true saprock but this alone cannot account for the significant difference in saprolith composition between the two areas.

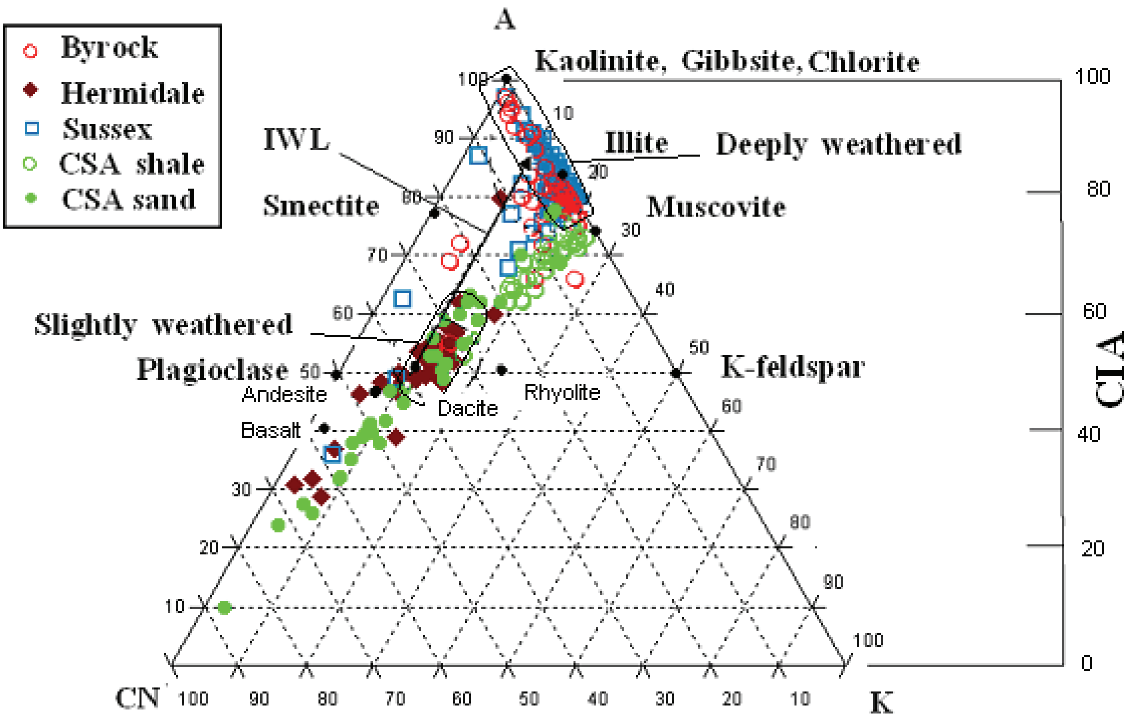


Figure 22. A-CN-K diagram (Nesbitt and Young, 1984) showing compositions for bottom of the hole samples from the Girilambone region. A=Al_2O_3; CN=CaO+Na_2O; K=K_2O (Molar proportions). Average values for basalt, andesite, dacite and rhyolite are from Roser *et al.* (2002). IWL is ideal feldspar weathering line.

Additional and more detailed information on the geochechemical characterisitics of the regolith in the Girilambone region are reported in Khider (2007).

5 REGOLITH AND LANDSCAPE EVOLUTION

Regolith materials contain important clues to the history of a landscape and the evolution of the regolith. Regolith and landscape evolution models can be useful tools for predicting physical and chemical dispersion processes and the resulting formation of geochemical anomalies. A model for the evolution of the Girilambone landscape and its associated regolith has been constructed from the results of regolith-landform mapping, drill hole information and observations of outcrops and exposures through the regolith (Figure 23). This model is partly constrained by dates for various regolith materials and landscape features (Table 2).

5.1 Early Jurassic

Weathering and ferruginisation.

Palaeomagnetic dating of oxidised saprolite at the New Cobar open cut mine to the west of the Girilambone study area indicates an episode of weathering-related oxidation and hematite fixation at approximately 180 Ma (Table 2). Preservation of this Early Jurassic weathering profile close to the present surface implies either prolonged exposure of this elevated site or possibly later burial and exhumation. Interpretation of apatite fission track data from five samples in the study area (Donelick and O'Sullivan, 2002; Table 2) indicates that the Hermidale and Sussex areas have been close to the surface (less than 1 km of cover) since at least the Early Jurassic.

5.2 Late Jurassic

Deposition of a fluvial sequence comprising sandstone, quartz-lithic conglomerate and minor mudstone with a southerly source. Ongoing weathering of bedrock in a temperate climate.

Topographically inverted remnants of Late Jurassic fluvial sandstones, quartz-lithic conglomerates and minor mudstones occur south of the Girilambone region in the Parkes area. These sediments have been dated by palynology as Late Jurassic, Surat Basin equivalent and have northerly palaeocurrent directions (Gibson and Chan, 1999a; b). They sit on top of the Canobolas Divide, at Killonbutta Forest east of Parkes and at Gunningbland and Milpose Gap to the west of Parkes. Sediments of similar appearance are widely scattered across the Girilambone and surrounding region (e.g. Gibson, 1999) and some of these deposits are possibly equivalent in age.

One example near Coolabah, comprises flat-lying sandstones, quartz-lithic conglomerates, and minor mudstones. This site is on a plateau on the north-south aligned drainage divide between the Mulga Creek and Bogan River catchments (Figure 4). The sediments are exposed in a borrow pit near the intersection of Coolabah Road with the Mitchell Highway and along the old railway cutting at Coolabah. A water bore for the railway at Coolabah revealed the sediments to be at least 30 m thick (Anderson, 1888). Clast orientations in the conglomerate and cross bedding in sandstones indicate northerly palaeocurrent directions. These sediments formed in a high energy, alluvial system with channels, perhaps separated by sand and mud bars.

Table 2. Summary of post-Palaeozoic age data for the Girilambone-Cobar region

Period	Age/Date	Method	Site	Material & Event/Environment	Reference
Mid Miocene	10±4 Ma	Palaeomagnetic	Elura backfill pit	Ferruginous mottles in saprolite. Deep oxidation/hematite fixation.	McQueen *et al*, 2007.
Mid Miocene	15±8 Ma	Palaeomagnetic	Wilga Tank leucitite	Weathering profile below leucitite flow. Deep oxidation/hematite fixation.	McQueen *et al*., 2007.
Mid Miocene	15±4 Ma	Palaeomagnetic	McKinnons open pit	Lower part of weathering profile. Deep oxidation/hematite fixation.	McQueen *et al*., 2007.
Mid Miocene	15.9±0.5 Ma	Radiometric Ar/Ar	New Cobar open pit	Coronadite-cryptomelane. Deposition of Mn oxides	Vasconcelos, 2004.
Early Miocene	17.1±0.20 Ma	Radiometric Ar/Ar	Wilga Tank leucitite plug 31º15.5' S 146º10.5' E	Leucite separate from leucitite. Leucitite eruption.	McQueen *et al*., 2007.
Early Miocene	16.8±0.2 Ma	Radiometric K/Ar	Bye Hill leucitite 30º41' S 146˚21' E	Biotite from leucitite. Leucitite eruption	Sutherland, 1985.
Early Miocene	C subdivision P. tuberculatus Zone	Palyno stratigraphic	Bore 36937 'Glen Villa' Darling River	Valley-fill sands 56-57 m. Terrestrial forest with abundant Casuarinaceae and Myrtaceae	Martin, 1992.
Paleocene	60±10 Ma	Palaeomagnetic	Ballast Quarry W of Hermidale	Upper part of weathering profile. Deep oxidation/hematite fixation	M. Smith pers. Comm.. 2005.
Paleocene	60±10 Ma	Palaeomagnetic	Road cutting E of Cobar	Upper part of weathering profile. Deep oxidation/hematite fixation.	McQueen *et al*., 2002.
Paleocene	60±10 Ma	Palaeomagnetic	Elura fill pit	Ferruginous mottles in saprolite. Deep oxidation/hematite fixation	McQueen *et al*., 2002; 2007.
Paleocene	60±10 Ma	Palaeomagnetic	McKinnons pit	Upper part of weathering profile. Deep oxidation/hematite fixation.	McQueen *et al*., 2002; 2007.
Mid Cretaceous	Aptian-basal Albian	Palyno stratigraphic	Bore 36853 'Jandra' Darling River	Mudstone bedrock at 147.3 m. Terrestrial- with some marine influences, upper estuarine	Martin, in Mount, 1992.
Mid Cretaceous	Aptian (113-119 Ma)	Palyno-stratigraphic	Drill hole CBAC242 NE of Coolabah	Organic-rich micaceous clay at 51-52 m. Lacustrine deposition.	Macphail, 2004.
Early Cretaceous	Probably Aptian (possibly reworked)	Palyno-stratigraphic	Drill hole CBAC 216 SW of Byrock	Clay-silt at 19-21 m. Lacustrine deposition.	Macphail, 2004.
Early Cretaceous	(possibly reworked)	Palyno-stratigraphic	Drill hole CBAC 222 SW of Byrock	Compacted clay at 47-48 m Lacustrine deposition.	Macphail, 2004.
Early Cretaceous	(possibly reworked)	Palyno-stratigraphic	Drill hole CBAC226 SW of Byrock	At 47-49 m depth.	Macphail, 2004.
Early Cretaceous	(possibly reworked)	Palyno-stratigraphic	Drill hole CBAC236 SW of Byrock	At 41-43 m depth.	Macphail, 2004.
Cretaceous	(uncertain age and location)	Palaeontological (foramanifera)	65 km west of Cobar	Thin flat capping of white sandstone. Possible marine deposition.	Rayner, 1969.
Mid Jurassic	180±10 Ma	Palaeomagnetic	New Cobar open pit	Highly ferruginous weathering profile/gossan. Deep oxidation/hematite fixation.	McQueen *et al*., 2002.

Timescale used is Harland *et al*., 1982.

Similar alluvial sediments and associated lag of rounded quartz pebbles and cobbles also occur as inverted remnants on rises in the central-north of the Coolabah map sheet area. The preserved outcrop pattern (portrayed by the regolith-landform units, Aer2 and Aer3, on the Coolabah 1:100 000 regolith-landform map) indicates a former dendritic drainage system with preserved drainage lines from 0.5 km wide in the upper reaches to 3 km wide in the lower reaches. However, widespread quartz-lithic sediments and quartz lag (Aep2 and Aep3), on the surrounding erosional plains indicate either a much wider depositional zone or an area of secondary redistribution.

Gibson (1999) has recorded similar inverted relief outcrops on both sides of all major drainage divides over the Cobar Uplands. This indicates a widespread north-flowing drainage system prior to the initiation of these divides, which may correlate with the maximum fluvial deposition in this region from 150 Ma to 148 Ma (Jurassic Time Slice 9, Palaeogeographic Atlas of Australia).

5.3 Earliest Cretaceous

Incision of saprolite to form relatively steep-sided, deep valleys, with topographic inversion of fluvial sediments, during a period of rapid sea level fall. Sediment exported from the catchment.

A rapid decrease in global sea level in the Earliest Cretaceous probably led to erosion of the older fluvial sediments and incision of saprolite, together with the export of sediments from the catchment (Figure 24). Erosion of the saprolite formed steep-sided deep valleys, such as the 5° slope between drill holes CBAC223 and CBAC224 in the Byrock area. The location of some deep narrow palaeovalleys (e.g. at CBAC221, CBAC226 and CBAC228) seems to relate to preferential erosion of less resistant bedrock material, such as shales and slates. Palaeohighs developed over more resistant rocks and areas of strong quartz veining (e.g. around CBAC229, CBAC230, CBAC245 and CBAC246). However, some deep narrow palaeovalleys are coincident with magnetic basement linears (Fleming and Hicks, 2004), and some palaeovalleys terminate abruptly in cross-section, (e.g. at CBAC13 and CBAC14; Figure 8). Their form may reflect faulting at a later stage (see below).

5.4 Early Cretaceous

Deposition of a proximal estuarine-marine and fluvio-lacustrine sediment sequence (clay, and minor quartz silt-sand-gravel) in a seasonally wet to very wet and cold climate.

Many of the drill holes across the study area intersected grey-white clays, mostly in the lower parts of palaeovalleys, but also exposed at or near the surface in the Sussex and Coolabah map areas (e.g. CBAC90 and CBAC96). The lowest elevation recorded for these clays is 82 m a.s.l. (CBAC236 at end of hole) and the highest elevation 230 m a.s.l (CBAC161 at 8 m depth). These clays have some inter-beds of coarser sediments, White sands and rounded quartz gravels were observed in drill holes CBAC237 (5 m thick) and CBAC228 (4 m thick), and a silt-sand in CBAC235 (3.5 m thick) – Appendix 1. The coarser fraction is interpreted as a fluviatile component in a package dominated by still water sediments. A ferruginous clay, silt, sand layer in CBAC228 may represent a buried palaeosol. This layer (at 23-25 m depth) overlies a coarsening up sequence (pale grey silt and clay, grading to white well-rounded very coarse quartz sand) and is below a fining up sequence (pale grey to white silt grading to dark grey clay; Appendix 1). A coarsening upward sequence (clay to silt) overlain by a fining upward sequence (silt to clay) was also observed in drill hole CBAC221 and may indicate regressive/trangressive intervals or, a change in sediment supply; possibly climate induced and possibly modulated by an internal catchment threshold. Isolated quartz clasts (medium to coarse sand size) in some clay units, may indicate vegetation rafting or occasional debris flows in a near shore environment. Many other clays have dispersed matrix-supported quartz grains (very fine to fine sand size), perhaps indicating further distance from shore or deposition in the tail of a debris flow.

Many clay and silt samples were checked for pollen and other palynomorphs but most were too oxidised for pollen preservation, especially in the higher terrain in the south of the area. However, there are a few indicative results which show that this sediment sequence does not equate to the Tertiary Lachlan Formation as surmised in an earlier Girilambone Project report (Chan *et al.*, 2003a). Early Cretaceous (Aptian) palynomorphs indicative of a freshwater pond or lake were found in micaceous silty clay at 51-52 m in drill hole CBAC242 (Appendix 4) on the western edge of the present Bogan River floodplain in the Coonamble Embayment. This sample may be correlated either with the Doncaster Member of the Wallumbilla Formation or the Minmi Member of the Bungil Formation within the Surat Basin (unpublished report, Macphail, July, 2004). An Aptian age was also obtained for a sample from 19-21 m in CBAC216 (Appendix 4), west of Tindarey Creek. Pollens and spores with wider age ranges (Late Jurassic to Early Cretaceous) were found at 41-43 m in CBAC236, at 47-49 m in CBAC226, and at 47-48 m in CBAC222, though the identification confidence rating is low (Appendix 4). Macphail (unpublished report, July 2004) notes that marine indicators are absent, and that microfloras in these drill hole samples are depauperate versions of that found in CBAC242 and therefore might represent the same Doncaster and/or Minmi Members. Two samples in CBAC236 (from 23-24 m and 24-25 m) yielded Early Cretaceous pollen and spores, and marine dinocysts in the 23-24 m sample (Macphail, pers. com., September 2004).

The microfloras found in the above drill hole samples are considered to be coeval with the sampled units (i.e. not recycled from older sediments), based on:

- the retention of fragile features of gymnosperm pollen that are unlikely to survive long distance transport or prolonged weathering, e.g. sacci or air bladders (Macphail, 2004);
- the consistency of the age of the palynomorphs across the area at different elevations, as well as for higher and lower levels within the sequence profile;
- the lack of any Cenozoic palynomorphs.

