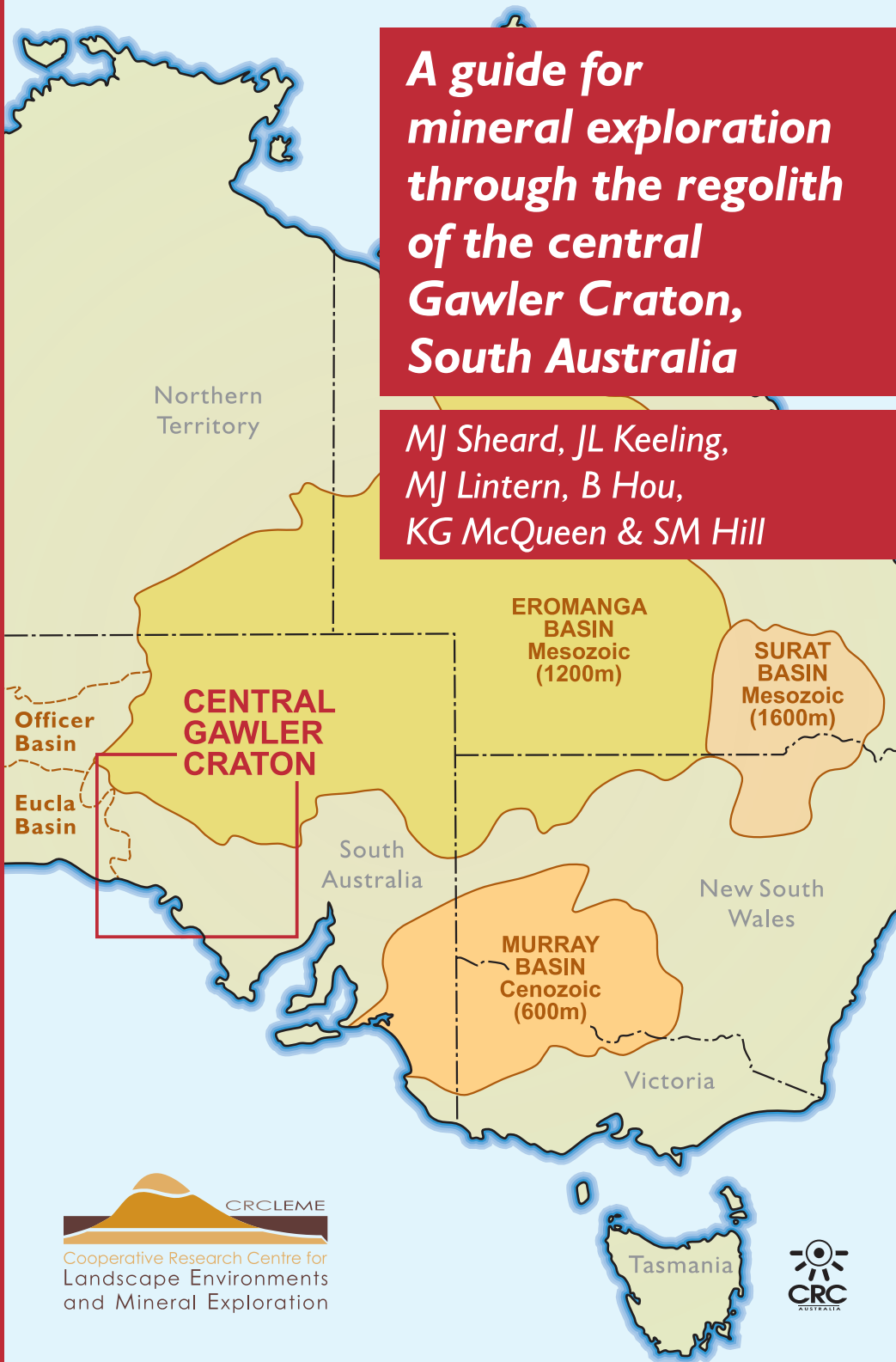
A guide for mineral exploration through the regolith of the central Gawler Craton, South Australia

MJ Sheard, JL Keeling,
MJ Lintern, B Hou,
KG McQueen & SM Hill



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Landscape Environments
and Mineral Exploration

CRC AUSTRALIA

A GUIDE FOR MINERAL EXPLORATION THROUGH THE REGOLITH OF THE CENTRAL GAWLER CRATON, SOUTH AUSTRALIA

MJ Sheard, JL Keeling, MJ Lintern, B Hou, KG McQueen and SM Hill

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CONTENTS

1. INTRODUCTION 1

1.1 Purpose of the Guide 1

1.2 Location and physical setting 1

1.3 Geological framework and basement rocks 5

1.4 Ore deposit types and exploration targets 9

Archaean Au 10

Proterozoic Au 10

Heavy minerals 12

Uranium 13

Other commodities 14

2. THE REGOLITH 19

2.1 Landscape history 20

2.2 Regolith architecture 27

2.3 Regolith materials 29

In situ regolith 32

Transported regolith 34

Indurated regolith (duricrusts, pans, cements) 37

Lag materials 46

Soils 48

2.4 Regolith minerals 50

2.5 Regolith geochemistry 52

Element dispersion controls 53

Weathering regimes 55

Examples of specific element dispersion features 56

Regolith element associations 61

Geochemical characterisation of regolith materials 63

2.6 Mapping surface regolith 63
2.7 Mapping Regolith in 3D with emphasis on palaeodrainage and palaeo-coastal deposits 67
Digital elevation models 67
Remotely-sensed Vis-IR spectral imagery 69
Night-time thermal satellite imagery 70
Geophysical methods 73
2.8 Mapping through the regolith 77
2.9 Mapping hydrothermal alteration 78

3. EXPLORATION CHALLENGES AND STRATEGIES . . .83
3.1 Key questions 83
3.2 Integrating regolith knowledge and exploration programs 84
3.3 Targeting mineral deposits within the regolith. 86
Identifying targets 86
Test drilling 87
3D computer modelling 91
3.4 Sampling the regolith 91
Calcrete 93
Soil 96
Lag 97
Siliceous materials 98
Ferruginous materials 98
Bedrock/saprock/saprolite 98
Sediments 99
Vegetation 102
Groundwater 106
3.5 Drilling, sampling and modelling 108

Drilling and drill hole sampling: diligence and cautions 108
What to look for in drilled samples 110
Logging 113
2D and 3D interpretation of the regolith 114
3.6 Analytical approach and methods 121
3.7 Quality assurance and quality control 123
3.8 Identifying anomalies 124
3.9 Concluding comments 126

ACKNOWLEDGEMENTS 129

REFERENCES 131

GLOSSARY 149

GUIDE SUMMARY AND KEY 157

APPENDICES ON CD

A1 Digital copy of Guide

A2 Regolith benchmark sites in the central Gawler Craton (Sheard 2008)

A3 Regolith mapping

A4 Regolith landform units code (Pain *et al.* 2007)

A5 Calcrete sampling for mineral exploration (Lintern 2002)

A6 Vegetation sampling in the Gawler Craton (S Hill)

A7 Identifying geochemical anomalies (KG McQueen)

1. INTRODUCTION

1.1 Purpose of the Guide

This Guide is designed to assist mineral explorers working in the regolith-dominated terrains of the central region of the Gawler Craton in South Australia: in particular those areas of weathered bedrock where dominantly terrestrial deposits form a patchy and comparatively thin (< 100 m) cover (*Figure 1*). From a mineral industry perspective, the Gawler Craton is renowned as host to the world-class Olympic Dam Cu–Au–U deposit. For exploration, the fertility of the Craton is confirmed by the recent discovery of a cluster of deposits and occurrences of Fe-oxide–Cu–Au (IOCG)-style mineralisation: mostly below thick sediment cover along the Craton's eastern margin. The central region of the Craton is largely under-explored. Before the 1990s, the only substantial metal production was 2.4 tonnes of Au from the Tarcoola Goldfield – discovered in 1900 – and from smaller workings at Glenloth and Earea Dam. Exploration over the past 20 years has identified significant resources of hypogene and intrusion-related Au, heavy mineral sands and Fe ore, and established the region as prospective for Pb–Zn, Cu–Au, Ni and sandstone-hosted U deposits. This Guide provides an introduction to the regolith and landscape history of the region, together with advice on strategies and methods that can assist with exploration for mineral deposits within, or beneath, the regolith.



Figure 1. Location and regional geomorphic setting of the central Gawler Craton.

1.2 Location and physical setting

The central Gawler Craton, (as outlined in *Figures 1 and 2*), covers an area of ~200,000 km^2 and takes in the small regional centres of Coober Pedy in the

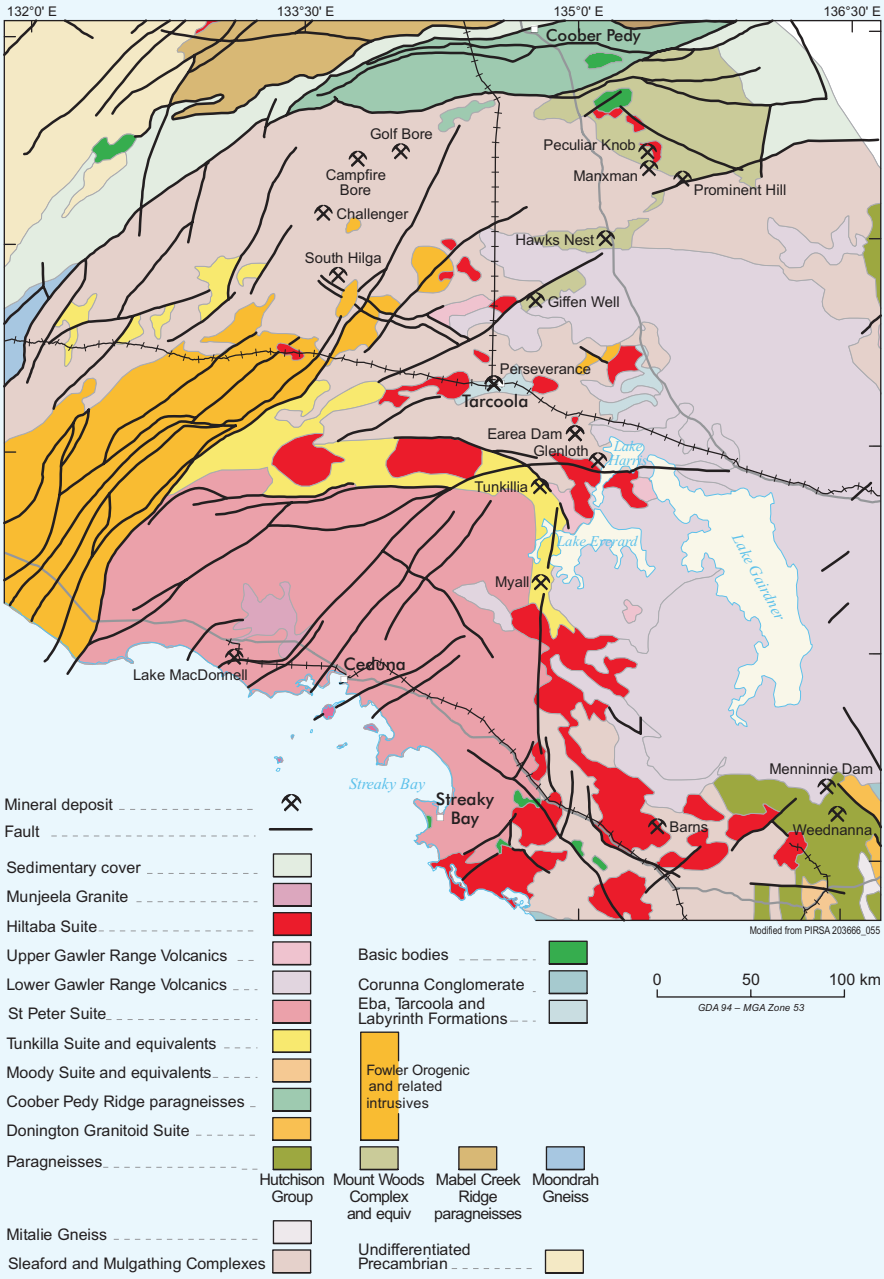


Figure 2. Basement geological framework of the central Gawler Craton showing major geological and structural features.

north, and Ceduna in the southwest. The area is characterised by a variety of landscapes: low-relief sandy deserts (*Figure 3*); low-to-moderate-relief erosional terrain interspersed with undulating plains; retreating escarpments adjoining gibber plains (*Figure 4*); upland ranges; large evaporitic playas/palaeoplayas (*Figure 5*), palaeovalleys; and the modern coastline. Areas with more striking relief include the Gawler and Middleback Ranges, and the isolated inselbergs of Mount Finke (*Figure 6*), Mount Christie, Tarcoola Ridge and Darke Peak. The terrain generally has less than 100 metres of relief, but includes small areas rising to 150 metres and, rarely, over 200 metres, with a maximum of 454 metres AHD at Paney Hill, south of the Gawler Ranges.

The climate varies from arid to semi-arid. An annual rainfall of about 150–200 mm is typical of the deserts, while more than 250 mm is common nearer the coast or around more elevated terrain. The vegetation is diverse and includes sparse arid-tolerant species in deserts (e.g. *Triodia, Maireana, Atriplex* and *Acacia*) to denser tree–shrub communities of mallee (dominated by such genera as *Eucalyptus, Acacia, Casuarina, Grevillea, Myoporum* and *Hakea*) in areas of higher rainfall, creek lines, sand dunes and where richer soils occur.



Figure 3. Aerial view (approximately west northwest) over part of the Great Victoria Desert dunefield fringing the Nullarbor Plain. The longitudinal dunes of late Pleistocene age are siliceous and stand 5 to more than 15 metres proud of the surrounding plain.



Figure 4. Breakaway–an escarpment cut into silica-indurated, deeply weathered marine bulldog shale, flanked by silcrete gibber-clad plains. These are recurrent landforms in the Gawler Province.

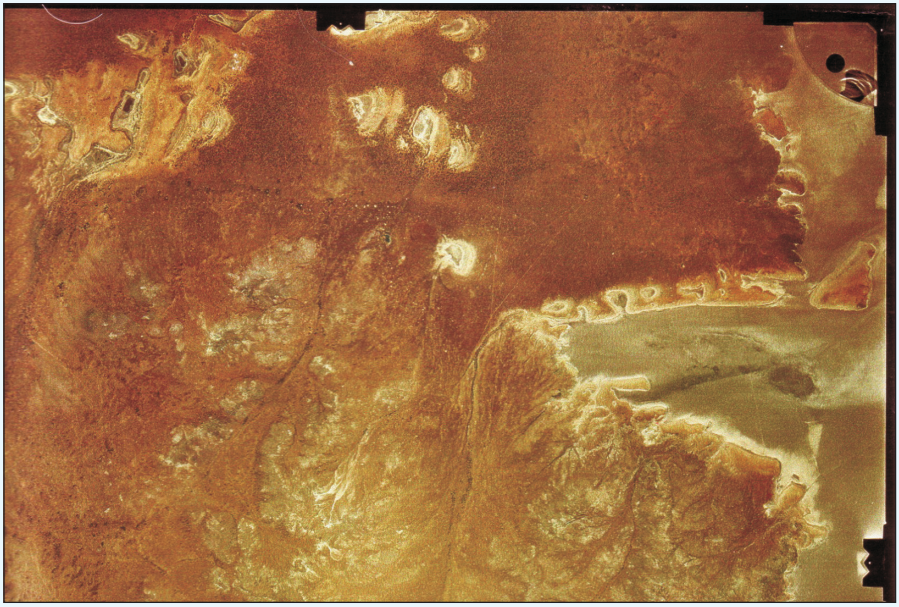


Figure 5. Aerial view, part of Lake Harris salt pan, northwest corner inlet. The inlet is coincident with part of the Kingoonya Palaeochannel topographic low. The northerly continuance of the channel is marked by a string of small salt pans. The image width is 15.6 kilometres.



Figure 6. Mount Finke–an inselberg of Tarcoola Formation quartzite, standing about 250 metres proud of the plain. View roughly north northwest from a dune crest within the surrounding Great Victoria Desert.

1.3 Geological framework and basement rocks

The area covered by this Guide incorporates about half the recorded extent of exposed or thinly-covered crystalline basement rocks of the Gawler Craton, and includes cover sequences of largely undeformed intracontinental basin sediments that range in age from Mesoproterozoic to Neogene. All are variably weathered, and much of the geological detail is hidden by a veneer of sand that reflects the change to arid climatic conditions since the Late Pliocene – around 2.4 million years ago.

The crystalline basement consists of Archaean to Mesoproterozoic metasedimentary rocks, volcanics and granitoids, and has been tectonically stable – apart from minor near-surface tectonic movements – for about 1450 Ma. Basement rocks record crust formation and tectonothermal events in the late Archaean to early Palaeoproterozoic (Sleaford Orogeny

~2440 Ma), Palaeoproterozoic (Neil Event and Kimban Orogeny 1845-1700 Ma), and Palaeoproterozoic to Mesoproterozoic (Kararan Orogeny 1650–1540 Ma) (Ferris *et al.* 2002; Schwarz *et al.* 2003). Details of the basement geology have been derived mostly from regional airborne magnetic surveys that define structural and lithological trends. The magnetic data – together with regional geological mapping, geochronology, isotope analyses and geochemistry – have been used to subdivide the basement into a series of domains (*Figure 7*) that are thought to represent major crustal components that were assembled during polyphase tectonic events during the Proterozoic (~1850–1540 Ma) (Ferris *et al.* 2002).

Regolith studies, which underpin much of the discussion and advice that follow, have focused on areas mostly within the Christie Domain, Harris Greenstone Belt, Wilgena Domain, western margin of the Nuyts Domain and the western and southern margins of the Gawler Range Volcanics (see Appendix A2, on CD, for detailed summaries of selected sites). A brief outline of the geology of the various domains is given below.

- **Christie Domain**. This includes Archaean to the earliest Palaeoproterozoic rocks. Major rock units include low magnetic intensity Mulgathing Complex paragneiss interlayered with magnetic zones of banded iron formation (BIF) and ultramafic rocks, including peridotite, all mostly recrystallised to granulite-grade metamorphics and later intruded (at around 1690–1670 Ma) by highly magnetic mafic dykes and sills (Fairclough and Schwarz 2003).
- **Harris Greenstone Belt.** This comprises supracrustal Archaean ultramafic (komatiite) and mafic volcanics, with Archaean paragneiss, felsic intrusions and syntectonic granite. The region differs from the Christie Domain in that the mafic rocks are dominantly extrusive.
- **Wilgena Domain.** This comprises high magnetic intensity Palaeoproterozoic metasediments with basal Wilgena Hill jaspilite, BIF, overlain by restricted, fault-bounded intracratonic basins infilled with conglomerate, quartzite, shale and intercalated volcanics.
- **Nuyts Domain.** This consists of probable Palaeoproterozoic, ductile deformed metasedimentary and meta-igneous rocks into which

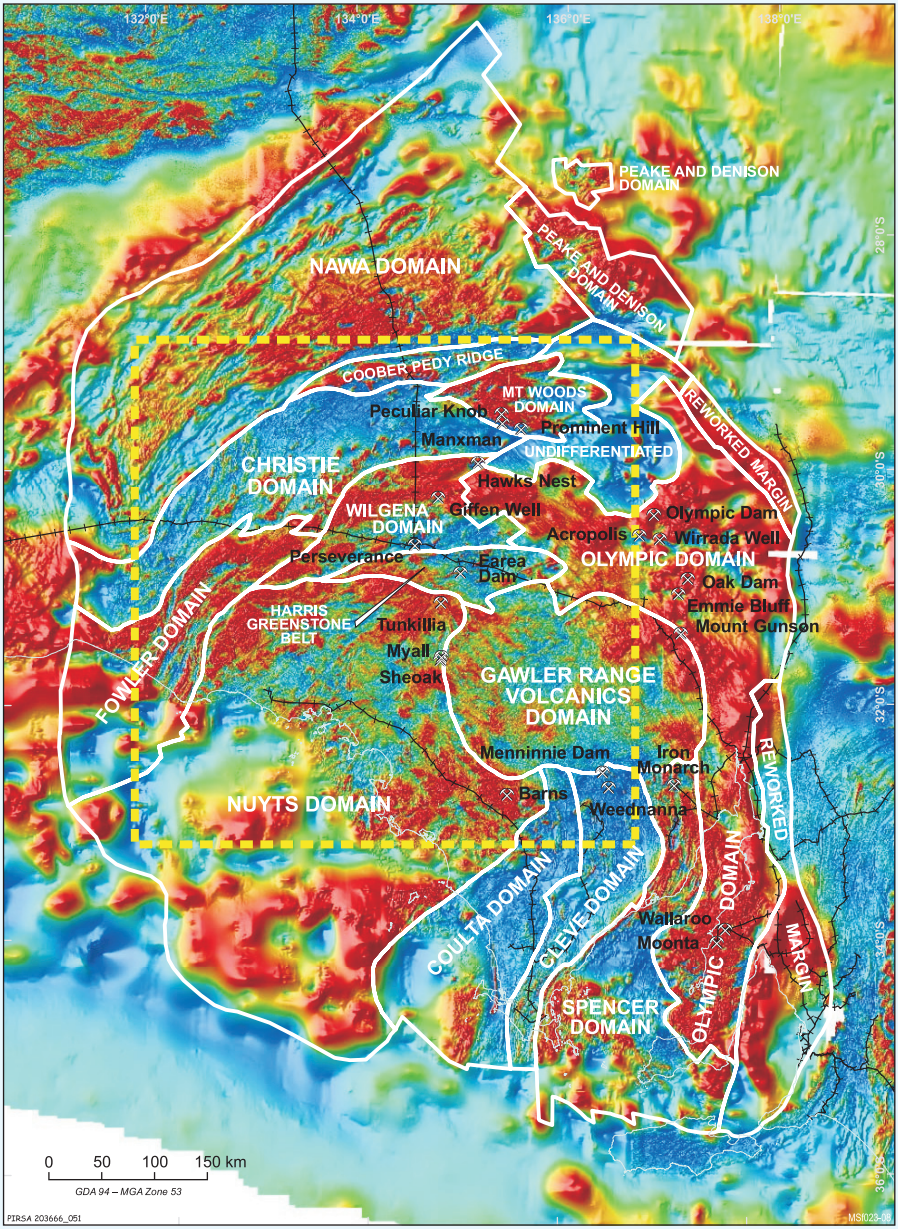


Figure 7. Gawler Craton, showing basement domains (white lines) on a total magnetic intensity image. The area of the central Gawler Craton is outlined. Selected mines and prospects are shown with crossed picks.

Palaeoproterozoic to Mesoproterozoic granitoids were emplaced. The domain is broadly delineated by a distinctive gravity low, reflecting the predominantly felsic igneous rocks and is bounded on the eastern and northern margins by major shear zones with a high concentration of Hiltaba Suite granite plutons.

- **Gawler Range Volcanics (~1590 Ma).** These constitute a vast outpouring of dominantly felsic volcanic deposits with over 25,000 km^2 of preserved outcrop. Two broad groupings are recognised: a lower unit that is gently to steeply tilted and more varied in composition, consisting of dacite–rhyodacite–rhyolite, ignimbrites and flows, with minor thick interlayered sequences of basaltic lavas; and an upper unit with thick, sub-horizontal, porphyritic dacite and ignimbrite. Hiltaba Suite granite (1600–1585 Ma) – in part co-magmatic with the Gawler Range Volcanics (GRV) – forms abundant outcrop on the western and southwestern margins of the GRV. The volcanics and granite are largely undeformed and thought to be derived from partial digestion of the crust by mantle plumes. This thermal event is regarded as the driving mechanism and possible source for widespread Au–Cu–U mineralisation in the Gawler Craton.

Overlying the basement units on the eastern margin of the Gawler Craton is a sequence of undeformed arenaceous redbed sediments of the Pandurra Formation that in places exceeds 1,000 metres in thickness and was deposited in the Cariewerloo Basin during the Mesoproterozoic, since around 1580 Ma (Cowley 1993). The redbeds were intruded by the Gairdner Dolerite dyke swarm around 827 Ma (Wingate *et al.* 1998). Neoproterozoic to Cambrian shallow marine sands and carbonate sediments were deposited over a portion of the eastern Cariewerloo Basin on the Stuart Shelf as a platform extension to sedimentation in the Adelaide Geosyncline.

Late Carboniferous to Early Permian post-glacial sediments are present in the Arckaringa Basin in the north of the region and in the Mulgathing Trough. These can exceed 1,000 metres in thickness, and include substantial coal deposits in the Phillipson Trough.

Late Jurassic to Early Cretaceous fluvial and marine sediments deposited in the southwestern extremity of the Eromanga Basin are up to 100 metres

thick in the northern part of the area. During the Late Cretaceous to early Palaeogene, a network of large rivers incised deep channels into the basement and older cover sediments. The channels were subsequently filled with sandy deposits. The rivers discharged sediment into the marine Eucla Basin in the southwest of the region. Longshore drift, under prevailing westerly winds, built extensive barrier sand deposits extending for hundreds of kilometres along the early Cenozoic coastline. These remain intact due to a combination of lower sea levels, a drier climate and the uplift of the southern margin of the Australian continent, which began in the Late Miocene (Hou *et al.* 2008). The thickness of Cenozoic sediment is variable across the region and may exceed 100 metres in river channels and on the margin of the Eucla Basin.

Drier conditions throughout much of the Pleistocene produced widespread siliceous dunes and sandplains that cover much of the earlier landscape and are up to tens of metres thick. Along the present coastline, 30 m-high calcareous sand (calcarenite) dunes formed during times of low sea level when marine carbonate platform sediments were exposed to erosion by strong westerly winds.

1.4 Ore deposit types and exploration targets

The Gawler Craton is host to Fe–oxide–Cu-Au ± U (IOCG±U) deposits and occurrences, of which the Olympic Dam deposit is world class. These cluster in an arcuate belt along the eastern margin of the Craton – mostly beneath thick cover of marine sediments – and to the east of the area covered by this Guide. Buried IOCGU deposits have proved to be difficult targets, with no surface technique regarded as being effective in directly detecting mineralisation. Within the central Gawler region, exploration is occurring for the following commodities: Au, Cu–Au, Pb–Zn, Fe ore and Ni in crystalline basement rocks; and heavy minerals, U and precious opal in the sediment cover. Historic and current mines in the area and immediate vicinity include: Olympic Dam (IOCG + U, Ag), Prominent Hill (IOCG + U, Zn, Pb), Tarcoola Goldfield (Au), Earea Dam Goldfield (Au), Glenloth Goldfield (Au) Challenger (Au), Middleback Ranges Fe mines (BIF, hematite, magnetite), Copper Triangle (Cu, Au), Coober Pedy Opal Field (gem opal) and Lake MacDonnell (gypsum) (*Figures 2, 7; Table 1*).

Archaean Au

Regional reconnaissance drilling with follow up calcrete soil sampling led to discovery in 1995 of Au within migmatite of Mulgathing Complex, Christie Gneiss. This led to development of the Challenger mine and a new exploration target for Au in Archaean gneiss of the Christie Domain. By June 2007, the mine had produced over 360,000 ounces of Au, with a further 1 M ounce Au resource defined by development and exploration drilling and with the ore body still open at depth (Alexander 2007). Current production is above 100,000 ounces/year at a head grade of around 9 g/t. The Au is thought to have been hosted initially by volcaniclastics that were deposited around 2,520 Ma (McFarlane *et al.* 2007). These were deformed during the Sleafordian Orogeny (~2440 Ma) under granulite-grade metamorphic conditions and recrystallised as quartz–feldspar–garnet–biotite–cordierite gneiss. Gold in the volcaniclastics was remobilised and concentrated in leucosomes in the hinge zones of an asymmetric fold system. Drag folds–having multiple separate fold closures–define individual shoots that plunge at about 30° towards 032° and persist for hundreds of metres (Poustie and Abbot 2006). The largest shoot, M1, has folds with an average amplitude of 25–30 metres and wavelengths varying from 5 to 20 metres, with the overall shoot width being 40–50 m. Mineralisation is coarse Au with minor arsenopyrite, lollingite and pyrrhotite with traces of Bi minerals, tellurides, chalcopyrite, pentlandite and sphalerite (Poustie *et al.* 2002). Prospects in the Christie Domain that may turn out to be similar include Monsoon, Typhoon, Challenger West, Kelpie, Mainwood Golf Bore and Campfire Bore (Birt and Reid 2007). Other styles of remobilised Archaean Au mineralisation may be associated with high-grade metamorphism of mafic, ultramafic and BIF lithotypes and are potential additional targets within the Christie Domain (Birt and Reid 2007).

Proterozoic Au

The around 1600 Ma Hiltaba Suite magmatic/tectonic event is associated with widespread mineralisation in the Gawler Craton. Two main mineralisation styles are attributed to this event: an Au-only event through the central Gawler and a Cu–Au (IOCG) event on the eastern margin of the craton

(Ferris and Schwarz 2003). The concept of a central, Au-only province grew from recognition of similarities in deposit style and mineral alteration associated with historic and recent Au discoveries (Budd 2002; Drown 2003). The Central Gawler Gold Province (CGGP) was proposed and outlined as an arcuate belt surrounding the western and southwestern margins of the GRV outcrop (Drown 2002). In this zone, fractured rocks and active faults adjacent to pluton margins are regarded as being most prospective (Daly and Conor 2006; Drown 2003; Budd and Skirrow 2007). The metallogenic province was extended by Ferris and Schwarz (2003) to include the Fowler Domain, which also has interpreted Hiltaba plutons in active shear zones, although potential for Au mineralisation in this region remains untested. Thermal fluid flow modelling by Potma and Zhang (2006) highlighted rocks within about 200 metres of the base of the GRV 'seal' as potentially being the most prospective for metal deposits. Their model predicts rapid cooling of the GRV, which then acted as a laterally extensive, very low permeability blanket to focus thermally driven fluid flow. Various potential traps have been identified for metals dissolved in the circulating fluids:

- reactive rocks in close proximity to the lower GRV, in particular mafic units and carbonaceous sediments
- fracture zones in the lower GRV resulting from deformation or localised fluid overpressure
- steep permeable structures, such as major shears that focus rapid up-flow of deep hot fluids leading to either rapid cooling, pressure drop or fluid mixing–all of which may facilitate mineral precipitation.

Styles of mineralisation in the CGGP include mesothermal and possible epithermal deposits, which are mostly associated with reduced hydrothermal fluids that do not show the extensive Fe-oxide alteration characteristic of IOCG deposits. Gold is deposited in narrow quartz veins–usually with pyrite or within zones of sericite alteration–and in a variety of host rock types. Sulphides of Cu, Pb, Zn and As may be present, together with Ag and occasionally Sn. Chlorite and sericite alteration of host rocks is common, and destruction of magnetite may accompany increased intensity of alteration (Budd and Fraser 2004; Fraser *et al.* 2007). Examples of this

style of mineralisation include historic Au deposits at Tarcoola, Glenloth and Earea Dam and new Au prospects at Tunkillia, Nuckulla Hill, Barns, Baggy Green, White Tank and Weednanna (Ferris and Schwarz 2003; Drown 2004). Recent prospects were located mostly by drilling Au-in-calcrete soil anomalies in areas close to major shear zones identified from regional airborne magnetic data.

Heavy minerals

Major river systems that drained the Gawler and Musgrave provinces during the early Palaeogene, transported vast quantities of sediment that were discharged into the sea. Marine transgressions, driven by sea level rise during the Middle-Late Eocene, increased sediment deposition in palaeovalleys and led to the accumulation and reworking of coastal sand into barrier deposits that extended for some 600 kilometres along the northern and eastern coastal margins of the Eucla Basin. The recognition that sand ranges, which occur up to 250 kilometres inland of the present coastline, reflect this remarkably well-preserved coastal barrier system (Benbow 1990) prompted exploration for heavy mineral sands in the area (Ferris 1994). The remote location, the extent and complexity of the barrier deposits and the influence of aeolian reworking during the late Neogene, hampered early exploration. Investigations to unravel the stratigraphy of the dunes and palaeovalley sediments by correlation with offshore deposits (Clarke *et al.* 2003; Hou *et al.* 2003a) led to a reconstruction of the palaeogeography and reinterpretation of scattered intersections of heavy minerals in terms of sedimentary facies models of heavy mineral accumulation (Hou *et al.* 2003b). During 2004, a reinvigorated company exploration program located world-class resources of high-grade, zircon-rich sands at Jacinth and Ambrosia (Hou and Warland 2005). These were followed by a succession of discoveries that include Tripitaka, Gullivers, Barton West, Typhoon, Dromedary and Willy Willy. Most discoveries have been in the Ooldea barrier system in unconsolidated sand above the water table, and are interpreted as stacked beach placer deposits. These commonly show a high-grade heavy mineral core with dominant zircon, overlain by lower-grade dune deposits. The thickness of economic intersections, at greater than 1% heavy minerals (HM), varies

from a few metres to 30 metres, and deposits are of the order of 4 kilometres long by 1 kilometre wide. Overburden thickness ranges from 0 to about 45 m. Jacinth is the richest discovery to date, with a measured resource of 111 Mt at 5.5% HM concentrate comprising 47% zircon, 5% rutile and 31% ilmenite (Iluka Resources 2008). Gullivers and Barton West deposits lie outside the Ooldea barrier. Both cover larger areas than the Ooldea beach placer deposits and have ilmenite as the dominant heavy mineral. Gullivers covers an area 7 kilometres in length by 2.5 kilometres in width and is interpreted as a possible offshore shoal deposit (Iluka Resources 2006). The deposit averages about 2% HM over a thickness of around 5 metres, below 25–30 metres of cover sediment.

Uranium

The Olympic Dam IOCGU deposit produces about 4,000 t/a U_3O_8 from a resource of 7,738 Mt at grade 0.029% U_3O_8 contained in hydrothermally altered and brecciated Hiltaba Suite granite (BHP Billiton 2007). The Olympic Dam breccia model is a prime exploration target in the region for large tonnage U, in association with Cu and Au mineralisation. Above-background levels of U in basement rocks–particularly in areas affected by Hiltaba magmatism–make other targets attractive for exploration. These include possible unconformity style mineralisation in the lower Pandurra Formation sandstone of the Cariewerloo Basin, and sandstone-hosted deposits–principally in the extensive network of Cenozoic fluvial channel sands and marginal marine deposits, but also in largely untested Palaeozoic and Mesozoic sand bodies. Exploration for U in Cenozoic palaeodrainage sediments commenced on the Gawler Craton in the late 1960s. During 1973–82, PNC Exploration Pty Ltd located anomalous U in seven discrete zones along 12 kilometres of the Warrior Palaeochannel–a tributary of the Kingoonya Palaeodrainage system (Curtis *et al.* 1990; McKay and Miezitis 2001). This sub-economic mineralisation remains the most significant discovery of sandstone-hosted U in the region to date. Uranium is present near the margins of the palaeochannel and occurs at the interface of fluvial sands with carbonaceous sediments, at around 30–40 metres depth. Recent aircore drilling has confirmed anomalous U over 1 to 7 m-thick intervals

with grades of 0.01–0.09% U_3O_8 (but mostly < 0.025%) in the thicker intervals (Hall 2007). Other prospects are located at Ealbara–also on the Kingoonya Palaeodrainage system, to the east of Warrior–and at Yarranna on the Narlaby Palaeodrainage system to the south (Binks and Hooper 1984). These occurrences are consistent with sedimentary, sandstone-style mineralisation where U in oxygenated groundwater within the channel sand is precipitated, usually as uraninite (UO_2) or coffinite ($USiO_4$), at a redox boundary such as the interface with organic or clay-rich sediments (Curtis *et al.* 1990; Hou *et al.* 2007b).

Other commodities

Other commodity targets in the region include Cu–Au (Mount Woods Domain), Pb-Zn (Menninnie Dam, Telephone Dam), Fe ore (Mount Woods Domain, Wilgena Domain), Ni (Harris Greenstone Belt), opal and gypsum (*Table 1*).

Iron oxide Cu–Au mineralisation associated with Hiltaba Suite magmatism occurs at Prominent Hill in the Mount Woods Domain. The Olympic Dam deposit, and other IOCG prospects, is further to the south and east. The Prominent Hill deposit is below 100 metres of Mesozoic sediments and was discovered in 2001 by drilling geophysical targets based on modelling magnetic and gravity data to differentiate areas of near-coincident magnetite and hematite alteration. Cu-Au mineralisation is hosted by a hematite-altered and brecciated volcaniclastic sequence equated with lower GRV (Belperio *et al.* 2007). Total resource estimates to June 2007 give contained metal of 1.9 Mt Cu, 3.7 Moz Au and 12.5 Moz Ag at grades for the measured resource category of 1.69% Cu, 0.52 g/t Au and 4.06 g/t Ag (Oxiana Limited 2008). Development of the deposit is at an advanced stage, with production of concentrates expected during the latter half of 2008.