Other evidence consistent with the sediments being older than Miocene and probably Mesozoic includes:

- the presence of deep water marine Mesozoic mudstones of the Great Artesian Basin overlying fluvial sandstone about 32 km north of Byrock (Mount, 1992);
- petrographic characteristics of the sediments indicating a low energy environment of deposition and lack of subsequent deformation (Fleming *et al.*, 2001);
- the likely existence of palaeovalleys in the Mulga Creek – Tindarey Creek area in Mesozoic times based on palaeotopographic mapping (Duk-Rodkin *et al.*, 2004);
- a minimum age of late Early Miocene as indicated by overlying and intruded leucitites dated at this age.

Elsewhere in the region, Aptian to basal Albian ages are indicated for a core sample from 147 m depth in Bore 36853 (NSW Department of Water Resources bore hole; Martin: cited in

Mount, 1992) at Jandra on the Darling River, between Yanda and Mulga Creeks about 70 km north-northwest of Byrock. These ages are based on abundant spores and pollen, which together with relatively few dinoflagellates indicate dominantly terrestrial deposition, possibly with some marine influence (Martin: in Mount, 1992). Martin suggests the upper reaches of an estuary, subjected to inundation from occasional high tides as a likely environment. A similar proximal estuarine environment of deposition is highly plausible for parts of the Girilambone study area. Several periods of transgression and regression, or alternatively one major period with fluctuations are indicated by the multiple and alternating fining up and coarsening up sequences capped by palaeosols. As there is evidence for both terrestrial (including fresh water) and marine environments of deposition, it is likely that these Early Cretaceous sediments belong to the Minmi Member of the Bungil Formation of the Surat Basin, which incorporates both coastal plain and marine shelf depositional environments. The Doncaster Member of the Wallumbilla Formation is dominated by a marine shelf depositional environment (Raza *et al.*, 1995).

The spore-pollen dominant nature of the sample from CBAC242 indicates a seasonally wet to very wet and cold environment with the source vegetation being an early Austral Conifer Forest. A close modern analogue is the boreal conifer woodland growing close to the Arctic Circle in North America (Macphail, 2004). A few isolated large rounded quartzite boulders to 1 m in size rest on the surface 64 km west of Cobar near a cutting on the old alignment of the Barrier Highway at "The Meadows". The cutting exposes almost flat-lying sandstones, dated as Early Cretaceous from foraminifera (Ludbrook: in Rayner, 1969), and conglomerate beds with isolated quartzite boulder clasts up to 1 m. These sediments unconformably overlie Devonian saprolite (Gibson, 1999). The large isolated boulders could have been deposited by ice rafting in a river system or by a high energy flood event.

Remnants of the grey-white clay sequence are found at elevations up to 230 m a.s.l. (in CBAC161). Reworked clays are preserved up to 285 m a.s.l. (CBAC171 at 7 m depth), and in many locations between 226 m a.s.l. and 232 m a.s.l. in the Sussex, Coolabah and Hermidale sheet areas (CBAC14, CBAC17, CBAC18, CBAC146, CBAC148, CBAC181, CBAC182). Since these clays are widespread and overlie the older primary grey to white clays, it is likely that they were redeposited from eroded older clays at higher elevations.

The formation of deep pallid zones in saprolite beneath palaeovalleys containing clay sediments may have been initiated by acid leaching in an estuarine environment, such as tidal flats, in the early stages of a fluctuating marine transgression. This acid leaching could have resulted from the alternate formation of authigenic sulfides under reducing conditions and later oxidation during exposure, resulting in acid sulfate weathering in the underlying saprolite (Worrall and Clarke, 2004).

In summary, proximal estuarine-marine and fluvio-lacustrine sediments (clay, and minor quartz silt-sand-gravel) were deposited in the Girilambone study area during the Early Cretaceous. Deposition was probably associated with the transgressive maximum in the Eromanga Basin (119 – 114 Ma; Cretaceous Time Slice 4, Palaeogeographic Atlas of Australia). During this time much of the study area would have been below or close to sea level. The minimum water level was probably about 230 m above present seal level as indicated by the present elevation of estuarine/lacustrine deposits adjacent to marine sediments in the northern part of the region (assuming no post-Cretaceous uplift). The climate would have been cold and seasonally wet to very wet.

5.5 Late Cretaceous to Early Miocene

Substantial erosion of the Early Cretaceous sediments and partial exhumation of the buried palaeotopography with minor erosion of the harder underlying bedrock. Continued erosion of higher elevation Jurassic fluvial sediments with further inversion of relief. North-south aligned faulting forms a tectonic depression which deepens to the north and preferentially preserves Early Cretaceous sediments in the Mulga-Tindarey palaeovalley system. Lowering of the water table, and ensuing weathering and ferruginisation of both sediments and exposed bedrock, especially on lower valley sides in a seasonally dry climate.

Remnants of the Early Cretaceous sedimentary sequence at the base and lower sides of palaeovalleys, especially in the Sussex- Coolabah area (e.g. CBAC78 and CBAC79; Figures 6 and 7), and variability in elevation of the top of the preserved sequence over short distances in the Byrock area (e.g. between CBAC219 and CBAC224; Figure 5) indicate a major period of erosion of these sediments. Also, there are numerous dry valleys that cut ridge crests in the higher parts of the Sussex and Coolabah areas. These saddles or wind gaps appear to be unrelated to bedrock lithology and structure, and may represent an older drainage superimposed from a sediment cover onto an exhumed underlying bedrock palaeotopography.

West of the possible Late Jurassic sediments at Coolabah there are dated Early Cretaceous sediments (grey-white clays) at very low elevations in the bottoms of deep palaeovalleys (Mulga palaeovalley system). This “low elevation” zone can be seen along the Coolabah Road between about 21 km and 46 km west of the plateau at Coolabah (220 m a.s.l.). Two major concealed faults diverging to the north, as mapped on the 1:2 500 000 Geological Map of NSW (1998), coincide with this low elevation zone. The north-trending fault on the eastern side of this zone is the Gilmore Suture (Glen *et al.*, 1996). Drill hole CBAC99 was collared in this depressed zone at 174 m a.s.l.. The base of Early Cretaceous sediments in the underlying palaeovalley is at 152 m a.s.l.. Further north, the north-northwest-trending fault on the western side of this zone is aligned with the western edge of the Tindarey palaeovalley system (Figures 5 and 25). It is possible that this depressed zone was down-faulted sometime after the Early Cretaceous. There are no fluvial, quartz-lithic sands and gravels, similar to those of possible Jurassic age at Coolabah, beneath the Early Cretaceous sediments in any of the palaeovalleys drilled to the west of Coolabah, or to the south in the other two drill hole traverses transecting the Mulga palaeovalley system, Also there are no locally derived colluvial sediments beneath the Early Cretaceous sequence, as might be expected if the steep sides of a faulted depression were eroded and reworked into the consequent valley. The western edge of the high bedrock zone between the Mulga and Tindarey palaeovalley systems in the Byrock regolith section (CBAC229 to CBAC234, Figure 5) also appears to have been faulted or tectonised. Breccias and highly silicified rocks were intersected in CBAC227 and CBAC229 respectively.

From the Late Cretaceous to the Palaeocene sea level continued to fall from its maximum level in the Early Cretaceous and the climate became warmer (“Australia Through Time”, AGSO poster, 1998; Figure 24). Palaeomagnetic dates of 60±10 Ma for weathering profiles in the Cobar area (McQueen *et al.*, 2002; 2007) indicate conditions favourable for hematite fixation and preservation in the Paleocene. This would be consistent with strong oxidation of the upper parts of weathering profiles associated with the lowering of regional water tables. Ferruginisation would have been prevalent on the lower valley slopes where iron-rich groundwaters permeated saprolite and sediments close to the land surface. Palaeobotanical evidence (Macphail, 2000) suggests a pronounced seasonality in rainfall during this period which may have led to the water table height fluctuating about the lowering trend. Lowering of the water table and continued weathering in the Miocene lead to further development and leaching of profiles. As the deeply and highly weathered bedrock beneath the clay-rich sediments was exposed it was progressively eroded and transported out of the system.

5.6 Late Early Miocene to Mid Miocene

Eruption of leucitite lava flows over the remnants of Early Cretaceous sediments, weathering profiles and bedrock. Continuing erosion and weathering, including ferruginisation in a drier phase of a warming climate.

Leucitite lavas erupted in the Sussex and Byrock areas during the Miocene. Radiometric dating of samples from Bye Hill (8 km southwest of Byrock village), El Capitan 15 km southeast of Tindarey Creek headwaters in the Sussex area) and near Wilga Tank (8 km south of El Capitan) indicate ages close to 17 Ma (Table 1). At Bye Hill lavas erupted through clays of the Early Cretaceous sequence and deposited a basal hyaloclastite (water-borne volcanic ejecta) layer on the clays (CBAC235 and CBAC236) beneath the lava. Drill hole CBAC235 intersected 17 m of fresh to moderately weathered leucitite over 6 m of hyaloclastite. In the El Capitan and Wilga tank areas leucitite flows issued from local vents, infilled shallow valleys and covered thin alluvial sediments. There is evidence of flow inflation at El Capitan and Bye Hill (McQueen *et al.*, 2007; Glanville, 2003; Gonzalez, 2001)

At Wilga Tank, high on the present drainage divide, fresh leucitite partially overlies mottled saprolith and a thin deposit of quartz gravels (McQueen, 2004). The mottling has been palaeomagnetically dated at 15±8 Ma (McQueen *et al.*, 2007). The quartz gravels overlying the weathered profile do not contain any ferruginous mottle fragments, which could suggest hematite fixation in the profile after the gravels were deposited and possibly after leucitite eruption. This would be consistent with drying out of a well-developed profile significantly later than its initial formation. This 15±8 Ma hematite fixation event has been recorded at a number of sites in the Cobar-Girilambone region (McQueen *et al.*, 2007).

The continuing trend to a warmer and drier, though seasonal, climate through the Miocene (Figure 24) resulted in further lowering of the water table, probably with fluctuations due to seasonality. This is consistent with oxidation of iron in the regolith, particularly along drainage lines where groundwater flow paths are close to the land surface (Chan *et al.*, 2003a).

5.7 Late Miocene to Early Pliocene

Continued erosion leads to further stripping of the Early Cretaceous sediments and weathered bedrock, resulting in the formation of shallow valleys as well as inversion of relief. The climate continued to be warm but for a short time became wetter.

In the Byrock area the palaeo Mulga Creek was diverted to the east of Bye Hill due to the lava mound blocking its path (Glanville, 2003). Erosion stripped the lava from the eastern side of the mound exposing the underlying hyaloclastite (e.g. at CBAC236). Mulga Creek continued to migrate to the east, further eroding the underlying Early Cretaceous sediments (compare base of younger sedimentary sequence in CBAC237 and CBAC236).

Broad relatively shallow valleys formed in the underlying Early Cretaceous sediments. The thalwegs of some of these valleys are displaced laterally with respect to the thalwegs of the pre-Cretaceous valleys (e.g. at CBAC237 and CBAC93) and some thalwegs remain coincident, (e.g. at CBAC226 and CBAC210). Leucitite lavas in the Bye Hill and El Capitan areas and ferruginous indurated regolith were more resistant to erosion than the surrounding older weathered bedrock and sediments and became inverted in relief. Exposed saprolite was also subjected to erosion.

Regional trends suggest that the climate during this period continued to be warm but became wetter for a period in the Early Pliocene, possibly resulting in greater erosion rates for a short time (Figure 24; Martin, 1991).

5.8 Late Pliocene to Holocene

Progressive change from a warm wet climate to a drier more arid climate results in falling water tables and decreasing stream capacity. Streams become choked with colluvial-alluvial sediments, including redeposited grey to white clays, and magnetic ferruginous pisoliths. Extensive lag deposits develop on the lower valley slopes. There is widespread accession of aeolian dust in the form of clay and quartz silt, which is incorporated into soil profiles throughout the area due to bioturbation and pedogenesis. Increased aridity is accompanied by widespread calcrete induration of saprolite and younger sediments. There is some neotectonic activity.

The change to a drier climate in the Late Pliocene with an essentially modern rainfall regime (Macphail, 2000; Figure 24) resulted in falling water tables and a significant decrease in stream capacity. Lowering of water tables resulted in ferruginous induration on lower valley slopes and local siliceous induration where drainage was impeded. Streams became choked with sediment eroded from less vegetated areas. Ferruginous lag and silcrete, where present, protected the underlying sediments and saprolite from erosion. Colluvial and aeolian processes dominated as the climate becomes more arid. Interspersed alluvial deposition largely resulted from flash flooding.

The colluvial-alluvial sediments deposited in the valleys typically consist of ferruginous pisoliths, lithic fragments (which may be ferruginised), quartz pebbles and granules, sand, and minor silt and clay. Additional silt was incorporated into the upper profile at a later stage (see below). Some ferruginous material (hematite-goethite) was converted to maghemite during surface exposure. Each layer of magnetic, maghemite-bearing sediment in the drill hole profiles may represent the first depositional event in a new erosion cycle within the local catchment, or perhaps a migrating channel. As infill proceeded, much of the sediment was redistributed, depositional plains were extended and rises and ridges were overtopped and buried. This is particularly evident in the Hermidale area which has enlarged catchments. However, all of the sediments deposited at this time have a local source constrained by the east-west aligned Canobolas Divide in the south and the north-south aligned Bogan River-Mulga Creek drainage divide through the centre of the study area.

Significant layers of grey to white clay occur within the younger colluvial-alluvial sequence in or adjacent to the higher eroded terrain of the Sussex, Coolabah and Hermidale areas, but not in the Byrock area. These clay sediments are interpreted to be eroded from inverted relief remnants of lacustrine clays and redeposited as clay glaebules in the colluvium and alluvium. It is unlikely that these grey to white clays are recently eroded saprolite deposited in a reduced environment, because they are not present in the lower elevation colluvial-alluvial sequence in the Byrock area (Figure 5). They are very similar, petrographically to the primary older clays from which they are believed to have been derived, but are distinguished by their association with underlying maghemite, and by their distinctive PIMA properties (see Appendix 1).

There is some evidence for tectonic activity in and around the study area during this period. In the Byrock area a northeast trending fault apparently controls palaeodrainage containing maghemite (Fleming and Hicks, 2003). To the west of the study area and north of Cobar, Ford (1996) also describes a north trending linear zone associated with the Rookery Fault, which is about 1 km wide up to 60 m deep and infilled with grey to white sandy plastic clays and layers of ferruginous gravel, mainly above, but also below the clay.

With increasing aridity carbonate was precipitated within the regolith. The resulting calcrete deposits commonly occur at the soil-saprock interface and in coarser sediments in the upper colluvial-alluvial sediment sequence, at and just below the sediment-saprolite boundary. Gypsum and minor alunite (e.g. CBAC235 and CBAC236) form in areas with high sulfate concentrations in the regolith.

Aeolian dust, mainly in the form of silt-size quartz particles (Tate *et al*., 2003; 2007) has been incorporated into the regolith profile across most of the Girilambone region landscape to a depth of 1-3m (Chan *et al.*, 2003a;b; 2004). These silts have been incorporated into sediments and soil profiles by bioturbation and pedogenesis. Prevailing wind directions throughout the Pleistocene imply that most of the aeolian dust in the Girilambone region was derived from the west. The immediate source area was most likely the Murray-Darling Basin, but the ultimate source area for much of this material was probably the Lake Eyre Basin, including the Simpson Desert, in Central Australia. There is at least a three-fold increase in dust influx, compared with the Holocene (10 Ka to present time) during the last glacial maximum (LGM; 18-20 Ka) due to weaker monsoonal rains and thus drier, not stronger, westerly winds (Hesse and McTainsh, 2003). Hesse and McTainsh (1999) suggest that the activation of desert dunefields during the LGM is due to a reduction in stabilizing vegetation.