Significant Pb–Zn–Ag mineralisation was discovered in 1981 at the Menninnie Dam and Telephone Dam prospects during drill testing of aeromagnetic anomalies near the southern margin of the Gawler Ranges (Horn and Morris 1990). Mineralisation, comprising massive pyrite-sphalerite-galena with minor chalcopyrite and pyrrhotite, is hosted by steeply dipping Hutchison

Group serpentine marble, laminated graphitic and dolomitic marble, and carbonate-facies BIF (Drexel *et al.* 1993). Sulphides have replaced carbonate and calc-silicate and the mineralising event may be related to the intrusion of Mesoproterozoic rhyolitic dykes. Typical drill intercept grades over 0.5 metres intervals, range from 5.8% Pb, 14% Zn, 60 g/t Ag and 0.45 g/t Au to 25.4% Pb, 7% Zn and 178 g/t Ag (DDH MD 6) (Higgins *et al.* 1990). An inferred resource of 3.8 Mt at 3.2% Pb, 4.0% Zn and 34 g/t Ag at a 3.5% Pb+Zn cut-off was reported in 2007 for the central ore zone at Menninnie Dam (Terramin Australia 2008).

The Gawler Craton hosts extensive BIFs in both Archaean and Palaeoproterozoic sequences. Over 200 Mt of high-grade hematite ore (> 62% Fe) has been mined from Palaeoproterozoic deposits in the Middleback Ranges, 40 kilometres west of Whyalla. Archaean iron formations are prominent in the Wilgena and Christie Domains of the central Gawler region. They form part of a sequence of high-grade metamorphic, multiply deformed, meta-igneous and metasedimentary rocks and are characterised by high-amplitude magnetic anomalies and near-coincident gravity anomalies. The Fe formation layers are typically less than 50 metres thick, with discontinuous strike lengths of up to 500 m. The Sequoia prospect is one of the larger bodies and contains an inferred resource of 20 Mt at an average grade 28% Fe (PIRSA 2004). Palaeoproterozoic BIFs are more extensively developed in the Mount Woods and Coober Pedy Domains. The BIFs can be up to 700 metres thick and persist along strike for up to 25 km. Magnetite is generally the dominant Fe mineral in the amphibolite to granulite-grade metasediments. Ore grades of around 35-40% Fe are typical but can include high-grade zones exceeding 60% Fe and zones of hematite ore (PIRSA 2004). Significant prospects under shallow cover have been identified by drilling magnetic anomalies at Cairn Hill, Peculiar Knob, Manxman, Joes Dam, Hawks Nest and Giffen Well. Inferred resources exceed 500 Mt (Davies *et al.* 2002). Massive magnetite skarn in carbonate and calcsilicate units in Hutchinson Group metasediments at Wilcherry Hill in the southeast of the region has a reported combined indicated and inferred resource of 44 Mt at 35.4% Fe (IronClad Mining 2007).

Komatiite and komatiitic basalt flows identified in the Archaean Harris Greenstone Belt are prospective for nickel sulphides and Au. The units vary in thickness from 300 to 2000 metres and occur within a shallow east–west trending isoclinal fold–or imbricate isoclinal folds–with a composite strike length of at least 350 km. Aeromagnetic data indicate zones of thickened sequence indicative of possible channel ways with potential for cumulate sulphide deposits. Prospective units defined from aeromagnetic data are mostly beneath shallow cover and are largely unexplored. To date, only minor nickel sulphide occurrences have been recorded in the area (Fairclough and Schwarz 2003).

Precious opal is present in deeply weathered Cretaceous marine sediment where it forms as rare thin seams sub-parallel to bedding, as cross-cutting veins and as replacement of fossil carbonate shells. The most prospective areas are included in the designated Coober Pedy Precious Stones Field. Exploration and mining is effectively restricted to individual prospectors or small syndicates by limits imposed on the size and number of precious stone prospecting claims and leases that can be held by individuals and companies.

Thick deposits of gypsum have formed adjacent to the present coastline as the result of seawater evaporation in drowned valleys behind large calcarenite dunes. The largest deposit at Lake MacDonnell contains a resource of some 500 Mt of grade 93% gypsum. Production is around 1.3 Mt of gypsum/year, which is railed to the port of Thevenard and shipped to plasterboard manufacturing plants and cement works–mostly on the eastern seaboard. Smaller deposits have been identified at other sites near the coast, but are undeveloped.

Table 1. Potential exploration targets in the central Gawler region.

Age	Sequence	Deposit Types			
Cenozoic	Coastal dunes/ swales	Gypsum	Limesand		
Cenozoic	Palaeochannel systems	Sandstone-hosted U	Placer Au	Placer diamonds	Palygorskite
Cenozoic	Beach barrier sands	Heavy mineral sands			
Cenozoic	Weathering profiles	Precious opal	Lateritic nickel	Kaolin	
Proterozoic	Pandurra Formation	Sandstone-hosted unconformity U			
Proterozoic	Hiltaba Suite granite	Fe oxide Cu Au U	Hypogene Au	Epithermal Au	Hydrothermal Pb, Zn, Ag
Proterozoic	Hutchinson Group	Banded Iron Formation (BIF)	Skarn Pb/Zn	Graphite	
Archaean	Harris Greenstone Belt	Komatiitic nickel	BIF	Hydrothermal Au	
Archaean	Christie Domain	BIF	Structurally-controlled Au		

2. THE REGOLITH

Regolith has been described as 'everything between fresh rock and fresh air' (Eggleton 2001). The term incorporates weathered rock, unconsolidated sediment, surficial cements, soil and the contained vegetation and biota. Commonly observed components of a regolith profile in weathered bedrock are shown in *Figure 8*. Regolith is being continuously formed and modified, and what we observe in the present day landscape is a composite of past and recent events.

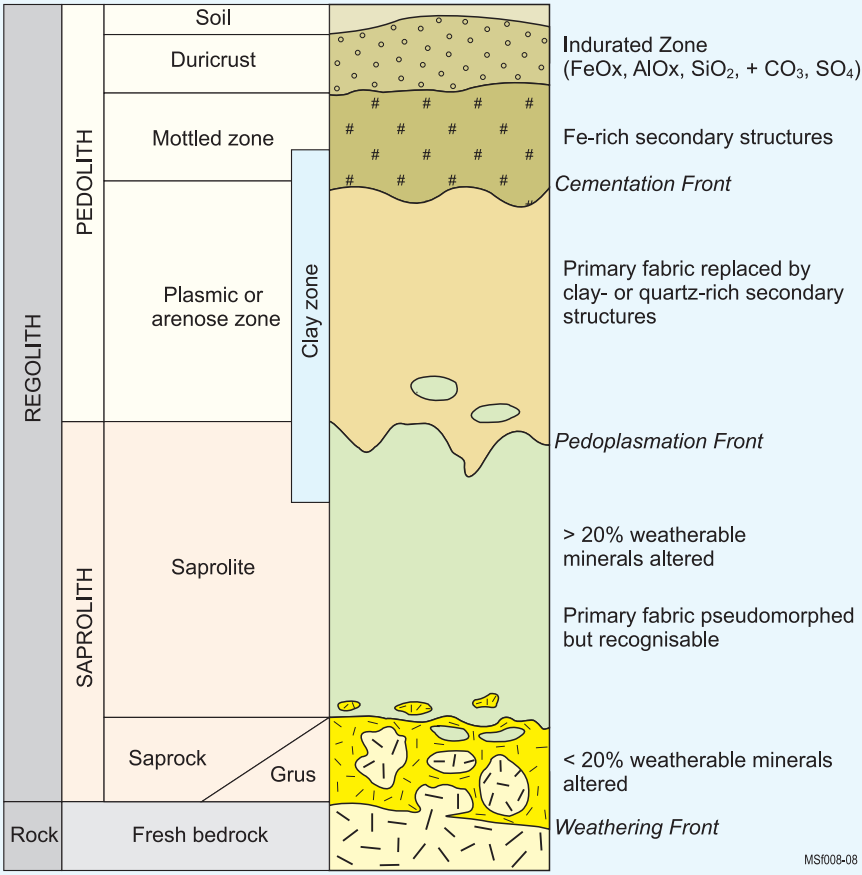


Figure 8. Generalised regolith terminology (modified from Robertson and Butt 1997).

2.1 Landscape history

The Gawler Craton consists of crystalline basement rocks of Archaean to Mesoproterozoic age that are the consequence of sedimentation, numerous intrusive phases, extensive volcanism, crustal suturing, shortening and extension, and extensive repeated erosion. The Craton is now bounded by crustal sutures and crustal sags containing, in clockwise order from the west: the Eucla, Officer and Eromanga Basins, Adelaide Geosyncline-Stuart Shelf and the Southern Ocean rift edge. Overlying the crystalline basement are Neoproterozoic, Palaeozoic, Mesozoic and Cenozoic sedimentary sequences, which may combine to form a significant transported cover. The geomorphic regime reflects the climate, as well as the topographic relief, events in the surrounding basins–particularly basin sag initiation–and repeated changes in base level. Basement rock types and structure have strongly influenced landform development in some areas (e.g. GRV).

Much of the material in this section has been derived from: Alley and Lindsay 1995; Benbow *et al.* 1995a, b, c; Hou 2004, Hou *et al.* 2000, 2007a; Lintern and Sheard 1999b; Lintern *et al.* 2006a; Sheard 1990, 2007b; Sheard and Callen 2000; Sheard *et al.* 2006. Additional sources are given in the text

Permian and Mesozoic

Continental scale glaciation occurred over most of remnant Gondwana during the Permian (~280 Ma). The glaciation is inferred to have effectively planed off most of earlier deep weathering profiles on the Gawler Craton, and reduced the extent and thickness of Palaeozoic sediment. From the very Late Permian (~250 Ma) onwards, exposed Gawler Craton rocks were open to weathering processes: eventually yielding a thick regolith (Drexel and Preiss 1995). A series of wetter climate excursions during the Triassic and Jurassic promoted a renewal of deep weathering. Cyclical episodes of weathering have stripped Fe and other mobile elements, producing regionally extensive, highly leached (pallid) saprolite profiles up to 30 metres thick.

Rifting within the remnant Gondwana began to form two separate continental masses (Australia and Antarctica) in the Early Jurassic (~180 Ma), resulting in basin formation along the southern edge of the Australian landmass

(Krieg 1995). Late Mesozoic terrigenous and marginal marine sediments were deposited on a predominantly crystalline basement of low relief with a thick regolith. Quartz and kaolinite from those deeply weathered, and easily eroded, terrains provided abundant source materials for Late Jurassic and Early Cretaceous deposition (~140 Ma), yielding extensive and predominantly sandy basinal sediments up to 100 metres thick (Algebuckina Sandstone ± Cadna-owie Formation.) (*Figure 9*). Marine sedimentation (dark muds, silts and minor sands) followed as Cretaceous seas transgressed the Eromanga Basin to onlap northeast and central Gawler Craton (Bulldog Shale, Coorikiana Sandstone and Oodnadatta Formation.). Deposition shifted away from basement uplands towards surrounding basin margins during Late Cretaceous, as terrigenous sedimentation followed the marine regression to the northeast.

During the Late Jurassic to Early Cretaceous, South Australia was situated at about 70–60°S and the climate was seasonally periglacial to glacial, but was also punctuated by numerous warmer phases (Alley and Frakes 2003). Coniferous forests covered large parts of the landscape (White 1993; Krieg 1995).

Early–middle Cenozoic

Ongoing rifting between Antarctica and Australia initiated marine transgressions into the southern basins where marine sedimentation continued into the early Neogene. These transgressions changed the existing patterns of erosion and drainage, and influenced climatic patterns further inland. As Australia drifted northwards (> 63ºS to < 40ºS over ~45 Ma; White 1994; Pillans 2006), the climate warmed and rainfall increased: promoting more rapid rock weathering and extensive fluvial erosion. Major river systems incised into and drained the Gawler Craton to the west and southwest. These were dominated by sand during the Eocene, but became progressively silt- to clay-filled during the Miocene. Large river systems sculptured the landscape to produce much more relief than is evident today. Some palaeochannels are incised into their substrate deeper than 120 m–many are kilometres wide and hundreds of kilometres long. Eocene fluvial sandy fills in the upper reaches of palaeovalleys give way to marginal marine fine sand and lignite in the

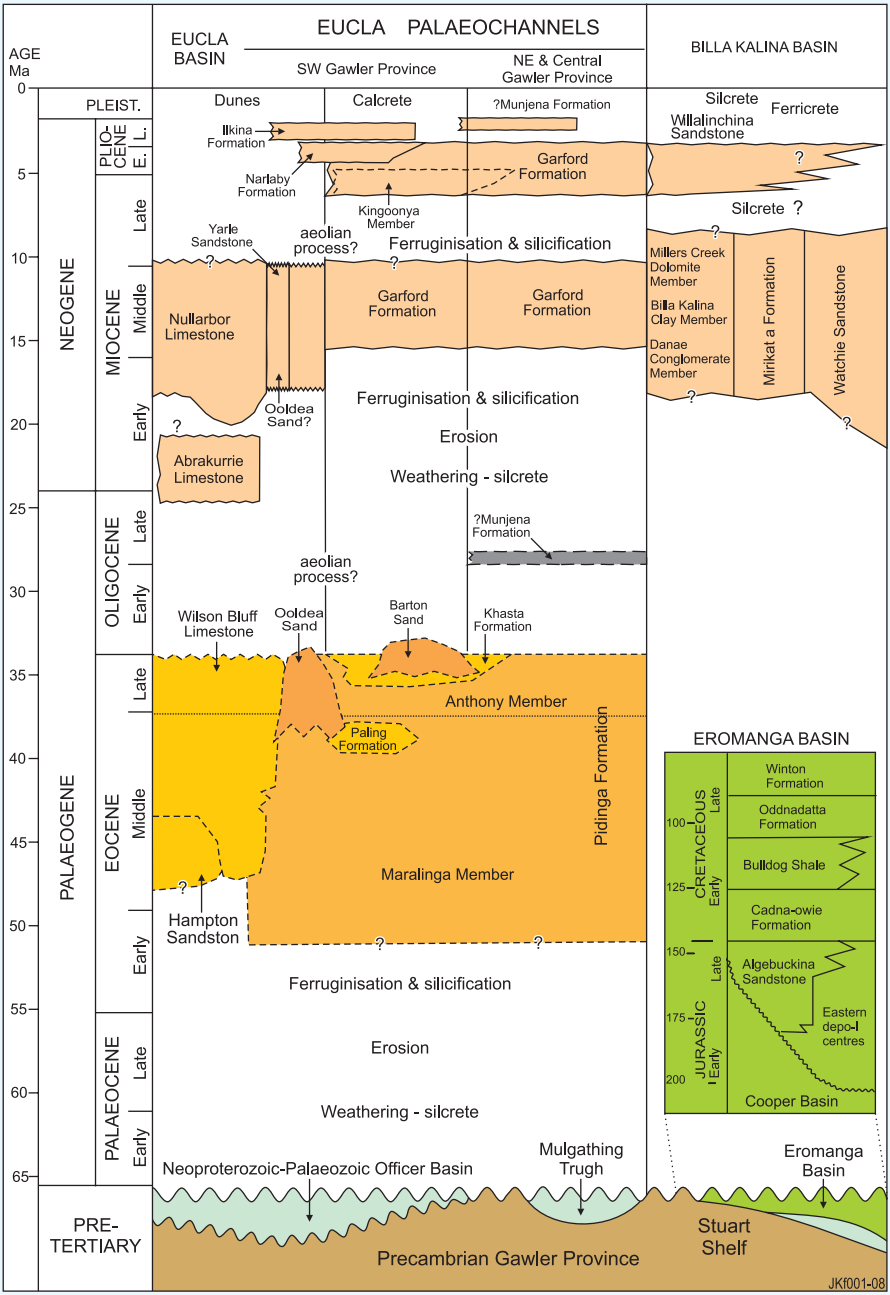


Figure 9. Stratigraphic correlation of post Permian sedimentary deposits on the central Gawler Craton.

lower reaches where swamps developed behind extensive beach barrier dunes of the Ooldea and Barton barriers.

The Eocene was characterised by a globally changing climate (Zachos *et al.* 2001, Svensen *et al.* 2004) that may have been responsible for the intense bleaching of exposed basinal sediments. It is clear from field observations that Fe and other trace elements were removed or displaced during those times, leaving behind regionally extensive pallid saprolite in transported regolith of Cretaceous age. Profile mottling across Australia reflects episodic intense weathering: allowing the redistribution of Fe and its fixation during times of seasonal desiccation and long-term drought. Thereby, fluctuating groundwater tables produced extensive ferruginous mottle and megamottle horizons. However, it is unclear for much of the Gawler Craton just what proportion of the overall pallid saprolite is due solely to the early-to-mid-Mesozoic bleaching and what is due only to the mid-Palaeogene bleaching. The later phase must have overprinted the earlier pallid zone, but it is likely that the later phase may have thickened overall pallid saprolite. Furthermore, there are basin margin exposures peripheral to the Gawler Craton where leached zones related to major regolith leaching episodes are separated by unweathered sediments. These have been variously dated by palynology and stratigraphic means, thereby providing indirect, but useful, time ranges for the weathering episodes. Palaeomagnetic studies of Fe oxides in weathered profiles in South Australia show that deep oxidation occurred during two main episodes at around 60 Ma and during the last 12 Ma (Pillans 2006, 2007).

During the Late Eocene, and again in the Late Miocene to Early Pliocene, broad-scale pedogenic silicification resulted in the development of extensive siliceous duricrusts in surficial deposits. Their vast distribution in South Australia reflects relative landscape stability regionally over a considerable time. On the Gawler Craton, pedogenic silcrete ranges in thickness from less than 1 to rarely more than 6 m. The silcretes are typically quite complex where there has been repeated silica overprinting, but, where ongoing sedimentation separates out silicification episodes, the silcretes generally have a simpler internal structure. Surface silicification in places overprints

megamottled saprolite, indicating that megamottles predate development of at least some siliceous duricrusts. Palaeogene to mid-Neogene vegetation for the central Gawler region ranged from angiosperm–gymnosperm mixed rainforest to moist-temperate, conifer-dominant rainforest (White 1993, 1994).

Late Cenozoic

By the Middle Miocene to Early Pliocene, Australia had drifted northwards and the central Gawler region lay between latitudes 35 and 40°S. Rainfall was still high enough to ensure that drainage systems remained active. An interior basin, the Billa Kalina Basin–located in the northeastern central Gawler Craton–formed at this time. This shallow basin contains mainly fluvial–lacustrine deposits of the Watchie and Willalinchina Sandstone in the east, and Mirikata Formation in the western regions, with sediment thicknesses up to 20 m. However, climate change due to build-up of the Antarctic ice resulted in longer dry periods, which are reflected by evaporitic carbonate sedimentation in the upper Garford Formation.

As the Pliocene climate became more arid, major river systems on the Gawler Craton waned and many ceased flowing. By the mid to late Pleistocene, strings of ephemeral playas and small clay pans pock-marked the original fluvial traces of palaeovalleys, which were almost totally infilled with sediment.

Erosion during the Pliocene to Quaternary cut into the landscape: extending from the exposed less-competent saprolitic lowlands towards the generally siliceous or ferruginous duricrust armoured upland surfaces. This process formed escarpments standing less than 5 to more than 20 metres above the surrounding terrain and these commonly expose softer pallid- to brightly coloured saprolite (*Figure 10*). The lowering of the landscape produced remnant plateaus, with marginal mesas and buttes on broad plains littered by siliceous and ferruginous lags. Topographic inversion is commonly expressed in these mesa and butte profiles, where the thicker silcrete horizons–originally occupying palaeovalleys–have resisted erosion and now stand above the general land surface (*Figure 11*).



Figure 10. Escarpment exposure of regolith, capped by dark red-brown collapsed megamottle horizon (pedolith) on megamottled and leached upper saprolite (off-white kaolinite with quartz). Iron oxide-stained quartz veins appear in the foreground (orange). This is an erosional landscape regime north of the Baggy Green gold prospect, in northwest Eyre Peninsula.



Figure 11. Escarpment, about 10 kilometres west of Lake Harris, cut into pallid saprolite. The top of the plateau is capped by silcrete encapsulating an unconformity over which fluvial gravelly sand was deposited (sheetwash and minor channel infill). This landform is an example of topographic inversion.

Increasing aridity and persistent strong winds during the Pleistocene caused extensive dune fields to develop over much of central and southern Australia. Siliceous sands of the Great Victoria Desert to the west of Tarcoola (*Figure 12*), spread across the Gawler Craton from about 250 ka (Callen and Benbow 1995). During those windy times, and continuing today, there was a variable influx of aeolian carbonate dust (Crocker 1946). Marine foraminifera (silt-sized) have been observed in calcrete over 200 kilometres inland from their likely source areas, and are evidence of carbonate that has been sourced



Figure 12. Regional distribution of dunes of the Great Victoria Desert and drainage patterns in the central Gawler Craton (from Sheard et al. 2006).

externally as dust. Strontium isotope data from calcrete across the Gawler Craton (Dart *et al.* 2007a) imply a marine primary source for the calcium carbonate, which was derived as aeolian dust from exposed marine shelves during the Pleistocene low sea stands. Pedogenic and biotic modifiers, together with meteoric water, have transformed the aeolian carbonate dusts into recrystallised, soil-borne segregations termed calcrete (Phillips and Milnes 1988; Belperio 1995).

Regional vegetation adapted to the increasing aridity by becoming sclerophyll dominant (toughened leaf cuticles, fewer leaf pores), sparse, tolerant of sodic, high-pH soils, and by becoming of moderate to low stature (Stace *et al.* 1968; Northcote and Skene 1972; Lange and Lang 1985; Urban 1993; White 1994). Throughout the Cenozoic, a diverse community of arid to semi-arid vegetation developed across the central Gawler region, which persists today (Rutsche and Lay 2003).

2.2 Regolith architecture

The distribution and architecture of regolith across the region are the result of *in situ* profile development, modification, erosion, renewed deposition and burial since the very Late Permian (*Figure 13*).

Weathering profiles show great variability of internal structure and thickness (typically < 1 to ~150 m), as a result of the following;

- variable depth of weathering, controlled by rock type, permeability, availability of water, biological activity and landscape position
- variable erosion related to rock type, induration, availability of water, landscape position and base level shifts driven by changes in sea level or tectonic activity.

Transported regolith is widespread and is typically less than 1 to about 60 metres thick, with thicker deposits (> 200 m) encountered in intracratonic Permian depocentres–mainly in the north. Palaeovalley sediments may attain greater than 100 metres in thickness, but are commonly less than 50 metres. Induration by Fe-oxides, silica, carbonate and gypsum has helped to preserve some areas of deeply weathered bedrock and transported regolith.

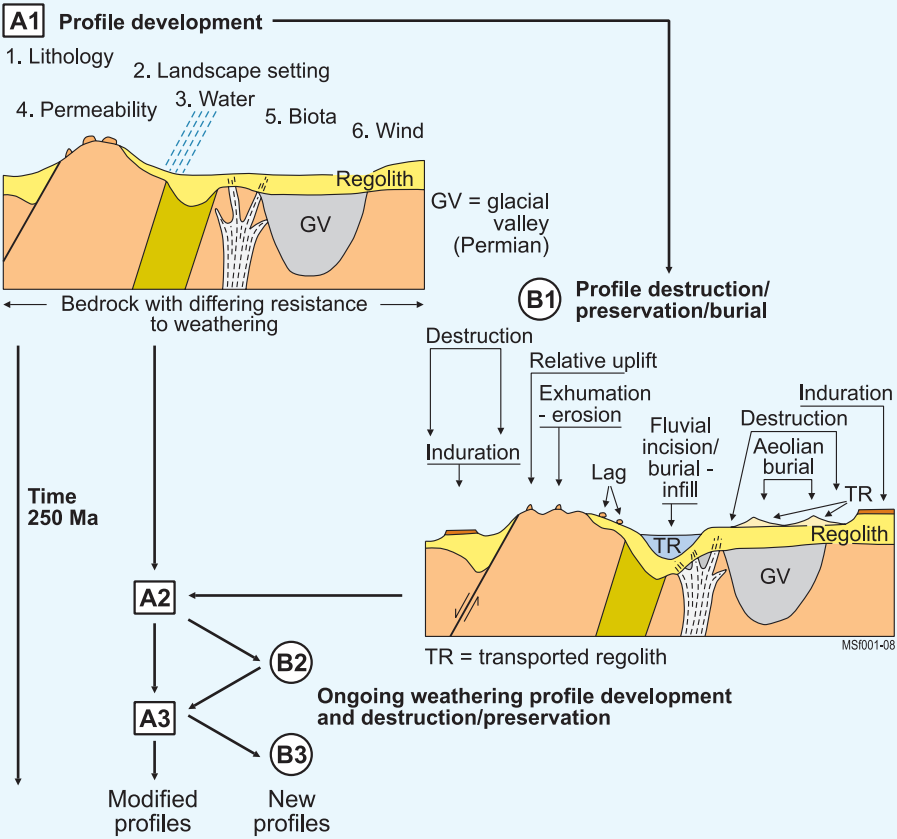


Figure 13. Schematic summary of the major controls on regolith development since Permian glaciation. Periods of profile development (A) may have been punctuated by periods of profile destruction or preservation and/or burial (B).

Topographic inversion, resulting from differential erosion of formerly low lying areas, is observed in certain landscape settings. Major landscape and palaeo-landscape components, and associated regolith materials, are summarised in *Figure 14*.

Typical regolith profiles are illustrated in *Figures 15-18*. These include sites from various landscape and palaeo-landscape settings, and with different histories of erosion and deposition. A common feature of many central Gawler Craton *in situ* weathered profiles is their truncation by erosion to some, or a significant, degree: leaving little or no pedolith, and an unroofed or truncated pallid saprolite.

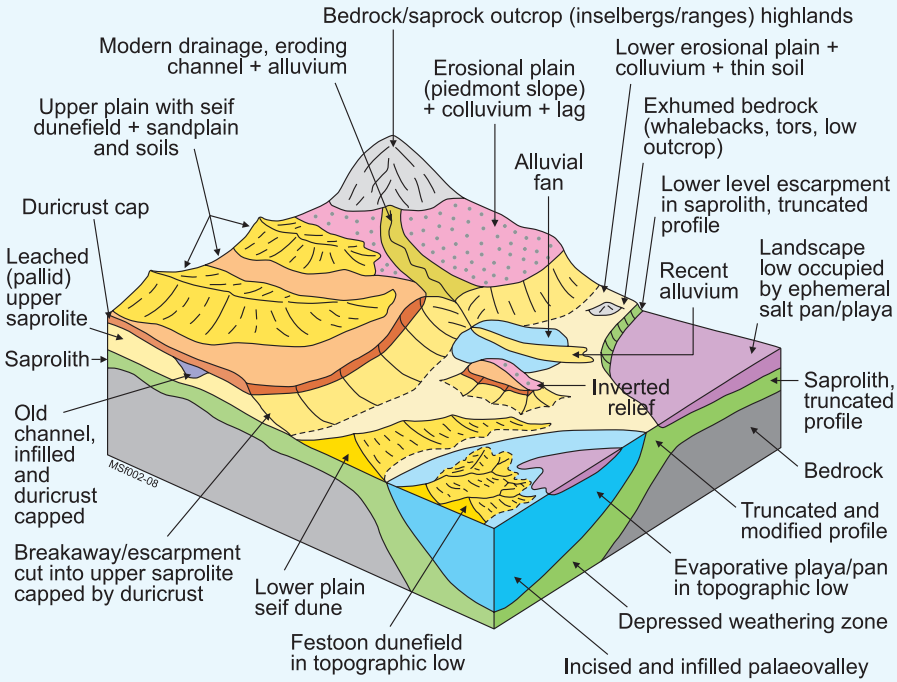


Figure 14. Block diagram summarising the main regolith-landform components of the central Gawler Province.

2.3 Regolith materials

From a mineral exploration perspective, the regolith can be divided into five broad types:

- *in situ*
- transported (basin and palaeovalley sediments, colluvium, dunes)
- indurated (duricrusts and pans)
- lag materials
- soils.

These are a mixture of rock-derived, extraneous and biogenic components. They may have previously existed as other types of regolith (e.g. indurated lag, saprolith-derived debris flows and talus, aeolian dust or precipitated salts).

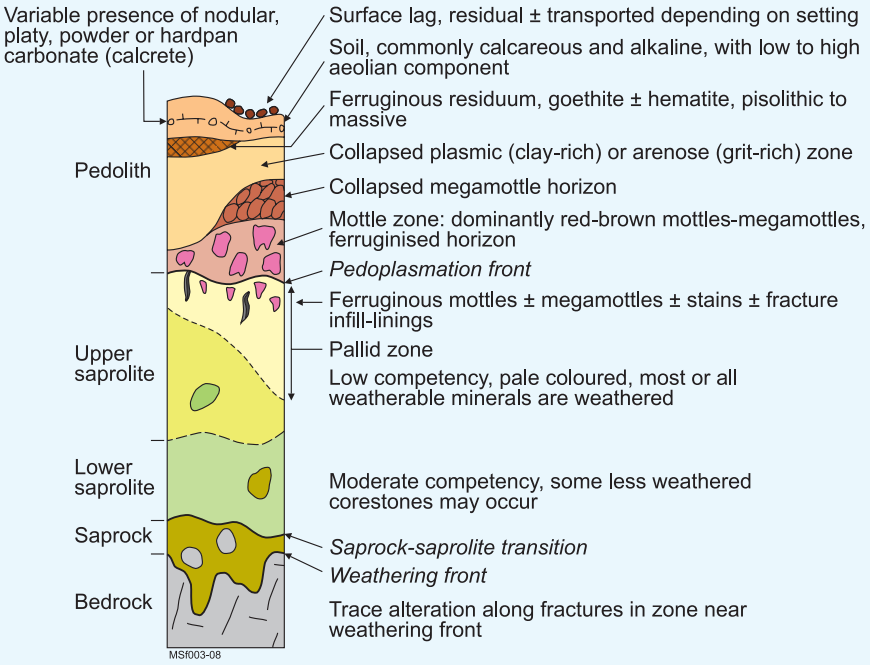


Figure 15. Typical 'complete' residual in situ weathering profile (5– > 100 m thick). Schematic, not to scale.

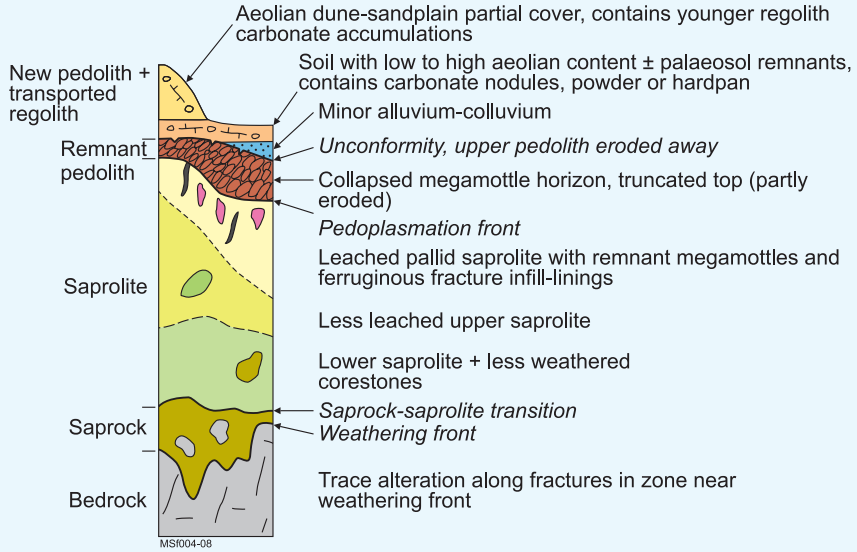


Figure 16. Typical partly truncated (and partly buried) in situ weathering profile (2– < 90 m thick). Schematic, not to scale.

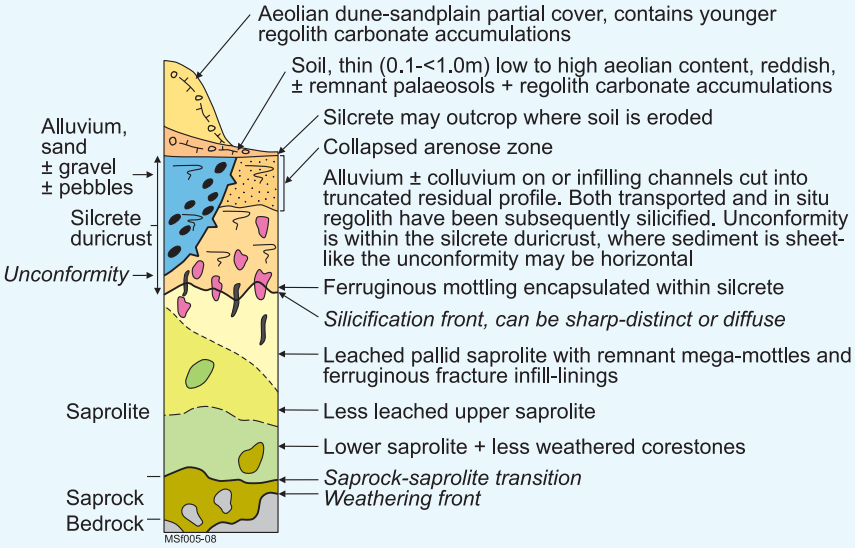


Figure 17. Typical truncated and duricrust capped in situ weathering profile (2– ~70 m thick) where erosion and fluvial activity have been preserved by near-surface silicification to silcrete (0.3– > 6.0 m thick).

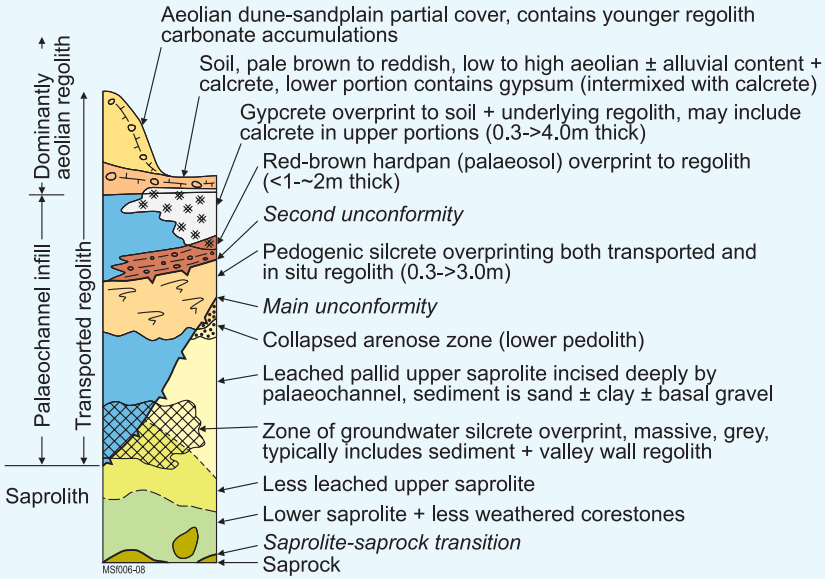


Figure 18. Typical palaeochannel edge profile; residual regolith is mostly truncated and buried by fluvial and, later, aeolian sediment. Duricrusts comprise silcrete, red-brown hardpan, gypcrete and calcrete. Deeper groundwater silcrete overprints sediment and residuum.

Much of the material in this section has been derived from Lintern 2004b; Lintern and Sheard 1998, 1999a, b; Lintern *et al.* 2002, 2003, 2006a, b; Sheard 2007a, b, 2008; Sheard *et al.* 2006. Additional sources are given in the text

In situ regolith

In situ regolith can be subdivided according to landform setting and degree of weathering. Well-developed weathering profiles display a progression of increasing alteration of weatherable minerals: moving from fresh rock (may be trace altered < 5%) to saprock (minor alteration > 5– < 20%) to saprolite (significantly to highly altered > 20%). This progression develops vertically, but may be quite uneven laterally and, in some cases, with less-weathered corestones persisting to the surface. In many profiles, the boundary between fresh rock and saprolith can be difficult to locate, particularly in drill cuttings. The incipient break down of amphibole, feldspar and mica and colour changes related to oxidation are useful guides near the weathering front.

Fresh rock (bedrock) in the region includes a wide variety of rock types, and this has an influence on regolith mineralogy developed during weathering. Outcropping bedrock on the Gawler is limited by the extent of transported cover, but may appear more extensive on geological maps where highly weathered forms are included within map polygons. Exposure depends upon rock weathering, uplift history, landform evolution and erosional history. Bedrock landforms include large inselbergs, whalebacks, windows in areas of dune cover, ridges, tablelands and eroding uplands.

The *in situ* regolith is described more fully under major divisions of saprolith (saprock and saprolite) and pedolith (*Figure 8*).

Saprolith

Within saprolith (saprock + saprolite), the primary rock fabric remains largely preserved (i.e. alteration by weathering has essentially been isovolumetric). Saprock tends to be a thin zone over much of the Gawler (< 1– < 10 m), but can have very gradational boundaries with fresh rock and saprolite–a feature enhanced in areas of fractured or sheared rock. Such gradual changes

are often very difficult to pick visually, particularly where bulk drill hole cuttings are the only sample available. Saprock commonly contains bedrock corestones and variable competence intervals. Outcropping saprock is rare on the Gawler; it may occur, however, on the margins of bedrock outcrop in eroding terrain or as remnants in exhuming uplands.

Gawler Craton saprolite commonly shows two distinct sub-zones: a lower and an upper saprolite.

- The lower saprolite–being less weathered (moderate to high > 20– < 40% alteration of weatherable minerals) –is more competent, retains coloured relict primary and secondary minerals (i.e. chlorite, feldspar, garnet, amphibole, serpentine and dark oxides), and is rarely, or only moderately, stained by secondary sesquioxides.
- The upper saprolite is more highly weathered (> 40% alteration of weatherable minerals), is much less competent and retains fewer coloured relict primary and secondary minerals. It tends to be dominated by resistate quartz and clay (mostly kaolinite ± illite ± smectite), can be stained by patchy goethite and/or hematite, typically is paler (even pallid) and more leached of many transition elements, and may contain significant megamottle patches extending down from the pedolith.

Saprolite on the Gawler ranges from less than 10 to about 80 metres in thickness and any pallid intervals can attain a thickness of greater than 30 metres (*Figures 10, 11*). Many of the retreating escarpments, mesas and buttes on the Gawler expose substantial portions of upper saprolite (which are typically pallid). Outcropping lower saprolite is usually only exposed in areas that have been deeply incised.

Pedolith

Pedolith develops above the saprolith and is the zone where primary rock fabric has been destroyed by pedogenic processes. At the base of the pedolith there may be a disrupted or collapsed interval of variable thickness containing residual quartz and clay. This is termed the plasmic zone if it is rich in clay, or the arenose zone if rich in grit. Landscape deflation–in areas where

megamottling has developed within upper saprolite and/or pedolith–can lead to the formation of a collapsed megamottle horizon (Anand and de Broekert 2005). These horizons consist of merged ferruginous megamottle blocks with some colluvium and Fe-oxide/oxyhydroxide cements, where clay and silt are virtually absent. When exposed, these intense red-brown to dark brown horizons typically form a conspicuous surface armour over a much less competent saprolitic profile (*Figure 19*). Pedolith also includes other duricrusts or pans (siliceous, ferruginous, calcareous or gypseous), soil and lags (see below).

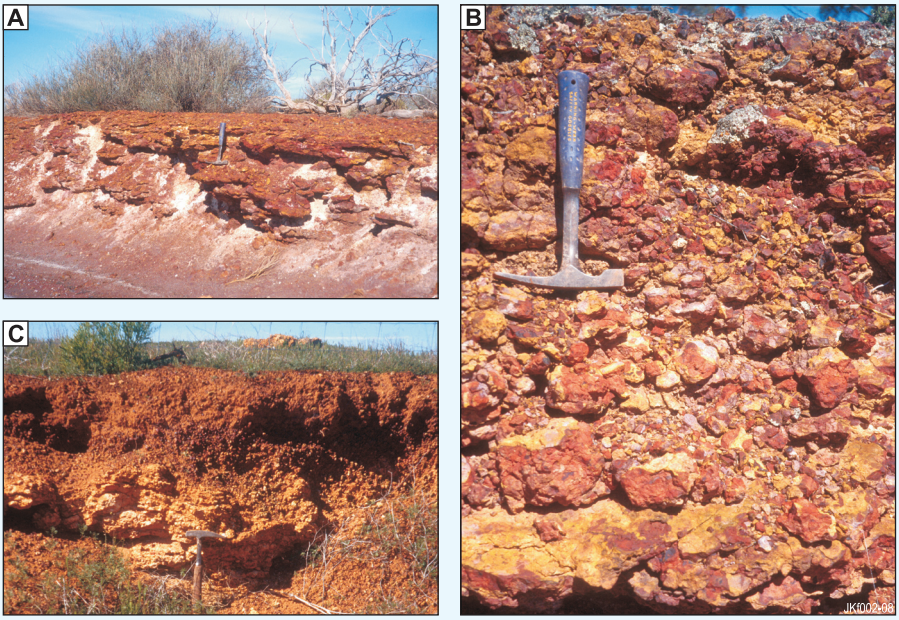


Figure 19. Gawler Craton ferruginous profiles. (A) collapsed megamottle horizon capping pallid saprolite. (B) detail of (A) showing coalesced megamottle blocks forming a breccia-like hematite and goethite rich interval. (C) ferruginous pedolith composed of collapsed megamottle lag and a colluvium of transported iron pisoliths and aggregates.

Transported regolith

Transported regolith includes alluvium, lacustrine and marine sediments, colluvium and aeolian deposits. Alluvium can occur at all levels in the landscape and includes fluvial sheetwash, channel and overbank sediment

(*Figure 20*). Exposed basal channel sediments are usually quartz-rich sand with minor clay lenses, gravel and commonly a basal pebble conglomerate–any of which may be cemented by silica (silcrete ± porcellanite). Broad Cenozoic palaeovalleys contain sediment-filled, inset valleys or channels that typically have a sand-dominant lower zone (Palaeogene) and a fine-sand-, silty clay- or carbonate-dominant upper zone (Neogene). Drainage patterns were disrupted as the climate became drier. River systems were replaced by discontinuous swamps and lakes. These, in turn, became choked with clays, silts and fine sands, before, in some instances, being overtopped by aeolian dunes. In the north of the region, thick clay sequences (up to hundreds of metres thick) are preserved in older lake, palaeovalley and estuarine-marine-terrigenous systems associated with the onlapping Mesozoic Eromanga Basin and terrigenous Permian Arckaringa Basin (including the Mulgathing Trough). Colluvium is widespread in thin, bedrock-masking deposits on depositional plains, slopes and rises, and less commonly in fans fringing range fronts and higher relief landforms. Colluvium is generally dominated by lithic and vein-quartz clasts in a silty-to-fine sandy matrix,



Figure 20. Small fluvial channel incised into pallid saprolite–exposed by a low retreating escarpment. The channel is infilled with brown locally derived alluvium and colluvium. Lake Harris northwest corner greenstone exposures.

where the mass is either clast or matrix supported. Clasts are typically coarse and angular on upper slopes and decrease in grain size down slope.

Debris flow deposits are a significant component of some sedimentary piles across South Australia (e.g. Harris Greenstone Belt, Coober Pedy area, Nuyts Domain and Flinders Ranges periphery). These can be extensive (several tens of km^2 and < 5 to ~10 m thick), and may closely resemble weathered basement or the sediments they bury (*Figure 21*) (Sheard and Robertson, 2004). As such, debris flows and talus aprons can be very difficult to identify from drill cuttings alone, and their extent is under reported.

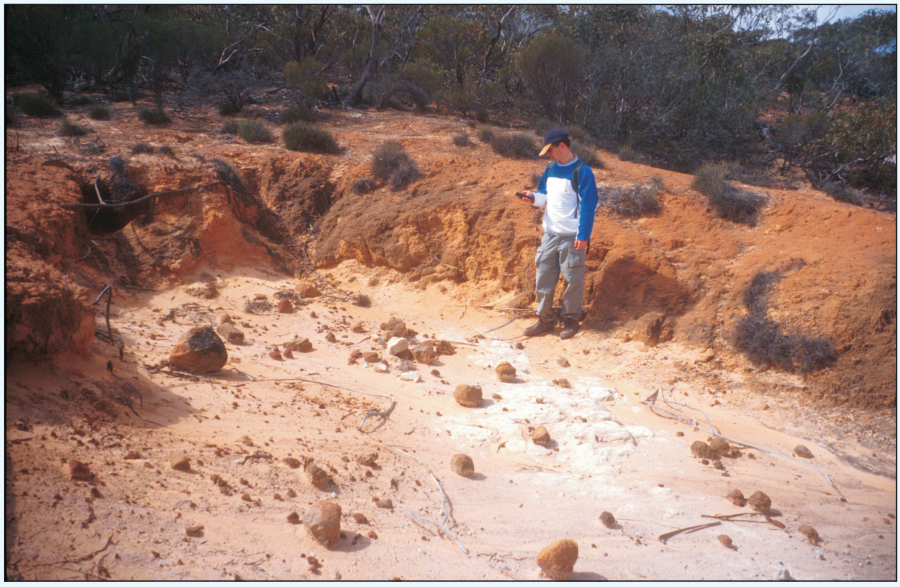


Figure 21. Eroding edge of a debris flow (brown bouldery colluvium) overlying pallid saprolite (highly weathered Tunkillia Suite granite). Debris from Mount Sturt (2 km north)–an outlier of the southern Gawler Ranges. The colluvial geochemical signal is quite different to that of the leached saprolite.

Aeolian deposits form widespread cover on the central Gawler region (*Figure 12*): predominantly as dunes and sandplains forming the eastern Great Victoria Desert, and the Tirari Desert to the northeast. Optical luminescence techniques date Great Victoria Desert dunes as spanning around 250 ka (cores) to 20 ka (crests). Dunes and lunettes are also associated with playas and ephemeral stream lines. Aeolian dust is a substantial

component of the transported regolith and is composed of locally and distally derived lithic silt, clay, calcium carbonate and gypsum. Soluble dust minerals are modified by rain and pedogenic processes to form calcrete and gypcrete.

Indurated regolith (duricrusts, pans, cements)

Indurated regolith–formed by the introduction and precipitation of silica, Fe oxide, carbonate or sulphate in pre-existing regolith (saprolith, pedolith, sediments and soils)–is present as distinctive cemented horizons termed duricrusts and pans.

Siliceous

Siliceous materials occur in a variety of forms, including silcrete, porcellanite, hardpan, chalcedony and opal (*Figures 22, 23*). Pedogenic silcrete is a secondary siliceous cementation developed in porous regolith, at or near the surface. It can form a durable armouring to many surfaces. Silcrete is widespread across the Gawler in both transported and *in situ* regolith. Silcrete consists of cryptocrystalline silica ± titania cements: replacing most or all fines, and infilling intergrain voids to yield a hard-brittle rock (grey to brown; *Figure 23D*). Silcrete tends to break across entrapped grains rather than around them. Typically silicified horizons range from less than 0.3 to more than 6 metres thick and may have an underlying incipient silicified zone of less than 0.1 to more than 3 metres thick (*Figure 22A*). Pedogenic silcrete exhibits similar morphologies to calcrete (pisoliths, nodules, pebbles, boulders or laminated forms). Columnar silcrete is also present in many areas. The columns appear to 'grow' upward as additional silica is deposited, and they are characterised by concentric to draped banding (*Figure 22F*).

In erosional regimes, silcrete yields conspicuous gibber and pebble lag that, when derived from silicified saprolite overlying mineralisation, can contain remnant ore and associated trace elements. Silcrete may entrap resistate minerals, including quartz, Au, graphite, ilmenite and zircon (*Figures 22C, 23C*). It may also preserve remnant metamorphic foliation if developed in saprolite, and ferruginous mottling if developed in mottled pedolith or saprolite (*Figures 22E, 23C*). Silicification of silt-rich and clay-

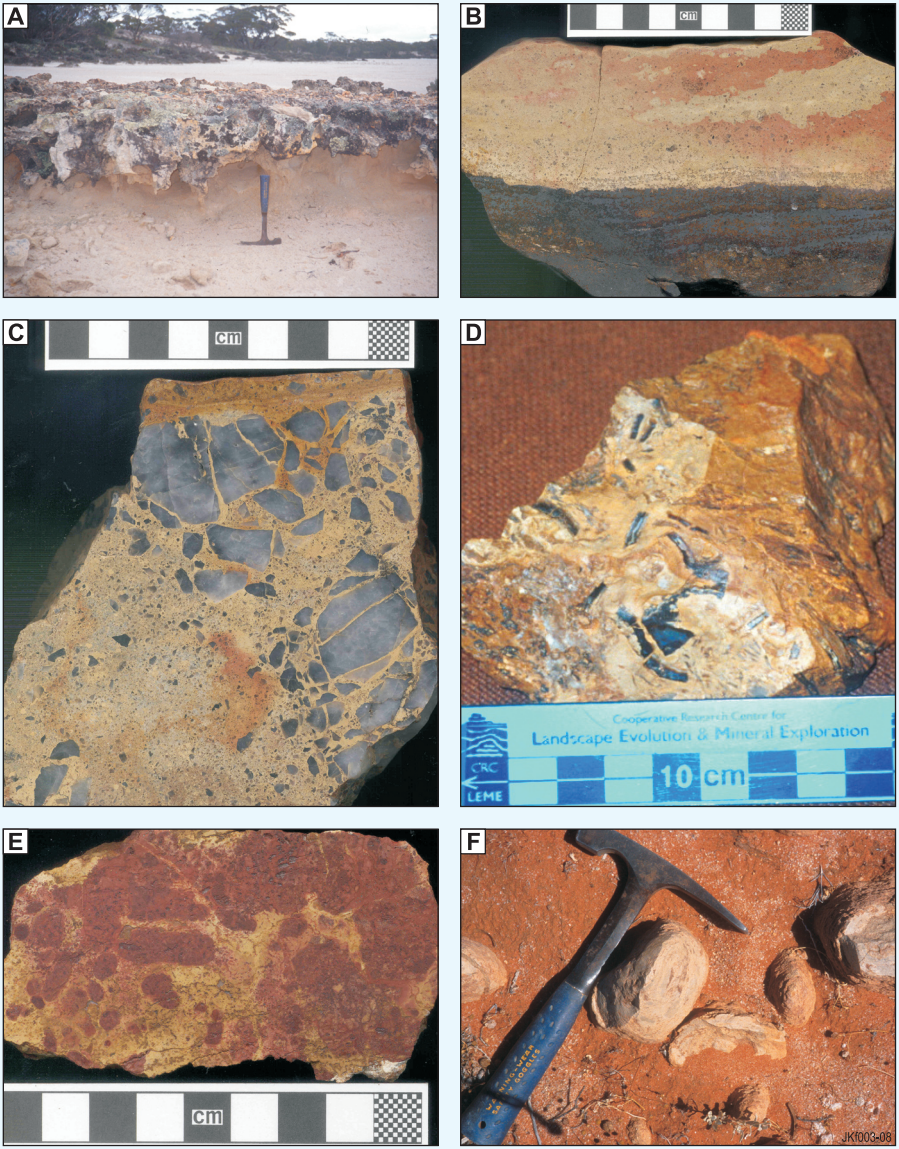


Figure 22. Various Gawler Craton silcretes. (A) eroding silcrete cap in arenaceous pedolith on intensely weathered granite. (B) silcrete on banded iron formation. (C) silcrete with collapsed jig-saw-fit quartz vein fragments (bluish). (D) silcreted colluvium containing chalcedony fragments derived from serpentinized komatiite. (E) silcreted megamottle in highly weathered granite. (F) columnar silcrete in plan– note the banded rinds exposed by fracturing.

rich sediments can lead to a form of silica overprint resembling unglazed porcelain, which is known as porcellanite. This can be as hard and brittle like massive silcrete, or quite friable. Porcellanite mineralogy can include chalcedony, hyaline opal or even potch and precious opal (*Figure 23A, B*).

Silicified channel sediments are resistant to erosion and may be preserved as remnants in inverted topography to form ridges and as mesa cappings on erosional plains. Silicification of bedrock has also occurred to yield silcrete armouring on granite, felsic volcanics, BIF, mafic rocks and metamorphic rocks (*Figure 22A, B*). Basin onlap sediments provide a record of episodic pedogenic silcrete formation: possibly towards the end of the Cretaceous and during the Cenozoic, at least once in the Palaeogene, and again in the Neogene (Thiry and Milnes 1991; Sheard and Callen 2000). Therefore, where silcrete has developed within *in situ* regolith or on bedrock, it may represent multiple silica overprinting.

Groundwater can also deposit silcrete: typically at the margins of channel sands. Groundwater silcrete commonly has a distinctive ropy upper surface (*Figure 23E*), a uniformly grey interior (no banding or cloudy silica), and a lower trace element content (very low Fe, Ti, V, Y, and Zr) than pedogenic silcrete. Groundwater silcrete is typically barren of most other targeted metallic elements.

Red-brown hardpan is a convenient field term applied to a widespread and easily recognised unit on the Gawler. The hardpan consists predominantly of colluvium with minor alluvium, within which an intensely coloured palaeosol has developed throughout. The hardpan has either a matrix- or a clast-supported framework, and was derived by erosion of *in situ* or transported regolith; the whole being cemented by precipitated silica ± Fe oxides ± carbonate into a hardened material or pan. Although locally discontinuous, the regional persistence of the cemented materials makes them a useful marker horizon. On the Gawler, this unit is up to 1.5 metres thick, mostly hard to very hard and commonly brightly coloured red or red-brown, with black, dendritic Mn oxides. Stratigraphic context indicates an age range of Pliocene to early Pleistocene for the cemented horizon.

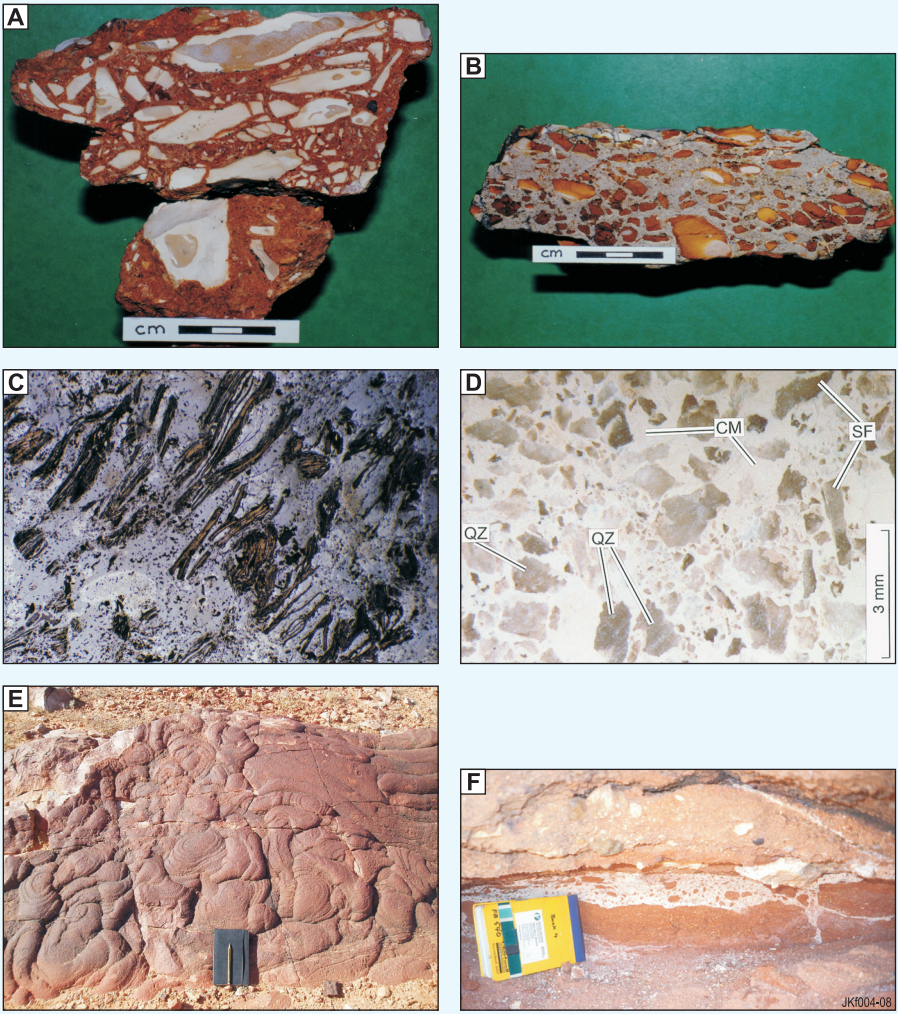


Figure 23. Gawler Craton silcretes and hardpan. (A) brecciated jig-saw-fit porcellanite fragments in silicified hardpan. (B) patches of yellow potch opal and grey porcellanite in silicified fluvial sediment. (C) reflected light photomicrograph; silcreted saprolite retaining graphite delineated gneissic fabric (dark grey); view 2.5 mm wide. (D) reflected light photomicrograph; silcrete on saprolite, SF = shardy quartz, QZ = quartz grit and CM = QAZ cement. (E) groundwater silcrete with typical ropy surface (iron-stained). (F) brown hardpanised colluvium, with hyaline silica cement, calcrete on joints; scale bar 120 mm long.

Ferruginous

Across the central Gawler region, silcrete typically occupies the regolith landscape position that ferricrete does in the Yilgarn Craton of Western Australia. Where ferruginous pedolith has developed, it is generally thin (< 300 mm) and is commonly partially truncated by erosion (*Figure 19A, 24B*). Eroded components of ferruginous profiles (pisoliths, Fe-rich granules ± fragments) reside in colluvial aprons and channels down slope (*Figures 19C, 24B, D*). Transported Fe pisoliths typically have broken or missing cutans (rinds) whereas those remaining *in situ* have complete cutans.

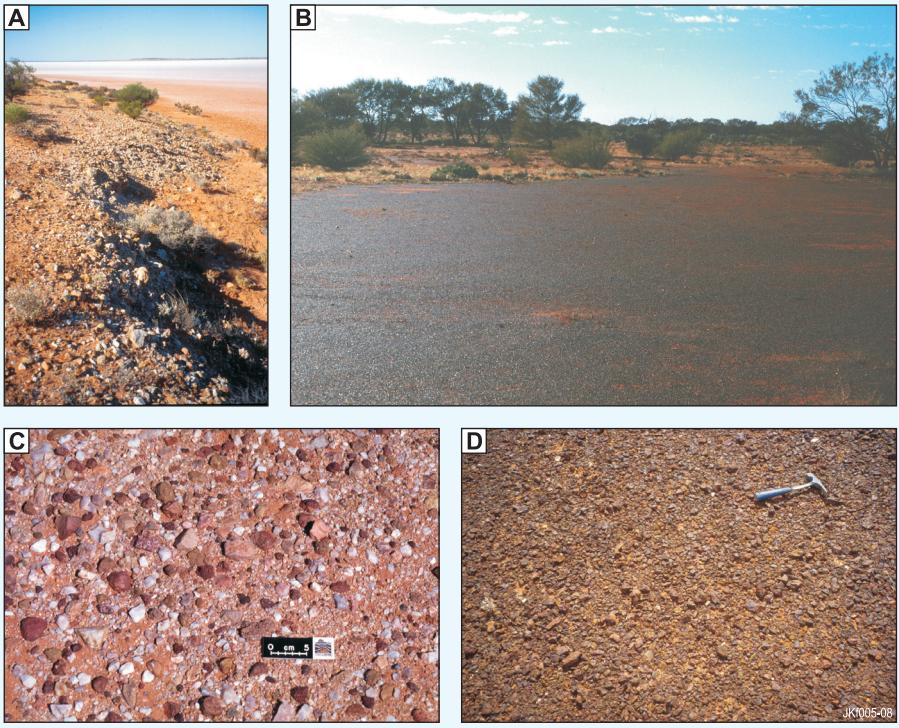


Figure 24. Various Gawler Craton lags. (A) polymict pebble lag terrace adjacent to Lake Harris. (B) ferruginous granule lag on transported regolith south of the Challenger gold mine. (C) polymict lag of exotic clasts + in situ regolith derived clasts + silcrete + local ferruginous granules. (D) ferruginous granule lag on ferruginous pedolith in greenstone.

Ferruginous pedolith on the Gawler is more typically a collapsed megamottle horizon (*Figure 19A, B*). Most horizons are about 0.3 to 1.5 metres thick, many are indurated and form armoured caps to less-competent saprolite zones. A collapsed megamottle horizon delineates a residual pedolith where profile collapse of about 40 to 80% may be observed based on the spatial distribution of Fe segregations in collapsed and intact zones (Fairclough and Schwarz 2003). Exotic lithic clasts (mostly quartz ± silcrete ± resistate metamorphics) may also be present–moved from the top down during profile collapse. The absence of a ferruginous pisolith horizon overlying the collapsed horizon may reflect truncation of the profile.

Groundwater-related Fe sesquioxide- and hydroxide-cemented sandstones occur in basin sediments onlapping the Gawler crystalline basement. Upon erosion, these typically give rise to extensive patches of ironstone and ferruginous granule or fragmentary gravel lags.

Calcareous

Regolith carbonate accumulations are very widespread throughout the region. Calcrete is a convenient field term, which refers to these accumulations forming more or less well-cemented aggregates or segregations composed largely of calcium carbonate, but not excluding dolomitic or magnesitic carbonates (Eggleton 2001). Calcrete occurs in semi-arid regions around the world (e.g. Milnes 1992) and is widely distributed in southern Australia (*Figure 25*).

There is a wide variation in calcrete morphology, including loose and aggregated nodules and pisoliths, earthy vermiform segregations and powders, laminated and massive forms (*Figure 26*). These are developed within substrates of saprolith, pedolith, duricrusts, residual soils, fluvial and marine sediment, hardpans and aeolian sand (Milnes 1992; Chen *et al.* 2002). Many of the indurated forms have complex internal fabrics and structures, indicating cyclical carbonate deposition, dissolution, disruption, redistribution and re-cementation. Calcrete cements pre-existing regolith and therefore commonly contains millimetre- to centimetre-sized fragments of saprolite (*Figures 26C, F*), hardpan, silcrete (*Figure 26E*), ferricrete

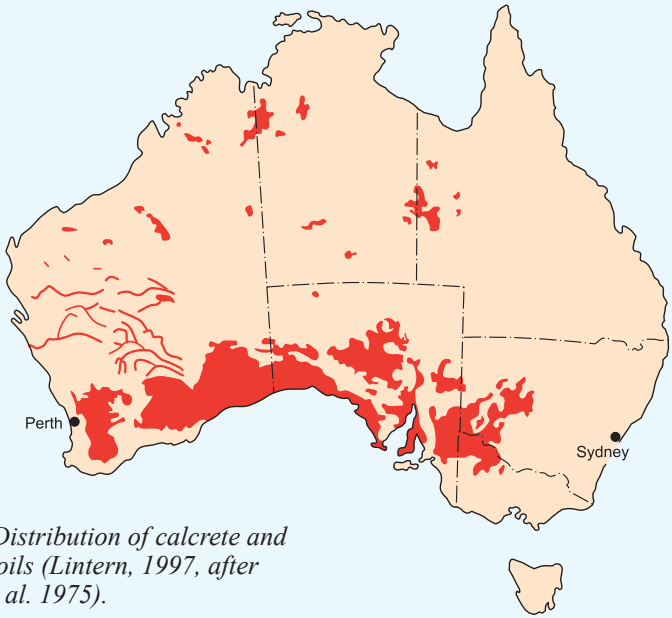


Figure 25. Distribution of calcrete and associated soils (Lintern, 1997, after Northcote et al. 1975).

(*Figure 26C*) and lags (*Figures 26B, C,E*). The colour varies from cream to pale pink and pale grey to rich red and brown (*Figures 26D, E*).

Most indurated calcrete is found towards the base of soil profiles, on top of underlying silcrete or other permeability barriers (*Figures 26E, F*). Indurated sheets can range from less than 100 to more than 500 mm in thickness and may form book-like stacks of 1 to more than 3 metres thick. Commonly, the thicker units have horizontal partings and vertical fractures exploited by plant roots. Karst development is observed as pipes or potholes (*Figure 27*), rillenkaren and enlarged joints. Calcrete in aeolian dunes includes rhizomorphs (derived from calcification of tree roots) and ranges from earthy powders to pisoliths and nodules to crumbly duricrust horizons (*Figure 28*). Dunes in the central Gawler may display many separate calcrete horizons. These overlie earlier calcrete developed in units buried by the dune (*Figure 29*).

Calcrete also occurs in modern ephemeral creek sediments as a massive horizon less than 1 to more than 3 metres thick and is related to creek line, base-flow groundwater chemistry rather than to pedogenic processes.

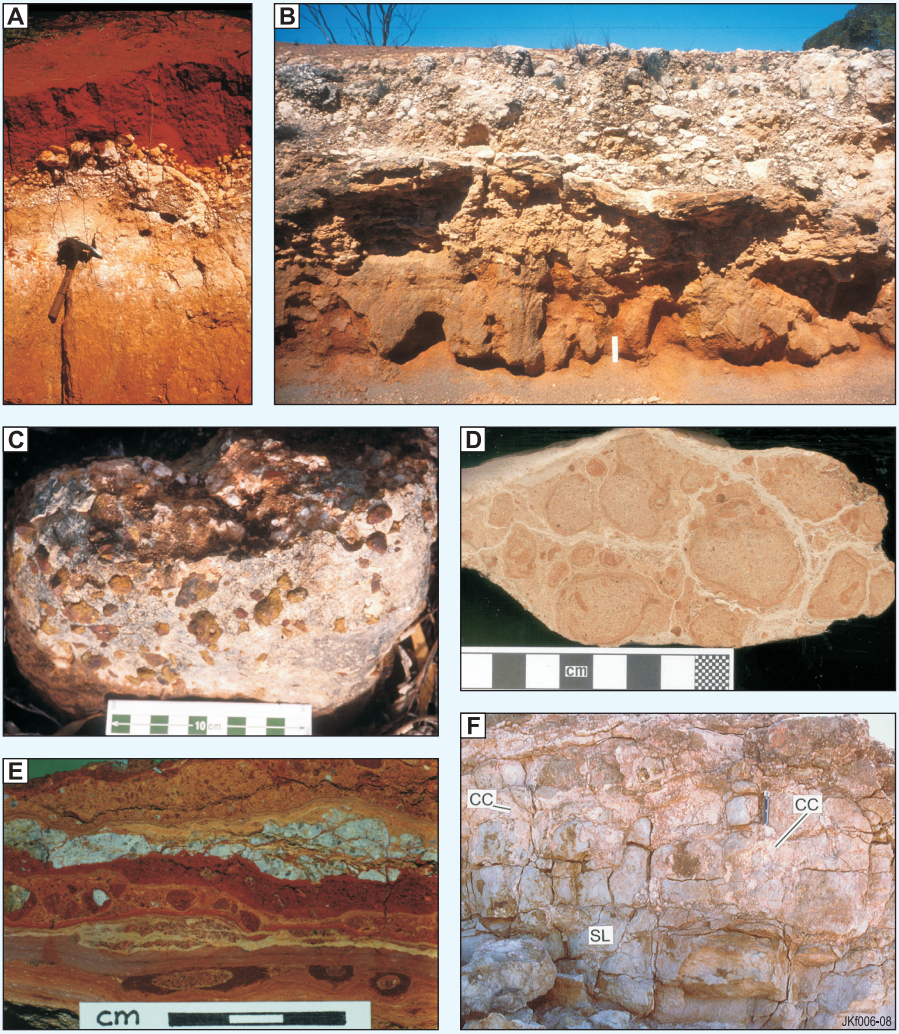


Figure 26. Typical calcrete occurrences and morphologies from the Gawler Craton. (A) calcrete nodules, aggregates, blocks and powdery forms in red earth soil. (B) calcrete impregnating weathered Hiltaba Suite granite. (C) calcrete enclosing ferruginous saprolite fragments. (D) sliced calcrete cobble revealing complex aggregated interior. (E) complex strongly coloured calcrete enclosing saprolite lag, hyaline silica and clay. (F) brown calcrete [CC] on and penetrating silcreted pedolith–saprolite [SL].



Figure 27. Pipe karst 'pothole' developed in an indurated calcrete horizon about 1 metre deep in late Pleistocene dune sand. ET gold prospect, about 20 kilometres southwest of Mount Christie. Scale bar in hole is 10 centimetres long.

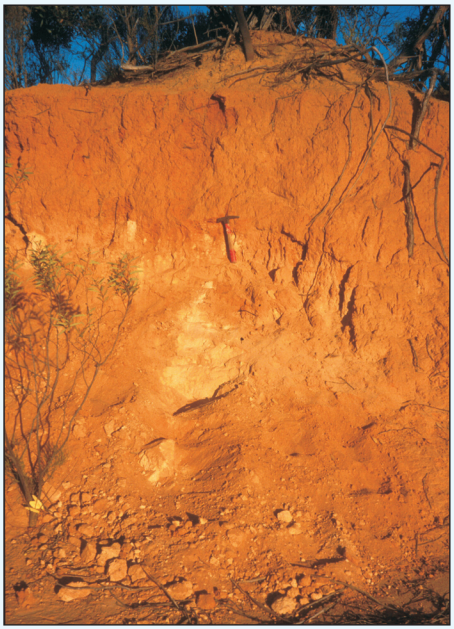


Figure 28. Roadside borrow pit exposure through a siliceous orange linear dune. A calcrete horizon is evident below the hammer. Calcrete is earthy at its top, but becomes more indurated and blocky with depth. Site about 15 kilometres north of Minnipa, Eyre Peninsula.

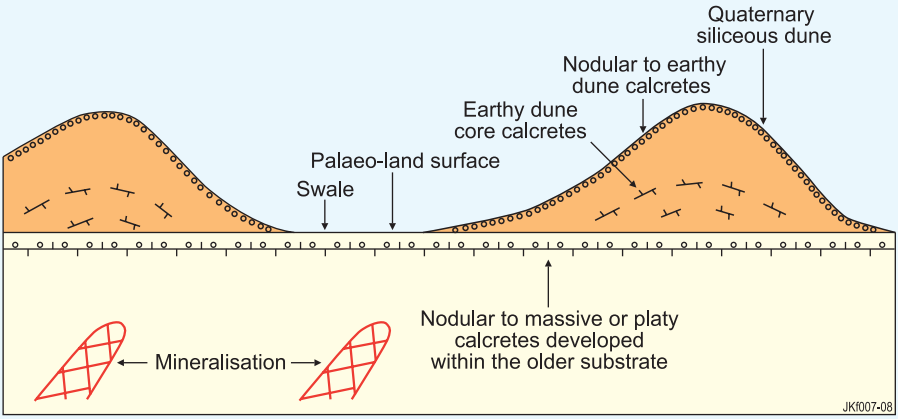


Figure 29. Diagrammatic cross-section showing the significance of landscape position on calcrete within a dunefield overlying an older mineralised substrate (Sheard et al. 2006).

Gypseous

The addition of gypsum to regolith via aeolian dust fallout, followed by dissolution and recrystallisation, can promote development of gypcrete pans in exposed porous materials. These are common near ephemeral playas containing evaporitic gypsum in the lake bed and accumulated gypsum in fringing lunettes. Areas near and within palaeovalleys containing sulphate-rich groundwater have substantial development of gypcrete pans. The Kingoonya and Garford palaeochannels contain intimately mixed horizons of calcrete and gypcrete. Gypcrete is also developed in permeable saprolith and pedolith in arid areas, where sulphate bearing groundwaters are concentrated by evapotranspiration. Horizons or pans of densely interlocking gypsum crystals (from less than 20 to more than 80% of bulk soil) have been observed. These are reasonably soluble when surface water is abundant, and exposed gypcrete can exhibit a karstic surface with rillenkaren, potholes and solution enlarged joints (*Figure 30*).

Lag materials

Surface lag is widespread in the landscape and has been derived from the full range of rock and regolith materials. Thus, it may reflect the immediately underlying bedrock (in areas of outcrop), a local source (in some colluvium)



Figure 30. Exposed gypcrete in soil-pedolith at Boomerang gold prospect about 9 kilometres south southwest of Tarcoola. Exposure is near an evaporitic pan and shows a karstic surface resulting from dissolution by rainwater. Coin scale is 25 mm.

or a distant source (overlying alluvium; *Figures 4, 24*). Lag is dominated by chemically and physically resistant minerals and rocks. It includes a macroscopic component of quartz, lithic fragments, ferruginous lithic fragments, and highly ferruginous pisoliths, granules or gravel. Pisoliths contain residual and surface deposited or cementing Fe oxides (predominantly hematite with some maghemite). There is also a micro-lag component of resistate minerals including zircon, rutile, ilmenite and other heavy minerals concentrated at the surface by the winnowing effects of wind and sheetwash following an intense rainfall event. Gold particles may be present in lag near eroding Au mineralisation (e.g. Challenger gold deposit). Some lags in South Australia have been reworked several times from eroded Permian glacials into Mesozoic strata, and eroded again into Cenozoic regolith. The origin of lag in some areas may therefore be very difficult to determine.

Soils

There are many soil types in the area covered by this Guide, but the most dominant are listed in *Table 2*. Most, if not all, have calcrete developed within the B_{Ca} horizons and, when proximal to playas, may also contain gypcrete horizons. Soils can incorporate surface lags of chemically and physically resistant materials (such as quartz, Fe-rich granules, quartz-rich lithotypes, silcrete and calcrete). Palaeosols are present throughout the area–the red-brown hardpan being an example–but these are generally thin and difficult to recognise in drill cuttings (*Figure 31*).