The present water table, where encountered during drilling, ranges from 55 m (CBAC219) to 66 m (CBAC225) in depth beneath the Tindarey Creek palaeovalley in the Byrock area, and up to 27 m (CBAC242) on the western alluvial plains of the Bogan River. In the Hermidale area the water table depth ranges from 33 m (CBAC173) to 67 m (CBAC160). Two yellow clay, silt and sand layers at 11-12 m and 19-21 m depth in CBAC242 indicate higher previous stands of the water table for this site.

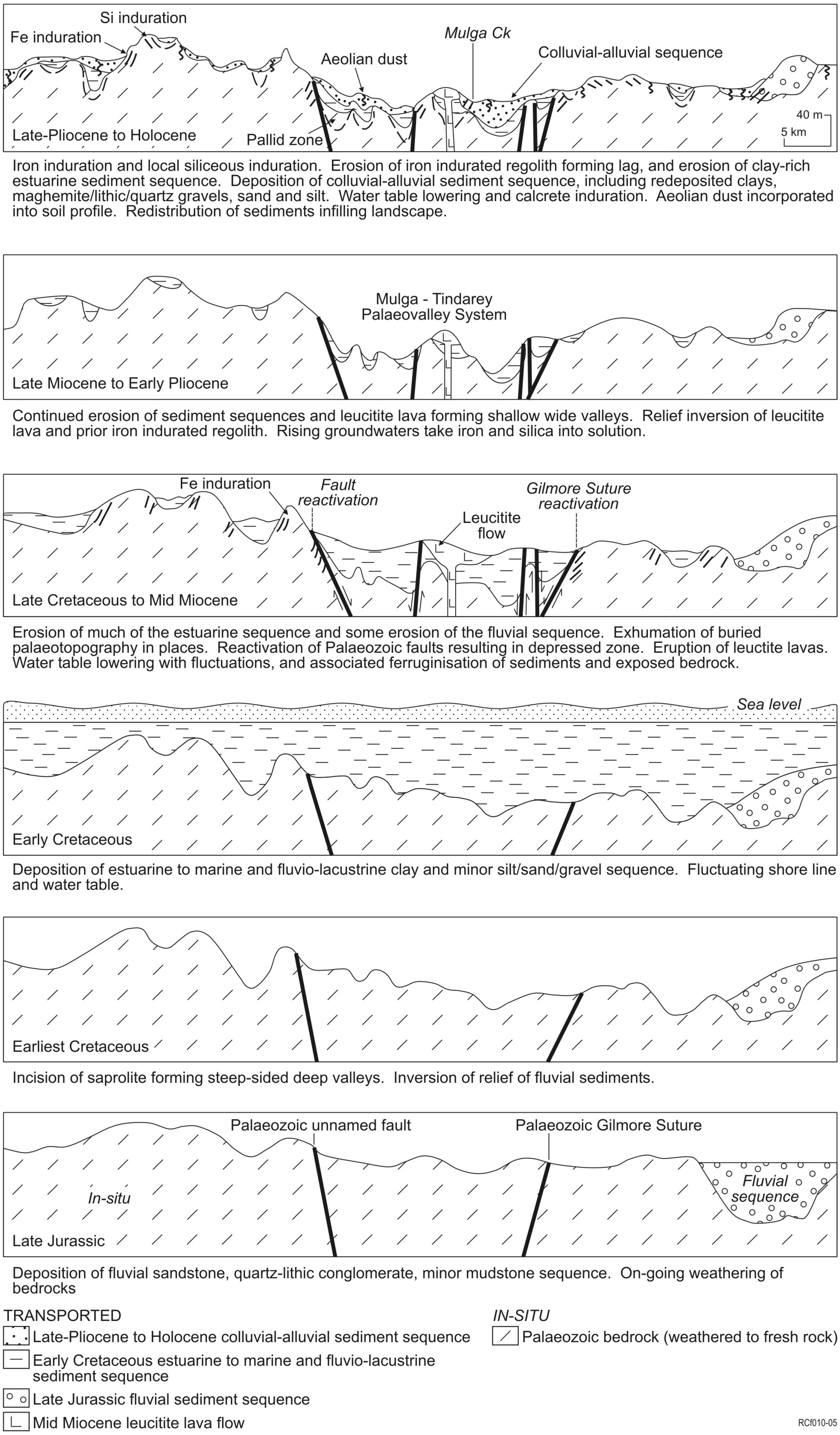


Figure 23. Diagrammatic summary of regolith-landform evolution in the Girilambone region.

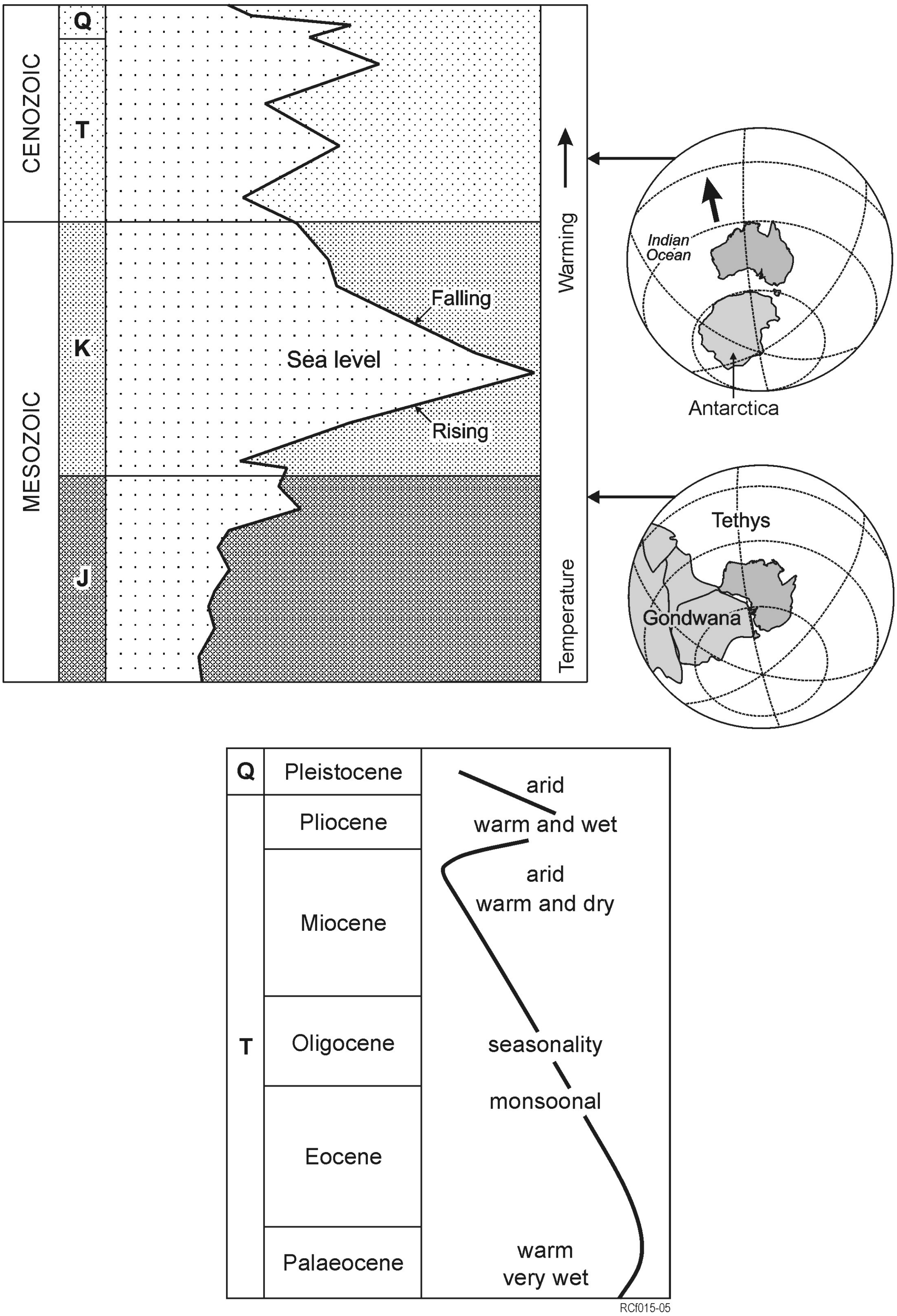


Figure 24. Global sea level and continental climate trends for southern Australia since the Jurassic. (Sources: "Australia Through Time", AGSO poster, 1998; and Simon-Coincon *et al.*, 1996).

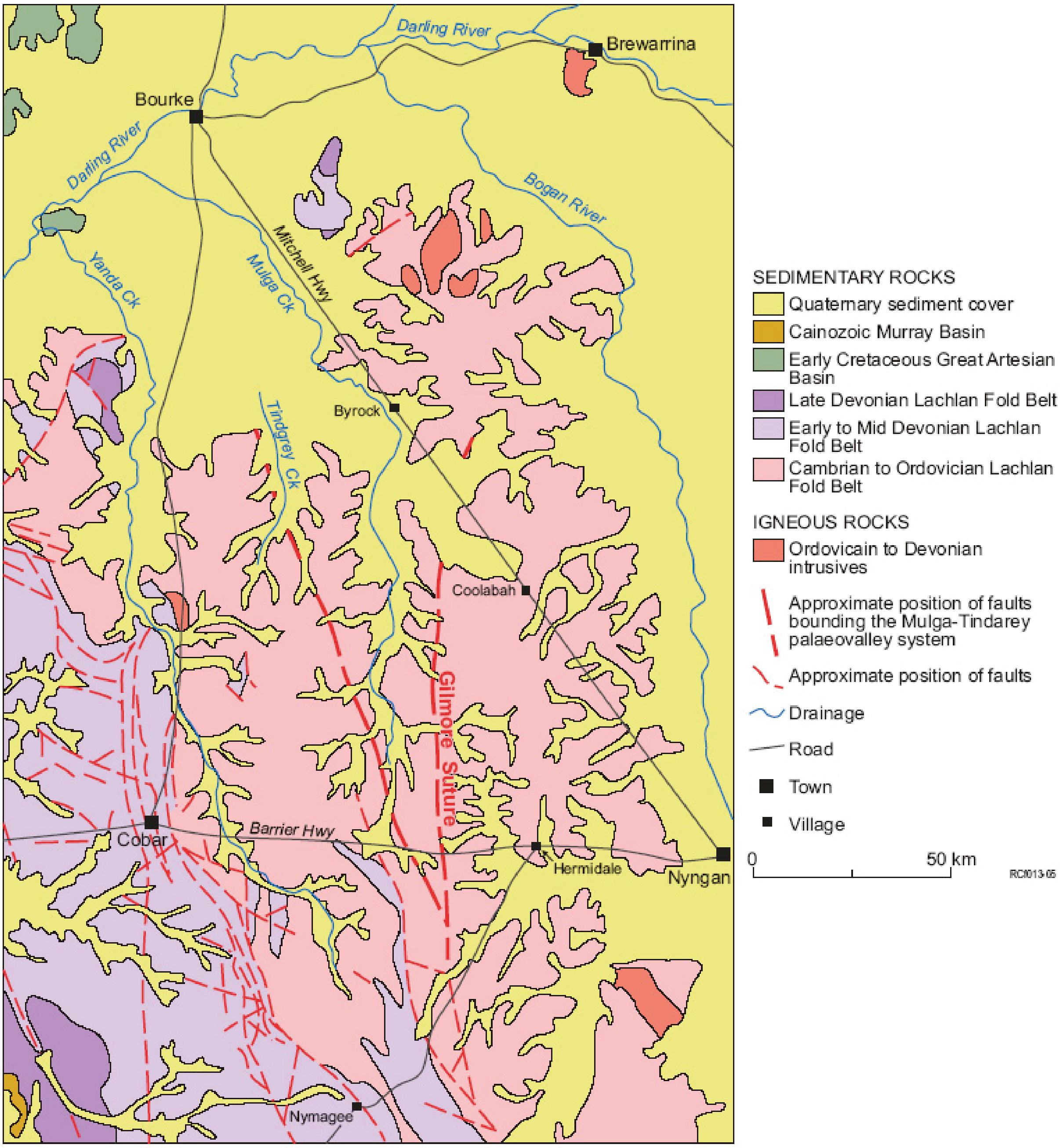


Figure 25. Simplified regional geological map of the Girilambone-Cobar region showing faults bounding the Mulga-Tinderry palaeovalley system.

6 IMPLICATIONS FOR MINERAL EXPLORATION

Better knowledge of regolith materials and regolith-landform evolution of the Girilambone region can be used to advise appropriate strategies for geochemical exploration. Particularly important aspects are the history of weathering and leaching, dispersion processes and pathways for target and pathfinder elements in the regolith and the likely host components for the dispersed elements. For suggested exploration strategies in regolith dominated areas of the region refer to McQueen (2008),

6.1 Element dispersion

Element dispersion during chemical weathering is largely controlled by Eh, pH and ground water chemistry. Within the regolith, dispersion is also controlled by such factors as:

1. the position of the weathering front;
2. the location of redox boundaries, commonly related to the water table;
3. ground water flow controls and vectors;
4. mechanical transport processes and directions.

Hydraulic gradient and regolith permeability will control dispersion below and along the water table. The landscape evolution model for the Girilambone region can help predict regional water table levels at particular times. The landscape morphology, evolving drainage patterns and accompanying changes in base level can indicate likely directions of hydraulic gradient and hence direction of dispersion. This will mostly be off the drainage divides and broadly similar to the direction of fluvial transport. The landscape evolution model for the Girilambone region indicates the existence of a major NW-SE trending divide in the centre of the area throughout most of the Cenozoic. Drainage was predominantly northerly towards the Eromangan-Surat Basin. The detailed pattern of drainage that evolved around this major feature at different at stages provides the directions of mechanical transport and also an indication of groundwater flow directions.

Figure 26 shows an image of the southern part of the Girilambone-Cobar region with the present drainage (in blue) and major palaeodrainage directions (in red) draped on a model of the present surface relief. This gives the sense of the regional transport vectors in the palaeolandscape and in more detail in the present landscape. Figure 27 shows the same area and the major palaeodrainage directions (in red) draped on an aeromagnetic image. More detailed trends for lower order palaeodrainage systems that contain magnetic gravels are shown in yellow. These trends indicate the transport vectors in the landscape during the later Cenozoic. The palaeolandscape and palaeodrainage pattern can also give clues to the likely direction of hydraulic gradients and hence ground water movement, at least in a regional sense. In detail, groundwater movement will be influenced by permeability, related to different regolith materials (e.g. sands vs clays), variations in bedrock lithology and structure.

Airborne radiometric imagery can be useful for identifying surface regolith materials (top 30 cm) in areas with limited vegetation cover, including parts of the Girilambone region. This imagery can indicate the relative abundances of potassium, thorium and uranium, usually as a ternary, red (K), green (Th) and blue (U) image. Some of these materials can be identified as significantly transported (hematite-rich lag) and give clues to dispersion pathways.

Figure 28 shows a collage of the available radiometric imagery over the Girilambone-Cobar region. Areas of exposed metasedimentary bedrock and saprock mostly show a similar response for the three elements (K,Th and U) and such areas appear bright or white.