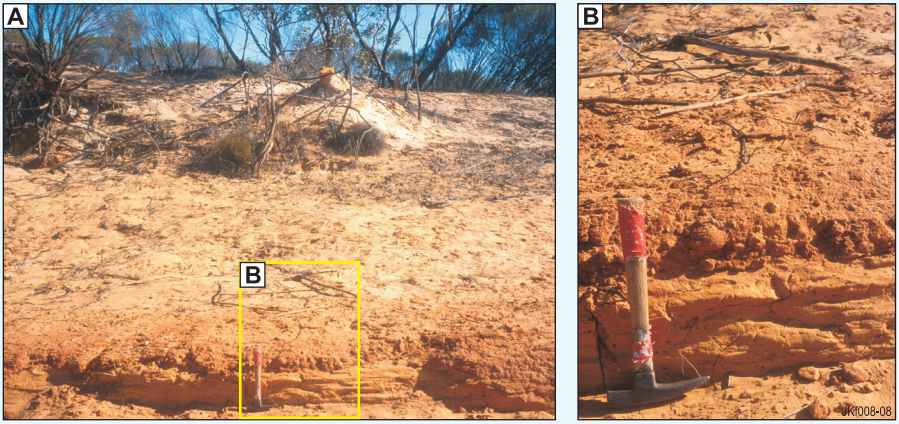


Figure 31(A). Roadside cutting in a siliceous orange seif dune. A ferruginous palaeosol B-horizon occurs at the hammer level. Inset box is enlarged at right (B). Site about 24 kilometres north of Minnipa, Eyre Peninsula.

Most soils of the region will contain some (< 5–25%), or a significant (> 25– > 65%), aeolian component, as fines (silt-sized dust) or as a coarse fraction (sand-sized). This exotic input forms a sample dilutant; the coarser fraction adds silica and alumino-silicate, while the dust fraction adds calcite ± gypsum ± clay minerals ± resistate minerals such as quartz, ilmenite and zircon. A significant aeolian input to a soil may be apparent by the high proportion of calcrete and gypcrete in B horizons.

In the central Gawler region, clayey soils (medium- to heavy-textured) are predominantly late Quaternary, although some may be considerably older. Some are uniformly textured, whereas others are gradational or even strongly

duplex textured (i.e. sandy on clayey or loamy on clayey). Soils developed on or near clayey substrates show more pedogenic organisation, such as horizonation, colour differentiation, pedality and texture contrast. In the arid zone, these tend to be sodic and alkaline (Northcote and Skene 1972). Away from dunefields and near retreating escarpments or eroding uplands, clayey soils are typically gibber-clad, primitive and lithic-rich, where the lithic clasts usually reflect a locally eroding substrate (*in situ* or transported).

Younger sandy-textured soils dominate much of the terrain and have only a small to moderate vertical texture contrast, minimal pedogenic differentiation and tend to occur mostly within sandplains and dunefields (*Figures 26A, 28, 31*). Luminescence dating of dune quartz grains gives ages ranging from around 250 ka (oldest dune cores) to around 10 ka (youngest dune crests) (Sheard *et al.* 2006; Lintern and Rhodes 2005).

Table 2. Dominant soils of the central Gawler region.

Soil Name[1]	Soil Key[2]	General Locality
Red siliceous sands	Uc1.23	Great Victoria Desert and outliers
Brown sands	Uc5.1	Plains west of Mount Hiltaba
Red earthy sands	Uc5.21	Officer Basin plains and outliers
Shallow calcareous loamy soils	Um5.11	Millers Creek Tablelands
Shallow compact loamy Soils	Um5.41	Gairdner Hills and small plains
Brown calcareous earths	Gc1.12 and Gc1.22	Tarcoola Plains with low hills, ridges and dunes
Grey-brown calcareous loamy earths	Gn1.12	Wudinna undulating plains
Neutral red earths	Gn2.12	Everard Plains with dunes, ridges and low hills
Crusty alkaline and neutral red duplex soils	Dr1.13, Dr1.32 and Dr1.33	Hammond Plains

Sources: 1. Wright and Northcote 1969; 2. Northcote *et al.* 1960–68 and Northcote 1979.

U = uniform texture, c = coarse-grained, m = medium-grained;
G = gradational texture, c = calcareous throughout, n = not calcareous throughout;
D = duplex texture (contrasting horizons), r = red B horizon.

The numbers relate to principal profile form—classes and subdivisions as described by Northcote *et al.* 1960–68 and Northcote 1979.

2.4 Regolith minerals

The common and widespread regolith-forming minerals of the Gawler region include residual and secondary quartz, residual muscovite, kaolinite, illite, smectite, hematite, goethite, hyaline silica (opal), calcite, dolomite and gypsum. Maghemite occurs in some surface lag. The relative abundances of these minerals vary with bedrock type, degree of weathering, regolith-landform setting and position within the weathering profile (*Table 3*). Less common regolith minerals include residual biotite, phengite, prehnite, graphite, serpentine and cordierite, along with secondary halloysite, vermiculite, talc, chlorite, chalcedony, halite, anhydrite, alunite, celestite, barite, dolomite, palygorskite, smectite, siderite, ankerite, magnesite, malachite, azurite and atacamite. X-ray diffraction analyses show a significant amorphous or poorly crystalline component in many regolith materials (mostly Si, Al or Fe-rich phases). Spectral measurements of regolith samples (e.g. using PIMA, ASD, FieldSpec, HyChips™ – see Glossary for definitions) provide mineralogical data that can assist with identifying bedrock type and in distinguishing transported regolith from *in situ* regolith. For example, Fe- or Mg-rich smectite clay may indicate weathered mafic and ultramafic rocks; an unconformity may be recognised in the transition from poorly crystalline kaolinite in transported regolith to moderately or well-crystalline kaolinite in *in situ* weathered bedrock (Pontual and Merry 1996; Pontual 2007).

Important host minerals for dispersed minor and trace elements are considered in Section 2.5 Regolith Geochemistry.

Table 3. Common regolith-forming minerals in a variety of regolith materials from the central Gawler region.

Regolith material or bedrock type	Typical mineral assemblage
In situ regolith	Hematite/goethite common, but variably present; quartz grain morphology reflects protolith quartz
Meta sedimentary rocks	Quartz + kaolinite (± illite ± smectite) + hematite ± goethite ± muscovite ± ilmenite.
Felsic rocks (granite, gneiss, volcanics)	Quartz + kaolinite (± illite) + hematite ± goethite ± muscovite ± zircon ± opaque oxides.
Mafic rocks (basalt, dolerite, gabbro)	Kaolinite (± illite ± smectite) + chlorite ± epidote + hematite ± goethite ± ilmenite.
Ultramafic rocks (greenstones)	Serpentine + smectite + illite ± kaolinite ± quartz + chalcedony + chlorite ± dolomite ± magnesite ±epidote ± vermiculite ± talc.
Transported Regolith	Hematite/goethite may be common, but variably present; abraded quartz grains.
Glaciogene sediment	Polymict materials, lithics-rich + quartz + feldspar + kaolinite (± illite) + hematite + chlorite ± goethite ± muscovite ± zircon ± opaque oxides.
Marine sediment	Quartz + kaolinite (± illite ± smectite) + hematite ± goethite ± muscovite ± ilmenite.
Thin (<5 m) colluvium/ alluvium	Polymict materials, lithics common + quartz + feldspar + kaolinite (± illite) + hematite ± goethite ± muscovite ± zircon ± opaque oxides.
Channel sediment	Quartz + kaolinite ± hematite ± goethite ± muscovite ± zircon ± opaque oxides.
Lake sediment	Quartz + kaolinite (± illite ± smectite) ± organics ± charcoal ± gypsum ± anhydrite ± halite ± calcite ± opaque oxides ± dolomite ± palygorskite
Aeolian sediment	Quartz ± feldspar± goethite ± zircon ± clay minerals ± opaque oxides.
Silcrete zone	Silica (quartz, anatase, zircon [QAZ]) cement (± chalcedony ± opal) + quartz grit/grains ± feldspar grit/grains ± kaolinite + anatase ± zircon ± opaque oxides
Calcrete zone	Calcite ± dolomite, with: quartz + kaolinite ± mica (and sericite) ± gypsum ± ferricrete ± opaque oxides.
Soils	Quartz + kaolinite (± illite ± smectite) + hematite ± muscovite ± calcite ± dolomite ± gypsum ± ferricrete ± opaque oxides.

Sources: Hou *et al.* 2000; Keeling *et al.* 1995, 1999b; Krieg 1995; Lintern *et al.* 2002, 2003, 2006a, b; Lintern 2004b; Lintern *et al.* 2002, 2003, 2006a, b; Lintern and Sheard 1998; Northcote 1979; Sheard and Robertson 2004; Sheard *et al.* 2006; Sheard 2007b, Stace *et al.* 1968.

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2.5 Regolith geochemistry

During exploration, it is important to know what part of the weathering history is preserved in a particular profile. Element dispersion patterns can be quite different for different deposits, or in different parts of the same weathering profile where these are related to different weathering regimes (Anand and de Broekert 2005; Butt *et al.* 2005). Regional and localised (prospect-scale) geochemical orientation surveys, which are carried out before more detailed work and drilling, should establish regolith provenance, target and pathfinder element background levels, detection limits, potential sample media and discrimination procedures.

Weathering of primary rock-forming minerals leads ultimately to residual profiles dominated by quartz, kaolinite ± Fe and Al oxides/oxyhydroxides (Robertson and Butt 1997). An accompanying series of chemical changes involve progressive loss of Na^{+}, K^{+}, Ca^{2+} and Mg^{2+}, and retention of Si^{4+} (in part), Al^{3+} and Fe^{3+}. The major element geochemistry of regolith is thus significantly fractionated with an increasing degree of weathering and leaching. Minor and trace elements are also fractionated, depending on the relative retention or dispersion from their primary host minerals and the adsorption or incorporation of released elements by new regolith minerals. In mineralised environments, this includes most target and pathfinder elements (e.g. McQueen and Munro 2003). Goethite, hematite, alunite–jarosite group minerals, manganese minerals and regolith carbonates are important trace element hosts that occur widely. Smectite group clays, and possibly also vermiculite, can incorporate a wide range of trace elements in their crystal structure (Taylor and Eggleton 2001). Smectite clays also have a high cation-exchange capacity. Depending on pH, they can host elevated concentrations of adsorbed trace element cations in mineralised environments (e.g. Cu, Zn, Ni and Co). Kaolinite and illite have low cation-exchange capacities and generally do not adsorb significant amounts of trace element cations.

Much of the material in this section has been derived from Lintern 2004a, b, c, 2005; Lintern and Sheard 1998, 1999a,b; Lintern *et al.* 2000, 2002, 2003, 2006b; McQueen 2008, Sheard 1990; Sheard and Robertson 2004. Additional sources are given in the text.

Element dispersion controls

The main controls on target and pathfinder element dispersion are:

- hydrological factors, particularly the presence, flow rates and flow directions of groundwater
- chemical conditions in different parts of the regolith, mainly redox potential (Eh) and hydrogen ion activity (pH)
- availability of complexing and oxidising agents (e.g. O_2, CO_2, SO_4^{2-}, NO_3^-, halides, organic compounds)
- temperature and evaporation
- physical processes causing mechanical dispersion (water, wind and gravity)
- biological activity.

Major weathering reactions for different rock types (and contained sulphide mineralisation) help to produce or modify these conditions, and the external drivers over time are climate, landscape position and biological activity.

Dispersing elements can become fixed: commonly by sorption onto, or incorporation into, regolith minerals. This results in predictable distributions for some elements within the weathered landscape. Some minerals are more abundant in certain types of regolith, and these are commonly preserved in particular landscape or palaeo-landscape settings. For example, indurated materials (including ferruginised saprolite and ironstones) commonly occur on hills or rises; thick clay-rich saprolite may be preserved in areas of limited erosion, including beneath duricrusts; eroded saprock commonly forms colluvium (talus fans or aprons, debris flows); whereas weathering-resistant vein quartz, quartz-rich rocks and ferruginous pisoliths become concentrated in surface sheetwash and alluvial channels. Landscape position will also influence surface and groundwater flow, and is an important control on both mechanical and hydromorphic dispersion.

Over the central Gawler Craton, intensely weathered profiles on the dominant crystalline rocks contain abundant kaolinite with quartz and minor illite. These minerals have a low ability to host trace elements. The presence of

goethite/hematite, smectite, alunite/jarosite and other secondary minerals in the profile may help to retain target or pathfinder elements released during weathering. For weathered sulphide mineralisation, the major host minerals for target and pathfinder elements progressively change from primary sulphide and specific secondary minerals (including supergene sulphides, arsenates, sulphates, carbonates, chlorides and oxides) in the lower part of the weathered profile, through smectite, vermiculite/hydrobiotite and possibly alunite/jarosite, to Fe- and Mn-oxides/oxyhydroxides towards the top.

Within the weathering profile, element dispersion is largely caused by chemical and hydromorphic processes. Where elements may become fixed in a stable ferruginous component near the surface, they are generally further dispersed by mechanical processes in the eroding landscape. This can result in markedly different dispersion patterns in different parts of the regolith. For example, Pb and As can show limited hydromorphic dispersion within the weathering profile compared with Cu and Zn, which may form a broad hydromorphic dispersion halo–generally fixed in goethite. At the surface, however, Pb and As (as well as Sb, Bi and Ba) may become strongly bound to hematite, which may be widely dispersed into colluvium, alluvium and soil by mechanical processes. Significant pH changes or boundaries, such as sediment cover/weathered bedrock interface and calcrete horizons (pH > 8.6) can result in precipitation or fixing of trace elements (e.g. Co, Cu, Ni, Zn, Pb and V).

Biogeochemical processes play a role in element dispersion through the regolith (e.g. Field 2006). The root networks of plants take up elements in solution. Plants can thereby potentially transfer or generate geochemical anomalies elsewhere in the regolith in a continuous and ongoing process (Butt *et al.* 2005). A study of Au dispersion in dune sand over the Barns prospect indicates that anomalous concentrations of Au may be accumulated by these processes in less than 10,000 years (Lintern and Rhodes 2005). Abundant microbiota (bacteria and fungi) within the regolith can also play a significant role in mineral weathering, biochemical dissolution and fixation of major and trace elements (Milnes 1992; Reith and Rogers 2004). Bioturbation of the upper parts of the regolith (e.g. by burrowing invertebrates and mammals,

or tree throws; *Figure 32*) results in mechanical redistribution of regolith components and their contained trace elements on both flat and sloping terrains (Field 2006; Field and Anderson 2003).



Figure 32. Tree-thrown soil and calcrete exposure. In many undeveloped areas, these and animal burrows will be the only natural exposures of subsurface regolith. Site southeast of Mount Finke, Harris Domain.

Weathering regimes

Chemical conditions in the regolith of the Gawler Craton have changed significantly through time–particularly in response to climatic, hydrologic and biological changes. Cold to cool- and-wet conditions, with high water tables, dominated from Late Cretaceous to Miocene times (Sheard, 1990; Alley and Lindsay, 1995; Alley and Frakes, 2003). These conditions generally favoured hydration: hydrolysis reactions that increase the mobility of reduced species (particularly Fe^{2+} and Mn^{2+}) in saturated profiles. Groundwater pH conditions would have been neutral to acid: the latter occurring particularly where sulphides were oxidising or where there was abundant decaying vegetation (such as in swamps). There is widespread evidence of high organic levels in soils, swamps and lakes (lignitic beds and carbonaceous horizons) whose

presence would favour organo-complexing of many elements.

A shift towards more regional arid conditions occurred after the Mid Miocene. Falling and fluctuating water tables resulted, which favoured oxidation reactions and more complex regional groundwater compositions:–particularly with higher salinity and increased carbonate or sulphate activity, and neutral to alkaline pH. Under arid conditions, the solubility and mobility of some elements, (particularly Au) would increase where chloride and thiosulphate complexing occurred; other elements (especially Pb, Ba and Hg) would be relatively fixed as insoluble chlorides, sulphates or carbonates. Marked pH gradients around sulphide deposits that continued to weather would have resulted in further dispersion of some elements (e.g. As, Cu and Zn) to form broader anomalies.

Examples of specific element dispersion features

Gold

Gold is mobile within the Gawler regolith, as indicated by:

- the presence of high fineness supergene Au in the oxide zones of some Au-bearing deposits
- association with calcrete
- presence in vegetation
- increasing solubility with increasing distance from source (i.e. from a cyanide-soluble form to more water-soluble forms).

The dissolution and dispersion mechanisms vary for individual sites, but may involve a combination of chemical and physical processes, together with Au halide dispersion and possibly thiosulphate-complexing–and organo-complexing–under different weathering regimes.

The form of primary Au influences how readily it is dispersed. Studies on the Gawler and elsewhere in Australia indicate that coarse Au, and Au 'locked' within vein quartz, remains relatively stable in the regolith, and can be residually concentrated near surface with only partial depletion from the upper regolith (Gray and Lintern 2004; Butt and Hough 2006). Gold

associated with sulphides is more mobile owing to its small particle size (commonly submicron), easy access by supergene solutions and increased concentrations of S-oxyanions that favour Au dissolution. Some rock types (e.g. mafic–ultramafic) are more effective at buffering groundwaters, and restrict Au mobility. Silica-rich rocks may inhibit Au depletion, due to silicification of the regolith occluding the Au grains.

Silver

Silver is associated with many of the mineralisation types across the Gawler Craton and it can be a useful pathfinder element, particularly for Au–Ag, Cu–Au–Ag, and Pb–Zn–Ag mineralisation. Dispersal of Ag from a source within the weathering zone is dependent upon groundwater salinity. Silver halides are relatively insoluble and tend to precipitate; their solubility increases, however, in highly saline groundwater. Silver abundance in near surface regolith materials collected over various Au prospects in the Gawler (all with Au-in-calcrete anomalism) shows variable ranges:

- lag (+9 mesh) less than 300 to around 700 ppb
- soil less than 10 to more than 150 ppb
- calcrete 0 to more than 800 ppb
- near surface colluvium–alluvium 500–1000 ppb
- red-brown hardpan 50–300 ppb; silcrete 100 –13000 ppb.

Copper

Although studies of Cu dispersion from Cu mineralisation in the Gawler Craton were located outside the area covered by this Guide, they may still have relevance to exploring in the central Gawler Craton and are summarised below:

- Where primary mineralisation crops out, Cu anomalies in soil are subtle and restricted in size; stream sediment sampling is useful where the fine fraction (< 75 micron) is taken to reduce dilution by barren country rock. Rock chip sampling is also effective.
- Studies at sites with thin transported regolith (< 10 m, Moonta on Yorke

Peninsula) record anomalous Cu in the upper transported regolith and in soil and calcrete (10– > 80 ppm Cu) (Hartley 2004; Keeling and Hartley 2005). Acid-saline groundwaters, a relatively high water table (~20 m) and calcrete are important factors affecting dispersion and precipitation of Cu. Strong acid digests are effective in identifying anomalous areas and partial and selective extractions can help to refine anomalies over mineralisation for drill targeting.

- Where transported regolith is more than 10 metres thick, near surface indication of Cu is generally more difficult to detect. Partial leach geochemical techniques may detect subtle anomalies or, alternatively, drilling to sample at the interface of transported and *in situ* regolith is recommended.

In weathering environments where the pH is alkaline–such as in areas of widespread calcrete–Cu is less widely dispersed, and commonly precipitates as malachite or azurite. At Moonta, atacamite ($Cu_2Cl(OH)_3$) is present in transported clay cover over narrow, shear-hosted sulphide deposits. Increased Cu levels in the clay are accompanied by higher levels of U (to 36 ppm) and rare earth elements (La, Ce, Nd and Sm) (Keeling and Hartley 2005). Advective transport of Cu ions by capillary action, driven by high evaporation, is a possible dispersion mechanism (Keeling 2004). The presence of Cu in thin alunite/halloysite seams within the clay is consistent also with 'seismic pumping' of acidic saline groundwater as a dispersal mechanism at around the time of sediment deposition and alunite formation, at around 2 Ma (K–Ar date on alunite, W.J. Dunlap, pers. comm.)

Nickel–chromium–vanadium

In the central Gawler, greenstone/mafic lithologies have been identified in regional airborne magnetic data by their distinctive magnetic signature. Where transported cover is thin (< 5 m), elevated levels of Ni, Cr and V in soils indicate greenstone bedrock and can be used to trace these lithologies into areas where the magnetic data are equivocal. Mineral species hosting the Ni, Cr and V in transported regolith include chromite, chrome-spinel, remnant antigorite, remnant vermiculite and residual smectites. Colluvial processes in association with bioturbation and tree throws are likely mechanisms for

bringing these *in situ* regolith-derived materials into the overlying sediment (Sheard and Robertson, 2004; *Figure 32*). The abundance of these elements in various sample media from transported regolith overlying greenstones at Lake Harris is given in *Table 4*.

Table 4. Geochemical ranges for Cr, Ni and V in transported regolith (< 5 m thick) overlying weathered greenstones in the Lake Harris area (data from Sheard and Robertson 2004).

Element	Magnetic granule lag	Soil	Calcrete	**Silcrete** at unconformity : felsic sourced grains, greenstone sourced grains.
Cr (ppm)	1200-17230	~50-200	~50-200	<15, 60-1200
Ni (ppm)	530-640	14-32	15-22	<5, 20-35
V (ppm)	720-1200	25-80	<60	<30, 50-115

Nickel can also be used to help identify regolith derived from other basement rocks. For example, the Sleaford Suite paragneiss under sand cover (1– < 5 m thick) east of the Baggy Green gold prospect, is indicated by relatively high Ni (20–26 ppm) contents in calcrete (Sheard 2007b).

Uranium and rare earth elements

Uranium and selected rare earth elements (REE) have been routinely analysed in regolith samples collected since 1997 for CRC LEME investigations in the Gawler Craton.

Uranium is ubiquitous in many of the Gawler Craton crystalline basement rocks, although its distribution within the regolith is more restricted. Uranium is released into the regolith during weathering of rocks with significant trace amounts of the element: typically granites, felsic volcanics or gneisses. Oxidising and acidic conditions will favour dispersion, with precipitation when Eh and pH change to reducing and neutral conditions. Uranium will accumulate in channel sediments in areas of decomposed organic matter, sulphide and carbonaceous clay. In general, U levels in pedogenic calcrete and other upper regolith materials are low (vegetation < 20–300 ppb; lags < 1–4 ppm; soil 0.1–0.8 ppm; calcrete 0–4.6 ppm; near surface sediment 0.4–3.7 ppm; silcrete < 0.1–3.7 ppm).

Delineation of palaeochannel-hosted U by surface geochemical methods is not well established–particularly for deeply buried deposits. No successful methods have been reported for South Australia (Hou *et al.* 2007b). Nonetheless, palaeochannel sediments do show different trace element chemistry to adjacent weathered bedrock. Multi-element analyses of samples from exploration drill traverses are helpful in defining channel sediment (e.g. a portion of the Kingoonya Palaeochannel; *Figure 33*). In particular, U (at 1.4– > 3.6 ppm) indicates channel sediments, while the light to moderately heavy REEs La, Ce, Pr, Sm, Eu, Gd, Tb, Dy, Ho and Er show higher levels in bedrock. Heavy REEs such as Lu, Tm and Yb occur both within the sediment and adjacent incised *in situ* regolith and Bi, Th, Cs and Nb show greater abundance in the palaeochannel sediment. Increased levels of light REEs (La, Ce, Nd, Sm) occur in transported clay over the Poona Copper Lode near Moonta on Yorke Peninsula (Keeling and Hartley, 2005).

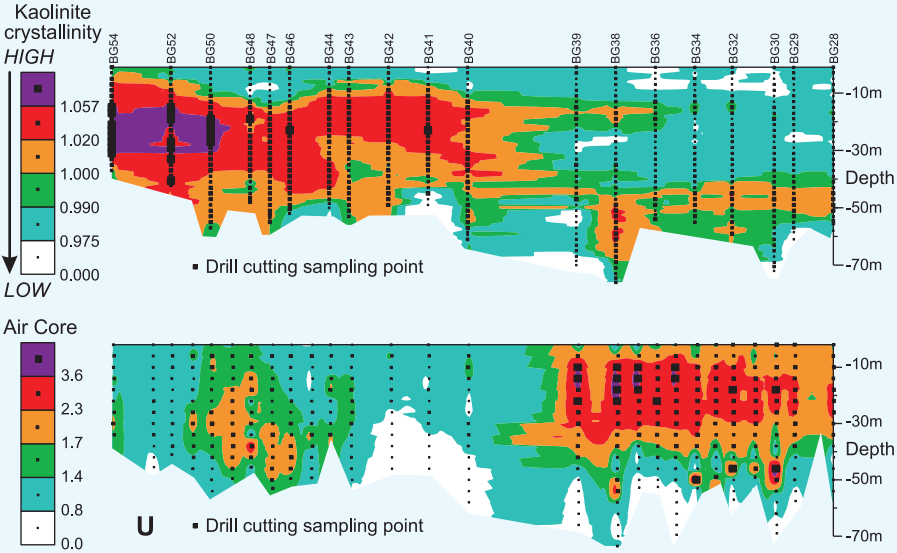


Figure 33. Boomerang gold prospect–regolith section across palaeochannel orientated south to north. Top profile shows the difference in regolith types as defined on kaolinite crystallinity indices from PIMA spectra: the palaeochannel unconformity is indicated by a dashed black line (palaeochannel is < 36 m deep.). Bottom profile shows contoured U levels (ppm) from drill cuttings. Higher U levels define the channel sediment (from Lintern et al. 2006b).

Arsenic

Arsenic is commonly used as a pathfinder element, particularly for Au, but also for base metal sulphide deposits. In primary mineralisation, As is a trace element in pyrite, or a major element in arsenopyrite. Under humid and moderate to low pH weathering conditions, As is dispersed by rapid weathering of pyrite and arsenopyrite, where the liberated As is adsorbed onto any available Fe oxides/oxyhydroxides. However, regolith investigations on the Gawler Craton indicate that As is an erratic pathfinder for Au, or can be completely misleading with respect to Au dispersal. Arsenic can be fixed in hematite-rich lag at the surface and may become widely dispersed by mechanical processes during erosion. Under both arid and high pH conditions, As may either combine with Cu and Pb to form relatively insoluble arsenates or remain in solution to become widely dispersed in groundwater.

The presence of As in calcrete horizons is quite variable. Lintern and Sheard (1999b) report calcrete over the Challenger gold deposit with As at > 5–200 ppm. Sheard and Robertson (2004) have demonstrated As (~20 ppm) in calcrete over granite-hosted Au-mineralisation at Glenloth goldfield, decreasing to < 7 ppm over nearby subcropping greenstones. Arsenic may be used to help map regolith derived from particular basement rock suites.

Regolith element associations

Aspects of regolith-related element associations and target and pathfinder element relationships relevant to exploration in the central Gawler Craton are set out below. These are drawn from Lintern 2004a, b, c; Lintern 2005; Lintern and Rhodes 2005; Lintern and Sheard 1998, 1999b; Lintern *et al.* 2000, 2002, 2003, 2006b; and Sheard and Robertson, 2004.

- Across the region there are 'evapo-transpirative' zones in the near-surface regolith, which are marked by the deposition of calcium and magnesium carbonate in particular, but also other salts. These have been found to be useful sampling media for Au, Ag, Cu, Zn, Pb, Ni and V.
- Dune-hosted carbonate accumulations can contain detectable Au, Ag and Cu where located above mineralisation, but the threshold is

generally one to two orders of magnitude smaller than that typical for calcrete in weathered bedrock over mineralisation.

- Unlike many other areas in Australia, widespread ferruginisation of the regolith is not present (or preserved) over most of the Gawler Craton, but, where present, Fe oxides and oxyhydroxides may incorporate Au and other trace elements (As, Bi, Cu, Sb, Se, Zn and W) and be a useful local surface sample to detect Au/Cu and Pb/Zn mineralisation in particular. The low and intermittent abundance of ferruginous weathered bedrock across the region generally dictates the use of other regolith components (calcrete, lag, soil, silcrete and vegetation).

Target elements and their respective pathfinder elements have been determined from investigations within specific domains of the Gawler Craton, as summarised below;

- **Christie Domain,** near surface regolith: target Au; associated elements Ag and Cu; potentially useful elements are Ag, As. Cd, Cr, Cu, In, Ni, Pb, Sb and Zn. **Additional targets:** Ni, Cr and PGE; associated elements Cr, V, Zn, W, Pb, Cu; potential useful elements are Ag, Au, Cr, Cu, Ni, Pb, V, W and Zn. ***In situ* versus transported regolith discrimination:** light REEs (Ce, La, Nd, Pr and Sm) appear to be more elevated in the *in situ* regolith.
- **Harris Greenstone Belt,** near surface regolith: targets Ni, Cr, PGE and Au; associated elements Cr, V, Zn, W, Pb and Cu; potentially useful elements Ni, Cr, Au, Ag, Cu, Pb, V, W and Zn. **Felsic versus greenstone-derived regolith discrimination;** greenstone generally has higher Ni, Cr and Ti and significantly lower Zr. **Greenstone-derived regolith versus cover sediments discrimination:** achieved with bivariate plots (K_2O versus MgO, K_2O versus Sr, As versus Cu) and a trivariate Rb–Sr–MnO plot.
- **Nuyts Domain,** near surface regolith: target(s) Au, Cu, Ag and U; associated element Th; potentially useful elements Ag, Cu, ?As, V, Th and U. Potential metasedimentary versus granitic basement geochemical mapping tools in covered terrain: As and Ni.

In view of the differences in element concentration in regolith in various domains and over particular lithologies, results for samples from one area

or sampling medium should be compared with others from similar sites and sampling media as far as is possible.

Geochemical characterisation of regolith materials

Regolith derived from different parent rocks, or from similar materials at different stages of weathering, may be distinguished by their geochemical characteristics (Robertson and Butt 1997; Robertson *et al.* 2001). During weathering the progressive loss of some major elements (Na^{+}, K^{+}, Ca^{2+}, Mg^{2+} and some Si^{4+}), and retention of others, changes the bulk composition of the regolith. Plots of the K/Al and Mg/Al ratios can provide a simple index for characterising differently weathered materials by comparing two mobilised elements with a relatively immobile major element. However, provenance, widely varying basement lithotypes, landscape position presentation, materials reworking, age and climatic regimes have also combined to induce significant geochemical overlaps in the regolith. Domain-specific *in situ* versus transported regolith chemical discriminators are listed in the regolith element associations summarised above. Moreover, spectral analysis (with PIMA, ASD, HyLogger™, HyChips™) of regolith samples provides useful mineralogical discriminators between clay saprolite and transported clays (Pontual and Merry, 1996).

2.6 Mapping surface regolith

Regolith-landform maps show the surface distribution of regolith-landform units. These are areas that have similar landform and regolith attributes at the mapping scale. There is commonly a strong correlation between regolith type and particular landforms, and thus the two features are best mapped together (see outline of steps in regolith mapping in *Appendix A3*, on CD). Landforms, and other features such as vegetation, can be used as useful predictors or surrogates for regolith-landforms at a local scale, but regional extrapolation across the Gawler is less reliable. The standard mapping method involves identifying the regolith material and the landform type for a particular site representing an area. Various regolith and regolith-landform mapping approaches have been used in Australia, and particularly for sites on the Gawler Craton. Of those, the RTMAP system and the RED scheme

(modified, see Sheard and Robertson, 2004) are the most commonly used (*Figures 34, 35*). The RTMAP scheme is descriptive and the RED scheme is interpretive. RED maps can be derived from RTMAP, but the reverse is more difficult to achieve, depending on the level of description included.

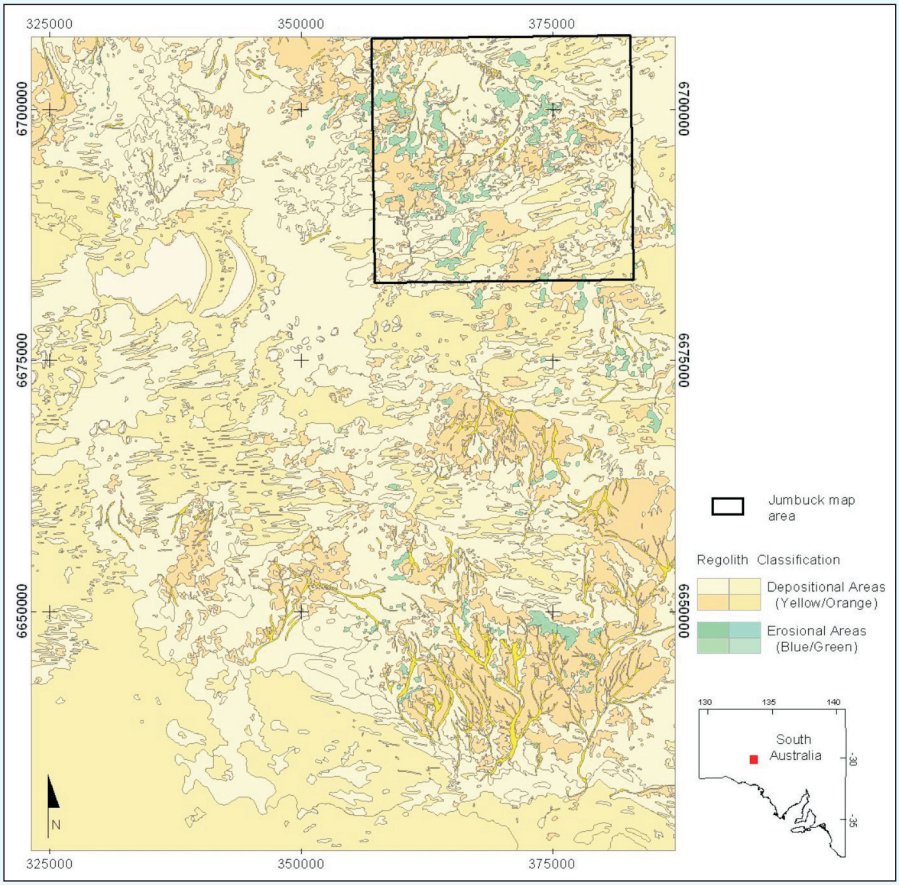


Figure 34. Simplified 1:100,000 scale regolith-landforms map of the Half Moon Lake area; includes the Jumbuck 1:50,000 scale detailed area (boxed) covering the Challenger gold deposit. Map shows the distribution of in situ and transported regolith units (Lintern 2004b after Craig and Wilford 1997a, b).

In RTMAP, units are described by a series of standard letter codes, where the first two upper case letters define the regolith material and the next two lower case letters describe the landform. A following subscript can be added as a

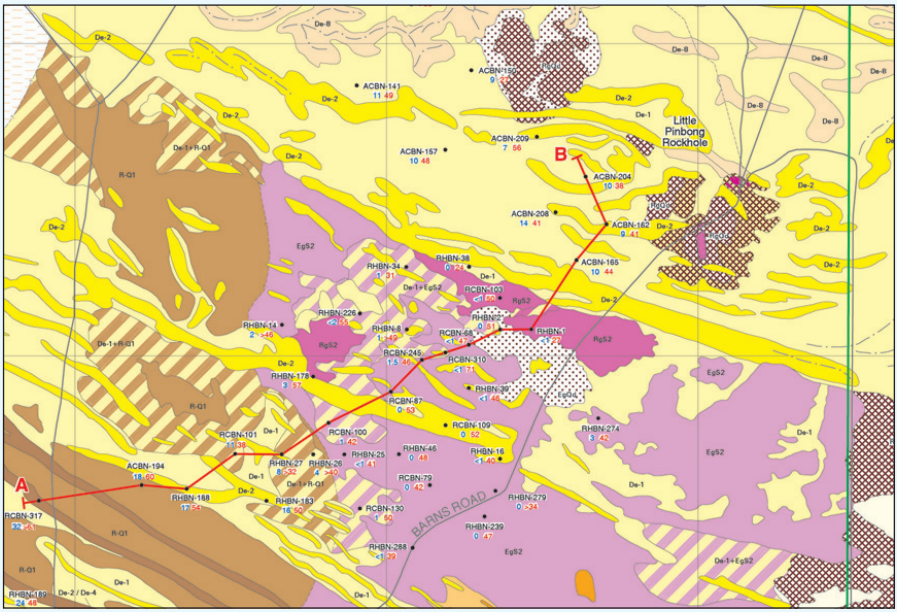


Figure 35. Excerpt from the Wudinna north 1:20,000 Regolith-Landforms Map A (Barns gold prospect is centre field) based upon a modified RED scheme. It shows the level of detail typical for this scale of mapping. Drill holes with transported regolith thickness and depth to fresh rock are marked. The red line A–B locates one of two regolith profile cross-sections available for this map (grid is 2 kilometres; Sheard 2007a. Grid lines, AGD 94: 6366000 mN to 6368000 mN; 540000 mE, 542000 mE, 544000 mE.

modifier to define more subtle differences between units. For example a map unit may be tagged as follows:

CHfs$_1$, where:

CH describes the main regolith type (sheetflow deposits)

fs describes the main landform type (sheetflood fan)

1 is a modifier for where there are a number of different regolith-landform units of this general type (a list of standard codes is given in *Appendix A4*, on CD)

In the RED scheme, landscape regimes are described as being dominantly relict/residual (R), erosional (E), or depositional (D). These can be subdivided further using alpha-numerical characters that emphasise the

in situ regolith source area, landscape position and degree of weathering, erosional dispersion pathways and sediment depocentres.

For many areas, constructing a regolith-landform map is a useful first step in deciphering the landscape history and the landscape (and palaeo-landscape) setting of regolith materials. From this, the origin and history of modification of those materials can be determined, and hence their suitability as geochemical sampling media. Regolith-landform maps are also the basis for constructing derivative maps, which have attributes specific to mineral exploration. At the most basic level, these identify areas of *in situ* versus transported regolith, which is fundamental to deciding how to explore and what to sample. Other attributes include regolith composition, degree of weathering, relative age and thickness, and the source of transported regolith. Landform information is useful for predicting element dispersion pathways. As for all maps, the scale of mapping depends upon the purpose and use. For regional exploration, a scale of 1:100,000 or more detailed is required (1:25,000 is optimal in many situations, but more detailed maps may be helpful at the prospect scale (1:10,000 or 1:5,000; *Figure 35*).

Regolith-landform mapping coverage of the central Gawler Craton has to date been limited to small, widely separated areas. The largest single map covers about 2,500 km^2 around Half Moon Lake (Craig and Wilford 1997a), and the smallest is that of Povey (1999), which covers about 12 km^2 over the Challenger gold deposit. Available regolith-landform maps for the region are referenced below:

- Christie Domain: regolith on mineralised Archaean gneissic basement (Craig and Wilford 1997a, b; Povey 1999; Craig 2001; Wilford *et al.* 2001; Lintern *et al.* 2003)
- Harris Greenstone Belt: regolith on greenstones and gneissic basement (Sheard and Robertson 2003, 2004; Lintern 2004a; Lintern *et al.* 2006b)
- Nuyts Domain: regolith on mineralised Proterozoic basement, NW Eyre Peninsula (Sheard 2007a, b).

2.7 Mapping Regolith in 3D with emphasis on palaeodrainage and palaeo-coastal deposits

Sedimentary deposits in Cenozoic drainage networks and associated estuarine and coastal barrier environments have particular significance for mineral exploration in the central Gawler region. The palaeochannel sediments are an exploration target for sandstone-hosted U, and the palaeo-coastal barrier sands contain important economic deposits of heavy mineral sands. Channel sediments have been shown to limit the effectiveness of surface geochemical techniques and influence element dispersion (Lintern 2004b). They may also contain the only local source of groundwater from which sufficiently high yields of mostly saline water can be extracted for mineral resource development. Palaeogene and Neogene sediments are widespread across the region, but their detailed distribution is poorly defined. It follows then that exploration for sediment-hosted deposits and shallow basement mineralisation in the region requires techniques that can map the areal distribution and thickness of Cenozoic terrestrial sediments.

Regional compilations showing the distribution of palaeodrainage and palaeo-coastal barriers (Hou *et al.* 2007b) provide an overview only (*Figure 36*). These are based on the integration of data from a variety of sources. The paucity of drilling data over much of the region, however, means that indirect methods have been used extensively to map the margins of major palaeo-river systems. The reliability of much of the interpretation remains untested and confirmation using other techniques is advised before any substantial program of exploratory drilling.

A combination of techniques generally gives a more satisfactory interpretation of the distribution of palaeodrainage and coastal barrier sediments. Useful approaches after Hou *et al.* (2001a, b), Hou and Mauger (2005) and Hou *et al.* (2007a) are discussed below.

Digital elevation models

For the central Gawler region, topographic data are useful in broad scale reconstruction of the earlier landscape. Essential elements of the Palaeogene-early Neogene landscape remain largely intact, despite modification by

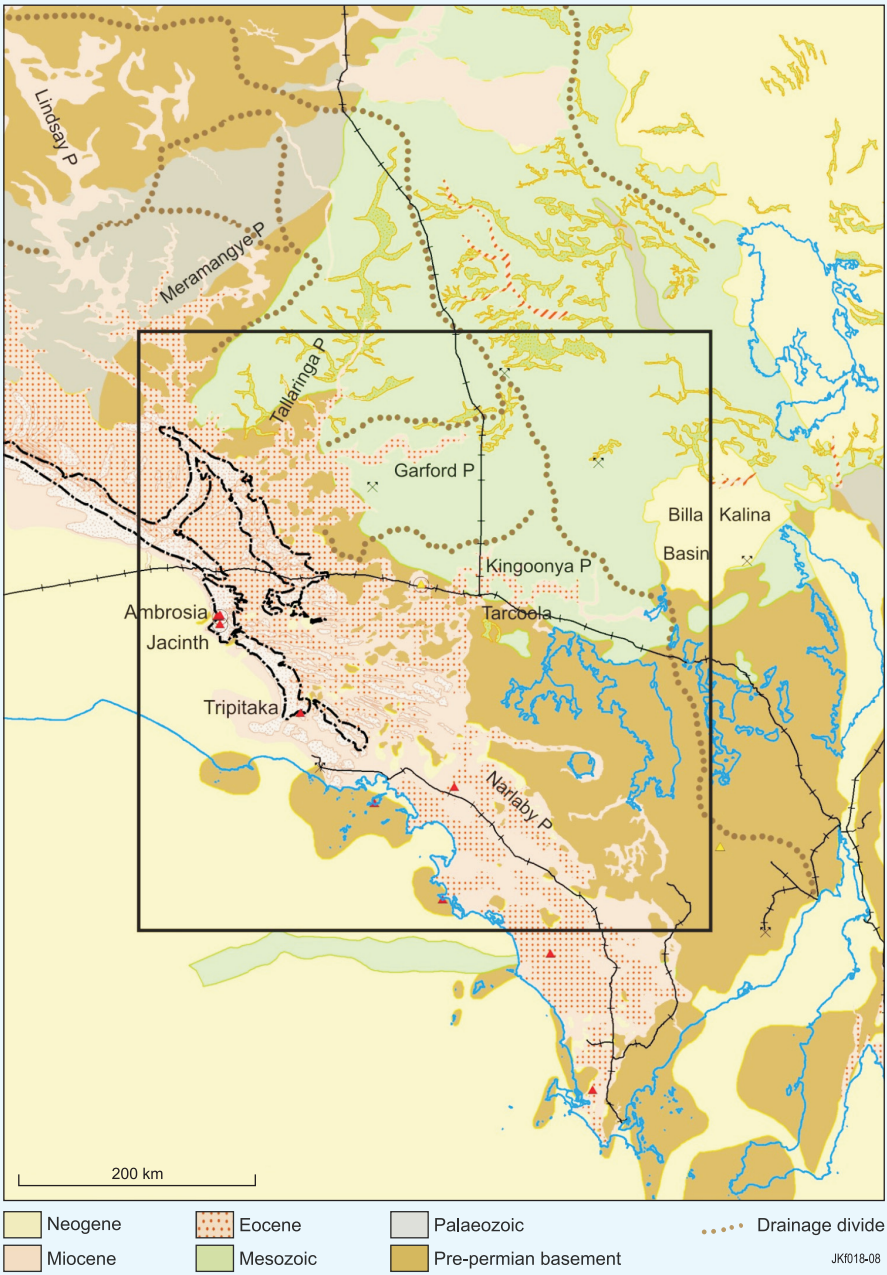


Figure 36. Distribution of selected basin sediments, Cenozoic palaeodrainage and coastal deposits on the Gawler Craton (from Hou et al. 2007b). Area covered by the Guide is outlined.

erosion and partial burial by sandplain and dunefields. A prime example is the excellent preservation of Palaeogene coastal barriers and backshore lagoons adjacent to the marine Eucla Basin (Benbow, 1990). Palaeodrainage channels and associated palaeovalleys still mostly occupy low-lying areas, with topographic highs reflecting the basement interfluves. Although low points in the present landscape may not necessarily correlate with buried palaeodrainage sediments, they reflect an association between floodplain–lacustrine plain and deeply weathered bedrock that predates aeolian infill. In some areas, detailed topographic data may help to resolve lower order tributary patterns in palaeodrainage that are not apparent in the 9-second Australian DEM or 90-m regional SRTM data most widely available. Regolith landform mapping combined with topographic data can reveal the detail of palaeodrainage networks, especially where the former drainage continues to influence the distribution of surface regolith deposits.

Remotely-sensed Vis-IR spectral imagery

The distribution of fluvial sediments is mappable on Landsat imagery where the sediments directly or indirectly influence surface features and regolith. The presence of carbonate, gypsiferous clay, silcrete and strings of playa lakes are all features with higher albedo than their surroundings. Where these correspond to palaeodrainage, the features generally string together in dendritic patterns that may be traced for kilometres before being obscured by sand cover. Dendritic drainage of the Tallaringa palaeo-river system and portions of the Garford and Kingoonya Palaeodrainage are readily identified.

Currently available remotely-sensed satellite datasets can provide useful information for mapping palaeodrainage. Where greater spatial resolution is required, ASTER at 15 metres, SPOT 5 at 2.5 metres, IKONOS at 1 metre and Quickbird at sub-metre resolutions, respectively, offer a range of products at increasing cost per unit area. The spatial resolution of an instrument is also linked to the capacity for spectral discrimination. If spectral discrimination is not sufficiently sensitive then the ability to observe small objects with low contrast is compromised. Spectral developments that give improved identification of surface materials–especially Fe oxide, clay and

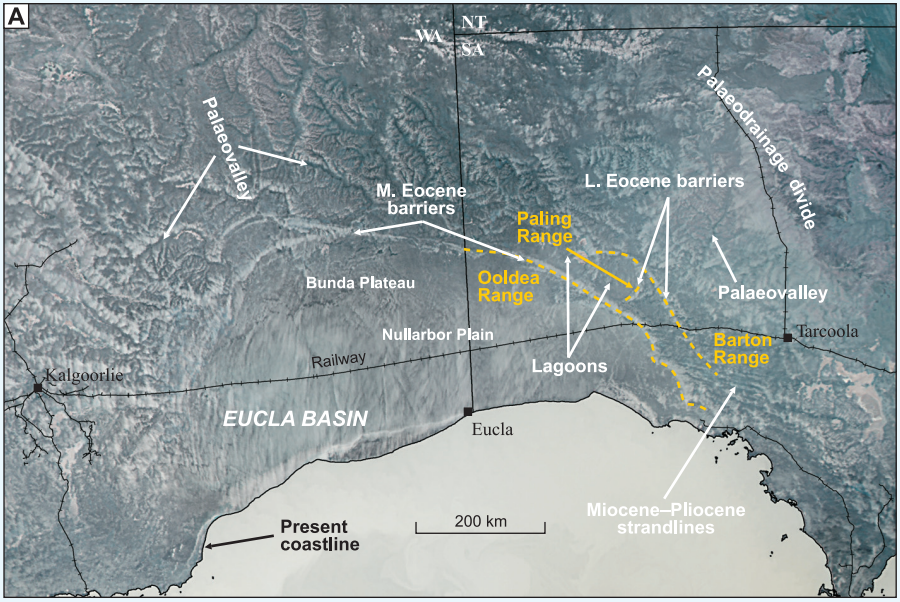
mica mineralogy–use a complementary suite of instruments. ASTER has 14 bands, five of which are in the thermal infrared, which, after processing, can map spatial distribution of clay, carbonate, Fe oxide and silicate. The airborne HyMap hyperspectral system with 125 channels is possibly the best mineral mapping instrument available in the marketplace. Data are captured in 2.5 kilometre strips at about 4.5 metre resolution, but, to maximise surface information, flying needs to be done under optimal weather and solar illumination conditions. For a more detailed discussion of these instruments see Mauger (2003).

Night-time thermal satellite imagery

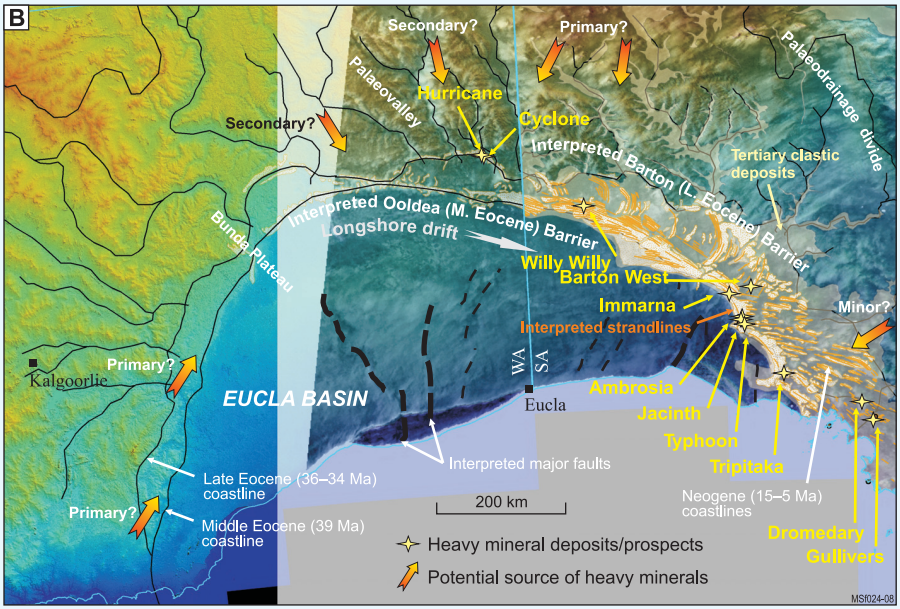
Satellite thermal infrared imagery can be used to detect palaeodrainage, especially in arid regions. The radiant temperature recorded by satellite is the product of the kinetic temperature and emissivity of a body: effectively a measure of its ability to absorb and radiate thermal energy (Kahle 1980). The amount of surface radiant temperature detected is related to night-time cooling mechanisms, the amount of insulation and the thermal properties of the material (Short and Stuart 1982). Diurnal cooling processes take time, so the hour of orbital overpass needs to be at a time when maximum thermal contrast is developed between bodies with different thermal properties (Tapley 1988).

The detector and orbital configuration of NOAA–AVHRR and ASTER night-time satellites provide thermal data that are potentially useful for detecting temperature variation in subsurface sediments. This may correlate with higher moisture content in channel deposits. The coverage of NOAA imagery makes it suitable for regional-scale interpretation. The technique has been shown

Figure 37. (A) NOAA-AVHRR night-time thermal imagery and (B) Shuttle radar topography mission (SRTM) imagery (90 m pixel) of the Eucla Basin and palaeodrainage area, overlain by interpreted Tertiary features, highlighting the Middle Eocene (39 Ma), Late Eocene (36 Ma) and Miocene (15–5 Ma) shorelines and filled palaeovalleys. The textural difference between palaeovalley sediments (dark tones indicating cooler features) and the sand barriers and surrounding basement terrain (brighter tones indicating warmer regions) is apparent. The locations of new beach placer discoveries: Jacinth and Ambrosia deposits, Tripitaka and Gullivers prospects (from Hou et al. 2008) are indicated.



SRTM DEM ⇐ Draped over ⇐ NOAA night-time thermal imagery



to be effective in identifying previously unmapped palaeodrainage sediments (Tapley 1988). NOAA images have also proved useful in providing additional information on sand distribution in palaeo-beach-barrier deposits. Mapping the spatial associations of these deposits is improved by using a combination of topographic and night-time thermal imagery (*Figure 37*). The advantage of ASTER over NOAA is in pixel resolution (90 m versus 1.1 km) and the number of channels (5 versus 3) (Stamoulis 2006). While acknowledging the successes, the combined effect of various components in surficial sediments on the thermal response is still poorly understood. Palaeochannel mapping is based largely on recognition of dendritic patterns of cooler pixels in the landscape. Confidence is higher where these are at a scale comparable with known palaeo-river systems in the region, appear as logical extensions to known drainage networks, or include supporting evidence from geophysical or drilling data.

Interpretation of night-time thermal infrared satellite imagery requires a level of care. Artefacts unrelated to ground temperature need to be considered. Among these are clouds, weather fronts, haze and a signal smearing, which may be attributable to wind. Examination of adjacent imagery in the same orbital acquisition can help to identify regional weather patterns that may affect the scene being interpreted. The actual temperature of the feature should be within an acceptable range for terrestrial land surfaces. Comparison of several images acquired over the same area on different days can identify and eliminate atmospheric effects. Variable thermal response over time is to be expected in a dynamic landscape. Water is absorbed in the soil, flows in subterranean channels and fracture pathways, and surfaces dry out. Images captured at different times over the same area may reveal elements of a particular palaeodrainage system or palaeo-coastal barrier sand on one image that are less apparent in another image of the same scene (A Mauger pers. comm. 2007).

Thermal data provide a quick and inexpensive means of assessing an area for possible palaeodrainage and for reviewing regional arrangement of palaeo-beach barrier sand deposits. Experience suggests that, for the central Gawler region, images acquired in the late evening, during late summer and autumn

give reasonably consistent results for interpretation–subject to weather conditions. However, different times and moisture conditions may favour interpretation of subtle palaeodrainage and other landscape features.

Geophysical methods

Cenozoic palaeochannel and barrier deposits in this region are not visible in regional magnetic data because the features are relatively shallow and bedrock magnetic response tends to dominate. Detailed magnetic surveys in other parts of the country have traced palaeodrainage by the presence of magnetic gravels (maghemite) in the sediments (Mackey *et al.* 2000). This is unlikely in the central Gawler, where channel sediments predate the onset of dry conditions and bushfires that produce widespread maghemite in soils. Since drying, the pattern of surface drainage has been modified by extensive dune cover, and maghemite accumulations reflect local drainage conditions. Heavy mineral sand deposits in the region generally contain a low content of magnetic minerals and are therefore less amenable to mapping by magnetic methods. Magnetics may help to discriminate lithologies in basement rocks that in turn influence development of palaeo-coastal landforms such as 'J'-shaped bays and headlands. Modelling the interaction of sea-level change with underlying basement lithology, interpreted from aeromagnetic images, may therefore help to identify repetition of heavy mineral traps in barrier sands.

Radiometric data are not generally regarded as a mapping tool for buried fluvial sediments, but can be useful in linking known palaeodrainage with patterns of dispersion from U-rich source regions. Zircon-rich beach placer deposits may give a radiometric response where the sediments are exposed.

Anomalies in the Earth's gravitational field can be used to define the thickness and extent of the fluvial sediments–and hence palaeochannels–provided there is sufficient contrast in density between the sediments (e.g. sand and clay having a density of around 1.8 g/cm^3; Berkman 1995) and fresh bedrock (e.g. granitic basement having a density of 2.7 g/cm^3; Berkman 1995). Ground gravity surveys across known or suspected palaeochannel sediments have been used to locate the point of thickest sediment fill. From successive

sections across the channel, the trace of the deepest part can be defined. In U exploration, this can help to model channel dynamics and identify target areas where organic matter and reduced sediments might accumulate (Hou *et al.* 2001b). Spacing of gravity stations at 50–100 metres is usual. The instrument needs to be levelled at each station and accurate geographic coordinates and elevation (±0.05 m) data obtained using differential GPS. This level of accuracy allows corrections for altitude, latitude and Earth tides to be within 0.01 mgal, which is compatible with the change in Bouguer gravity that can be measured with modern gravity meters. Sediment thickness estimates are improved where local drill hole control is available to provide data on sediment density, base of channel and thickness of weathered bedrock.

Electromagnetic methods (AEM and TEM) measure the electrical conductivity of the ground: both laterally and vertically. The data can be processed to show ground conductivity as a function of depth, and can define channel sediments because of their porosity, moisture content and the conductivity of saline groundwater within them. Ground TEM surveys successfully located buried portions of the Garford Palaeochannel (Dodds 1997a; Hou *et al.* 2001a, b). A trial airborne EM survey over the Challenger Au prospect identified thick channel sediments that were not previously known (*Figure 38*) (Lane and Worrall 2002b). The 180 m-deep palaeochannel, situated 2 kilometres west of Challenger, was later drilled and developed as a source of water for the newly commissioned Challenger gold mine.

Airborne EM surveying is potentially an ideal means of mapping the regolith in 3D (*Figure 39*). The technique has been widely adopted by U explorers in the central Gawler to gather data on the distribution and thickness of palaeochannel sediments. The fixed-wing, time-domain airborne system TEMPEST has flown many of the surveys and this platform is preferred for large areas and deep ground penetration to around 150 m. The helicopter-borne, HoistEM system has also been used successfully to define palaeochannels in the area, and may offer finer spatial resolution. A HoistEM survey for Iluka–in search of groundwater sources for their proposed heavy mineral sands development at Jacinth and Ambrosia–located an Early-Middle Eocene palaeodrainage network west of the Ooldea Range. This channel is beneath

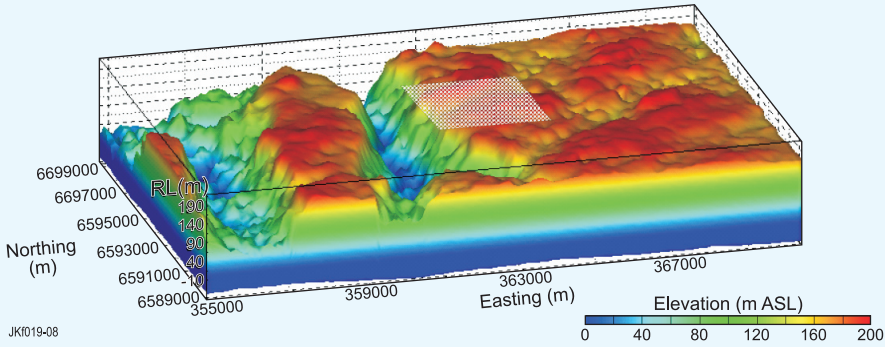


Figure 38. Elevation model of the airborne electromagnetic basal conductor surrounding the Challenger gold deposit (Lane and Worrall 2002b). Area of lag survey (Povey 1999) shown by hatching. Note two deep, sediment-filled palaeochannels to the west of the hatched area (from Lintern 2004b).

about 20 metres of Nullarbor Limestone and 10–20 metres of marginal marine sand and silt. Good yields of saline water were established in the channel sands (Bull *et al.* 2007). The channel is also an exploration target for U. Choice of spacing for airborne survey lines to map palaeodrainage varies from 400 metres to several kilometres. This compares with about 150 metre spacing for basement targets below cover (e.g. Challenger gold deposit). EM methods have not been applied specifically to mineral sands exploration in the Eucla beach barriers, but might have a role in mapping out clayey facies to assist with reconstruction of the palaeo-environment.

Conversion of raw AEM data to conductivity depth images involves several steps of complex processing. This requires specific mathematical and physical assumptions for data correction and a choice of approaches in converting the data to a vertical representation of conductivity. Airborne EM systems can detect, but usually not resolve, conductivity distribution in the top 5–10 m. Experience with using AEM to map regolith for environmental studies elsewhere in Australia has demonstrated that data processing and interpretation are improved by incorporating geological constraints (Spies and Woodgate 2005). These may be provided through strategic drill holes in the survey area, with lithological and conductivity logging and surface mapping to verify and quantify relationships (Lane 2002).

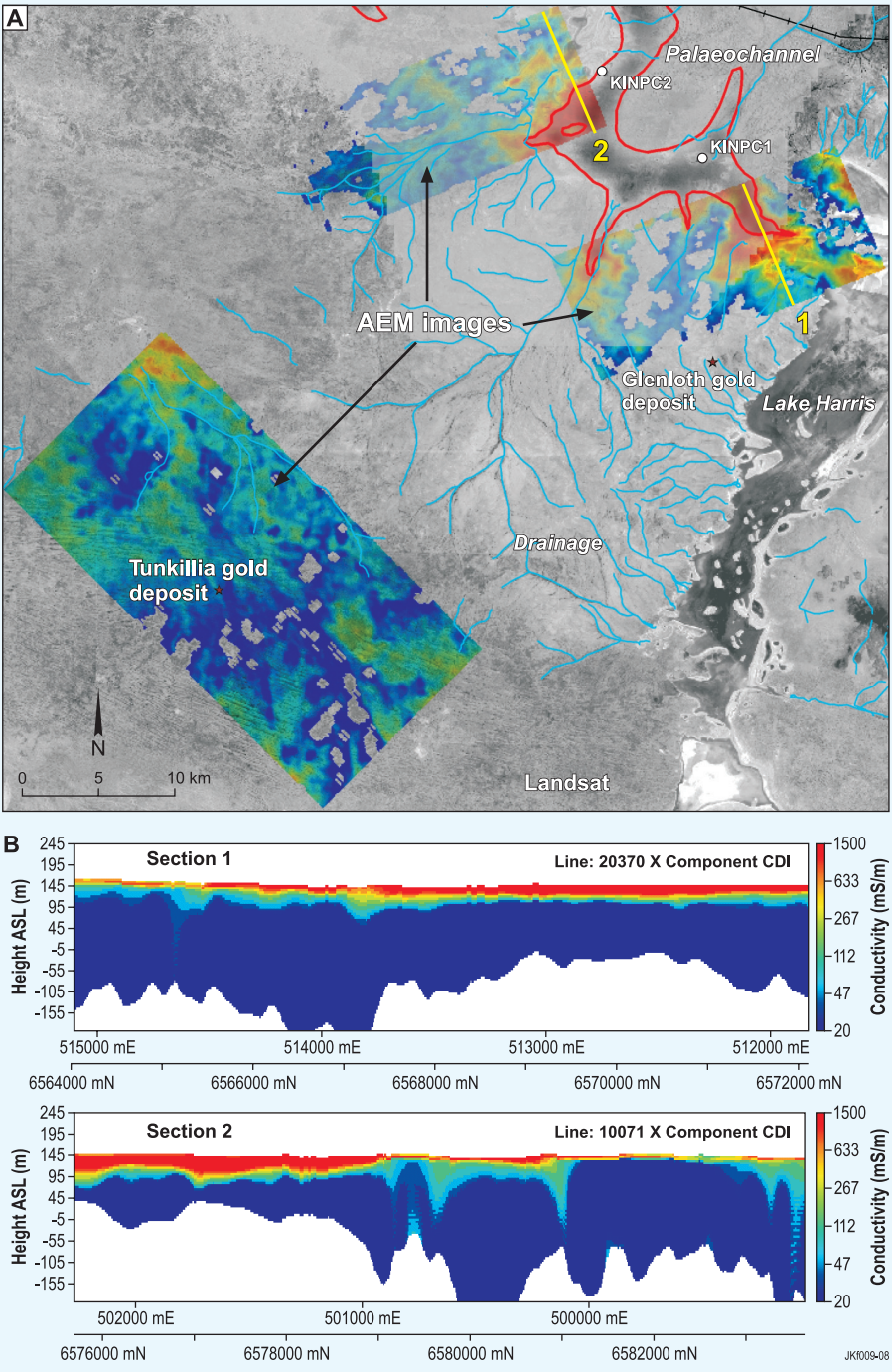

A
Palaeochannel
KINPC2
KINPC1
2
1
AEM images
Glenloth gold deposit
Lake Harris
Drainage
Tunkillia gold deposit
N
0
5
10 km
Landsat
B
Section 1
Line: 20370 X Component CDI
Height ASL (m)
245
195
145
95
45
-5
-55
-105
-155
Conductivity (mS/m)
1500
633
267
112
47
20
515000 mE
514000 mE
513000 mE
512000 mE
6564000 mN
6566000 mN
6568000 mN
6570000 mN
6572000 mN
Section 2
Line: 10071 X Component CDI
502000 mE
501000 mE
500000 mE
6576000 mN
6578000 mN
6580000 mN
6582000 mN
JKf009-08

Figure 39(A) and (B). Airborne electromagnetic trial surveys over Tunkillia gold prospect and Glenloth Goldfield showing conductive zones (red) that reflect channel sediment distribution (from Hou and Mauger 2005)

Shallow seismic reflection and refraction imaging can be used for investigating subsurface structure (particularly in sedimentary terrains) and therefore have application for delineating palaeochannels. By integrating reflection and refraction techniques, it is possible to determine palaeochannel depth, variability in sediments and the morphologies of both shallow and deeper strata (Drummond 2002). The technique has not been used in the Gawler to specifically investigate palaeodrainage because of the high cost of surveys.

Ground penetrating radar (GPR) is a surface technique that measures reflections of UHF/VHF radio frequencies to image the subsurface. The depth range of GPR is limited by the electrical conductivity of the ground, moisture content and the transmitting frequency. Optimal depth penetration of around 15 metres is achieved in dry sandy soils. In these conditions, detail of the geometry, structure and thickness of channel or dune deposits is displayed as a high-resolution image in cross-section view. In moist and/or clayey ground–or ground with high electrical conductivity–penetration can be limited to a few centimetres. The technique may have application in imaging dry beach barrier structures that have not been buried by thick aeolian dune deposits.

2.8 Mapping through the regolith

Regional aeromagnetic surveys conducted at 400 metre line spacing and 80 metre flight height over much of the Gawler Craton–acquired jointly with companies through state government exploration initiatives SAEI and TEiSA–have substantially revised interpretations of basement tectonic models, structure and lithology. Magnetic data in combination with gravity and, to a much lesser extent, electrical geophysics have proven to be essential tools to see through regolith cover and to model the physical setting of mineralisation within basement rocks. The models have been applied across the Gawler to generate exploration targets and to plan drilling: particularly through deep cover. Selected examples and case histories on deposits and

prospects in South Australia, including several from the central Gawler Craton, are described in Dentith (2003).

In the Gawler region, airborne and surface geophysical methods rarely detect mineralisation directly. Iron ore deposits are the exception: where combined magnetic and gravity surveys have proved effective in mapping structure in BIF and in direct targeting of Fe ore (e.g. Morris *et al.* 1998; Bubner *et al.* 2003). Extensive hematite and magnetite alteration associated with hydrothermal activity are also mappable, and these are prime targets for possible IOCG-style mineralisation. Highly conductive regolith and saline groundwater create a difficult environment in which to delineate conductive sulphide bodies using electrical methods. Shear zones are often mappable as linear non-magnetic features because of destruction of magnetite by fluids preferentially channelled through these zones of high permeability (e.g. Parker 2003). They are also more deeply weathered and may show higher electrical conductivity than adjacent bedrock, owing to greater thickness of clay (Lane and Worrall 2002a). Undeformed Hiltaba Suite granite has a distinctive magnetic signature, and the association of granite and shear zones is mappable in regional magnetic data and are target for possible Proterozoic Au, Cu–Au and Pb–Zn mineralisation.

2.9 Mapping hydrothermal alteration

Spectral and magnetic techniques can be used to map mineral alteration associated with hydrothermal fluid activity in the central Gawler Craton. The current models for formation of Proterozoic Au deposits in the central Gawler Craton involve fluid circulation on regional and local scales driven by thermal gradients established during and after the Hiltaba Suite magmatic event. Gold from mafic magmas or leached from basement rocks was precipitated at chemical or physical traps in areas of high fluid flow, notably near the base of GRV and in nearby high permeability shear zones (Potma and Zhang 2006). Interaction of fluids with rock in the surrounding country resulted in a hydrothermal mineral assemblage that is characteristically zoned around Au mineralisation: intense sericite–pyrite alteration and quartz veining are proximal to Au mineralisation, and chlorite±epidote±hematite

distal to mineralisation (Drown 2003; Skirrow *et al.* 2004; Budd and Fraser 2004). Iron oxide content–mostly as hematite–is very low in the mineralised zone which appears as a de-magnetised zone that may be mappable in magnetic images (Skirrow *et al.* 2004; Fraser *et al.* 2007).

A close spatial relationship between Au distribution and zones of increased sericite (muscovite and phengite) content is evident in spectral logging of drill cores from the Barns Au prospect (Keeling *et al.* 2004; *Figure 40*). Within broad sericite alteration zones, Au trends towards the margins of

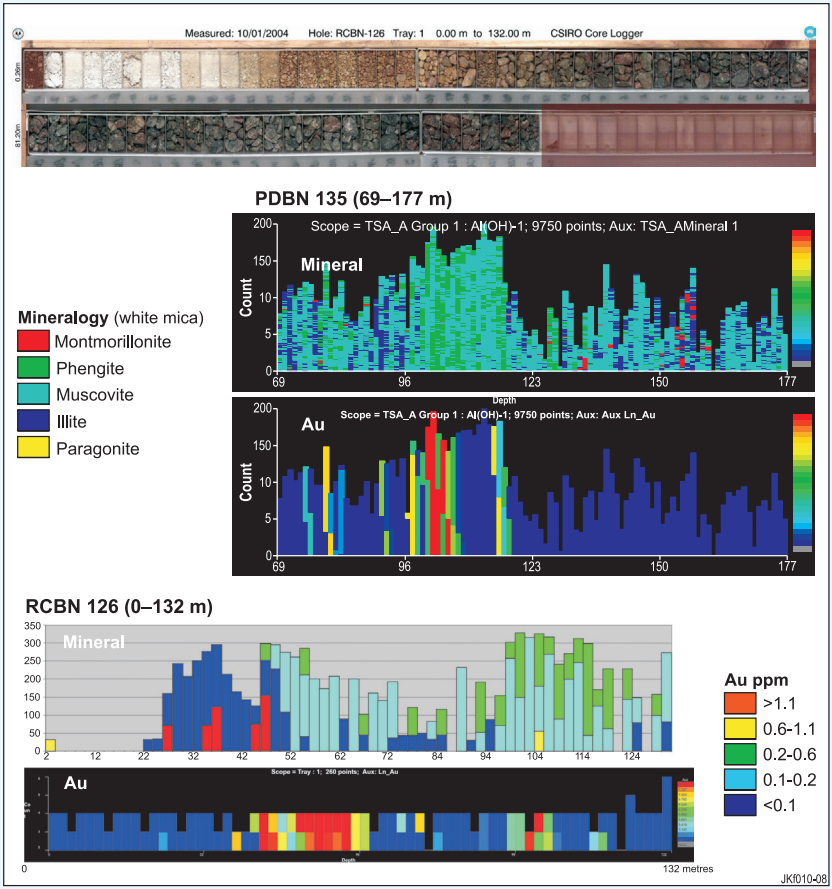


Figure 40. Spectral logs of mineralogy from paired diamond (PDBN 135) and reverse circulation (RCBN 126) drill holes from the Barns gold prospect showing increased Au content in areas of high muscovite–phengite in bedrock and at the base of high illite–muscovite in lower saprolite (from Keeling et al. 2004).

the alteration and areas of higher phengite content. Comparison of paired holes (*Figure 40*), shows a second alteration zone in the lower saprolite identified by higher illite (weathered sericite) content. Here the associated Au distribution is modified by supergene mobilisation and concentration in the saprock.

Zones of strong sericite alteration in areas of exposed bedrock and saprolite can be mapped using airborne hyperspectral survey, as demonstrated over the Tarcoola Goldfield (Mauger *et al.* 2007). A zone of crystalline illite, crosscutting Paxton Granite, incorporates Au mineralisation defined by drilling on the western margin of the alteration along the Perseverance Fault trend (*Figure 41*). The area of historic Au production in fine-grained, carbonaceous and micaceous quartzite units of the Tarcoola Formation is also delineated on the spectral image by high 'crystalline' illite content. Although airborne hyperspectral surveys may be less effective where sediment cover and highly leached upper saprolite dominate, there are extensive areas around the margin of the GRV that are potentially suited to the technique. Available satellite spectral data (Hyperion, ASTER) do not have the spatial or spectral resolution to map the level of detail required, but are useful for assessing the suitability of an area for airborne spectral survey (Mauger *et al.* 2007).

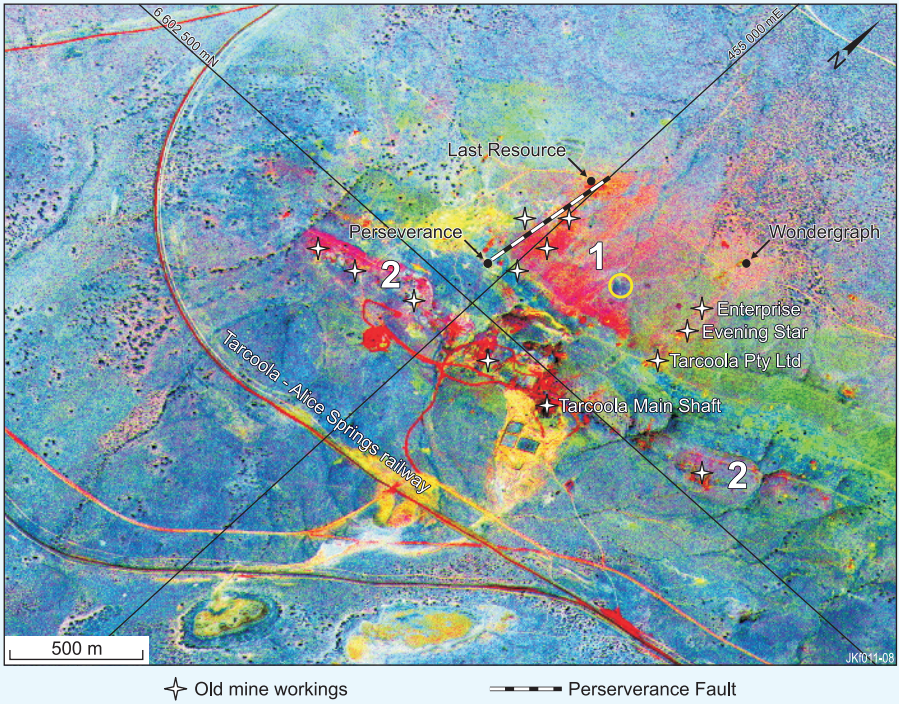


Figure 41. HyMap airborne spectral image over the Tarcoola Goldfield showing an area of sericite alteration (red) in Paxton Granite (Area 1) flanked by unaltered granite (yellow/green and green) and highlighting mica-rich units (Area 2) in Tarcoola Formation sedimentary rocks that preferentially host Au-bearing quartz veins (after Mauger et al. 2007). Note Perseverance Fault Trend (dashed white line) and selected historic Au workings concentrated along the margins of the alteration. Outcrop of Lady Jane diorite intrusion circled in yellow.