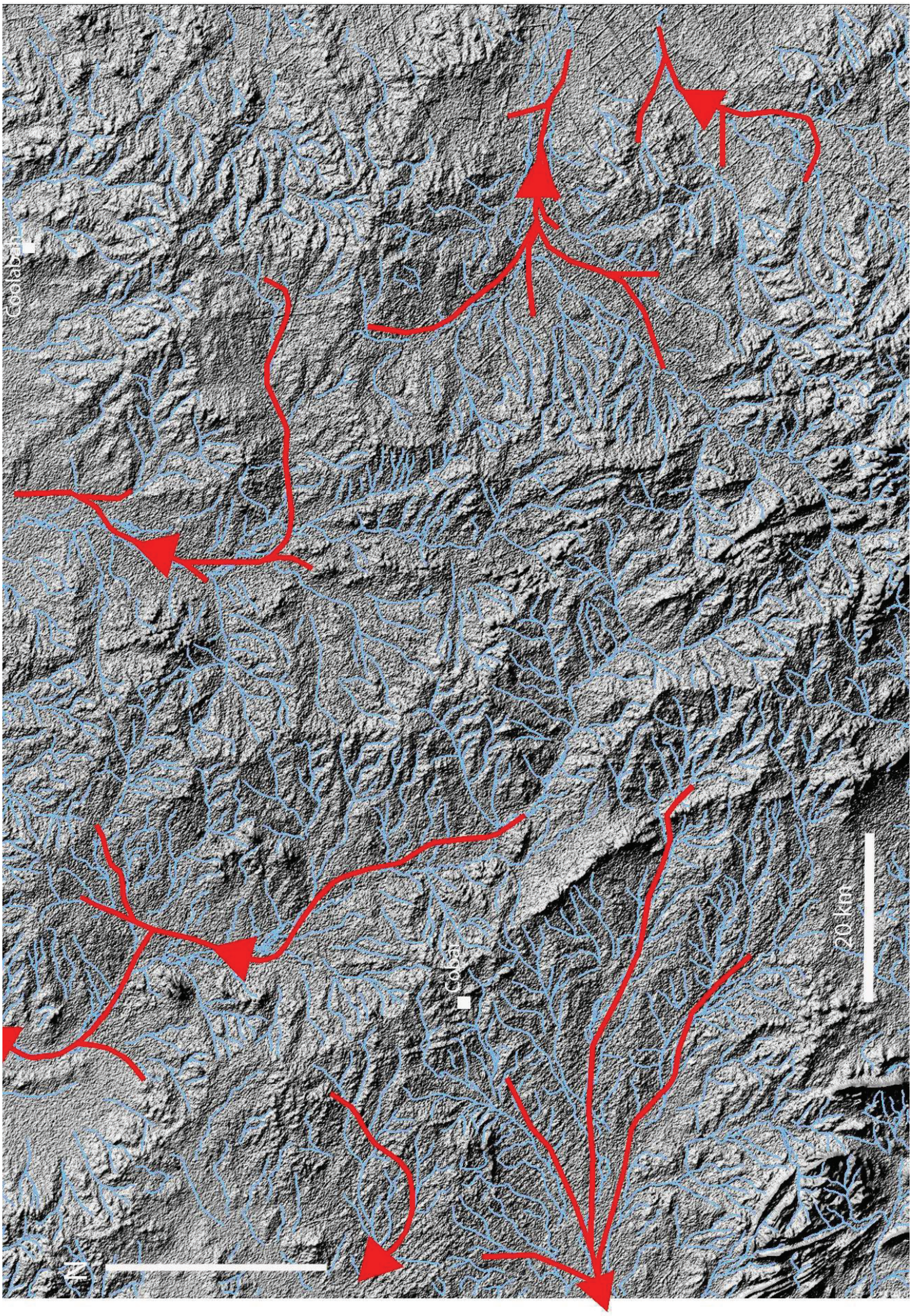


Figure 26. Relief model of the Cobar 1:250 000 sheet area showing present drainage (blue lines) and major palaeodrainage trends and vectors (in red). Topographic data from the National Topographic Map Series, Geoscience Australia.

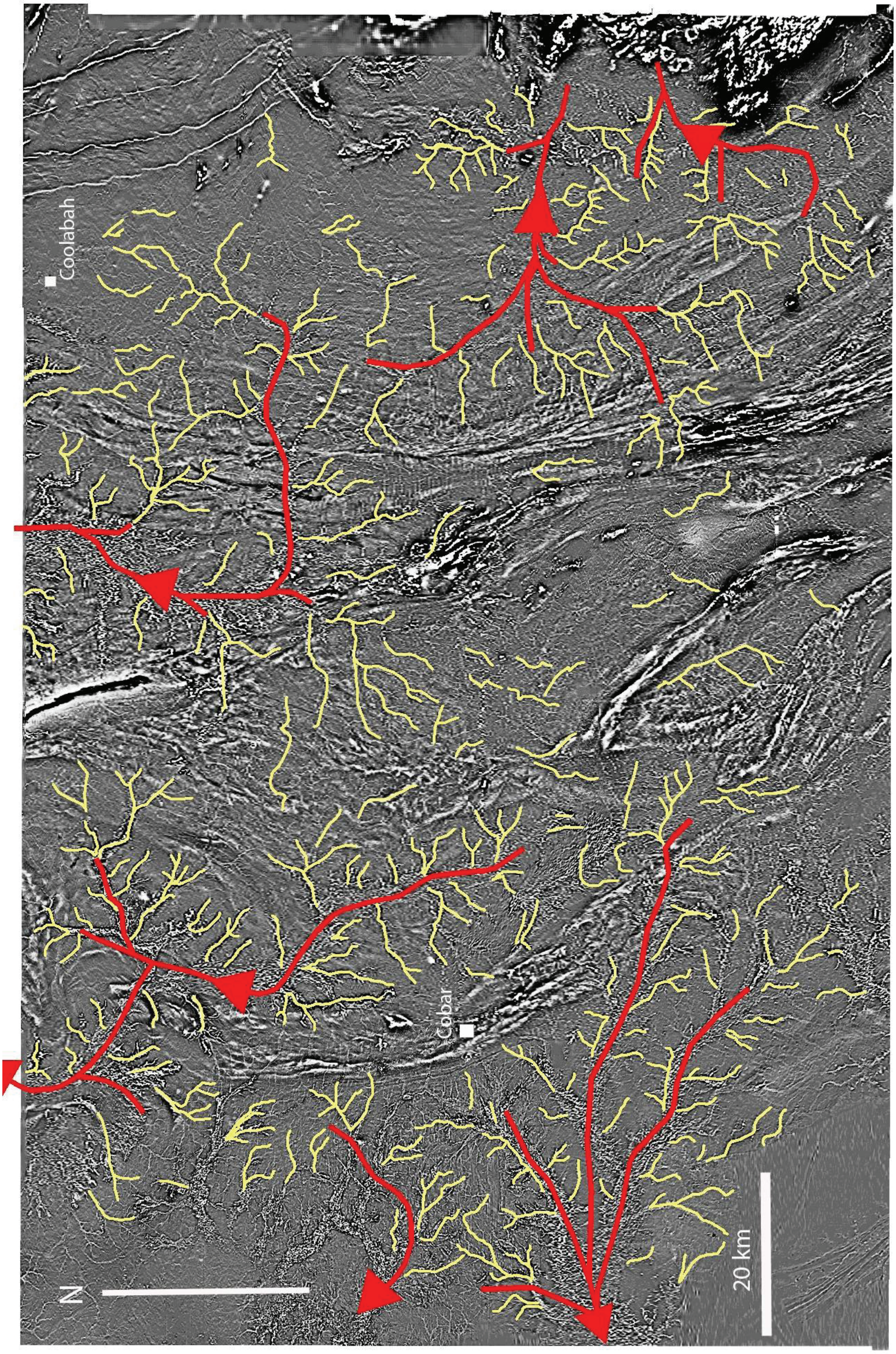


Figure 27. Aeromagnetic image (1.5 VD TMI) of the Cobar 1:250 000 sheet area showing major palaeodrainage trends and vectors (in red) and detailed trends of lower order palaeovalleys containing magnetic gravels. Aeromagnetic data: Discovery 2000, NSW DPI.

Bright red areas reflect regolith with high K and include *in situ* and locally transported regolith from granites, felsic volcanic rocks and K-rich mafic rocks (around Bald Hills). There is a strong plume of K-enriched transported regolith in the southeast coming from the exposed and eroding Erimeran Granite to the south Pinkish areas contain regolith with unweathered muscovite. Thorium is concentrated in hematite-rich (commonly reworked and transported) ferruginous lag (McQueen and Munro, 2003; McQueen *et a*l., 2004). These areas highlight depositional channels in eroding areas of the landscape, broader alluvial systems in low relief depositional areas and eroding palaeochannel deposits with ferruginous gravels that have been inverted in the landscape. Areas of thicker vegetation are dark.

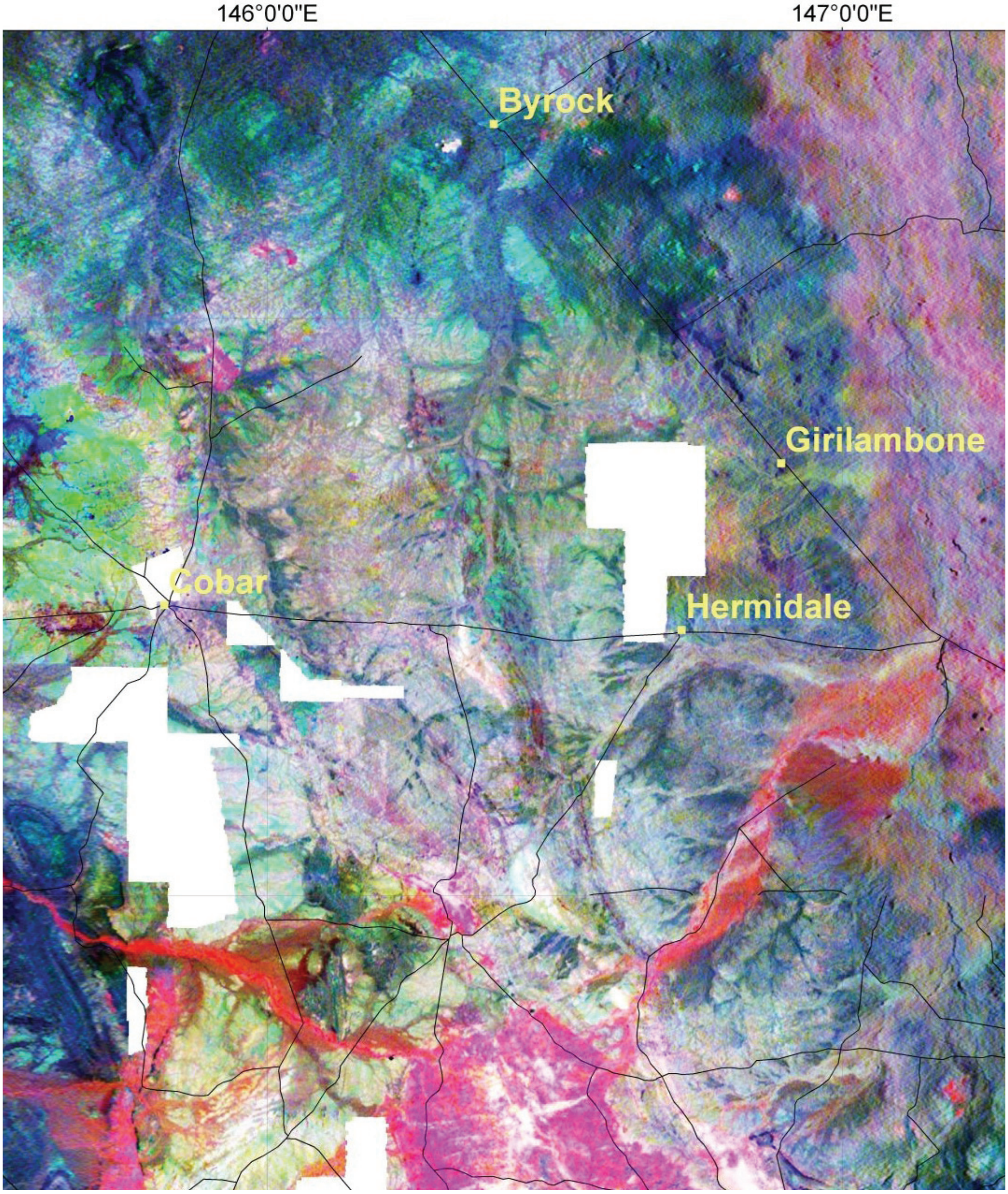


Figure 28. Radiometric image of the Girilambone-Cobar region. Imagery: Discovery 2000, NSW DPI.

6.2 Geochemical dispersion under different weathering regimes

The regional weathering history of the Girilambone region has been strongly influenced by major climatic variations through the long period (>60 Ma) of subaerial exposure and regolith development. In general terms this has resulted in deep chemical weathering under predominantly warm humid conditions in the Late Cretaceous to mid Miocene and superimposed drier chemical weathering under increasingly arid conditions from the late Miocene. In detail the picture is more complex with fluctuations to at least two cooler-dry episodes prior to the Oligocene (McGowran and Li, 1998) and a wetter period in the early Pliocene (Figure 24; Simon-Coincon *et al.*, 1996; Martin, 1991). Parts of the region, particularly in the north, were inundated by marine and esturine/lacustrine systems in the Cretaceous, which may have produced a reduced alkaline chemical environment (subsequently exposed and oxidised). Element dispersion processes need to be considered in terms of these quite different chemical weathering regimes.

Warm and wet climatic conditions, with high water table levels, would have favoured hydration/hydrolysis reactions and mobility of reduced species, particularly Fe^{2+}. Groundwater pH conditions would have been neutral to acid, the latter particularly where sulfides were oxidising. It is also likely that high organic content would have favoured organo-complexing of many elements. Arid climatic conditions, with falling and fluctuating water tables, favoured oxidation reactions and a change to more complex groundwater compositions, particularly with higher salinity, increased activity of carbonate and sulfate and regional neutral to alkaline pH. Under these superimposed arid conditions the solubility and mobility of some elements, particularly Au was increased where chloride and thiosulfate complexing occurred, whereas other elements, especially Pb, Ag, Ba and Hg became relatively fixed as insoluble chlorides and sulfates. Marked pH gradients around sulfide deposits that continued to weather resulted in dispersion of elements such as Cu and Zn to form broad anomalies.

Iron oxides/oxyhydroxides exert a major control on element dispersion/fixation and the sequence of iron mobility and precipitation of the major stable phases of goethite, and hematite is critical to the distribution of dispersed elements in the regolith. These iron phases typically show different distributions around weathering mineralisation and have different preferences for hosting trace elements. Studies of weathering profiles over mineralisation in the Cobar area (e.g. Scott *et al.*, 1991; Cairns *et al.*, 2001; McQueen and Munro, 2003; Leverett, *et al.*, 2004) indicate a progressive change in mineral hosts for target and pathfinder elements from primary sulfide and specific secondary minerals (including supergene sulfides, arsenates, sulfates, carbonates, chlorides and oxides) in the lower part of the profile to more generic Fe- and Mn-oxides/oxyhydroxides towards the top. Within the weathering profile element dispersion is largely by chemical processes. However after elements become fixed in the stable ferruginous component near surface they can be dispersed by mechanical processes in the eroding landscape (Figure 29). This can result in markedly different dispersion patterns in different parts of the regolith. For example, Pb and As can show limited chemical dispersion within the weathering profile compared to Cu and Zn which may form a broad chemically dispersed halo, generally concentrated in goethite. However at the surface, Pb and As (as well as Sb, Bi and Ba) become strongly fixed in hematite which may be widely dispersed into colluvium, alluvium and soil by mechanical processes.