3. EXPLORATION CHALLENGES AND STRATEGIES

The central Gawler Craton includes some of the most prospective terrain in Australia, but exploration effort is only just beginning to be rewarded with mineral discovery and mine development. As more information is revealed about key characteristics of economic deposits in the region, the models for mineral exploration will evolve and further discoveries will follow. What will remain constant is the widespread regolith cover. The rush of new discoveries in shallow bedrock, and within the transported regolith cover, is testament to those companies who have had the confidence to use the regolith as an exploration tool. It is reasonable to expect that further shallow deposits remain to be discovered, and techniques will continue to be developed to target deposits at greater depths.

The regolith cover across the central Gawler Craton has encouraged a mineral-systems-model approach to exploration in the region. Components of the model include the primary source of the target elements, how and where these are mobilised, and trap sites that can concentrate elements to form an ore body. The emphasis in mineral exploration is often on identifying trap sites. When selecting areas for exploration, it is as important to consider source and mobilisation, because these factors underlie the fertility of a region and the potential to develop ore bodies. Various models have been proposed for different styles of mineralisation known from the central Gawler Craton (Daly and Conor 2006). Brief summaries of some of these are given in Section 1.4. Other models will be applicable based on the tectonic, stratigraphic, structural, metamorphic and weathering history of the region.

3.1 Key questions

Key questions for mineral exploration in the central Gawler Craton include:

- Are the current mineralisation models the most applicable to the region?
- What additional data are needed to assess the fertility of the region for a particular commodity?
- What is the evidence for element mobilisation?
- What are the physical and chemical requirements for trapping or

concentrating elements to make ore grade?

- What techniques are available to identify potential traps?
- How do we identify and rank anomalous data?
- Can we refine anomalies to improve targeting?
- What are the most cost effective techniques to test anomalous sites?

Answers to these questions require the integration of studies on the basement geology, tectonic and structural setting, dynamics of fluid flow and associated chemical interactions, regolith processes, and the interrogation of regional datasets collected using various remote sensing, geophysical and geochemical techniques. In areas where fresh rock is not at the surface, regolith is the most accessible physical component to study and sample. Answers to questions of identifying traps, ranking anomalies and improving targeting may be found in case studies that detail the successful application of regolith sampling to locate near-surface bedrock mineralisation. In the central Gawler Craton, regolith studies can contribute to identifying aspects of the fluid plumbing system in basement rocks by discriminating between hydrothermal and supergene mineral alteration. For ore deposits within the regolith, such as sandstone-hosted U and heavy mineral sands, an understanding of landscape history and regolith architecture will help to provide answers to many of the key questions. These include developing the most appropriate mineral-system model, identifying source areas, clarifying mechanisms of mobilisation and concentration, and defining ore targets.

3.2 Integrating regolith knowledge and exploration programs

Regolith case studies and knowledge of regolith materials and processes provide additional geological tools to aid mineral exploration. In considering a mineral exploration strategy in the central Gawler Craton, some assessment is required of how the most accessible surface materials can assist in providing answers to key exploration questions.

Regolith sampling and geochemical investigations over the past decade in

areas of deeply weathered bedrock have led to modified sampling practices that have now been widely adopted by mineral explorers in the Gawler Craton: in particular, the use of pedogenic 'calcrete' as a sampling medium for Au exploration (Lintern 1997). Knowledge of weathering processes and element dispersion from near-surface mineralisation underpin strategies for sampling that take into account, for example, zones of element depletion in deeply weathered bedrock and landscape factors affecting dispersion. Knowledge of where in the soil profile–or in what soil medium–elements dispersed from an ore body may accumulate, can identify a preferred sampling and analytical approach. The objective is to improve the detection of elements of interest above background levels, especially when present at very low levels.

Mechanisms that can transport ions from sites of mineralisation upwards through substantial thicknesses of transported regolith are reviewed in Cameron *et al.* (2004) and Aspandiar *et al.* (2004). For many field situations, it is not clear which, if any, mechanisms may have operated in the past, or continue to operate. The factors that limit or facilitate the movement of ions are poorly understood. In arid environments, where the depth to the water table is tens of metres, deeply rooted vegetation and associated soil biota play a role in cycling elements through the unsaturated zone to the surface. Where the potential for evaporation is well in excess of precipitation, elements will accumulate in zones of high evaporation/transpiration. Although the details of regolith processes affecting element mobility in unsaturated profiles are uncertain, conceptual models based on observations such as those above can provide strategies for geochemical sampling in areas of cover. Current investigations into the controls on Au distribution in dune-sand cover at the Barns prospect in the central Gawler are helping to extend our knowledge in this area (Lintern 2007; Schmidt-Mumm and Reith 2007).

Regolith studies–supported by dating techniques–underpin landscape evolution models and assist with interpretation of past climate, eustacy and neotectonics. For example, the evolution of palaeodrainage and the development of coastal barriers during the Cenozoic directly influence models of source, mobilisation and entrapment of U in palaeochannel deposits, and heavy mineral source, transport and concentration in beach

placers. The distribution of primary ages of zircon grains in Eucla Basin placer deposits indicates a dominant source from the Musgrave Province (Reid and Hou 2006). We can deduce, therefore, that at the time of barrier dune development in the late Middle Eocene, sand input was largely via the central Eucla Basin palaeodrainage network and redistributed west to east by longshore drift, which is consistent with dominant westerly winds. The very high concentration of zircon in these placer deposits reflects both source and sorting, with further studies needed to clarify which is more significant.

Aspects of regolith mapping and sampling are integral to many current exploration activities in the central Gawler Province. The following sections summarise useful techniques and approaches based on case studies and company experience in the region, or from similar environments elsewhere in Australia.

3.3 Targeting mineral deposits within the regolith

Sandstone-hosted U in Cenozoic drainage channels and heavy mineral sands in Cenozoic coastal deposits are targets of active exploration within the regolith of the central Gawler region. Surface geochemical techniques have not been considered an effective strategy. Rather the focus has been on identifying the package of prospective sediments, and in reconstructing the depositional environment. This is followed by close-spaced drilling of selected targets to obtain samples for analysis to identify mineralisation or prospective zones within the sediment.

Much of the material in this section has been derived from Hou 2004; Hou and Mauger 2005; Hou *et al.* 2001b, 2003b, 2007b, 2008. Additional sources are given in the text.

Identifying targets

Initial assessment of an area for targets can be done at relatively low cost using available DEM, satellite data and regional compilations of the distribution of Cenozoic sediments. Combining topographic data with remotely-sensed imagery such as Landsat or night-time thermal infrared–as outlined in Section 2.7–can help to refine the possible distribution of sediments in

the area under investigation. Reconstruction of sediment distribution in two dimensions highlights potential targets. For instance, exploration for palaeochannel-hosted U deposits has focused on defining palaeochannels and changes in a channel's course resulting in a reduction of channel flow, accumulation of organic matter (reducing material) and build up of medium- to coarse-grained sediments (point bar and overbank deposits). Other targets include channel confluences that provide an opportunity for mixing fluids of different oxidation potential (Eh). Initial interpretations can be tested using geophysical techniques, such as gravity or EM, and targeted drilling to confirm the presence of sediments and to provide data on sediment fills.

For heavy mineral sands, individual strandlines may be identified from detailed topographic data, especially in combination with night-time thermal infrared imagery to assist with identifying areas of thick sand deposits. Preliminary reconstruction of the depositional environment in combination with models of heavy mineral trap sites provides targets for drill testing. Another approach has been to modify topographic data to remove the effects of post-Miocene uplift (Ruperto *et al.* 2006) and establish base levels for an early Cenozoic landscape. Effectively 'flooding' the modified dataset to different elevations can assist with visualising the impact of sea-level change on palaeo-shorelines. The objective is to identify heavy mineral traps, and the potential for extension or repetition of known deposits. Of particular interest is the effect of Miocene marine transgression/regression in reworking Eocene barriers: particularly at the southern end of the barrier dunes. In this area, younger strandlines, which are delineated in the topographic data, are clearly discordant with respect to the earlier Eocene barrier deposits (*Figure 42*).

Test drilling

Test drilling is required to confirm the presence of channel sediments or barrier sands, to provide samples and to test for mineralisation. Aircore drilling is preferred because it minimises sample contamination. Full-core drilling in unconsolidated sediments is often problematic. Triple-tube coring devices are effective. Sonic drilling techniques have also been used successfully to sample channel sands in the area (Hall 2008). Sufficient



Figure 42. Distribution of heavy mineral occurrences in Eocene beach barrier deposits and position of sea-level-high stands (after Hou and Warland 2005).

descriptive information needs to be collected to confirm or refine initial interpretations, and to continuously update the exploration model. Spectral logging of samples using PIMA, or a similar spectral analyser, has proved useful in providing a consistent independent means of classifying regolith samples and in identifying palaeo-surfaces for input into palaeochannel 3D reconstructions (*Figures 43, 44*). Samples need to be dry to give consistent results. Downhole geophysical logs (e.g. gamma, electrical and neutron) are now commonly used in U exploration to define stratigraphic parameters used to distinguish prospective host units. In the case of gamma and prompt fission neutron (PFN) tools, estimates of the grade of *in situ* U mineralisation can be made: given appropriate calibration and some knowledge of the radioactive minerals present. In combination with visual logging of cuttings, these data provide inputs for sedimentary facies analysis and reconstruction

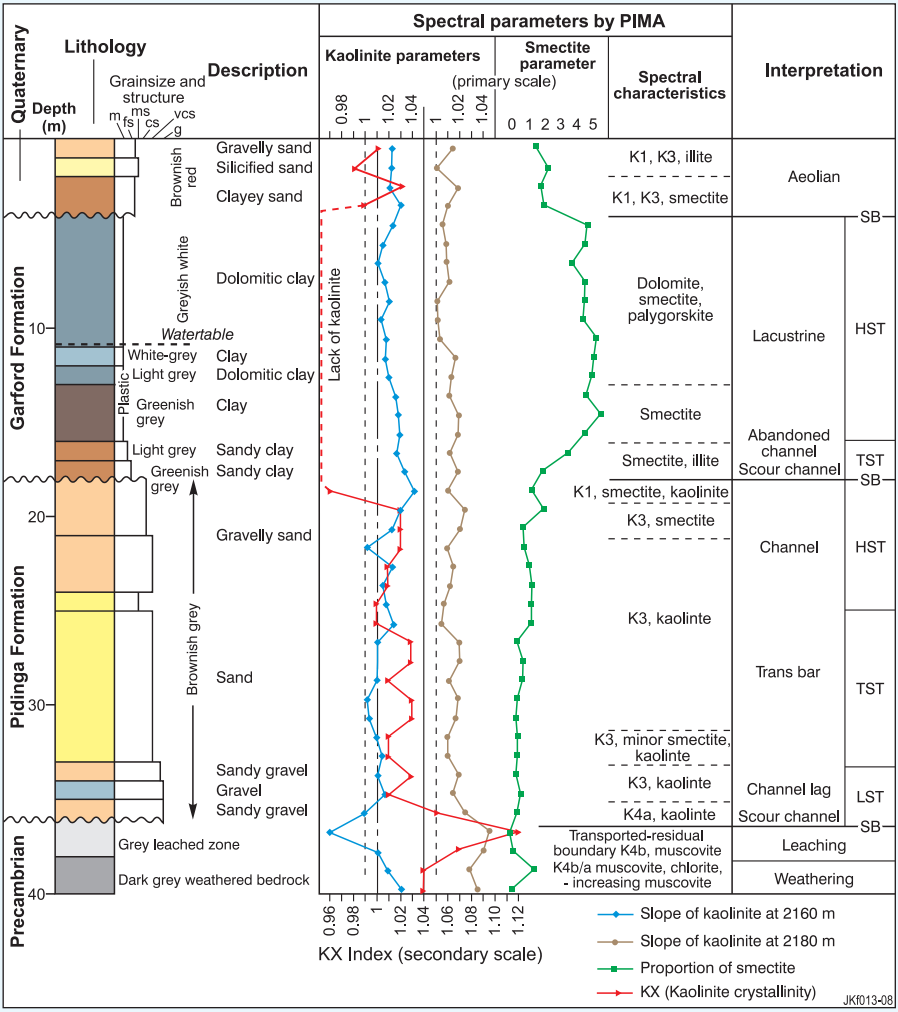


Figure 43. Logging techniques in Garford Palaeochannel sediment using IR spectral measurements for mineralogy and kaolin crystallinity KX (in red) to define unconformity with weathered basement (from Hou et al. 2001a).

of palaeochannel architecture to model the orientation and sedimentological constraints on mineralisation.

Sedimentological analysis

Sedimentological data and interpretation, when combined with other geological and geophysical information, can be used to provide a general

reconstruction of the palaeochannel architecture and history. Knowledge of the stratigraphy and landscape evolution of the area is needed in order to interpret the regional depositional, environmental and palaeographic framework (*Figure 44*). Sequence stratigraphic methods–together with knowledge of palaeoclimate and data on palynology, mineralogy, petrology and geochemistry of the sediments–are useful inputs for a fully integrated

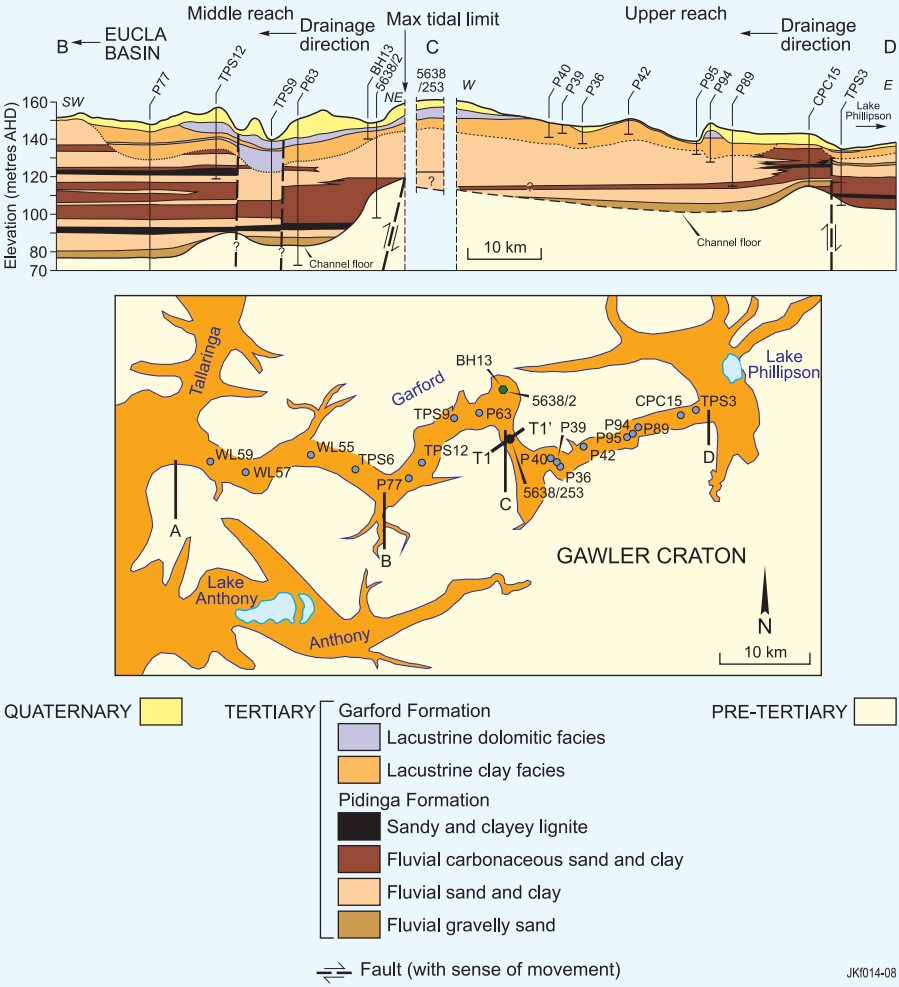


Figure 44. Longitudinal section through the middle and upper reaches of the Garford Palaeochannel system with lithofacies interpretation based on electromagnetic and drillhole data (from Hou et al. 2001a).

study of palaeodrainage in the Gawler region. This level of analysis is more likely to be justified once deposits have been identified and exploration focus shifts to establishing the extent of mineralisation and locating additional ore zones.

3D computer modelling

Where sufficient data are available, 3D visualisation models of the palaeo-valley landform and inset valley sediments can provide insights into the landscape evolution and controls on the dynamics of palaeo-rivers. Drill hole data and geophysics interpretation can be combined in GIS and viewed either as 3D plume diagrams (mapped onto surfaces) or as slices, such as the palaeochannel and palaeo-landscape, with exploded layers separating variously aged palaeo-surfaces (*Figure 45*).

3.4 Sampling the regolith

In geochemical surveys, the choice of sampling media can be a contentious issue and this will strongly influence analysis results. An understanding of local and regional regolith landforms, sample provenance and transport history will all assist in making an appropriate sample choice and meaningful interpretation of the geochemical data.

In general, calcrete sampling has proven to be a suitable regional geochemical strategy over much of the Gawler: particularly, but not exclusively, for Au. Anomalous sites can be refined with infill sampling using either calcrete or other sample media. Pedogenic calcrete in the central Gawler Craton is the product of externally derived aeolian carbonate added to the landscape, mainly since Late Miocene times. Calcrete requires semi-arid to arid conditions to develop. The element association with calcrete reflects dispersal and concentration in the soil mostly by evaporative processes during recent geological times.

In some other areas of Australia, ferruginous materials are preferred for regional and local surveys. Their use in the central Gawler Craton is problematic because of the general paucity of this material. Also, many of the ferruginous gravel and granule lags in the region are derived from

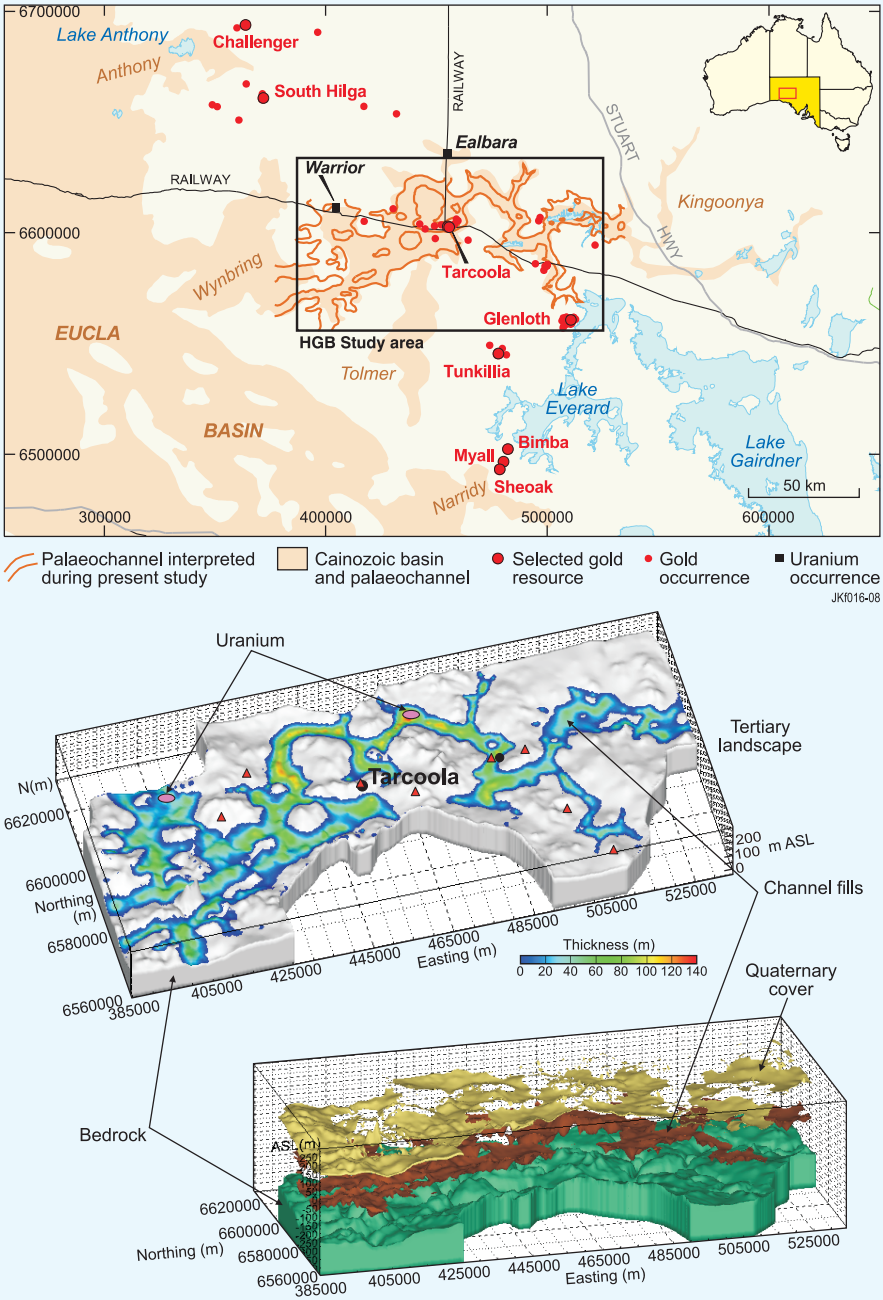


Figure 45. Visualisation of 3D modelling results of palaeolandscape evolution based on analysis of sediment fill in the Kingoonya Palaeochannel (from Hou 2004).

ferruginised sediment, rather than weathered bedrock, and unless sample provenance is known, interpretation of analytical data is problematic. Trace element concentration in ferruginous and calcareous materials reflects very different patterns of element dispersion. Ferruginous materials, formed during bedrock weathering, can incorporate elements released by the weathering process.

Specific sample media are discussed below. Much of the material in this section has been derived from Butt 1992, 1997; Chen *et al.* 2002; Lintern 1997, 2004b, 2005, 2006; Lintern and Sheard 1998; Lintern *et al.* 2002, 2003, 2006b; McQueen 2008; Sheard 2007b; Sheard and Robertson 2004; Sheard *et al.* 2006. Additional sources are given in the text.

Calcrete

Calcrete became the dominant sample medium in southern Australia after the association of anomalous Au with pedogenic calcium carbonate over concealed mineralisation was demonstrated during the late 1980s. The use of calcrete sampling in South Australia resulted in discovery of the Challenger gold deposit in early 1995, and renewed exploration for Au over much of the Gawler Craton (Edgecombe 1997).

After nearly two decades of use, calcrete sampling continues to be an effective exploration tool for Au and Cu and possibly other elements (Ag, Ni, Zn and Pb). Calcrete sampling is useful for both regional surveys and follow-up definition of prospect-scale anomalies to define drill targets (see *Appendix A5*, on CD; McQueen *et al.* 1999). Sampling experience has demonstrated that calcrete morphology is probably irrelevant in regard to sample utility (i.e. powdery, nodular or indurated coatings are all effective). Also, the amount of carbonate in the sample is less important than using the presence of carbonate to choose the sample depth. It is important, however, to maintain a consistent sampling position within the calcrete horizon because this will give more consistent analyses (typically, the calcrete top). The provenance of the host material is critical: especially *in situ* bedrock versus transported sediment cover. Geochemical analyses from different provenances typically have background and anomalous thresholds that can differ by an order of

magnitude or greater, and should be treated as separate datasets. Background values for both the target and pathfinder elements need to be established before deciding on what is truly anomalous for buried mineralisation. This will also determine detection limits to achieve maximum benefit. A threshold value of 10 ppb Au is commonly used for calcrete in weathered bedrock on the Gawler: requiring a detection limit of 1 or 0.3 ppb. Regional- and prospect-scale orientation surveys before large sampling programs are strongly recommended, and will assist in setting the parameters. Anomalous and background values from one area are not necessarily transferable to an adjacent or distal area without confirmation by orientation sampling.

Gold-in-calcrete anomalies can be offset from source mineralisation. Causes include lateral displacement through down-slope colluvial and fluvial processes and down-slope water movement through the regolith. A calcrete anomaly may be present in transported regolith and laterally displaced by hundreds to thousands of metres from the source of mineralisation. Whether or not calcrete sampling can detect mineralisation through more than 10m of transported cover has yet to be demonstrated. The role of deep rooted vegetation and burrowing invertebrates in transporting metal ions and mineral grains to the surface is the focus of current research projects. Preliminary interpretation of data suggests this mechanism may be significant through about 20 metres of transported cover sediment (Petts and Hill 2006; Reid *et al.* 2008).

Advantages of calcrete as a sampling medium are as follows:

- calcrete has a well-documented close association with Au in the weathered profile above Au mineralisation
- calcrete is ubiquitous throughout much of the Gawler Craton
- calcrete represents a consistent, easily identified sampling medium, generally corresponding to a soil B or an illuviated horizon, and is relatively easy to sample for exploration purposes
- calcrete sampling has a track record for Au discovery–including the first significant Au deposit (Challenger) in a new exploration province (Gawler, Archaean, Christie Domain) –and subsequently has led to further Au discoveries elsewhere in southern Australia and overseas.

Disadvantages of calcrete as a sample medium include the following:

- pedogenic calcretes represent absolute additions to soils. Where anomalous metal values are pre-existing in the soil, any addition of calcrete may cause dilution and depress anomaly contrast
- the high pH prevailing in calcrete reduces chemical mobility of many elements (but, significantly, not complexed Au and Ag) and hence restricts the development of epigenetic anomalies in the soil
- calcrete forms in various substrates, representing different ages, stages of development or climatic episodes that may have different levels of metal content. Calcrete in dunes can have threshold values one to two orders of magnitude lower than those developed in weathered basement (*Figure 29*)
- the presence of non-pedogenic carbonates (e.g. groundwater calcrete), which may be difficult to distinguish from pedogenic varieties, and do not typically have an Au association.

Calcretes commonly contain mesoscopic fragments of saprolite, hardpan, silcrete, ferricrete and lags (*Figure 26*), which affect the overall chemical composition. It is therefore prudent to inspect the internal structure of calcrete and understand its provenance, as well as any localised or regional variability, to reliably interpret anomalous metal values. In general, the host material and any host-related trace element signatures are diluted by the added carbonate.

Karst is observed in massive calcretes and indicates the solubility of calcrete and any associated trace metals by infiltrating surface water. There may be many calcrete horizons present in arid-zone dunes. These overlie calcrete developed within underlying deposits. The level of trace elements in dune carbonate may be anomalous, but is generally one to two orders of magnitude lower than that within calcrete developed in underlying weathered bedrock.

The widespread adoption of calcrete sampling since the mid 1990s for Au exploration on the Gawler Craton has resulted in several hundred thousand samples being analysed. A compilation of the analytical results from some 165,000 calcrete samples contributed by 24 companies was distributed by PIRSA in 2005. The results were well received, but the choice and range of

elements analysed reflected the focus on Au. All samples were analysed for Au, and many for Cu, but relatively few for any other elements. The Gawler Craton Calcrete Reanalysis Project was initiated by PIRSA and Geoscience Australia using laboratory surplus samples released by exploration companies. Currently some 13,000 samples have been analysed in the project for 32 elements: Au, Cu Ni, U, V, As, Ag, Bi, Ca, Cd, Co, Cr, Fe, Ga, Mg, Mn, Mo, P, Pb, Pt, Sb, Se, Te, Th, Tl, W, Zn, Ce, La, Rb, K and Al (Fidler 2007). The data from this project are available for download from the PIRSA website at www.pir.sa.gov.au/minerals/geology/geological_provinces/gawler_craton/gawler_calcrete.

Soil

Soil can be an appropriate and convenient sampling medium where it overlies *in situ* regolith, shallow transported regolith or contains significant bedrock-derived components (via bioturbation or down-slope processes).

Most soils of the Gawler Craton region contain a variable aeolian content (< 5– > 65%) as fines (silt-size dust) or sand-size fraction. These dilute locally derived soil components: the coarser fraction adds silica and alumino-silicate, while the dust fraction adds calcite ± gypsum ± kaolinite ± resistate minerals such as quartz, ilmenite and zircon.

Aeolian silt particles are about 70–80 microns in size, and minimising this fraction during sampling will reduce their influence on assay results. Sieving samples in the field to below 70 microns is, however, not always practical. Deeper sampling (> 300 mm), or sampling near the soil–saprolith/bedrock interface are other options, because the abundance of aeolian additions generally decreases with depth. The more than 100 micron fraction is generally enriched in lithic and ferruginous fragments and is an appropriate fraction for geochemical sampling, provided the target elements are hosted by those components. Generally, the fine fraction (< 75 microns) in near-surface soils (100–200 mm depth) has been effective in areas of the Gawler Craton.

Clayey soils–away from dunefields and near retreating escarpments or eroding uplands, which can be gibber-clad–are primitive (poorly horizon

organised) and lithic-rich, where the lithic clasts usually reflect the locally eroding substrate (*in situ* or transported), and therefore can make a good bulk sample medium.

Lag

Surface and buried lags vary in distribution and presence (common to rare) over the Gawler Craton. Their presence is terrain dependent and lags indicate either a prevailing or palaeo-erosional regime (*Figure 24*). Lag sampling was a common exploration sampling practice before the introduction of calcrete sampling during the 1990s. In recent times, lag sampling has been reinstated as a supplementary geochemical exploration tool. Generally, the 3–15 mm fraction is used–particularly at the reconnaissance phase of exploration. In many situations, lag has a complex transport history and a highly variable mineralogy that can affect its usefulness. In some areas of the Gawler, resistate lags have originated from late Palaeozoic sediments that have undergone erosion. Where released, resistate lithics have been repeatedly reworked and incorporated into Mesozoic and Cenozoic cover units (*Figure 24A*). An understanding of lag provenance and transport history is essential before using any lag as a sample medium. Careful examination of lag morphology (size, degree of rounding or roughness, retention or loss of pisolith-granule cuticle, etc.), as well as its landscape and palaeo-landscape setting, give clues to transport history.

Bulk lag samples containing lithic and ferruginous fractions are most useful where they are locally derived from *in situ* regolith (*Figure 24D*). Selective sorting of lag into specific types or provenance can be a useful orientation refinement (*Figure 24C*) (see Povey 1999, Challenger gold deposit). Lag mapping can also provide useful patterns of distribution that trace back to areas of thinly covered, weathered basement subcrop. Micro lag (< 250 micron) or sand-sized particles accumulated on clayey substrate, generally contain a concentrate of dense resistate mineral grains and, in some settings, may also be a useful medium to sample for Au, for Cr, Ni and V over subcropping greenstones, and for elements hosted by rutile, ilmenite, cassiterite, spinel and tourmaline.

Siliceous materials

Pedogenic silcrete is widespread across the Gawler and affects both transported and *in situ* regolith (*Figure 22*). In erosional regimes, silcrete yields conspicuous gibber and pebble lag that may retain remnant-ore and trace-element signatures. Silcrete can entrap various resistate minerals, fabrics and textures (e.g. Au particles, graphite, ferruginous mottling and metamorphic foliation). Pedogenic silcrete might be used, where Au mineralisation subcrops, as a preferred sample medium to trace the source of Au in bedrock.

Red-brown hardpan is a widespread, but discontinuous, palaeosol on the Gawler. Where this unit is developed in colluvium that overlies or flanks subcropping *in situ* regolith, it has potential as a sampling medium because it may contain mechanically dispersed or hydromorphic Au readily traced back to source (Mahizhnan *et al.* 2005).

Ferruginous materials

Widespread ferruginous accumulations, such as those on the Yilgarn Craton, are rare on the Gawler. A ferruginous pedolith is present in some areas, but is typically thin (< 300 mm) and often partially truncated by erosion (*Figure 24D*). Other ferruginous horizons are interpreted as collapsed megamottle zones. The Fe oxides in these profiles formed in highly leached saprolite and generally have low trace element contents, and are not usually suitable for sampling. True gossans–developed from weathering of sulphide mineralisation–are also rarely encountered in the central Gawler Craton.

Bedrock/saprock/saprolite

Outcrops of fresh rock and saprock are very limited in the region, outside the area of GRV. When present, rock chips can be sampled from outcrop or bedrock exposed in costeans excavated in areas of thin regolith. Generally, bedrock has to be sampled by drilling through the *in situ* or transported regolith. Dispersion patterns are typically very limited in weakly weathered rock, or restricted to primary dispersion halos. Sampling fresh bedrock–usually by drilling–is obviously the main method for directly identifying

mineralisation. Supergene dispersion of metals provides a broader target, which is usually restricted to lower saprolite and saprock. In the Gawler Craton, this zone is invariably sampled by drilling and sampling strategies as discussed in Section 3.6. Upper saprolite and lower pedolith are more likely to be encountered at the surface. These are typically highly leached and any retained metals or pathfinder trace elements are most likely to be hosted in resistate minerals or ferruginous segregations. In these terrains, lag sampling is generally preferred.

Sediments

Palaeochannel deposits

Cenozoic palaeodrainage sediments are widespread in the region and are a conduit for groundwater. Saline, acidic water is commonly encountered in lower channel sands and is an effective carrier of U and other metals in solution, which can precipitate when there is a change in chemical conditions. The potential for local deposits of chemically precipitated U and Au is recognised in the region. The main challenges with using the chemistry of palaeochannel sediments to locate mineralisation in bedrock are determining what element levels are indicative of ore-grade mineralisation in bedrock, and being able to trace anomalous areas back to the source. The mineralogy and chemistry of detrital grains–in conjunction with palaeochannel mapping–may assist in locating source areas. The possibility of placer Au and diamond in channel sediments should not be overlooked (Hou *et al.* 2000). Kimberlite and lamprophyre intrusive rocks are known from the Gawler Craton. Testing channel sands for kimberlite indicator minerals–particularly in first and second order tributaries–may be effective in tracing back to a primary source. On Flinders Island, (south of the area) microdiamonds, chromite, pyrope garnet and picroilmenite have been recovered from young cover sediments on the island (Stoian and Cooper 2003). Kimberlite indicator minerals–predominantly chromite–are present in Late Miocene–Early Pliocene Garford Formation sandy clay, and kimberlitic chromite was identified in sediment recovered from the contact of the Garford Formation with underlying Late Eocene Pidinga Formation. The source has yet to be discovered.

Anomalous Au values in pedogenic calcrete within or overlying palaeodrainage sediments–at almost all scales of channel development–have largely proved to be a false indicator of Au mineralisation in buried bedrock below the anomaly. This is assumed to be due to either physical or hydromorphic mobilisation of Au and Au-in-carbonate from bedrock source areas to be deposited or precipitated along with carbonate in topographically low areas occupied by the palaeodrainage. A large, more than 15 kilometres long Au-in-calcrete anomaly (> 10 ppb) in channel sediment at Old Well, north of the Tunkillia Au prospect, is interpreted as hydromorphic or physical dispersion down slope from the Tunkillia prospect (Dart *et al.* 2007b). Silver (10– > 100 ppb) is reported to occur along with Au in pedogenic calcrete in palaeovalley sediment immediately north of the Barns Au prospect (Sheard 2007b).

Dunes

Aeolian dunes are ubiquitous over much of the central Gawler region. These have been largely ignored as a sample medium in preference to samples taken in the interdunal corridors (swales). In areas of broad sandplain or thick dune cover, samples have been taken in aeolian sediment without differentiating these from other sample media. This may have implications for interpretation of assay data as indicated in *Figure 29*. Dune deposits can host anomalous amounts of trace elements related to underlying mineralisation (particularly Au). An argument can be made therefore, for regolith carbonate sampling in dune deposits–provided assay results are interpreted separately from those for other sample media–because both background and anomalous trace elements levels in dune samples are generally lower (*Figure 46*).

Eocene coastal barrier dunes along the margin of the former marine Eucla Basin host heavy mineral sands, but have been largely excluded from sampling to detect basement mineralisation. Calcrete in swale sediments is the preferred geochemical sample medium. For heavy mineral sands, the full profile of the dune is normally sampled by reverse circulation drilling, with the presence of heavy minerals in samples estimated by panning. This provides the basis for sample selection for further analysis.

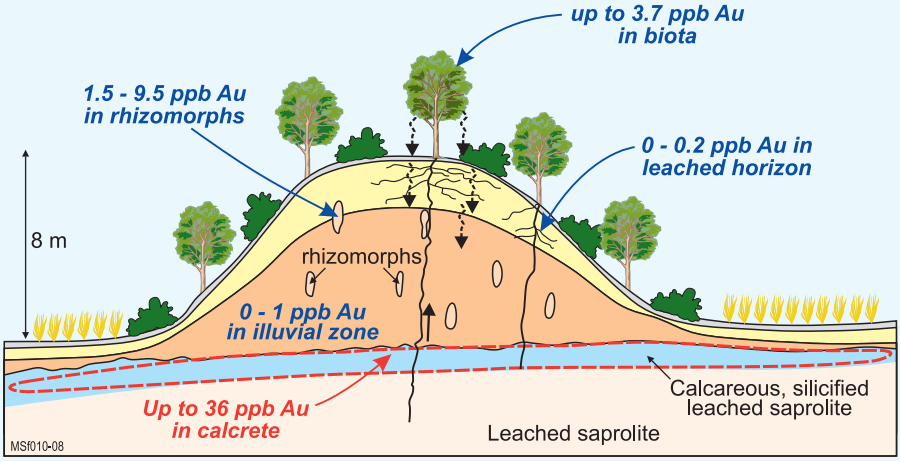


Figure 46. Barns gold prospect–model for vegetation cycling of Au and through sand dune cover and formation of anomalous Au in calcareous rhizomorphs within the sand dune (after Lintern 2007).

Calcarenite dunes close to the modern coastline may be tens of metres high and have not been considered as a potential sample medium for detecting mineralisation in underlying bedrock.

Marine sediment

Cretaceous marine sediments onlap basement rocks in the northern portion of the central Gawler Craton: notably Cadna-owie Formation, Bulldog Shale, Coorikiana Sandstone and Oodnadatta Formation (see Rogers and Zang 2006). These sediments are generally regarded as an effective barrier to geochemical signatures from underlying bedrock mineralisation. Surface sampling at Hawks Nest prospect for BIF-hosted Au and base metals reported thin (< 10 m) cover of Cretaceous sediments was sufficient to reduce levels of Ag, As, Au, Cu and Pb–in soils over mineralised ground–to that of background (Morris and Flintoft 1999). No geochemical signature was detected in surface samples over the Prominent Hill IOCG deposit with about 110 metres of sediment cover (Heithersay 2002). Similarly, Neoproterozoic and Cambrian sediments of the Stuart Shelf on the eastern margin and Cenozoic marine carbonate of the Eucla Basin to the south west are regarded as effective barriers to the development of any surface geochemical expression of mineralisation in the underlying crystalline basement.

Glaciogene sediment

Permian fluvio-glacial and periglacial deposits form substantial sedimentary piles within the late Palaeozoic Arckaringa Basin (0–250 m) including the Phillipson Trough (< 1,200 m), Wallira Trough (> 250 m) and Boorthanna Trough (< 1,000 m), and south in the isolated Mulgathing Trough (> 800 m), (Hibburt 1995; Rogers and Zang 2006). These sediments have not been reported as showing any geochemical evidence of underlying basement mineralisation. Trace element content and detritus reflect glaciated terrain distant from the site of deposition. For example, Devonian fish fossils in quartzite and brown cordierite-bearing volcanic porphyry pebbles (Rb-Sr age of 383±6 Ma) have source areas determined to be in the Lachlan Fold Belt (Cobar and south thereof) of New South Wales (NSW). These are a common feature of some Permian fluvio-glacials and Mesozoic reworked equivalents in South Australia (Alley and Gravestock 1995; Teale *et al.* 1995).

However, glaciogene deposits may still be useful to explorers. Permian coarse sands and gravels below diamictite beds in palaeo-valleys and troughs flanking the Mount Woods Inlier contain useful supplies of groundwater (4.5–45 kL/hr, with TDS ~7,800–11,000 mg/L at depths of 120–180 m; Belperio 2005).

Lacustrine deposits

Large dry salt lakes are present in the area including Lake Gairdner (the largest) and Lakes Everard, Harris and Acraman. The lakes mostly contain thin sediment cover on bedrock, with salt crusts at the surface. The soft sediments are difficult to traverse with heavy vehicles and have been excluded from recent exploration activity on account of their significance with respect to aboriginal heritage. Lake Gairdner overlies GRV and, from limited previous drilling, contains gypseous and saline sediments up to 18 metres thick (Callen and Benbow 1995).

Vegetation

The basic principle of analysing plants for mineral exploration (biogeochemistry) is that plant roots take in metals and trace elements from the

ground and transfer these within the plant. Geochemical variations between different geological substrates can provide different amounts of metals and trace elements for plants to take up, and therefore the plants growing over these substrates may have different biogeochemical compositions. In the simplest cases, substrates that contain more of particular elements are more likely to support plants that also contain more of these elements. In extreme cases, these substrates may include mineralisation that may then be reflected in elevated levels of key elements in plant organs. A biogeochemical program therefore exploits these interactions by taking samples of plant tissues and relating these to the underlying geological substrates in the search for mineral deposits.

Increasingly, mineral explorers are considering the advantages of taking plant samples in mineral exploration programs when trying to explore through transported cover. Some of the advantages of this technique include:

- widespread and, in some places, abundant plant cover across the landscape
- easy access to samples that in many cases are convenient to take
- an ability for plant roots to penetrate transported cover and transfer elements from depth to the surface
- the ability to selectively extract and concentrate some elements (e.g. hyper-accumulators)
- a potential ability to integrate a chemical signature from an enlarged and potentially heterogeneous substrate
- environmentally passive exploration approach, with minimal site disturbance and need for remediation
- some proven exploration success and expression of buried mineralisation.

The main vegetation communities in the central Gawler region include:

- Low open woodlands dominated by sugarwood (*Myoporum platycarpum*), western myall (*Acacia sowdenii*) and mulga (*Acacia aneura*). This is typically of mixed species composition in the

southeast, with mulga becoming more frequent towards the north. Mulga and localised occurrences of pearl bluebush (*Maireana sedifolia*) understorey have been the main plant species biogeochemically characterised from these communities (refer also to Robinson *et al.* 1988).

- Open mallee shrubland mostly comprising ridge fruited mallee (*Eucalyptus incrassata*), red mallee (*Eucalyptus socialis* and *Eucalyptus oleosa*), and yorrell (*Eucalyptus gracilis*). A mixed understorey with broom-bush (*Melaleuca uncinata*) and spinifex (*Triodia*) occurs on sandier dunes. *Callitris spp.* become a more frequent component to the south (e.g. *Callitris preissii*) and in the east (e.g. *Callitris glaucophylla*). Many of the mallee eucalypts (e.g. *Eucalyptus socialis* and *Eucalyptus incrassata*) and spinifex (*Triodia irritans*), and local occurrences of broom-bush (*Melaleuca uncinata*) and chenopod shrubland species in dune swales and dunefield margins have been biogeochemically characterised from this community (refer also to Robinson *et al.* 1988).
- Chenopod shrubland, with minimal tree cover, such as near the western shores of Lake Torrens, but also in many parts of the central Gawler region with black oak (*Casuarina pauper*), mulga and rosewood (*Alectryon oleifolius*) trees: particularly associated with calcareous soils, and around the margins of many of the ephemeral salt lakes. The main species that have been biogeochemically characterised from this community in the region include pearl bluebush (*Maireana sedifolia*), black oak (*Casuarina pauper*) and local occurrences of mulga and bluebush daisy (*Cratystylis conocephala*) (refer also to Robinson *et al.* 1988).

There have been several biogeochemical case studies in the region, but, outside these restricted study areas, the characterisation and understanding of the biogeochemistry of widespread and abundant plant species is poorly understood (Mayo and Hill 2005; Lintern 2004b, c, 2007; Lowrey and Hill 2006; Lowrey 2007). What emerges however, is that some of the mallee eucalypts (e.g. *Eucalyptus socialis, E. incrassata* and *E. concinna*), broom-bush (*Melaleuca uncinata*) and many of the species that colonise dune swales and erosional plains, such as pearl bluebush (*Maireana sedifolia*), black oak (*Casuarina pauper*) and bluebush daisy (*Cratystylis conocephala*),

have potential to be used in programs exploring through transported cover (*Figures 47 and 48*). In particular, the ability of plants to provide a penetrative geochemical expression allows more confident assessment of surface geochemical anomalies, such as Au-in-calcrete responses. Biogeochemistry can also be used to test for the geochemical 'fertility' of subsurface geophysical signatures, as well as providing a first-pass evaluation of the chemical expression of palaeodrainage and structurally extrapolated targets under cover. This exploration technique also has low environmental and cultural impact. Regolith-landform context, seasonality and species and plant organ differentiation appear to be major controls on plant biogeochemistry that need to be constrained if this approach is to be used successfully (see *Appendix A6* for further details on vegetation sampling and useful plant species in the central Gawler Craton).



Figure 47. Black oak (Casuarina pauper) in dune sand at the Tunkillia gold prospect.

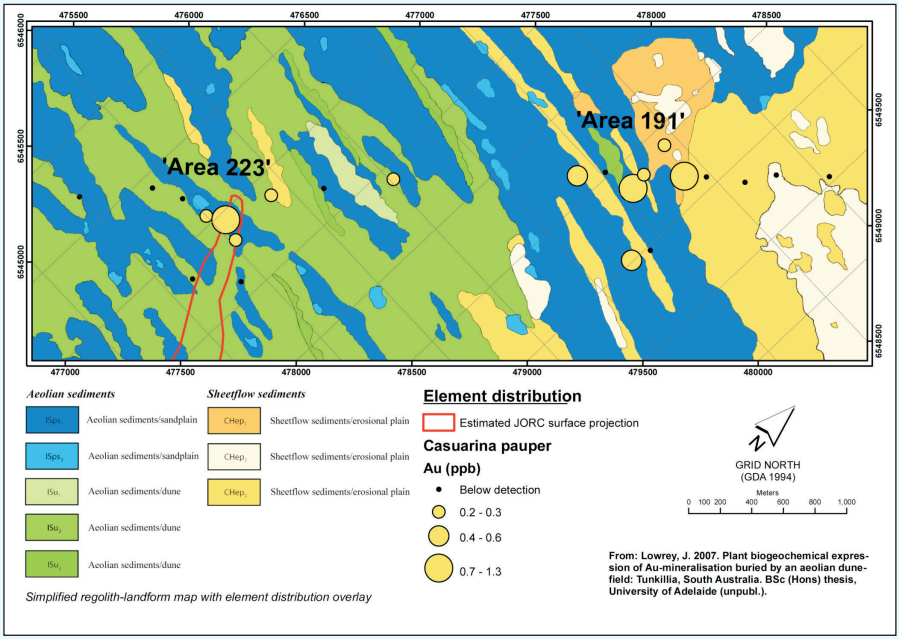


Figure 48. Tunkillia gold prospect–vegetation sampling results for Au in Casuarina pauper branchlets (from Lowrey 2007).

Groundwater

Groundwater in the central Gawler region is generally saline (> 10,000 mg/L) and at depths ranging from more than 100 metres in the north to more than 20 metres in the south. There are no permanent surface water resources in the region and the small local demand for stock water and mining operations is met from groundwater resources. Various hydrological domains are broadly identified, reflecting basin sediments or bedrock as the primary aquifer, with small localised hydrological features that include palaeodrainage channel sands, minor perched water in inland and coastal dunes, and shallow sands marginal to exposed bedrock (Dodds 1997a). High salinities and depth to the water table reflect low rainfall, high evaporation and limited recharge. Recharge is most likely during rare high rainfall events and in areas where ponding of run-off coincides with effective connection to aquifers or the water table. Groundwater data coverage is minimal and little is known about groundwater flow in the region, which is assumed to be overall towards the south.

Few hydrogeochemical surveys have been conducted in the region. Preliminary assessment of groundwater sampling for mineral exploration using water samples collected during 1979–80 from 266 bores across the state concluded that the technique had potential to identify areas of mineralisation in the southern Gawler Ranges (Morris 1982). A low-density geochemical survey across the Gawler Craton in 2005, in which 25 existing stock bores and wells were sampled, identified As as a potential pathfinder element for Au mineralisation (de Caritat *et al.* 2006). Water samples from 94 exploration drill holes in bedrock at the Tunkillia Au prospect reported an average salinity of around 35,000 mg/L and bimodal pH values centred on pH 4 and pH 6 (Gray and Pirlo 2005). The data indicate essentially 'ponded' groundwater in felsic rocks in which dissolved elements (Au, V, Te) show some correspondence with mineralisation. In bedrock areas, depth to groundwater, lack of background data and typically very low yields make hydrogeochemical surveys less attractive than alternative sample media. Techniques developed to sample and analyse groundwater for NiS exploration in the Yilgarn Craton (Gray and Noble 2007) may have relevance to greenfields exploration for Ni in the Harris Greenstone Belt.

Groundwater quality in Eocene palaeochannel sands is variable, but generally saline to very saline 5,000–70,000 mg/L, with an acidic pH < 4 to 6, high content of dissolved Fe and, in some areas, elevated radioactivity (Dodds 1997b). Saline and acid waters commonly have a high concentration of dissolved metals such as Fe, Cu, Zn, Pb, U and Ra. High Ra content in palaeochannel waters has implications for U exploration approaches that rely on gamma-ray or radon gas detection, because the radium responsible for radon gas may no longer be in equilibrium with U (Binks and Hooper 1984; Dickson and Giblin 2007). Direct measurement of U in solution is preferable, but, in acid and oxidising water, this reflects U solubility rather than proximity to ore. A high level of U of 12 mg/L was reported in groundwater from the Narlaby channel (Binks and Hooper 1984), but was not associated with economic mineralisation. According to Dickson and Giblin (2007), the full chemistry of groundwater–with major elements determined by ICP-AES and trace elements by ICP-MS–can readily model the stability of U in solution. When combined with analyses of Pb isotopes in solution,

they conclude that groundwater offers a powerful tool to identify regions of a palaeodrainage network where U precipitation is favoured, together with evidence of U accumulation.

3.5 Drilling, sampling and modelling

Drilling and drill hole sampling: diligence and cautions

Drill sampling of regolith is ideally done by coring (using diamond-bits or a hollow-flight tungsten tipped auger). The more commonly employed techniques in reconnaissance exploration are rotary air blast (RAB, with or without hammer assist), aircore and reverse circulation hammer (RC). Core, aircore and RC methods provide the least contaminated samples by minimising the potential for drill hole wall spall to add to the sample. Drill cuttings can provide only about 20% of the available regolith information of that obtained from drill cores, because of imprecise depth and destruction or reduction of useful features such as mottles, megamottles, staining patterns, layering/banding, subtle cementation variations, fragile texture components and growth structures.

For this reason, in an extensive RC, RAB, or aircore drilling program, it is advisable to include at least one triple-tube diamond drill hole through the regolith for each prospect. This will greatly facilitate interpretation of the more generalised 1 and 2 m sample intervals in the RC, RAB, or aircore drilling.

Possible contamination from one drill hole to the next–and between prospects–should be carefully monitored. Bottom-of-hole mineralised cuttings can remain within drill rig airway/mud plumbing, sample cyclone separator and/or drill rods, with the result that these bottom cuttings can contaminate the upper regolith samples of the next hole. The cyclone sample separator should be cleaned before each new hole by drilling a short (~2 m) 'clean-out' hole next to the new pegged site. This helps to minimise contamination.

Wear on drilling bits, as well as greases and lubricants used on drill rods, can introduce contamination to samples and may need to be monitored.

In particular, W auger bits often use Ag solder and bronze welds that can add Ag, Cu, Au, Sn and Zn. Patterns of element change that relate to more abrasive ground need to be reviewed with respect to bit wear. A check of metal additives to greases and lubricants will determine if these are likely to interfere with the element suite chosen for analysis (Mo and Cu are common additives to greases).

RAB drilling methods invariably induce downhole contamination of deeper samples, therefore sampling should include a field logging process to pick up obvious exotics or artefacts, and exclude these from assay samples, while also noting their presence to account for unusual results. Calcrete nodules have been observed in saprolitic drill spoil at intervals up to 30 metres below their source horizon; rounded fluvial pebbles have a similar tendency to be displaced downhole and contaminate deeper level samples (Lintern *et al.* 2002).

Making sure a drill hole reaches its targeted termination level (fresh rock preferred) is a drilling supervision task. Experience on the Gawler, and elsewhere, has demonstrated that the practice of drill hole termination at bit refusal or hard rock is often misleading, and may be well short of the intended target, because of indurated regolith, gravel and boulder beds. The presence of quartz veins with saprock and bedrock corestones within saprock (and occasionally within saprolite), can also mislead and result in terminating a drill hole prematurely. Drilling an additional metre or two to confirm the target lithotype, weathering and oxidation state should reduce this problem.

Sampling drilled materials during exploration may involve bulk sampling intervals for various assay purposes and budget control. In some cases, sampling has been restricted to a single sample from a particular depth within the regolith. Although these may be cost-effective strategies, they can yield misleading results if there are no other reference drill holes available. Regolith profiles have considerable variability in materials, and there is a heterogeneous uptake of dispersed elements into those materials. Therefore, it is useful to have single metre intervals assayed for one in ten, or one in fifteen, drill holes as controls. The control drill holes will provide a greater level of confidence to any profile sections and element contouring of

results. This type of reference (orientation) will indicate how the chemical composition of the regolith varies through the profile and assist with identifying the most appropriate sampling horizons and materials.

Another common cost-saving approach is to sample only specific target horizons, such as the base of transported cover. Early in an exploration program, it may not be clear which horizon is the best target and an overly prescriptive approach may lead to significant anomalies being missed. It is therefore advisable to sample and assay the entire drilled intersection, at least until the geochemical distribution patterns become clear. Even in well understood areas, it can be useful to assay all the contents of some drill holes: perhaps one in ten. Remember that the cost of drilling a hole is almost always much greater than the cost of analysing samples from that hole.

What to look for in drilled samples

Regolith features observable in drill cuttings will vary with material provenance (*in situ* versus transported), the degree of weathering and preservation. Well-developed *in situ* profiles typically display reddish, orange and yellow-brown colouration in an upper mottled zone, grading to white or cream in leached saprolite, while yellow-brown and orange zones appearing lower in the profile can indicate old redox fronts–generally related to palaeo or perched water tables. Goethite dominance is indicated by yellow and brown colours, while hematite dominance appears as purplish, red and pink shades. Mixtures typically result in different orange hues.

The transition from weathered rock to fresh rock is usually marked by a change from coloured to more neutral hues (e.g. from pale or moderate yellow, brown or orange hues to grey, green-grey, dark grey-brown or near black colours), commonly close to, or just below, the active redox front.

In drillcore, it is possible to see most of the detailed regolith components and their vertical distribution, but drillcore only represents its own width laterally. For drill cuttings–even where larger fragments are present–the level of regolith detail is much reduced. Regolith zonation may be indicated by colour, but this is not always a reliable identifier. Mineral assemblages, textures, fabrics, competency, intergrain cements and grain morphology are

more reliable indicators. Manganese oxides may present as black powdery coatings, fillings or dendrites. Massive goethite/hematite fillings can be dark brown or black, but show a yellow or brownish streak–as distinct from Mn oxides, which have a black streak.

Redox fronts are important chemical transition zones where species in solution may precipitate or be adsorbed, particularly if their solubility is strongly Eh (redox) dependent. Redox zones generally form above the weathering front and close to the water table, where elements are dispersed laterally by groundwater movement. They are commonly marked by ferruginisation, due to Fe^{2+} in solution oxidising to Fe^{3+} and precipitating ferrihydrite and insoluble goethite and/or hematite. These minerals adsorb or incorporate many trace elements used in geochemical exploration (particularly As, Ba, Bi, Cu, Pb, Sb and Zn). Where multiple redox or ferruginous zones are preserved, the one closest to the present weathering front will generally relate to the most recent dispersion. Upper and older redox fronts may have formed under quite different climatic regimes, with different dispersion characteristics and element associations.

Although ferruginisation and the location of potential redox boundaries can be estimated visually from colour changes, this is prone to error, because of the ability of small amounts of finely divided hematite to strongly colour clay-rich regolith. Spectral analysis (e.g. by PIMA or ASD AgriSpec) may give a more reliable estimate of the relative abundance of goethite–hematite. Assessment of the geochemical data can also help. A ferruginisation index based on Fe/Ti ratios (or alternatively Fe/Al) of regolith samples through the weathered profile can help locate redox zones. Aluminium and Ti are the least mobile of the major and minor elements during weathering, and provide a basis to compare total Fe variation. Typically, the least-weathered saprock samples plot at the centre of this range of values, with a trend to lower ratios where significant Fe^{2+} has been leached from saprolite; a trend to higher ratios occurs with ferruginisation (concentration as Fe^{3+}) (*Figure 49*).

In a single profile, an abrupt change from a negative (leaching) trend to a positive (ferruginisation) trend will typically mark the redox boundary: being reflected by Fe oxide/oxyhydroxide precipitation.

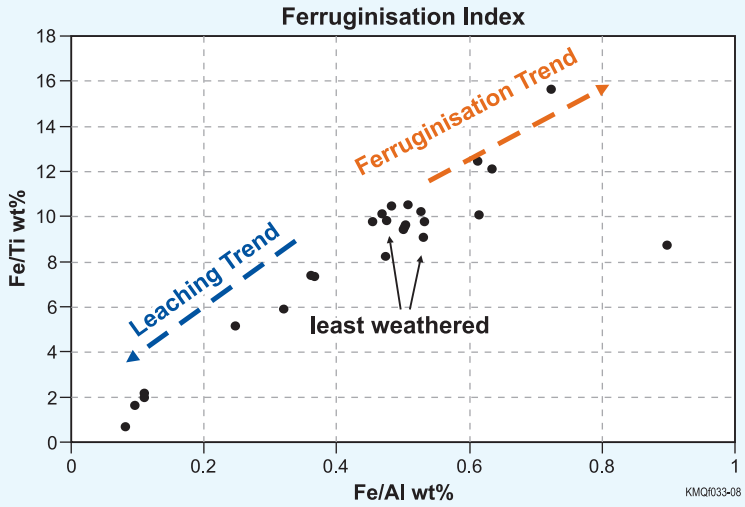


Figure 49. Plot of Fe/Al versus Fe/Ti for saprolite samples from four weathered profiles in the Cobar region, showing the different trends for iron leaching and ferruginisation (McQueen 2006).

Calcrete horizons within *in situ* and transported regolith mark another type of chemical transition (pH > 8.6), where evaporative accumulation of dissolved species and complexes has occurred. This is a zone where elements mobilised under acid to neutral pH conditions, may be strongly affected by the pH increase (e.g. Cu, Ni, Pb and Zn), and therefore precipitate. Dispersed carbonate can be difficult to see in powdered drill cuttings, but can be detected by testing with acid (10% HCl for calcite and 15% for dolomite).

In areas of transported cover, the unconformity between transported regolith and underlying *in situ* saprolith may retain quartz granules, lithic fragments and ferruginous lag derived from the underlying weathering profile. This is a sensible material to sample, because it will retain dispersed elements that may have been leached from the underlying saprolite. Ferruginous sediments from just above the base of the transported regolith may include detritus transported from mineralisation, or elements dispersed hydromorphically by groundwater flow (i.e. displaced anomalies).

Zones within *in situ* regolith with gossanous fragments and ferruginous quartz veins should be sampled because these may represent the remnants

of mineralisation not obvious at the surface owing to soil cover or burial by transported regolith. Shear zones–indicated by brecciated, veined and deformation fabrics in cuttings fragments or core sticks–should also be sampled because they may contain elements dispersed from related mineralisation.

Logging

As with geological logging, regolith logging should be systematic and consistent. Inconsistent regolith logs have been problematic in the past owing to poorly defined or highly subjective use of terminology and individualistic logging methods. To improve regolith logging LEME has provided a 'Regolith Glossary' (Eggleton, 2001), and has published a field guide on preferred approaches to describing and sampling regolith materials (Pain 2008). CRC LEME has also helped to develop objective regolith logging methods for high-throughput sample spectral loggers, i.e. HyLogger™ and HyChips™, as well as promoting the use of portable logging devices such as PIMA and ASD infrared spectral mineral analysers. Drill cuttings can also be checked with a magnetic susceptibility meter or a radiation scintillometer (these are quick and semi-quantitative ways to detect some non-visual variations in regolith and bedrock). Analysis by portable XRF can be useful for detecting variations in Fe content and high concentrations of some target and pathfinder elements.

Digital databases work best with quantitative descriptors (e.g. X% quartz rather than 'quartz-rich'). It is important to log and describe the regolith separately from the unweathered bedrock. Avoid mixing regolith and fresh rock terms. In addition, avoid the urge to interpret and describe the regolith as the weathering product of a particular parent rock type. Describe it as it is: any interpretation comes afterwards and forms a separate item.

Dry and washed cuttings should be laid out and described on site by the geologist as drilling proceeds. Samples of dry raw cuttings and a few washed chips should be kept as an archival reference (e.g. in plastic chip trays or in labelled plastic bottles). Ultimately, at prospect relinquishment stage or earlier, all, or a representative set of, samples should be offered for archiving

with the relevant state Geological Survey Drill-core Storage Facility, where more permanent housing will make sure those samples are available to future explorers and researchers.

It is useful to draw up rough drill sections in the field to help with correlation and recognition of distinctive regolith units. These can be refined later as more specific test and sample data become available. Entry of all this information into a digital database is an essential exploration management process and forward planning tool. Good visual, textural and spectral logs of regolith from all drill holes in a prospect are essential for developing 3D knowledge of the regolith and to identify consistent and appropriate sampling media.

2D and 3D interpretation of the regolith

Logged drill holes or outcrop profiles can be assigned regolith architectural zonation, provenance and a dominant weathered mineral assemblage, before preparing 2D or 3D representations. Preparation of regolith cross-sections, fence diagrams, landscape catena sections, stacked plan slices and block models all require well-established principles used in geology and geomorphology. An end product can be either factual or more diagrammatic: as the purpose dictates. Accidental or deliberate distortions can be misleading. All vertical exaggerations, distortions or approximations need to be noted. Regolith profiles usually require some vertical exaggeration factor (2– > 10 times) to adequately display zonal complexity or lateral variability. Exaggerated representations have not always been compiled correctly, especially where moderately angled boundaries and drill holes are involved (e.g. with a vertical exaggeration of ten times the horizontal, a true dip of 6º is represented by an exaggerated dip of ~45º; or for a 60º angular drill hole/boundary true dip, the exaggerated reference line becomes ~87º or is subvertical!). When compiling profile sections and block models involving vertical exaggeration, use appropriate dip conversion nomograms and cross-section construction principles (e.g. Rod 1974; Berkman 1995).

Regolith block models can be very instructive, especially when compiled using proprietary computer software, where free rotations of the model may display new or unexpected aspects. By incorporating additional data– such as digital terrain data, radiometrics, magnetics, thermal imagery, high

resolution seismic, geochemistry, mineralogy, alteration halos and standard colours (Munsell) –additional dimensional perspectives become available for interpretation (*Figures 38, 50, 51*–sites 1-12).

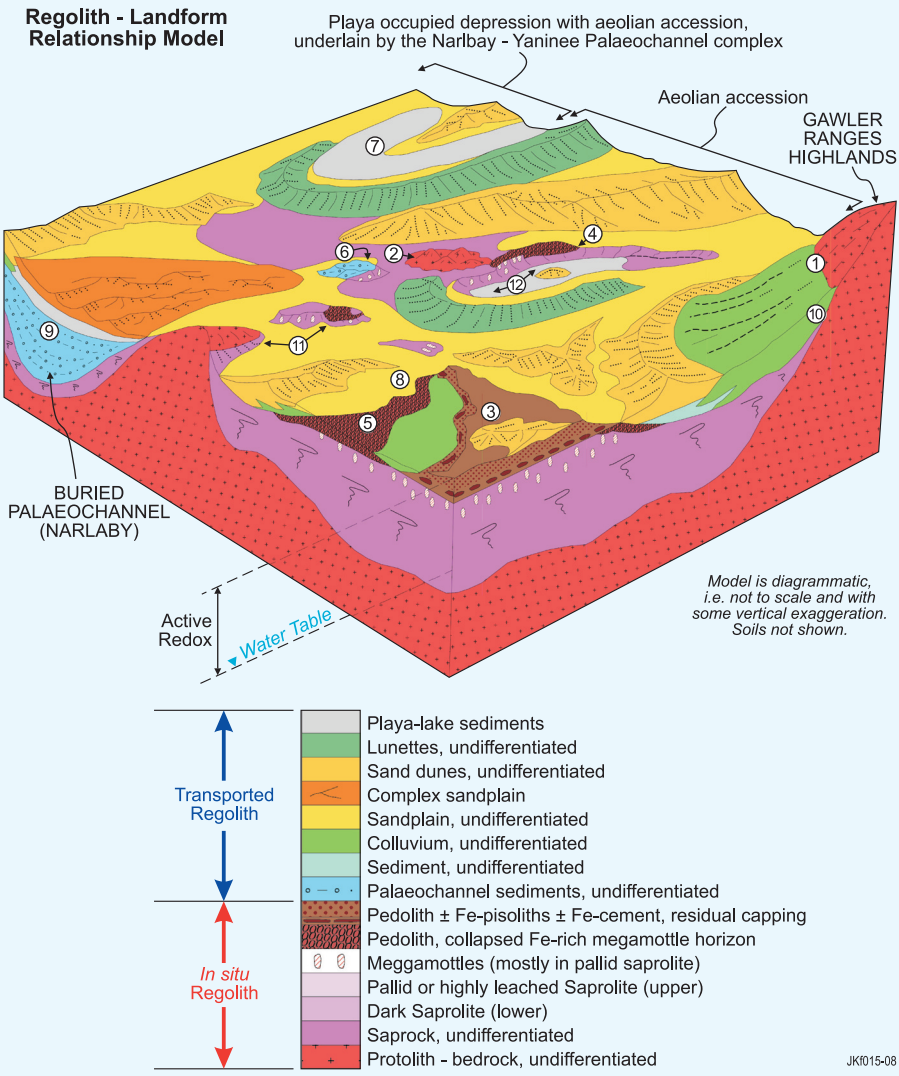
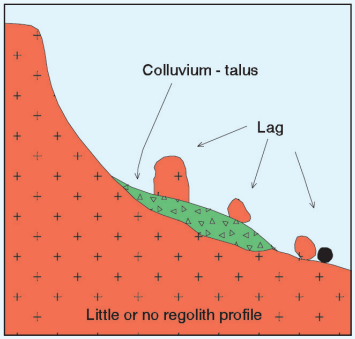
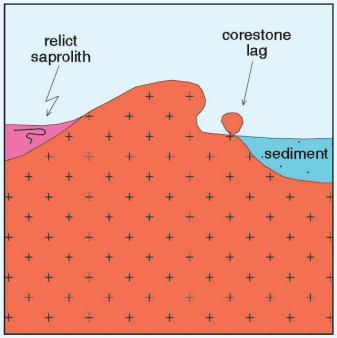


Figure 50. An example of a diagrammatic regolith-landform relationship model developed for the area surrounding the Barns and Baggy Green gold prospects, northwest Eyre Peninsula. A vertical exaggeration of about two to three times has been applied (Sheard 2007a, b). The numbers indicate the locations of the schematic regolith profiles in Figure 51.

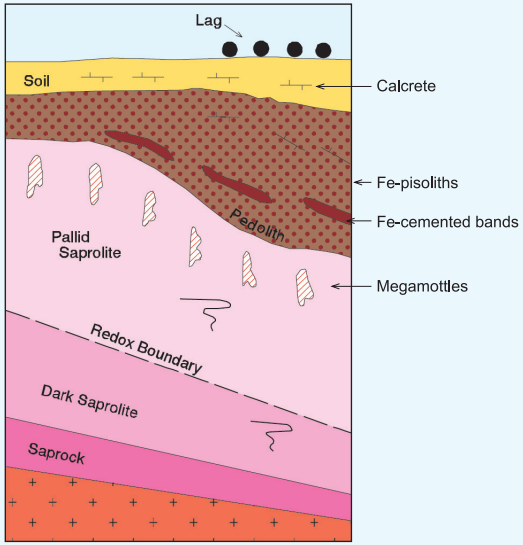
1. Outcrop, protolith-saprolith (mostly unweathered)



2. Exhumed outcrops: tors, whalebacks, etc., eroded out from weathered in situ profile



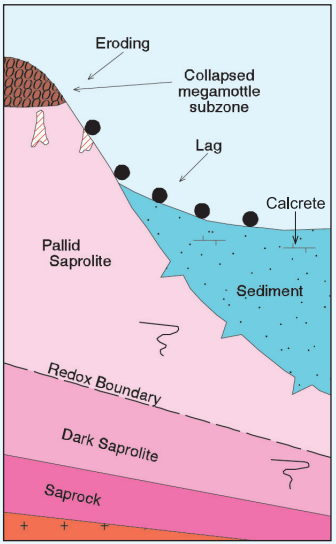
3. Uneroded residual weathering profile. Relict land surface



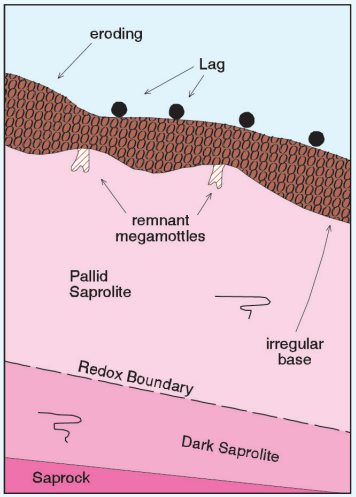
Suggested sampling media

Surface		
Rock chip	Rock chip	Calcrete, soil, lag
Talus + lag	Saprock + lag	Soil (B-C horizon)
Soil (B-C horizon)	Soil (B-C horizon)	Ferruginous pedolith
Drill		
Bedrock	Bedrock	Bedrock (? or saprock)

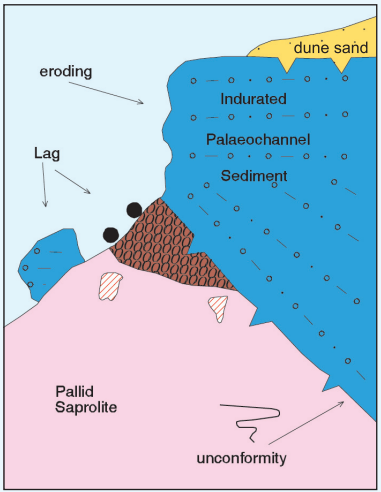
4. Truncated (eroding) weathering profile



5. Collapsed weathering *in situ* profile

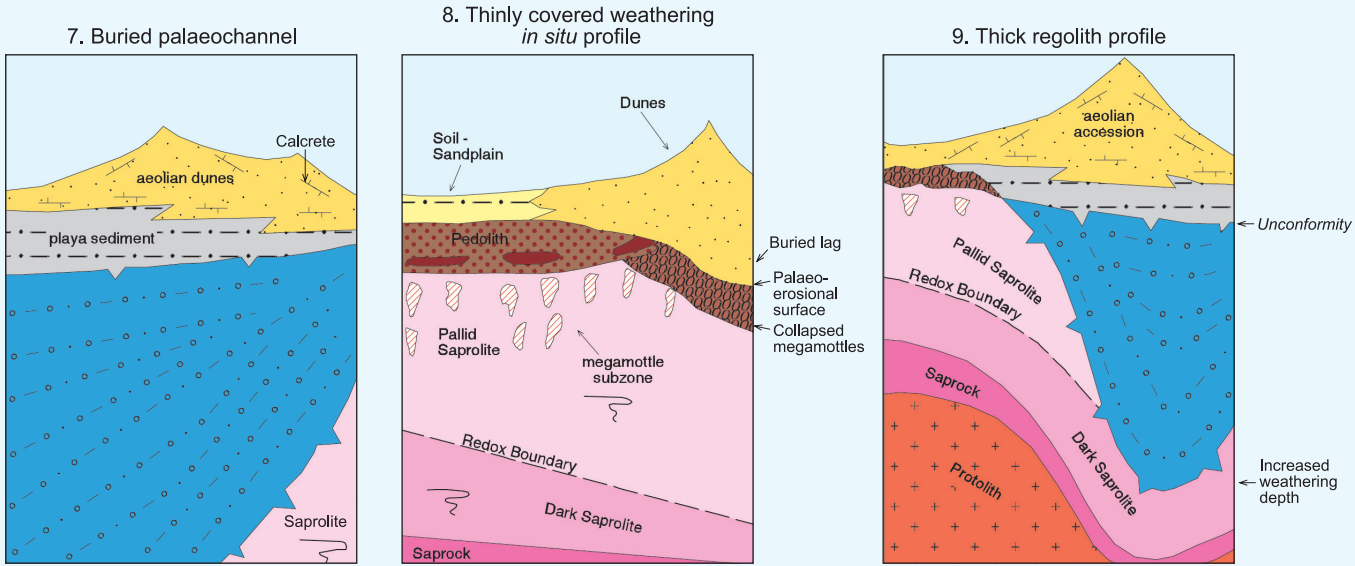


6. Inverted topography, remnant palaeochannel sediment on weathered *in situ* profile



Suggested sampling media

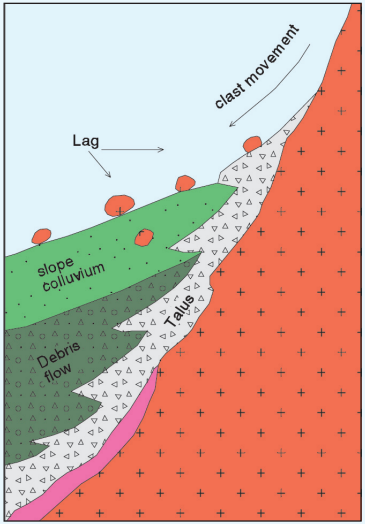
Surface		
Lag (local displaced anomaly)	Lag (local displaced anomaly)	Lag (regional displaced displaced anomaly)
Ferruginous pedolith	Ferruginous pedolith	Ferruginous pedolith
	Vegetation (local anomaly)	Vegetation (local anomaly)
Drill		
Bedrock (? or saprock)	Bedrock (? or saprock)	Bedrock, unconformity interface



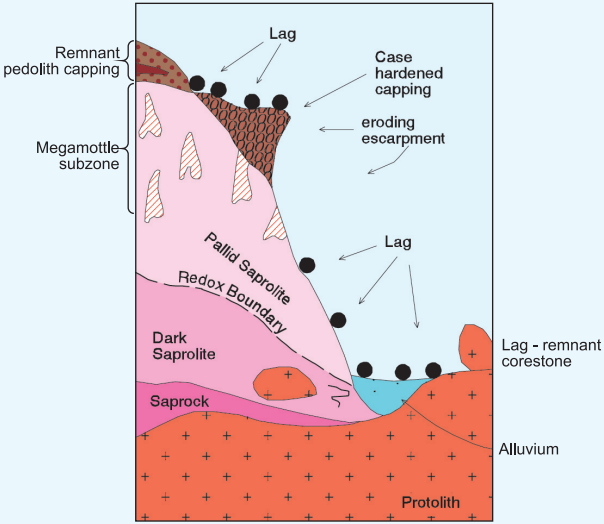
Suggested sampling media

Surface		
? Calcrete (regionally displaced anomaly)	Calcrete, soil	Calcrete, soil
	Ferruginous pedolith	Ferruginous pedolith
Vegetation (local anomaly)	Vegetation (local anomaly)	Vegetation (local anomaly)
Drill		
Bedrock (or saprock), Unconformity interface	Bedrock (or saprock)	Bedrock (or saprock), Unconformity interface (regionally displaced anomaly)

10. Colluvial regime



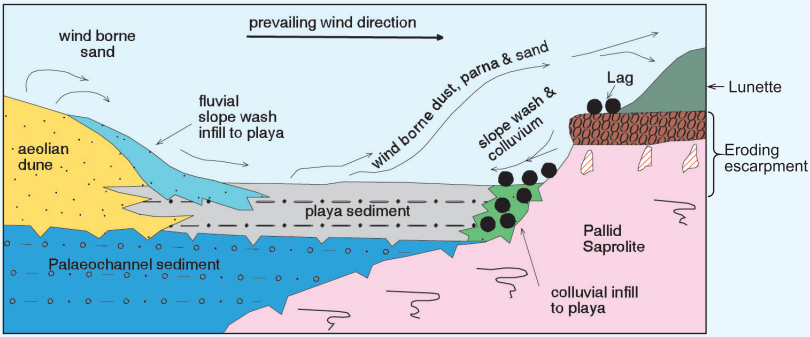
11. Eroding profile



Suggested sampling media

Surface	
Talus, lag, colluvium	Lag (locally displaced anomaly)
Rock chip, soil	Ferruginous pedolith
Vegetation (locally displaced anomaly)	Vegetation (locally displaced anomaly)
Drill	
Bedrock (? or saprock)	Bedrock (or saprock)

12. Depositional & deflational regimes



Suggested sampling media

Surface

- Lake sediment probably not suitable
- Lag, soil, colluvium
- Unconformity interface (displaced anomaly)
- Ferruginous pedolith

Drill

- Unconformity interface (displaced anomaly)
- Bedrock (or saprock)

Figure 51. An example set of regolith profile schematics constructed for the 12 numbered locations on Figure 50. Collectively these profiles portray regolith complexity (or simplicity), and individually display local variations for a relatively small area (~450 km^2, north of Wudinna). The effects of erosional truncation on residual profiles and/or profile burial are also evident. These can assist with appropriate sample media and depth selection, and with later interpretation of assay results (Sheard, 2007a, b).