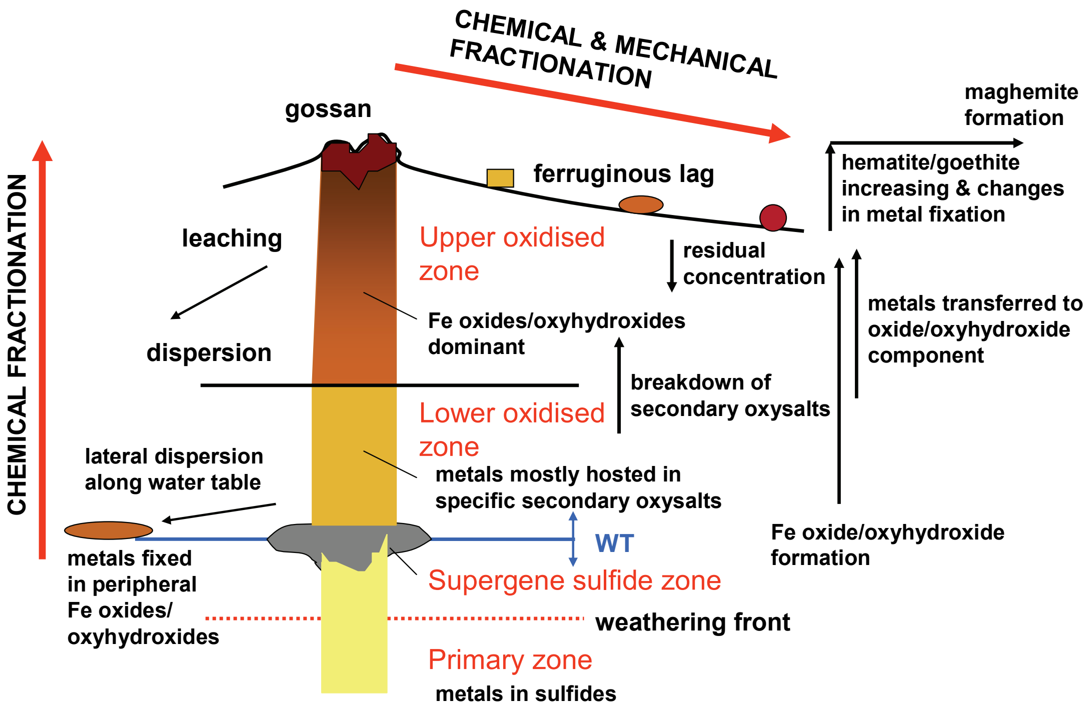


Figure 29. Schematic model of weathering profile on sulfide mineralisation for near surface oxidising conditions. Chemical weathering within the profile and surface water penetration leads to element leaching (both vertical and lateral) and fractionation above the water table. Dissolved species are also dispersed laterally, at and below the water table by ground water movement. Material exposed to erosion undergoes physical dispersion (downslope), mechanical fractionation (as surface materials are selectively transported) and further chemical fractionation.

Materials exposed at the surface undergo a range of transformations with time and changing environmental conditions. These include variable transport and physical degradation as well as chemical leaching and precipitation. This results in element fractionation by combined mechanical and chemical processes (Figure 29). The degree of fractionation will vary depending on the age or life cycle of the material and commonly there is intermixing of materials with differing maturity.

Under the most recent semi-arid conditions regolith carbonates (calcrete) have precipitated in the regolith throughout the Girilambone region. The calcrete zone defines the "evaporative" element association of Ca-Mg±Au±Ba-Sr (section 4.2). A regional study of calcrete in the Cobar-Girilambone region (McQueen, 2006) has established the nature and geochemical characteristics of calcrete accumulations and clearly demonstrated the relationship between calcrete and gold, as well as a number of other elements (including Ag, Cu, Bi, Ni and Co) where these element have been dispersed in the environment. The zone of calcrete development is commonly found in the lower part of the soil profile or at the soil saprolith interface in areas of *in situ* regolith, but may also occur at deeper levels in transported regolith (Figure 30). The zone of calcrete development can be of variable thickness and typically consists of dispersed calcite-dolomite, generally with calcite predominating in the upper part and dolomite towards the base. The highest gold contents in a profile are not necessarily associated with the position of maximum calcrete development. Typically the highest Au concentration is at the top of the calcrete zone, but not in all cases (Khider and McQueen, 2006). The calcrete zone is an important chemical transition in the regolith, particularly marking a change to higher pH. It reflects a chemical environment within both transported and *in situ* regolith that is conducive to precipitation of gold and some other target and pathfinder elements in solution. The association of these elements with calcrete is probably not directly controlled by fixation in calcrete. During geochemical exploration, sampling the regolith carbonate zone, particularly the upper part, should be as effective for detecting mobilised gold and other element anomalies as sampling the calcrete itself.

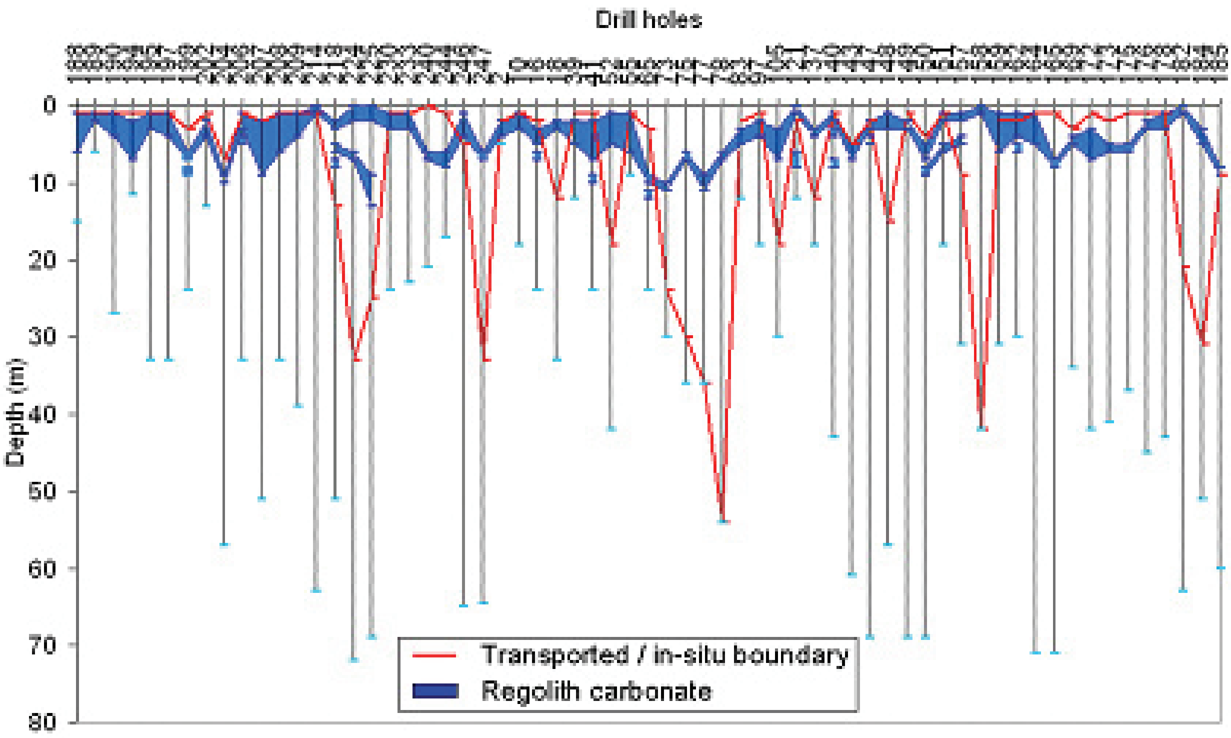


Figure 30. Fence plot of selected drill holes from the Girilambone region showing the transported/*in situ* regolith boundary and distribution of calcrete-bearing zones.

6.3 Weathering episodes and landscape evolution

Weathering profiles and their contained geochemical anomalies are preserved according to their position in the regolith and the history of landscape development, relative uplift, erosion and deposition (Figure 31). Different weathering features and episodes may be manifest and preserved in separate parts of the weathering profile if there has been erosional lowering of the land surface or burial of older profiles. Alternatively younger and older features may be superimposed if the land surface has been relatively stable. Where climatic, hydrologic and biological conditions have changed, particular parts of the regolith reflecting the different weathering episodes will be characterised by different geochemical dispersion and fixing processes. In many cases the earlier dispersion patterns are overprinted by patterns developed during contrasting conditions. This combination can result in very low concentrations of many target and pathfinder elements over mineralised sites, particularly in the non-ferruginous saprolite (i.e. a double or multiple 'whammy' dispersion scenario). During exploration it is important to know what portion of the weathering history is preserved in a particular profile.

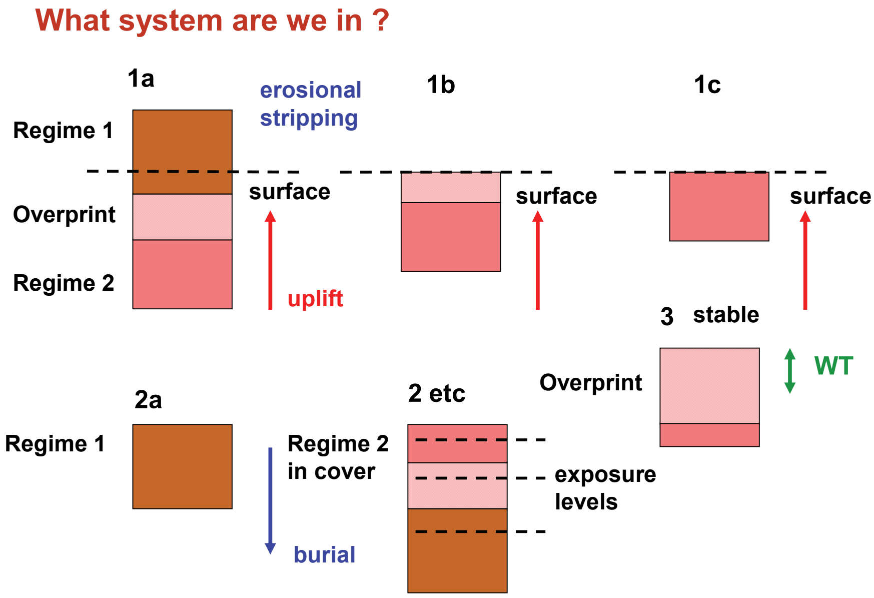


Figure 31. Interaction of multiple weathering regimes and some possible resulting regolith profiles. Profile 1a shows two partly overprinting regimes; profiles 1b and 1c show the effects of later progressive erosional stripping. Group 2 profiles show the effects of a single weathering regime subsequently buried with later weathering and dispersion into the cover (these profiles may then be exposed at different levels). Profile 3 shows the effects of overprinting regimes in a relatively stable environment, possibly with changing water table levels. Timing of exposure to the weathering front the prevailing climatic-chemical regime/s and hydromorphic vs mechanical transport critically affect element dispersion. Position within the regolith evolutionary model is therefore important for determining the geochemical expression of contained mineralisation.

6.4 Geochemical dispersion models

The largest dispersion footprints in the near-surface regolith of the Girilambone landscape are probably related to mechanical dispersion rather than hydromorphic dispersion. This reflects the semi-arid conditions that have prevailed through the later Cenozoic and the prior accumulation of target and pathfinder elements in ferruginous regolith (goethite and hematite) and some other chemically stable regolith minerals, particularly manganese oxides, sulfates, carbonates, chlorides, phosphates and arsenates. These patterns include transported anomalies in ferruginous palaeochannel gravels and in widely distributed, surface ferruginous lag derived from the erosion of these deposits.

Hydromorphic dispersion patterns are related to earlier climatic regimes (now partly eroded or leached) and to deeper zones in the regolith around the more recent water table levels (these range in depth from 12 to 140 m across the region). Detecting these anomalies beneath transported regolith and in strongly leached *in situ* regolith will require drilling and sampling of the appropriate parts of the subsurface regolith. It is likely that some dissolved target and pathfinder elements have been brought up from the water table by vegetation pumping of deep rooted species. There has also been some limited hydromorphic dispersion from transported materials.

Figure 32 summarises the common regolith-landform settings and element dispersion pathways in the Girilambone region. It also shows the typical profiles for a number of different settings and the best sampling techniques for anomaly detection during geochemical exploration.

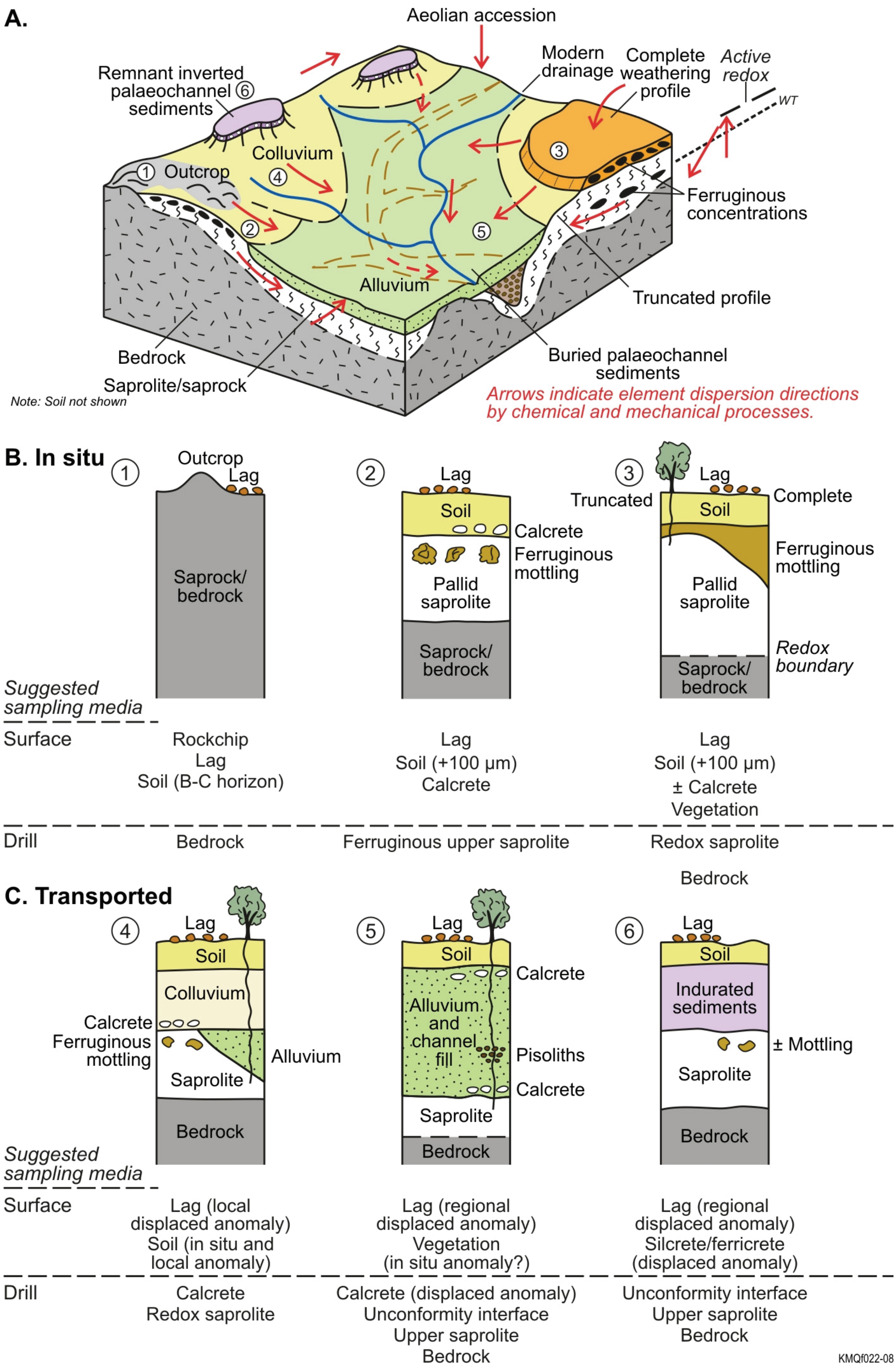


Figure 32. (A) common regolith-landform settings and element dispersion pathways in the Girilambone region. (B) profile models for different settings with *in situ* and transported regolith and suggested sample media for surface and sub-surface (drilling) methods.

ACKNOWLEDGMENTS

This report is a synthesis of research carried out as part of the Girilambone Project within the Cooperative Research Centre for Landscape Environments and Mineral Exploration. This project was conducted in collaboration with the New South Wales Department of Primary Industries (Geological Survey) with support from the Australian Government's Cooperative Research Centre Program and the New South Wales Department of Primary Industries. A large number of researchers and students have contributed to the study. We thank Peter Buckley, Guy Fleming, Michael Hicks, Jason Needham (NSW DPI); Austin Alorbi, Nadia de Souza Kovacs, Osvaldo Gonzalez, Hugh Glanville, Maite Le Gleuher, Ben Maly, Angelina McRae, Dougal Munro, Susan Orgill (nee Tate), Brad Pillans, Anthony Senior, Martin Smith, Ian Roach, Michael Whitbread, Paul Wilkes, Tom Woolrych (CRC LEME); Joe Schifano (UNSW). Geochemical analyses were conducted by Analabs (multi-acid digest ICP OES/Ms and Au for Stage 1 Sussex-Coolabah), ALS Chemex (multi-acid digest ICP OES/Ms and Au for Stages 2 and 3 Hermidale and Byrock) and Geoscience Australia (whole rock and trace element XRF). Bill Papas, Tan Kok Piang and Algis Juodvalkis (Geosceince Australia) provided technical support. Peter Milligan, Luisa Ruperto and John Wilford (Geoscience Australia) and Clive Hiliker (ANU) assisted with some of the diagrams and images. Nigel Radford, Lisa Worrall (Program Leaders in CRC LEME) and John Watkins (NSW DPI) supported and encouraged the work. We would also like to thank land owners and lease holders in the Girilambone region who gave permission to enter their properties. Ian Roberston (CRC LEME) assisted in reviewing and editing the final version of the report. Angelo Vartesi and Travis Naughton from the Visual Resources Unit at CSIRO, Division of Exploration and Mining, Bentley produced most of the diagrams and figures.

REFERENCES

Anderson, W., 1888. Report on the geology of the Byerock district. NSW Dept. Mines, Annual Report for 1887, pp. 161-163.

Barron, L.M., Ohnenstetter, M., Barron, B.J., Suppel, D.W., Falloon, T., 2004. Geology of the Fifield Alaskan-type complexes, New South Wales, Australia. Geological Survey of NSW Report No. GS2004/323, 36 pp.

Binns, R.A. and Appleyard, E.C., 1986. Wallrock alteration at the Western System of the CSA Mine, Cobar, New South Wales, Australia. Applied Geochemistry 1, pp. 211-225.

Blevin, P.L. and Jones, M., 2004a. Granites of the Bourke-Byrock-Brewarrina region. In: McQueen, K.G. and Scott, K.M. (eds) Exploration Field Workshop Cobar region 2004 Proceedings. CRC LEME, pp. 10-14.

Blevin, P.L. and Jones, M., 2004b. Chemistry, age and metallogeny of the granites and related rocks of the Nymagee region, NSW. In: McQueen, K.G. and Scott, K.M. (eds) Exploration Field Workshop Cobar Region 2004 Proceedings. CRC LEME, pp. 15-19.

Buckley, P.M., 2004. Byrock regolith-landform map, 1:100 000 scale. CRC LEME. Perth.

Burton, G.R., Trigg, S.J. and Campbell, L.M., (in press). Sussex 8135 and Byrock 8136 1:100 000 Geological Sheets and Explanatory Notes. Geological Survey of New South Wales, New South Wales Department of Primary Industries.

Byrnes, J.G., 1993. Bourke 1:250 000 metallogenic map SH/55-10. Metallogenic study and mineral deposit data sheets. Geological Survey of New South Wales, Sydney, 127 pp.

Cairns, C.J., McQueen, K.G. and Leah, P.A., 2001. Mineralogical controls on element dispersion in regolith over two mineralised shear zones near the Peak, Cobar, New South Wales. Journal of Geochemical Exploration 72, pp. 1-21.

Chan, R.A., Greene, R.S.B., de Souza Kovacs, N., Maly, B.E.R., McQueen, K.G, and Scott, K.M., 2003a. Regolith, geomorphology, geochemistry and mineralization of the Sussex-Coolabah area in the Cobar-Girilambone region, North-Western Lachlan Foldbelt, NSW. CRC LEME Open File Report 148, 56 pp.

Chan, R.A., Greene, R.S.B., Hicks, M., Maly, B.E.R., McQueen, K.G., and Scott, K.M., 2003b. Regolith architecture and geochemistry of the Hermidale area of the Girilambone region, North-Western Lachlan Foldbelt, NSW. CRC LEME Open File Report 149, 48 pp.

Chan, R.A., Greene, R.S.B., Hicks, M., Le Gleuher, McQueen, K.G., Scott, K.M. and Tate, S.E., 2004. Regolith architecture and geochemistry of the Byrock area, Girilambone region, north-western, NSW. CRC LEME Open File Report 159, 71 pp.

David, V., 2005. Metallogenesis of the Cobar region, central New South Wales. Australian Journal of Mineralogy 11, pp. 55-61.

Donelick, R.A. and O'Sullivan, P.B., 2002. Girilambone area: apatite fission track data. Apatite to Zircon Inc. Report No. 368 (unpublished report for CRC LEME).

Duk-Rodkin, A., Chan, R.A. and McQueen, K.G., 2004. Drainage evolution and implications for neotectonics and mineral exploration in the Cobar Uplands, NSW. In: McQueen, K.G. and Scott, K.M. (eds). Proceedings: Exploration Field Workshop, Cobar region 2004, pp. 37-42. CRC LEME, Perth.

Eggleton, R.A. (ed.), 2001. The regolith glossary: surficial geology, soils and landscapes. CRC LEME, Perth, 144 pp.

Fleming, G. and Hicks, M., 2003. Preparations for third programme of shallow reconnaissance aircore drilling, Byrock area, Cobar NSW. Interim Report, March 2003. GS2003/065. Geological Survey of New South Wales.

Fleming, G. and Hicks, M., 2004. Summary of work conducted in the Byrock-Hermidale district, NSW. Final Report, July 2004. GS2004/210. Geological Survey of New South Wales.

Fleming, G., Hicks, M. and Barron, L., 2001. First programme of shallow reconnaissance aircore drilling, Sussex area, Cobar, NSW. Yearly Report, June 2001. GS2001/200. Geological Survey of New South Wales.

Ford, A.J.H., 1996. Re-interpreting the north eastern margin of the Cobar Basin, using drainage channel morphology. In: Cook, W.G., Ford, A.J.H., McDermott, J.J., Standish P.N., Stegman, C.L. and Stegman, T.M. (eds). The Cobar Mineral Field – a 1996 Perspective, pp. 113-123. The AusIMM Spectrum Series No 3/96.

Garcia, D., Fonteilles, M. and Moutte, J., 1994. Sedimentary fractionation between Al, Ti and Zr and the genesis of strongly peraluminous granites. Journal of Geology 102, pp. 411-422.

Gibson, D.L., 1999. Explanatory Notes for the 1:500 000 Cobar regolith landform map. CRC LEME Open File Report 76.

Gibson D.L. and Chan R.A., 1999a. Aspects of palaeodrainage in the north Lachlan Fold Belt region. In: Taylor, G. and Pain C. (eds). Proceedings Regolith 98: New Approaches to an Old Continent. 3rd Australian Regolith Conference, Kalgoorlie, 1998, pp. 25-37. CRC LEME, Perth.

Gibson D.L. and Chan, R.A., 1999b. Regolith and landscape mapping and evolution. In: Lyons, P. and Wallace, D. (eds). Field Conference Guide: Geology and Metallogenesis of the Parkes – Grenfell – Wyalong – Condobolin region, New South Wales, Forbes 1:250 000 Geological Sheet. AGSO Record 1999/20, pp. 24-32. Australian Geological Survey Organisation (Geoscience Australia), Canberra.

Gilligan, L.B. and Byrnes, J.G., 1995. Cobar 1:250 000 metallogenic map, SH/55-14. Metallogenic study and mineral deposit data sheets. Geological Survey of New South Wales, Sydney, 240 pp.

Glanville, D.H., 2003 Regolith-landform mapping, leucitite basalt and the landscape evolution of the Byrock region, north western NSW. Honours Thesis Australian National University, CRC LEME (unpublished), 69 pp.

Glen, R.A., Clare, A. and Spencer, R., 1996. Extrapolating the Cobar Basin model to the regional scale: Devonian basin – formation and inversion in western NSW. In: Cook, W.G., Ford, A.J.H., McDermott, J.J., Standish P.N., Stegman, C.L. and Stegman, T.M. (eds). The Cobar Mineral Field – a 1996 Perspective, pp. 43-83. The AusIMM Spectrum Series No 3/96.

Gonzalez, O.R., 2001. The geology and landscape history of the El Capitan area, Cobar, NSW. Honours Thesis University of Canberra, CRC LEME (unpublished), 109 pp.

Hallberg, J.A., 1984. A geochemical aid to igneous rock identification in deeply weathered terrain. Journal of Geochemical Exploration 20, pp. 1-8.

Harland, W.B., Cox, A.V., Llweellyn, P.G., Pickton, C.A.G., Smith, A.G. and Walters, R., 1982. *A Geologic Time Scale*. Cambridge University Press, Cambridge. 131 pp.

Hesse, P.P. and McTainsh, G.H., 1999. Last glacial maximum to early Holocene wind strength in the mid-latitudes of the southern hemisphere from Aeolian dust in the Tasman Sea. Quaternary Research 52, pp. 343-349.

Hesse, P.P and McTainsh, G.H., 2003. Australian dust deposits: modern processes and the Quaternary record. Quaternary Science reviews 22, pp. 2007-2035.

Khider, K., 2007. Regional geochemical dispersion of elements in the regolith of the Girilambone Region, Central West NSW. PhD Thesis Australian National University, CRC LEME (unpublished), 245 pp.

Khider, K. and McQueen, K.G., 2006. Gold dispersion in calcrete-bearing regolith of the Girilambone Region, Western NSW. In: Fitzpatrick, R.W. and Shand, P. (eds) Regolith 2006 Consolidation and Dispersion of Ideas. CRC LEME, pp. 190-195.

Leverett, P., McKinnon, A.R. and Williams, P.A., 2004. A supergene exploration model for Cobar style deposits. In: McQueen, K.G. and Scott, K.M. (eds) Exploration Field Workshop Cobar Region 2004 Proceedings. CRC LEME, pp. 46-50,

Maly, B.E.R., 2004. Hermidale regolith-landform map, 1:100 000 scale. CRC LEME, Perth.

Maly, B.E.R., Chan, R.A. and Senior, A., 2004a. Sussex regolith-landform map, 1:100 000 scale. CRC LEME, Perth.

Maly, B.E.R., Chan, R.A. and Senior, A., 2004b. Coolabah regolith-landform map, 1:100 000 scale. CRC LEME, Perth.

Macphail, M.K., 2000. Australian palaeoclimates: Cretaceous to Tertiary – review of palaeobotanical and related evidence up to 2000. (Volume 1). Unpublished report in 2 volumes to CRC LEME.

Macphail, M.K., 2004. Pollen analysis of CBAC core samples Byrock district, Northwestern New South Wales. Unpublished report. Consultant Palynological Services, 10 pp.

Martin, H.A., 1991. Tertiary stratigraphic palynology and palaeoclimate of the inland river systems in New South Wales. In: Williams, M.A.J., De Deckker, P. and Hershaw, A.P. (eds). The Cainozoic in Australia: A re-appraisal of the evidence. Geological Society of Australia Special Publication 18, pp. 1881-194.

McGowran, B. and Li, Q., 1998. Cainozoic climate change and its implications for understanding the Australian regolith. In Eggleton, R.A. (ed.) The State of the Regolith. Geological Society of Australia Special Publication 20, pp. 86-103.

McQueen, K.G., 2004. The nature, origin and exploration significance of the regolith, Girilambone-Cobar region. In: McQueen, K.G. and Scott, K.M. (eds) Exploration Field Workshop Cobar Region Proceedings: 2004, pp. 51-56. CRC LEME, Perth.

McQueen, K.G., 2006. Calcrete geochemistry in the Cobar-Girilambone region, New South Wales. CRC LEME Open File Report 200, 27 pp.

McQueen, K.G., 2008. A guide for mineral exploration through the regolith in the Cobar Region, Lachlan Orogen, New South Wales. CRC LEME, Perth, 109 pp.

McQueen, K.G., Pillans, B.J. and Smith, M.L., 2002. Constraining the weathering history of the Cobar region, Western NSW. In: Preiss, V.P. (ed.) Geoscience 2002: Expanding Horizons, 16th Australian Geological Convention, Adelaide, 1-5 July 2002, Abstracts Volume No 67, p. 426.

McQueen, K.G. and Munro, D.C., 2003. Weathering-controlled fractionation of ore and pathfinder elements at Cobar, NSW. In: Roach, I.C. (ed.) Advances in Regolith, CRC LEME, pp. 296-300.

McQueen, K.G., Munro, D.C., Gray, D. and Le Gleuher, M., 2004. Weathering-controlled fractionation of ore and pathfinder elements Part II: The lag story unfolds. In: Roach (ed.) Regolith 2004, CRC LEME, pp. 241-246.

McQueen, K.G., Gonzalez, O.R., Roach, I.C., Pillans, B.J., Dunlap, W.J. and Smith M.L. 2007. Landscape and regolith features related to Miocene leucitite lava flows, El Capitan northeast of Cobar, NSW, Australia. Australian Journal of Earth Sciences 54, pp. 1-17.

Mount, T.J., 1992. Yanda Creek salt inflows project, Bourke NSW: hydrological framework studies, 1991-92. Report TS92.032, Technical Services Division, NSW Department of Water Resources.

Nesbitt, H.W. and Young, G.M., 1982. Early Proterozoic climates and plate motion inferred from major element chemistry of lutite. Nature 299, pp. 715-717.

Nesbitt, H.W. and Young, G.M., 1984. Prediction of some weathering trends of plutonic and volcanic rocks based on thermodynamic and kinetic considerations. Geochimca et Cosmochimica Acta 48, pp. 1523-1534.

Pain, C.F., Chan, R., Craig, M., Gibson, D., Kilgour, P. and Wilford, J. 2007. RTMAP Regolith Database Field Book and Users Guide (Second Edition). CRC LEME Open File Report 231, 92 pp.

Phillips, D., 2001. K-Ar analyses of leucitite sample WT6. Prise Report R2K-1070 (unpublished), 3 pp.

Rayner, E.O., 1969. The copper ores of the Cobar region, New South Wales. Memoirs of the Geological Survey of New South Wales, Geology No. 10, p. 21.

Raza, A., Hill K.C. and Korsch, R.J., 1995. Mid-Cretaceous regional uplift and denudation of the Bowen-Surat Basins, Queensland and its relation to Tasman Sea rifting, In: Follington, I.L., Beeston, J.W. and Hamilton, L.H. (eds). Bowen Basin Symposium 1995 – 150 years on. Geological Society of Australia, supplement.

Roach, I.C., 2008. Canbelego 1:100 000 regolith-landform map and explanatory notes. CRC LEME Open File Report 238, 40 pp.

Roser, B.P. and Korsch, R.J., 1988. Provenance signatures of sandstone-mudstone suites determined using discriminant function analysis of major-element data. Chemical Geology 67, pp 119-139.

Roser, B.P., Coombs, D.S., Korsch, R.J. and Campbell, J.D., 2002. Whole-rock geochemical variations and evolution of the arc-derived Murihiku Terrane, New Zealand. Geological Magazine, 139, pp. 665-685.

Scott, K.M., 1988. Phyllosilicate and rutile compositions as indicators of Sn specialization in some southeastern Australian granites. Mineralium Deposite 23, pp. 159-165.

Scott, K.M., Rabone, G. and Chaffee, M.A., 1991. Weathering and its effect upon geochemical dispersion at the polymetallic Wagga Tank deposit, NSW. Journal of Geochemical Exploration 40, pp. 423-426.

Simon-Coincon, R., Milnes, A.R., Thiry, M. and Wright, M.J., 1996. Evolution of landscapes in northern South Australia in relation to the distribution and formation of silcretes. Journal of the Geological Society of London 153, pp, 467-480.

Stace, H.C.T., Hubble, G.D., Brewer, R., Northcote, K.H., Sleeman, J.R., Mulcahy, M.J. and Hallsworth, E.G., 1968. A handbook of Australian soils. Rellim Technical Publications: Glenside, South Australia.

Suppell, D.W. and Gilligan, L.B., 1993. Nymagee 1:250 000 metallogenic map. Metallogenic study and mineral deposit data sheets. Geological Survey of New South Wales, Sydney, 171 pp.

Sutherland, F.L., 1985. Regional controls in eastern Australian volcanism. In: Sutherland, F.L., Franklin, B.J. and Waltho, A.E. (eds). Volcanism in Eastern Australia. Geological Society of Australia, NSW Division, 1, pp. 13-32.

Tate, S.E., Greene, R.S.B., Scott, K.M. and McQueen, K.G., 2003. Characterisation of regolith materials in the Girilambone region, north-western Lachlan Fold Belt, NSW. In: Roach, I.C. (ed.). Advances in Regolith: Regional Regolith Symposia 2003, pp. 399-405. CRC LEME.

Tate, S.E., Greene, R.S.B., Scott, K.M. and McQueen, K.G., 2007. Recognition and characterisation of the aeolian component in soils in the Girilambone region, northwestern New South Wales, Australia. Catena 69, pp. 122-133.

Taylor, S.R. and McLennan, S.M., 1985. The continental crust: its composition and evolution. Oxford: Blackwell Scientific, 312 pp.

Vasconcelos, P., 2004. 40Ar/39Ar geochronology of Mn-oxide samples from the Cobar weathering profile. CRC LEME Cobar Project. Unpublished report, UQ-AGES Laboratory, 6 pp.

Walker, P., 1991. Land systems of western New South Wales. Soil Conservation Service of NSW. Technical Report No. 25.

Whitbread, M.A.I., 2004. Lithogeochemical alteration around the Century and Elura Zn-Pb-Ag deposits: Detecting alteration expressions in deep and near surface environments. PhD Thesis, University of Canberra, CRC LEME (unpublished), 331 pp.

Worrall, L. and Clarke, J.D.A., 2004. The effect of Middle to Late Tertiary fluctuations of sea level on the geochemical evolution of west Australian regolith. 11th ANZGG Meeting, Mt Buffalo, Victoria, 13-20th February, 2004, Abstracts and Program, p. 80.

Appendix 1

Characterisation of regolith types from drill hole materials
(R. Chan)

A technique was developed for identifying the different regolith types in air core drilling samples for the Cenozoic (A,C/A,C*) and Mesozoic (OE) depositional sequences and underlying Palaeozoic bedrocks (SP,SS) of the Girilambone region. This technique employs petrographic examination and the Portable Infrared Mineral Analyser (PIMA). The letter symbols in brackets above are based on the RTMAP database symbology (Pain *et al*, 2007), with the letter symbol, OE, referring to the dominant inferred depositional environment, ie. coastal estuarine.

Petrographic attributes for the regolith types are:

- Saprock (SS): less than 20% weatherable minerals altered (Eggleton, 2001); resistant lithologies, such as chert and quartzite, may occur at shallow depth; lithology determined from petrographic examination of slightly weathered drilling chips and sticks (cores);
- Saprolite (SP): greater than 20% weatherable minerals altered (Eggleton, 2001); includes indurated (siliceous and ferruginous) regolith and clays (clays tend to break easily with fingers and may retain bedrock textures, such as laminations); lithology determined from petrographic examination of moderately to highly weathered drilling chips with remnant textures, which may be preferentially preserved due to induration; the lithology of very highly to completely weathered rock flour is determined from petrographic examination of the composition of resistant minerals together with mineralogy from PIMA and selected geochemical ratios, such as Ti/Zr (CBAC246 – mylonitised granite, not metasedimentary bedrock);
- Proximal estuarine to marine and fluvio-lacustrine sediment sequence (OE): grey to white clays and lesser silt to rounded quartz sands (<2mm) to granules (2-4mm); clays are compacted and hard to break with fingers, massive, often containing rounded to sub-angular floating quartz grains or larger clasts, and may have fractures due to lithification with black manganese coatings (also noted in Mount, 1992); sediments are yellow where near to present water table (CBAC242);
- Alluvial/colluvial redeposition of eroded sequence OE (A,C*): grey to white to mottled yellow grey massive clays with internal structure as in OE, and lesser silts; either associated with or occur above sediments with maghemite and angular to rounded quartz and lithic clasts and gravels;
- Alluvial/colluvial deposition A,C): gravels (maghemite and/or angular to rounded quartz and lithics) commonly ferruginised and/or silicified, red-brown sand and silt, brown clay, weakly cemented sands to silts.

PIMA methodology used for the analysis of regolith samples is described in Chan *et al.* (2003a, Section 3.6). Refer to Chan *et a*l. (2003a,b; 2004) for both stacked spectra and selected algorithm logs for drill hole samples.

Significant PIMA attributes for definition of the regolith types are:

- SS: Spectra troughs at 1350-1400 nm, 1850-1950 nm and 2150-2250 nm are all diminished in depth (though the first 2 troughs are deepened if the water table is encountered, e.g. CBAC182), the kaolinite crystallinity (KC) shoulder at 2160 nm is not apparent, and the amplitude of spectra between 2250 and 2500 nm is generally reduced; the PIMA log shows low water depth, low AlOH depth, low KC and high AlOH wave algorithms. CBAC143 at 59-61 m depth exemplifies these PIMA spectral and log characteristics for saprock (Fiugre A1-1); these are the same characteristics as for quartz veins within saprolite, e.g. CBAC164 at 63 -69 m depth, though the KC shoulder may be apparent but reduced in depth due to saprolite mixture.

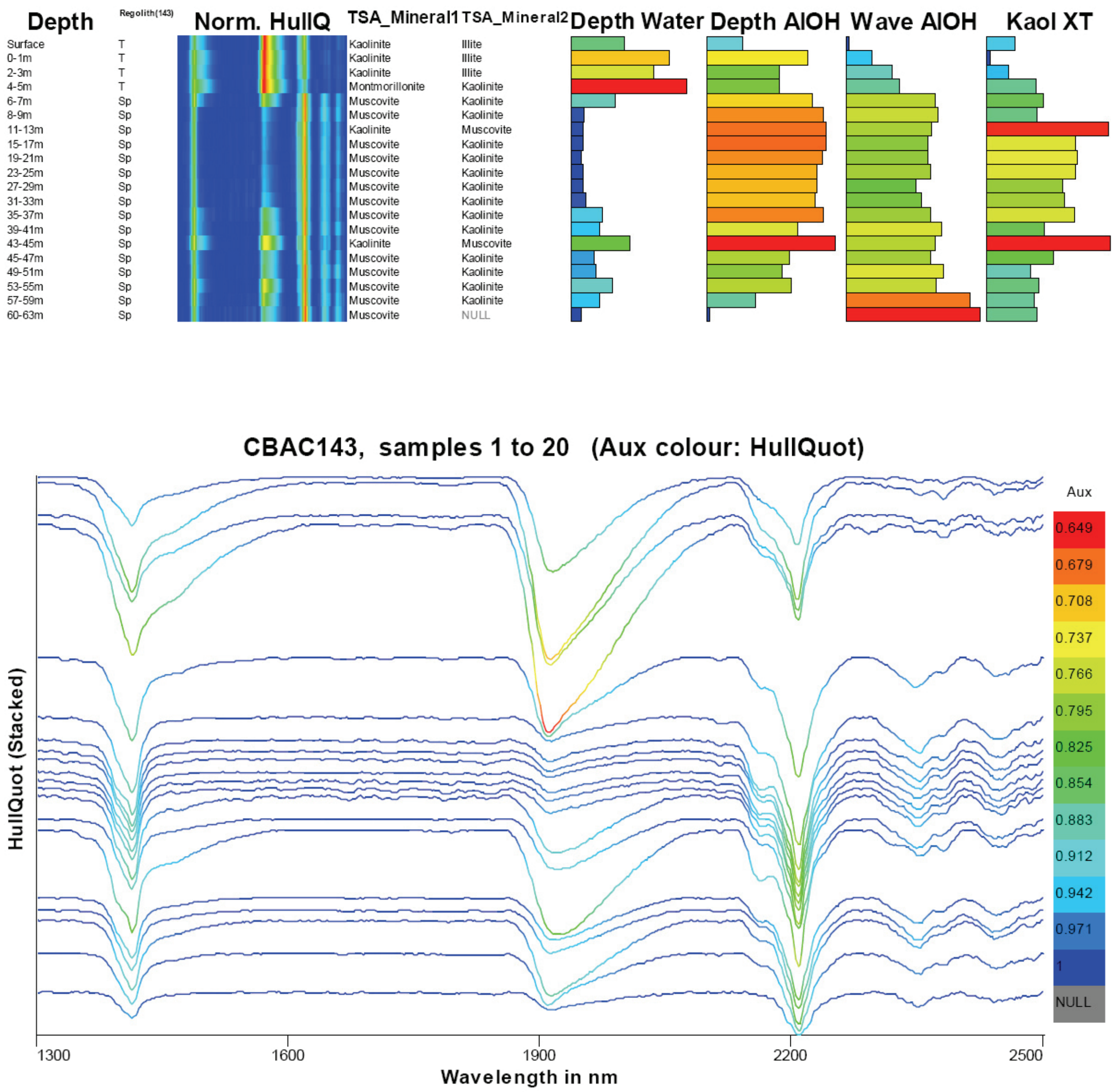


Figure A1-1. PIMA log and spectra of the regolith profile for drill hole CBAC143.

• SP: The most distinctive spectral feature of saprolite is the small trough at 2160 nm indicating ordered KC, such as in CBAC182 at 19-49 m depth (Figure A1-2); the 1850-1950 nm trough may be of variable depth, and the 1350-1400 nm trough does not normally have a shoulder at 1350 nm; the spectra between 2250 and 2500 nm are generally wavy; the PIMA log shows consistently high KC, high AlOH depth and AlOH wave, low water depth, and bedrock mineralogy, e.g. muscovite (CBAC182).

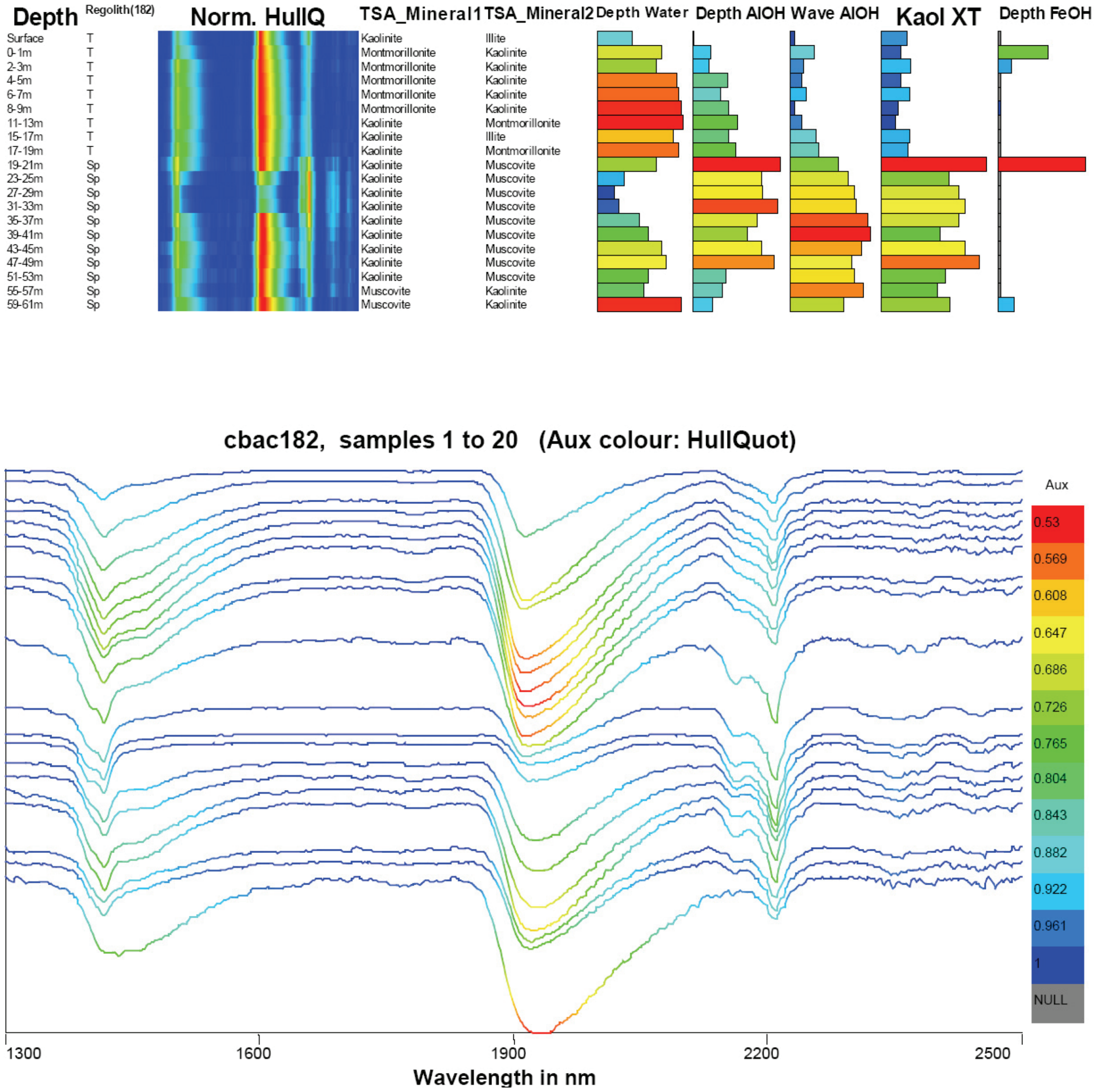


Figure A1-2. PIMA log and spectra of the regolith profile for drill hole CBAC182.

- OE: Both Sequence OE (older sequence), and unit A,C* (below) within Sequence A,C (younger sequence), share similar AlOH intensity, and quantitative XRD results suggest abundant kaolinite and illite. The two distinctive spectral features of Sequence OE are downward sloping shoulders around 1350nm and 2150nm, the latter indicating poor KC, such as in CBAC210 from 4-16 m depth (Figure A1-3); the spectra between 2250 nm and 2500 nm are generally wavy; the most significant PIMA log indication of this regolith type is a sustained increase in the AlOH depth algorithm while the KC remains low (e.g. CBAC210).

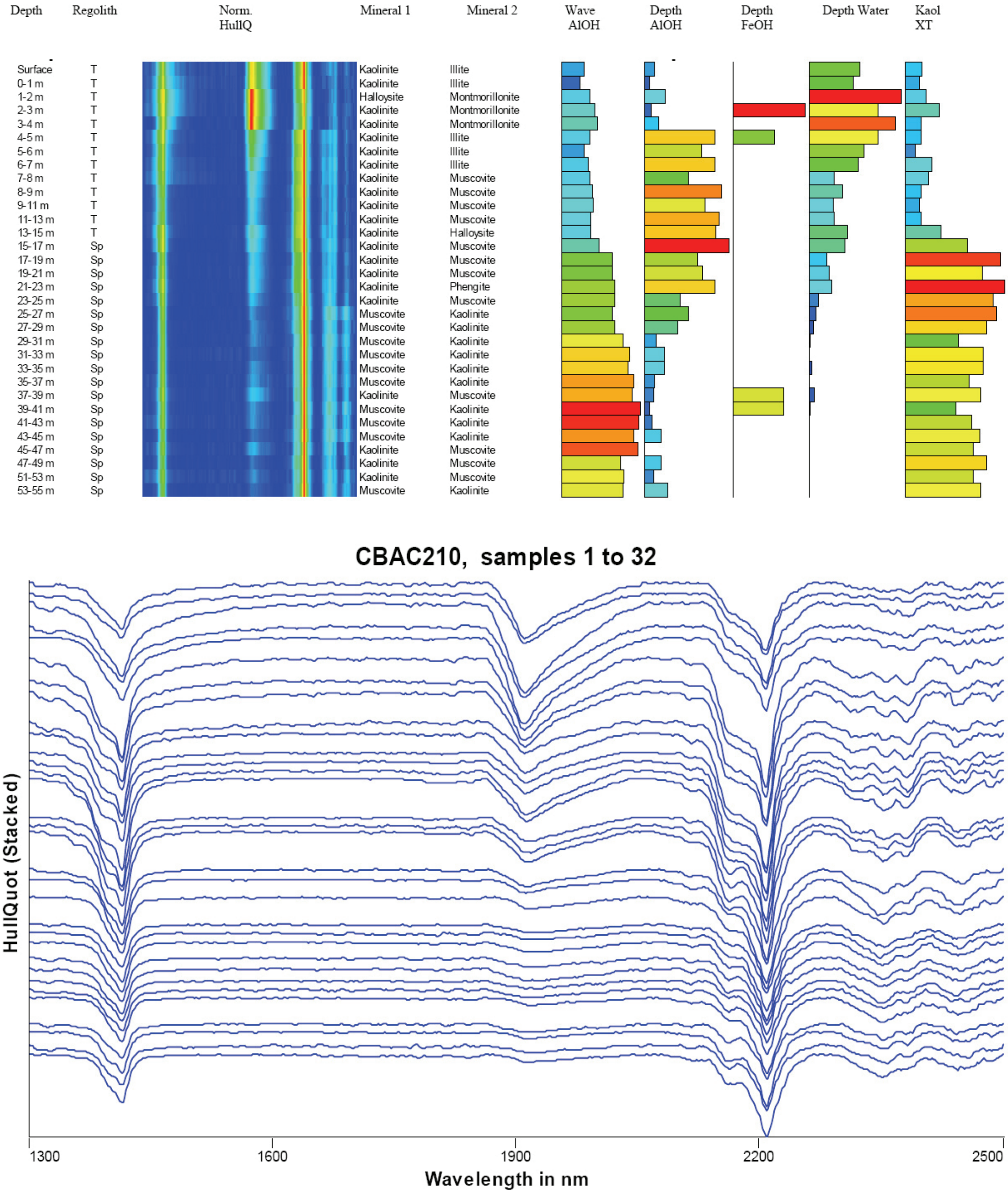


Figure A1-3. PIMA log and spectra of the regolith profile for drill hole CBAC210.

• A,C*: The distinctive spectral feature of these redeposited clays is a similar but less clear downward sloping shoulder around 2150nm as for OE from whence the clays were eroded, however, there is no downward sloping shoulder around 1350 nm, and the spectra between 2250 nm and 2500 nm are relatively flat; the main feature of the PIMA log is the low AlOH depth algorithm compared with OE, and perhaps a change in mineralogy from kaolinite to montmorillonite, e.g. CBAC182 at 2-9 m depth (Figure A1-2).

• A,C: This A,C sequence does not have strong intensity around 2150 nm, suggesting that this sequence is not dominated by clay. The relatively unconsolidated mixed sediments of sequence A,C do not display the KC shoulder around 2150nm, and the spectra tend to have a more convex slope to the 2150 nm side of the trough; otherwise spectral properties are similar to those of A,C*; KC in the PIMA log is variable depending on composition with increased KC indicating lithic/quartz gravels, e.g. CBAC153 at 1-6 m depth (Figure A1-4).

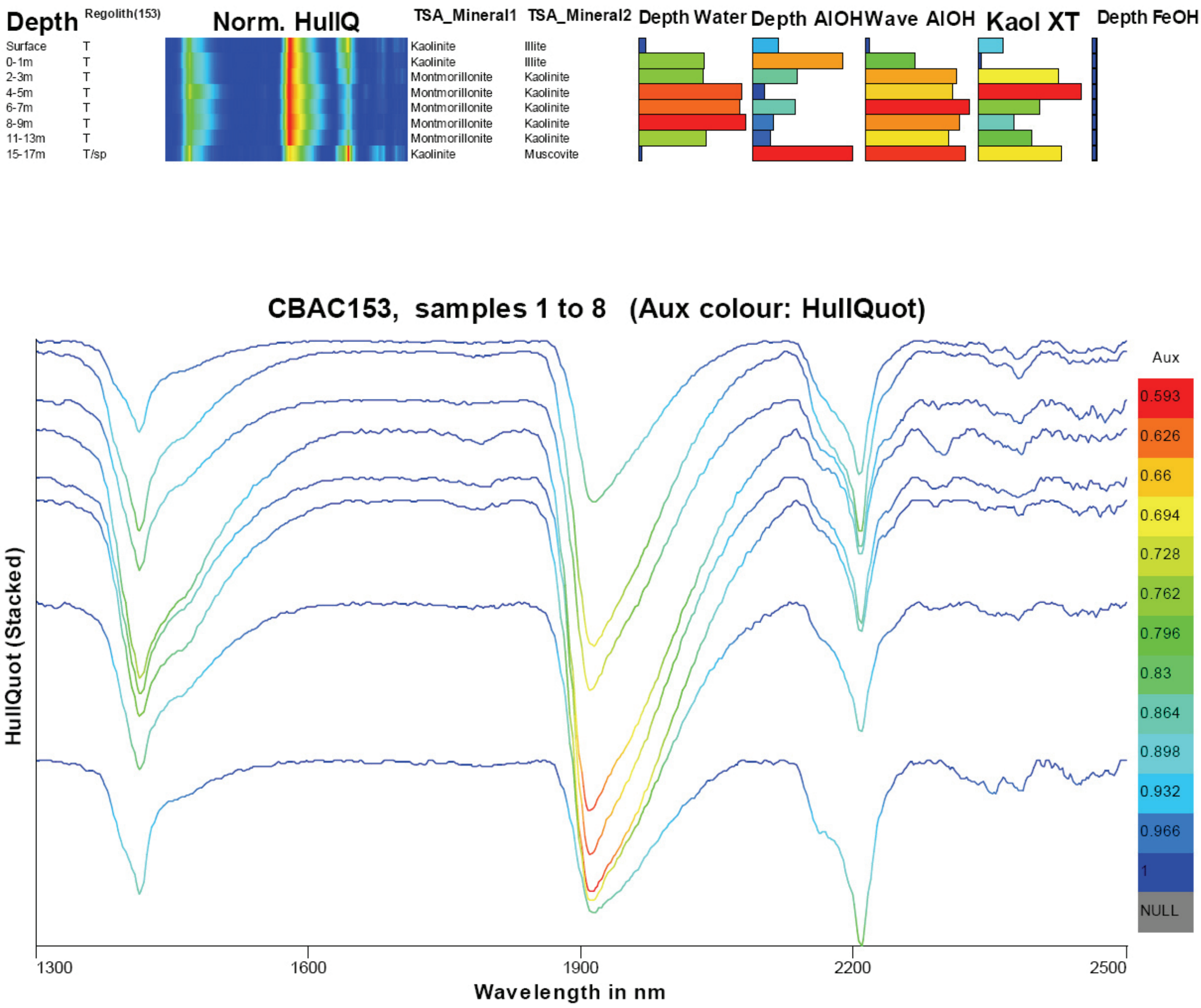


Figure A1-4. PIMA log and spectra of the regolith profile for drill hole CBAC153.

Appendix 2

Geochemical features of specific interest
(K. McQueen, K. Scott and M. Le Gleuher)

The geochemical data base from this study (Appendix 4) potentially contains many features of interest and relevance to mineral exploration in the region. The following are examples of such findings noted during the project.

Indications of bedrock sequences below transported cover
Drill holes through cover along the Byrock Road indicate that the area of mafic rocks that crops out in the Mount Dijou – Bald Hills area extends significantly further to the east. Based on regolith logging and geochemical features (higher MgO, TiO_2, Cr and V contents) mafic rock compositions are indicated for bottom of hole samples (analysed by XRF) between CBAC198-CBAC205 and CBAC212-214 (Appendix 4).

Regolith developed over the felsic Babinda Volcanics in the Hermdale Sheet area has elevated Zn contents (>100 ppm) on a regional scale.

Identification of mafic rocks in profiles
Mafic rocks, commonly dykes within Ordovician rocks, are widely distributed throughout the Girilambone region and have been encountered in 20 of the drill holes. In weathered profiles they contain elevated Fe, Mn, Ti, Cr and V. However, Ti and Cr contents can appear low in the analyses obtained following multi-acid digest due to incomplete dissolution of resistate Ti- and Cr-bearing phases and the absence of these elements does not necessarily discount elevated Ti and Cr in samples. Thus, the fact that the PIMA spectra of weathered mafic material reveal either one (Fe-bearing kaolinite) or no phyllosilicates in their spectra is very useful in rapidly confirming their mafic nature. Some mineralisation is commonly associated with or adjacent to these dykes. For example, in drill hole CBAC16 (17 km north of Canbelego), Ba up to 8800 ppm and S up to 4200 ppm (but not directly correlated with Ba) occur in the mafic material. The Ba and S are suspected to be in both barite and an alunite – jarosite mineral. Furthermore, drill hole CBAC198 (south of the Mt Dijou-Bald Hills deposits) contains mafic material (from 48-51 m) characterised by elevated Fe, Mg, Mn, Ni, P, Sr, Ti, V and Ti/Zr = 91 *plus* no phyllosilicates indicated in the PIMA spectra for that interval. Samples from this hole show elevated Zn (averaging 180 ppm between 1-5m) and anomalous Pb (>100ppm from 3-18 m, especially between 6-15 m where Pb is commonly >1000 ppm) but no other associated pathfinder elements, although 20 ppb Au occurs between 14 and 18 m. Mineralisation in the hole varies upwards from Au to Pb to Zn with distance from the mafic material.

Anomalous Au
Weak but extensive zones of Au-anomalism in the Byrock region deserve further investigation. A thick sequence with anomalous Au (40 m @ 40 ppb) occurs between 27 and 66 m in CBAC 238. This is within a probable shear zone in the Lord Carrington Hill area, 20 km northeast of Byrock. Three meters of transported material occurs in this hole with calcrete developed at about the unconformity. The Au content of the calcrete-bearing samples is slightly elevated (4 ppb) relative to non-calcareous material above and below (2 ppb). The phyllosilicates of the residual saprolite are kaolinite and phengite, but magnetite, feldspars, quartz and hematite are also present with chlorite present at depth. High Ca and P contents between 33-47 m reflect apatite (also detected by XRD). Although Zn varies from >100 ppm

below the unconformity to 15 m and >150 ppm below that, no other chalcophile elements are present in the Au-rich interval.

Further south, in the Hermidale area, Au occurs associated with elevated As, Sb and Zn in drill hole CBAC142, 6 km along strike from the Muriel Tank Goldfield. Between 29-48 m up to 21 ppb Au is present and As contents are generally >20 ppm. Below 29 m other geochemical data, particularly Fe, but also Al, Cu, Ti and Zn are elevated. From 39 m downwards, Zn tends to be further elevated relative to abundances higher in the profile. The PIMA spectra also suggest a decrease in the kaolinite crystallinity and an increase in the abundance of mica at about 29 m. Only 1 m of transported material occurs in this profile and dolomite, reflected by elevated Ca, Mg and Sr contents is strongly developed at the top of the residual saprolite (especially between 1-3 m). There may be some enrichment of Au associated with the carbonate in that interval.

In the central and southern portions of the Girilambone region, the common association of As with low level Au anomalies in regolith materials appears useful as an indicator of derivation from a Au-pyrite association. In the northern (Byrock) area Au anomalies are generally bereft of pathfinder elements. The association of some Au with Ca in calcrete confirms previous findings that calcrete can be used as a sampling medium provided the cover is not too deep (McQueen, 2006).

Significant base metal contents in the saprolite
Substantial As, Sb, Cu, Mo, W and Zn contents occur through the length of CBAC167 through the Babinda Volcanics (30 km northeast of Nymagee), with isolated anomalous Au also present at the top and bottom of the hole. Zinc contents are particularly high (1400 ppm) toward the end of the hole at 21 m and maintain abundances >700 ppm up to 7 m. PIMA spectra also show a change from dominant illite to kaolinite above this level, and indicates that the decrease in Zn content reflects dispersion of mobile elements with intense weathering. Some carbonate is developed at the transported/saprolite interface, with the increased Ca below 15 m reflecting the presence of residual plagioclase in lower saprolite/saprock. Dump material from an old shaft, 30 m away from this hole, contains 1.8% Pb plus anomalous Au, As, Cu, Mo, Sb, W and Zn and hence this hole must be regarded as representing the edge of a mineralised zone.

Elevated Pb contents (>50 ppm, associated with elevated As, Sb and S) in samples from 7-24 m in CBAC16 possibly reflect weakly mineralised (probably pyritic) mafic rocks over this interval.

Significant Zn (>100 ppm) is present below 11 m in CBAC176 (26 km east of Nymagee). Zinc abundances increase down the profile, reflecting normal dispersion of Zn during weathering, although the highest Zn content is associated with Co, Mn, Ti, Fe and P with a mafic dyke. PIMA spectra indicate a change from muscovite/phengite- to kaolinite-rich assemblages above 7 m (*i.e.,* close to where the Zn anomalism stops). This coincidence again suggests that Zn is depleted as weathering intensity increases. In fact, because muscovite (and phengite) may contain hundreds of ppm Zn (*e.g.,* Scott, 1988) but kaolinite does not, the destruction of its host may be responsible for its depletion higher in the profile. Carbonate is present at the transported/residual saprolite interface in this hole. The presence of intermittent anomalous Bi and/or W with the elevated Zn in this hole indicates that this region within and about the Babinda Volcanics in the extreme south west of the Girilambone region (including hole CBAC167, which is weakly mineralised) deserves further investigation.

In CBAC201, south of the Mt Dijou-Bald Hills deposits, Zn and Co occur associated with Mn between 15-72 m. Although this association reflects the presence of mafic material from 51-72 m, the strong association between 15-33 m and the low abundance of pathfinders like Pb and As suggests that the anomalous upper zone may represent incorporation of Zn and Co into Mn oxides at a former water table.

Anomalism in transported material
Detrital transport of material from gossans and *in situ* geochemical anomalies has been a feature of the regolith-landscape history of the Girilambone region. Detecting these transported anomalies and tracing them back to their source in the present and buried palaeolandscape is a valid approach to exploration. A complicating factor is the high threshold levels of some trace elements (including mainly As, Pb, Sb and Bi) in ferruginous, transported regolith, particularly pisolitic lag enriched in hematite-maghemite, that has been concentrated in palaeochannels and then reworked as these have been later eroded.

Drill hole CBAC 80 has anomalous Pb value (495 ppm) with associated As and Sb in samples of transported regolith from 6-7 m. PIMA results clearly indicate that this interval is within transported material. Such high values for Pb may reflect gossanous fragments in the transported material possibly derived from higher up the palaeodrainage system, not too far distant.

The reader is also referred to contributing reports Chan *et al*., 2003a; 2003b and 2004).

Appendix 3

Introduction to the geochemical data set for the Girilambone region.
See separate PDF file.

Appendix 4

Geochemical data, sample locations and regolith logs for air core samples from the Girilambone Project.
See separate XLS file.