3.6 Analytical approach and methods

Effective geochemical exploration for the various ore deposit types in the central Gawler Craton region should involve a multi-element approach: using a range of target and pathfinder elements. Analysing for selected major elements can help greatly with interpreting the geochemistry. A spatial association of anomalies for a number of key ore-related elements provides a more robust indicator of mineralisation than single element anomalies. This is particularly the case in the regolith, where some elements may be strongly depleted by weathering processes, or where anomalies are very subtle, or fall within the range of highly variable regolith-related background levels. The suite of target and pathfinder elements will depend on the known or expected element associations of the target deposit. For the Gawler Craton these would typically include Ag, As, Au, Cr, Cu, Ni, Pb, Zn, and U, with the variable inclusion of Cd, In, Mo, PGE, Rb, REE, S, Sb, Se, Sr, Th, Ti, V, W and Zr. Major/minor elements such as Al, Ca, Fe, K, Mg, Mn and Si can be used to monitor the main host components for trace elements in the regolith and help identify different regolith materials. If necessary, trace element data can be normalised for varying abundances of the hosting minerals; for example Fe and Mn oxides/oxyhydroxides or Ca and Mg for regolith carbonates, and S to check whether Ca may be present as gypsum. Major element data can also aid interpretation of profiles and guide consistency of sampling. Modern methods of analysis are suited to multi-element measurement at low cost, and the extra expense of analysing additional elements is usually far outweighed by the benefits of the additional knowledge. Ultimately, the practicalities come down to choice of an appropriate digest for key elements, preferred analytical technique and cost.

Regional studies in the Gawler Craton (Lintern 2004b) indicate that multi-acid or strong acid (*aqua-regia*) digest followed by analysis using inductively coupled plasma optical emission spectrometry and mass spectrometry (ICP-OES/MS) are good 'first pass' methods for geochemical exploration of the regolith. The multi-acid digest is often described as 'total', although this is far from the case for a wide range of refractory minerals such as chromite and zircon. *Aqua-regia* digest is preferred if Au and Ag are the

key targets. With this approach, the maximum information is obtained on the overall geochemistry of the regolith (particularly from drill profiles) at reasonable cost. ICP-OES analysis is used for major and minor elements because it gives a detection range that covers their typical abundances. Many trace elements (including target and pathfinder elements) have very low abundance,–particularly in strongly leached regolith–and ICP-MS is the preferred method because it has detection limits that are acceptably below these abundances for many elements.

Gold in the regolith is commonly present as elemental Au particles, with the particle size dependent on the primary mineralisation style and mechanisms of supergene dispersion and reprecipitation. Coarse primary Au tends to be unevenly distributed or 'nuggetty' in the regolith, whereas very fine-grained Au is more evenly distributed. Gold present in pedogenic calcrete tends to be very fine grained and evenly dispersed (Lintern 2004b). The particle size and degree of dispersion are factors that determine the most appropriate sampling medium, sample size, sampling method and analytical technique for exploration. For fine-grained evenly dispersed Au, a suitable assay method is an *aqua-regia* digest of small samples (30–50 g) followed by analysis using either ICP-MS or graphite furnace atomic absorption spectroscopy (GF AAS). Coarser 'nuggetty' Au will require larger samples (3–5 kg) and methods such as bulk cyanide leach (BLEG) or screened fire assay.

Partial leach methods may be useful where the element dispersion controls and regolith host sites are well understood (e.g. from an orientation study). These methods also have the advantage of lowering detection limits by excluding from solution the non-selected sample component. Generally, the lower the total dissolved solids in solution the more sensitive the analysis (e.g. by ICP-MS). On the other hand, if the regolith is poorly known, or highly variable in the way it hosts dispersed elements, anomalies may be missed or 'spotty'. Some selective leach methods are designed to extract the most recently mobilised and deposited trace elements that are loosely bound or hosted by particular amorphous phases: particularly in soils (e.g. Enzyme Leach, MMI and Regoleach). This approach tests for currently active dispersion patterns, but in some settings these may be very deep. Being less

robust, partial leach digestions require consistent laboratory handling and treatment.

Where total analysis data are required–for example, to assist with interpretation of parent rock type, or apply element ratio techniques to detect primary alteration patterns–analysis by X-ray fluorescence (XRF), instrumental neutron activation analysis (INAA) or sample fusion followed by ICP-OES/MS is recommended.

3.7 Quality assurance and quality control

Geochemical procedures and data should be critically assessed at all stages using well-understood quality controls. Aspects to consider are: sampling procedures, sample preparation, detection limits, analytical accuracy and precision.

The degree to which a sample can represent a larger volume from which it is extracted is a fundamental question. Sample size, its degree of mineral homogeneity, particle size and sample collection method are all important criteria to consider and monitor.

Contamination between samples can be a problem during RAB and percussion drilling. This can occur by abrasion of the drill hole walls (RAB), as well as sample residence time and mixing in the drill line (which can produce 'smearing' of high element values over apparently broader intervals). Reverse circulation (aircore and RC) avoids contamination from hole wall spalling, but there may still be some mixing of residual material in drill rods, circulation hoses and the cyclone collector. Additional sources of sample contamination during preparation or storage may come from using inappropriate metal riffle splitters, sieves, sample trays or containers, or may involve airborne dust in areas around operating mines and ore/mullock storage sites.

Bulk drill chips and pulverised cuttings can be sampled with a sample spear/pipe inserted across the whole volume (several times) or by splitting using a riffle splitter. Drill cores can be selectively halved or quartered, where representative portions are retained for later reference or additional testing. When combining samples from different intervals to make composites, it is

important to maintain equal sample size (weight).

It is important to avoid inadvertent sample contamination; this applies at primary, secondary and tertiary sampling stages. To achieve this, all metallic jewellery should be removed, and hands should be washed before sampling. This is a critical protocol where low detection limits will be applied (e.g. 1 ppb to ppt Au and Pt group elements, Ag and biota assays).

Assay quality control and repeatability can be achieved through use of strategically placed sample duplicates, replicates and standards (at every 20th or 30th sample in a batch). In this way, an assessment can be made of just how representative and effective the sampling procedure and assay precision are. Standards–matched as closely as possible to the expected sample matrix and element concentrations–provide an effective way to check on laboratory pre-assay preparation hygiene (contamination) and assay drift (within a batch or over time). Check the facilities and practices of commercial laboratories with an inspection visit. Most commercial laboratories carry out quality control using duplicates and their own internal reference standards, and will report the results, but it is advisable to include in-house standards and duplicates also. Analytical precision and accuracy should still be independently checked. For some elements (e.g. Au) it is good practice to cross check analyses using a different analytical method (e.g. *aqua-regia* digest with graphite furnace versus fire assay versus instrumental neutron activation).

3.8 Identifying anomalies

A geochemical anomaly is a feature geochemically different from that which is considered to be background for a particular site, prospect or region. Therefore identifying what is anomalous requires knowledge of, or a method for, defining the range of natural variation in both target and pathfinder elements (background range). Anomalism in element abundances is not defined by absolute values but by comparative values, and those will vary depending upon analytical method, sampling medium, regolith-landform setting, weathering history and parent rock types. Furthermore, there are no common background levels for all regolith materials across a region or sub-region, but there can be at prospect scale. It is critical to examine the

spatial distribution of element abundances and element associations for each prospect. Geochemical anomalies associated with mineralisation are spatial patterns as much as abundance patterns.

Orientation surveys and case studies that compare typical background materials and sites with materials from areas of known mineralisation can be used to establish thresholds. This approach assumes that all the natural variability is covered in the orientation survey. However, it may miss very subtle anomalies or those associated with a different or unknown style of mineralisation.

When data from a geochemical survey are received, their quality should be checked and some initial assessment made regarding the distribution pattern of element values, presence of outliers, and element correlations. This is referred to as exploratory data analysis (EDA) and commonly uses frequency plots, correlations matrices, bivariate scatter plots and, in some cases, cluster analysis or multivariate analysis to examine the data. EDA can indicate very obvious anomalies, the presence of multiple populations of data and likely element associations. Multiple populations may be indicated by distinct groupings in the frequency distribution of a dataset and, in some cases, these can be highlighted by careful assessment of transformed values (e.g. log transformed data versus probability is commonly used). The population of highest values may represent anomalies, but there may also be anomalies present in the upper values of other individual populations.

Groups of geochemical values that are statistically defined should always be examined in terms of their spatial (geographic and three dimensional) relationships and linked to their regolith and geological context. This can often clear up uncertainties about multiple populations and appropriate thresholds for defining anomalies.

Where there is a consistent background relationship between particular elements and specific regolith host minerals (e.g. As, Pb, Bi and Sb in hematite-rich lag), it is possible to construct templates showing the normal correlation of these elements with varying mineral or related major element abundance (e.g. Fe for hematite, Ca for calcrete). Outliers from the

template trends represent anomalies and can be identified, either visually or mathematically, and further investigated. An alternative approach is to subtract the regression values (i.e. related to the background correlation) and examine the residuals (for additional information on identifying anomalies see *Appendix A7*, on CD).

3.9 Concluding comments

Recent discovery of high-grade Au at Challenger and world-class zircon deposits at Jacinth and Ambrosia confirm the presence of significant shallow mineralisation, concealed by widespread regolith cover, on the central Gawler Craton. Although regolith cover impedes mineral exploration in the region, it is also an opportunity in that easily accessible deposits have remained hidden to earlier exploration. As mineralisation models are developed for the new discoveries, further deposits will be found. Extracting maximum information from the regolith and developing techniques to 'see' within and through the regolith are strategies that will improve the likelihood of exploration success. This Guide summarises aspects of the regolith for mineral exploration and provides an introduction to techniques likely to be effective in discovery in the region. Refinement of techniques will come with increased uptake and application, exploration demands and knowledge derived from development of deposits. In particular, mapping out the palaeodrainage in greater detail will highlight areas of shallow basement that are largely unexplored and where additional techniques are needed to detect mineralisation below the channel sediments. The discovery of economic U mineralisation in channel sands will escalate the demand for new data on the distribution of channel networks. Refinement of geochemical surveys in areas of widespread dune and sandplain cover will assist with rapid assessment of structures in bedrock: in particular, those structures identified from airborne geophysics as potential conduits for hydrothermal fluids. Airborne hyperspectral surveys can map aspects of hydrothermal alteration in saprolite/bedrock outcrop with the margins of the GRV being a prime exploration target. Improved models that relate alteration mineralogy to preferred sites of mineral deposition will develop from the mass of new data generated from routine spectral logging of drill hole samples and multi-element geochemistry. Landscape

evolution models and developing ideas on neotectonics underpin innovative approaches to exploring for minerals in the cover sediments. Integrating regolith knowledge with other aspects of mineral exploration approaches and techniques has proved to be an effective strategy–leading to new mineral discoveries in the region–and this will undoubtedly continue to be so for future exploration.

ACKNOWLEDGEMENTS

Regolith studies in the central Gawler Craton by participants in CRC LEME commenced in 1996 during the period of renewed exploration activity following discovery of the Challenger gold deposit through the use of calcrete sampling. Their work built on the legacy of earlier regional geological surveys and exploration that established the foundations for our understanding of the region. The information included in the Guide draws on contributions from many individuals. Those from whom specific advice or assistance was sought are acknowledged as follows: Neville Alley, Ravi Anand, Chris Anderson, Tony Belperio, Tim Birt, Robert Dart, Chris Drown, Martin Fairclough, Adrian Fabris, Garry Ferris, Roger Fidler, Larry Frakes, Georgina Gordon, George Gouthas, David Gray, Paul Heithersay, Peter Hill, Richard Hill, Steve Hore, Jack Lowrey, Alan Mauger, Geoff McConachy, Mark McGeough, Tony Poustie, Ian Robertson, Paul Rogers, Louisa Ruperto, Andreas Schmidt-Mumm, Michael Schwarz, Roger Skirrow, Matilda Thomas, Kevin Wills, Lisa Worrall and Wenlong Zang.

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GLOSSARY

Refer also to The Regolith Glossary (Eggleton 2001).

AAS = Atomic absorption spectroscopy: an assay method using sample acid digests aspirated into a standardised flame where spectral absorption is then analysed.

AEM = Airborne electromagnetic geophysical technique.

Aeolian = Transported and deposited by wind.

AHD = Australian height datum.

Aircore = A type of drilling used in reconnaissance drilling and sampling through regolith; similar to RAB but with an improved sample recovery system. Compressed air is blown down an outer annulus of the drill rods forcing cuttings and, in some cases, small sticks of core up the inner drill tube.

Anomaly = A deviation from common or normal experience. Geochemical anomalies are generally defined by elemental abundances outside a devised threshold value that is taken to represent background.

Aqua regia = Mixture of hydrochloric and nitric acids (usually $3HCl:1HNO_3$) used to provide a strong acid leach prior to multi-element analysis. Will dissolve Au, Ag and platinum group elements. It does not provide a total digest; resistate minerals and many silicates will not dissolve.

ASD (AgriSpec) = Portable spectroradiometer, manufactured by Analytical Spectral Devices, used for analysis of regolith and other materials.

BIF = Banded iron formation: chemically precipitated Fe-rich layers in Archaean or Proterozoic metasedimentary rocks, usually recrystallised to magnetite, and sometimes altered to hematite.

BLEG = Bulk leach extractable Au; a method for dissolving Au from large (5–10 kg) samples to overcome the 'nugget' effect, where Au occurs as irregularly dispersed particles. The sample is leached with cyanide over an extended period–usually in containers that are rolled or rotated and the Au extracted from solution onto activated charcoal before analysis.

Calcrete = General term for accumulations of carbonate in the regolith formed by precipitation from solution; there are a range of morphologies and the carbonate is commonly calcite or dolomite, and less commonly magnesite.

Catena = A sequence of soils (regolith) from hill top to valley floor: mostly derived from similar parent materials, but where the differences relate to landscape position.

Conceptual model = With reference to mineral deposits, refers to a visual representation–usually in 2D or 3D–of the components or processes involved in forming a particular style of mineral deposit.

CRC LEME = Cooperative Research Centre for Landscape Environments and Mineral Exploration. Head Office: Perth, Western Australia–web address: < www.crcleme.org.au>

DEM = Digital elevation model (analogous to DTM – digital terrain model).

Duplex = Soil profile dominated by the mineral fraction with a texture contrast of one and a half texture groups or greater between the A and B horizons.

Duricrust = Indurated regolith occurring at or near the surface; may consist of silcrete (silica cement), calcrete (calcium-magnesium carbonate), ferricrete (Fe oxide) or lateritic duricrust (Fe and Al oxides).

EM = Electromagnetic geophysical technique; used to penetrate regolith and rock to locate resistive and conductive zones.

Ferricrete = An indurated material formed by the *in situ* cementation of regolith by Fe oxyhydroxides: mainly goethite and/or hematite. The fabric, mineralogy and composition of the cemented materials may reflect those of the parent material.

Ferruginous = containing Fe; commonly used to describe regolith with obvious Fe oxides/oxyhydroxides (mainly hematite and goethite).

Gibber = Pebble or boulder that comprise the desert pavement, or lag gravels of an arid region.

GPR = Ground penetrating radar, a near surface profile exploration tool.

Grus = Fragmented disintegration product of coarse-grained igneous rock, especially granite.

GRV = Gawler Range Volcanics.

Gypcrete = Duricrust cemented mainly by gypsum.

ICP-AES = Inductively coupled plasma with atomic emission spectroscopy: an assay method using sample acid digests aspirated into a standardised plasma where resultant atomic emission spectra are analysed.

ICP-MS = Inductively coupled plasma mass spectrometry: an assay method using sample acid digests aspirated into a standardised plasma coupled to a mass spectrometer where atomic masses are separated out and abundances measured.

INAA = Instrumental neutron activation analysis: a laboratory assay method.

Induration = hardening of rock or regolith, commonly by an introduced cementing material.

In situ = In its original place.

ka = Kilo annum, a thousand years.

Karen = a form of karst development in limestone where solutions enlarge pre-existing joints, or form solution tubes and/or clay pots.

Lacustrine = Related to lakes.

Lateritic = Laterite or lateritic regolith that commonly has a hard, more or less prominent, ferruginous surface expression, with some degree of chemical and mineralogical differentiation below, characterised by varying colour reflecting varying Fe and silicate distribution. Laterite is a product of weathering. Laterite as a term may be controversial in that some definitions attach specific climatic conditions for formation.

Laterite profile = A vertical sequence of regolith facies showing some or all of the following, from the bottom up: bedrock, saprock, saprolite, plasmic zone, mottled zone, lateritic residuum, lateritic duricrust, lateritic gravel; refer to *Figure 8*.

Ma = Mega annum, million years.

Megamottle = A large mottle (see mottled zone); generally megamottles are > 200 mm across.

Mottle = Segregation of subdominant colour different from the surrounding region's colour. In regolith, mottles may have sharp, distinct or diffuse boundaries. Size range typically 10–100 mm.

Mottled zone = Part of a weathering profile showing mottles, commonly of concentrated coloured material such as Fe oxide/oxyhydroxide.

Nomogram = A graph or chart reducing a mathematical formula to curves so that its value can be read from the chart for any value assigned to the variables involved.

Pathfinder element = An element not necessarily of economic interest, but found associated with the other elements in ore such that it can be used to help locate the ore (e.g. As is commonly used as a pathfinder for Au deposits).

Ped = an individual, natural soil aggregate, smaller than clods and not the same as nodules or pisoliths (Northcote 1979).

Pedality = refers to the relative proportions of peds in the soil: Highly pedal has more than one third of the soil mass being pedal when moist; Weakly pedal has less than one third of the soil mass being pedal when moist; Non pedal has essentially no peds when moist (Northcote 1979).

Pedogenic = Pertaining to soil formation.

Pedogenesis = Soil formation.

Pedolith = Upper part of the regolith, above the pedoplasmation front, that has been subjected to soil-forming processes resulting in the loss of the fabric of the parent material and the development of new fabrics.

Pedoplasmation front = Boundary between the pedolith and saprolith–a transformation front at which the lithic fabric is destroyed, although commonly with little chemical reworking.

Phyllosilicates = Sheet silicate minerals such as those of the mica, clay, chlorite and serpentine groups.

PIMA = Portable infrared mineral analyser: measures the spectra (1300–2500 nm) of rock and mineral samples; useful for identifying phyllosilicates + some other minerals and mineral properties in regolith materials. Other devices such as the ASD FieldSpec or AgriSpec and the CSIRO HyLogger™ extend the spectral range to the near infrared (350–2500 nm); these are useful for identifying Fe oxides/oxyhydroxides.

Pisolith = A spherical or ellipsoidal clast resembling a pea, 2–64 mm in diameter; commonly ferruginous.

PGE = Platinum group of elements (Ir, Os, Rh, Ru, Pd and Pt).

Playa = Vegetation-free, flat area at the lowest part of an undrained desert basin, underlain by stratified clay, silt and sand, and commonly soluble salts; dry most of the time.

Porcellanite = silicified siltstone or claystone having the appearance of unglazed porcelain.

Potch = amorphous opaline silica that does not show the play of spectral colours associated with precious opal.

Pseudomorphic = replacement of pre-existing minerals or mineral aggregates by new minerals through alteration or weathering where the original outward shape of the former mineral species has been retained.

RAB = Rotary air blast: a type of open hole, generally shallow drilling, that is widely used in reconnaissance drilling and sampling through regolith. The drill uses a blade or hammer bit and compressed air pumped down the drill rods to return cuttings up the outside of the rods.

RC = Reverse circulation drilling: a type of rotary percussion drilling in which compressed air is pumped down an outer annulus of the drill rods to operate a down hole hammer bit and force the cuttings up an inner drill tube. This avoids abrasion of the sides of the hole, reducing sample contamination and helping to support the hole.

RED scheme = Scheme for mapping surface regolith in deeply weathered terrain based on modification of the weathered profile as either residual, erosional or depositional. A practical guide for geochemical sampling and interpretation.

Redox = Abbreviation for reduction–oxidation; a redox boundary in regolith marks the transition from relatively reducing (lower Eh) to relatively oxidising (higher Eh) conditions sufficient to cause Fe^{2+} to oxidise to Fe^{3+}.

REE = Rare earth elements, or the Lanthanide group: consisting of both light and heavy REE.

Regolith = Everything from fresh rock to fresh air, including particularly weathered rock, unconsolidated sediments, soil, organic material and groundwater.

Regolith-landform = A recognisable geomorphological feature; dune, swale, hill or mountain, escarpment (breakaway) or cliff, lake or playa, creek or river, valley, inselberg or whaleback, spring or seep, etc.

Regolith-landform unit = A land area characterised by similar landform and regolith attributes; it refers to an area of any size that can be isolated at the scale of mapping.

Residual = Left in its original place. Residual regolith results from the weathering of rock without significant lateral movement of the solid weathered products (= *in situ*).

Residuum = Specifically, that which is left after weathering.

Rillenkaren = a form of micro-karst development in limestone where solutions etch the surface in the direction of water flow to leave near parallel solution groves.

Saprock = Slightly weathered rock having less than 20% of the weatherable minerals altered; generally requires a hammer blow to break, and rock texture and fabric preserved.

Saprolite = Weathered bedrock with more than 20% of the weatherable minerals altered; collapses under a light blow, and rock fabric is preserved.

Saprolith = Saprock + saprolite. A major portion of the regolith developed by weathering that retains fabric of the parent rock and by implication has been essentially isovolumetric, pseudomorphic and *in situ*.

Seismic pumping = mechanism for transient movement of groundwater to lower or higher levels by dilation and compression of open fractures during episodes of seismic activity.

Silcrete = Strongly silicified, indurated regolith; generally of low permeability, commonly having a conchoidal fracture with a vitreous lustre. Silcrete forms by silica precipitation from solution; there are a range of morphologies. Pedogenic silcrete forms in the pedolith, groundwater silcrete forms below the water table at significant pH–Eh boundaries in porous sediment.

SRTM = Shuttle radar tomography mission, digital elevation model.

Swale = Linear, open depression excavated by wind, or left relict between sand ridges built up by wind.

TDS = Total dissolved solids: a measure of the soluble salt content in water.

TEM = Time-domain electromagnetic geophysical technique.

Titania = TiO_2

Topographic inversion = Where a feature formed low in the landscape is now high in the landscape because of its greater resistance to erosion than the surrounding materials.

XRF = X-ray fluorescence, a non destructive method for determining elements and their abundance in rocks and minerals.

GUIDE SUMMARY AND KEY

PART 1. INTRODUCTION (pp. 1–17)

Gawler Craton setting (pp. 1; Figures 1–6)

- Located in central and western South Australia.
- Low to moderate relief and undulating terrain, with extensive plains and sandy desert, low hills and ranges.
- Semi arid to arid climate: hot dry summer, cool winter with some rain.
- Sparse to moderate vegetation cover, on mainly pastoral leases and regional reserves.
- Limited infrastructure: Railways–Transcontinental and Adelaide-Darwin; Sealed Roads–Stuart and Eyre Highways; Towns/villages–Ceduna, Challenger, Coober Pedy, Glendambo, Kimba, Kyancutta, Streaky Bay, Tarcoola and Wudinna.

Geological framework and basement rocks (pp. 5–17; Figures 2, 7; Table 1)

- Archaean-Palaeoproterozoic basement (mostly high-grade metamorphic rocks, granitoid, felsic volcanics, greenstone and siliclastic) intruded by Mesoproterozoic granite and Neoproterozoic mafic dykes. The rocks were deformed during the Sleafordian and Kimban orogenies.
- Mesoproterozoic basement comprises Hiltaba Suite granite, GRV, mineralising systems and younger siliclastics. Basement rocks were in part deformed during the Kararan Orogeny, intruded by Neoproterozoic mafic dykes and overlain in part by Neoproterozoic–Cambrian Stuart Shelf sediments.
- Permian glaciation–post glacial sediments in part overlie crystalline basement and infill glacial valleys and troughs.
- Mesozoic: Triassic–Jurassic–deep weathering; Jurassic–deep weathering, erosion and terrigenous sedimentation; Cretaceous–terrigenous sedimentation and marine transgression.
- Cenozoic: Palaeogene–Australia–Antarctica break-up, uplift, erosion

and fluvial sedimentation, deep weathering; Neogene–drier climate, reduced fluvial sedimentation, deep weathering; Pleistocene–ice ages with associated windy and arid climate, aeolian, fluvial and lacustrine sedimentation, weathering and erosion.

- Ore deposit types and exploration targets (pp. 5–17; Table 1).
- Gawler Craton hosts Fe ore (BIF, magnetite, hematite), Fe-oxide–Cu–Au ± U (IOCG±U), Au and Pb–Zn deposits with potential for Ni sulphides in greenstone belts. Deposits of zircon-rich heavy mineral sands are present in palaeo-beach barriers and there is potential for sandstone-hosted U in palaeochannel sediments. Precious opal is mined from weathered Cretaceous sediments near Coober Pedy, and gypsum is extracted from recent chemical sediments near the coast.

PART 2. THE REGOLITH (pp. 19–81)

Aspects of regolith and landscape history relevant to exploration (pp. 19–27; Figures 3, 6, 8–12)

- Much of the Gawler Craton basement has been exposed to weathering since the late Permian (~250 Ma), with intense chemical weathering probably during early-mid Mesozoic times.
- Large rivers drained the Gawler bedrock in the early Cenozoic, transporting substantial quantities of sediment to the marine Eucla Basin. Extensive coastal barrier dunes formed along the southeastern margin of the Eucla Basin. The drainage networks gradually filled with sediment and lacustrine deposition was more widespread in the Miocene.
- Arid and windy conditions prevailed during Pleistocene glacial periods, with widespread development of sandy deserts.

Regolith architecture and typical profiles (pp. 27–29; Figures 13–18)

Regolith architecture in the region is a reflection of the combination of deep weathering, profile truncation, cementation and transported cover.

Landscape position and profile variability are illustrated to assist with field interpretation of regolith units and to indicate factors that may influence geochemical sampling strategies.

Regolith materials (pp. 29-49; Figures 4, 8, 10–12, 19–31; Table 2)

Regolith materials are conveniently grouped as, *in situ*, transported, indurated (duricrusts, pans and cements), lags and soils.

- *In situ* weathering profiles display a progression from fresh rock, to saprock, to saprolite, to pedolith–reflecting increasing alteration of the weatherable minerals from minor < 20% to > 80%. These profiles can exceed 80 metres in thickness.
- Across the Gawler region, leached upper saprolite is often exposed or overlain directly by soil or transported regolith due to *in situ* regolith profiles being truncated and the pedolith zone stripped or deeply eroded.
- Transported regolith is widespread and variable in character. It includes glaciogene, alluvial, lacustrine, aeolian and colluvial deposits. These are mostly less than 25 metres thick, but can exceed 100 metres in thickness in palaeochannels and glacial valleys.
- Indurated regolith includes siliceous, ferruginous, calcareous and gypseous cements. These mark intervals of landscape stability and may be present at various levels within the regolith.
- Surface lags of chemically resistant materials are widespread across the region. Lag is derived by erosion of various regolith materials and, in many cases, has been recycled and widely dispersed across the landscape. Provenance may be difficult to establish.
- Approximately nine soil groups, consisting of some 12 broad soil types, have been identified in the region. Most contain aeolian components as silt or sand fractions. Calcrete and gypcrete develop from aeolian inputs. Alkaline and sodic soils are common.

Regolith minerals (pp. 50–51; Table 3)

The common and widespread regolith-forming minerals of the Gawler

region include residual and secondary quartz, residual muscovite, kaolinite, illite, smectite, hematite, goethite, hyaline silica (opal), calcite, dolomite and gypsum. Maghemite occurs in some surface lag. The presence and relative abundances of these minerals vary with bedrock type, degree of weathering, regolith-landform setting, age and position within the weathering profile.

Regolith geochemistry (pp. 52–63; Figures 32–33, Table 4)

- Element dispersion controls include: variation in chemical conditions within the regolith, mainly redox potential (Eh) and hydrogen ion activity (pH); hydrological factors; availability of complexing and oxidising agents; temperature and evaporation; and physical processes causing mechanical dispersion. Lead and As can show limited hydromorphic dispersion within the weathering profile, while Cu and Zn may form a broad hydromorphic dispersion halo–generally fixed in goethite. At the surface, Pb and As (± Sb, Bi and Ba) may become strongly bound to hematite, which may be widely dispersed in colluvium, alluvium and soil. Significant pH boundaries, such as sediment cover/weathered bedrock interface and calcrete horizons, can precipitate or fix trace elements (e.g. Co, Cu, Ni, Zn, Pb and V). Biogeochemical processes play a role in element dispersion through the regolith.
- Weathering regimes: chemical conditions in the Gawler Craton regolith have changed significantly through time–particularly in response to climatic, hydrologic and biological changes. Under arid conditions, solubility and mobility of particular elements is affected–particularly for Au–whereas Pb, Ba and Hg remain relatively fixed as insoluble Cl^{-}, SO_4^{2-}, or CO_3^{2-}. Sulphide deposits undergoing weathering produce pH gradients that influence the broader dispersion of some elements (e.g. As, Cu and Zn).
- Examples of specific element dispersion features:
  Gold is mobile within the Gawler regolith. The form of primary Au influences how readily it is dispersed. Coarse Au and Au 'locked' within vein quartz remains relatively stable in the regolith, while Au with sulphides is generally more mobile.
  Silver is associated with many of the Gawler Craton mineralisation

types and it can be a useful pathfinder element, particularly for Au–Ag, Cu–Au–Ag, and Pb–Zn–Ag mineralisation. Dispersal of Ag from a source within the weathering zone is dependent upon groundwater salinity.

Copper dispersed from outcropping mineralisation usually gives subtle Cu anomalies in soil that are restricted in size. Sites with thin transported regolith (< 10 m) may show anomalous Cu in the upper transported regolith, soil and calcrete. Where the pH is high because of widespread calcrete, Cu is less widely dispersed and commonly precipitates as malachite or azurite.

Nickel–Chromium–Vanadium content in soil samples can be used to identify mafic or ultramafic bedrock in areas of thin transported cover (< 5 m).

Uranium and rare earth elements are commonly associated with basement rocks in the area. Oxidising and acidic conditions favour dispersion of U with precipitation at change in Eh and pH to reducing or neutral conditions. Uranium minerals will accumulate in channel sediments in areas of decomposed organic matter, sulphide and carbonaceous clay. The distribution of REEs in weathered bedrock and palaeochannel sediment is different, and may be used to distinguish bedrock from transported sediment.

Arsenic has proved to be an erratic pathfinder for Au in the Gawler Craton. Arsenic can be fixed in hematite-rich lag at the surface and may become widely dispersed by mechanical processes during erosion.

- Regolith element associations:

  Calcrete ($CaCO_3 \pm Mg$) is a widespread 'evaporative' pedogenic horizon on the Gawler Craton and a useful sampling medium for Au, Ag, Cu, Zn, Pb, Ni and V.

  Dune-hosted carbonate can contain anomalous (low order) Au, Ag and Cu where located above mineralisation.

  Ferruginous materials from weathered bedrock are not widespread on the Gawler Craton. Where present, they may incorporate Au and other trace elements (As, Bi, Cu, Sb, Se, Zn and W) and be a useful local surface geochemical sample particularly for Au/Cu and Pb/Zn mineralisation.

  Target elements and their respective pathfinder elements are

summarised from geochemical investigations in the Christie, Harris and Nuyts Domains of the Gawler Craton. **Geochemical characterisation of regolith materials** can be used to discriminate between regolith derived from different parent rocks or from similar materials at different stages of weathering. Spectral analysis of regolith samples provides useful mineralogical discriminators between clay saprolite and transported clays.

Mapping regolith (pp. 63-81; Figures 34-41)

- Mapping surface regolith. Regolith-landform maps show the surface distribution of regolith-landform units (i.e. land areas that have similar landform and regolith attributes at the scale of mapping). In the Gawler Craton, the RTMap system and RED scheme (modified) have been used to compile maps. RTMap scheme is descriptive and the RED scheme is interpretive. Regolith-landform map coverage of the central Gawler is limited to small, widely separated areas.
- Mapping regolith in 3D with emphasis on palaeodrainage and palaeo-coastal deposits. Sediments in Cenozoic drainage networks, estuarine and coastal barriers are potential hosts for U and heavy minerals. Digital elevation models, remotely-sensed Vis-IR spectral imagery and night-time thermal satellite imagery are useful regional mapping techniques, while geophysical methods (i.e. electromagnetic, gravity and seismic) can assist with defining sediment thickness and extent.
- Mapping through the regolith. Regional geophysical surveys over much of the Gawler Craton have substantially revised the interpretation of basement tectonic models, structure and lithology. Magnetic data, in combination with gravity and, to a lesser extent, electrical geophysics, have proved to be essential tools to 'see through' regolith cover. These can be used to model the physical parameters of basement rocks including magnetite/hematite alteration and demagnetisation along fractures that may be associated with mineralisation.
- Mapping hydrothermal alteration. Spectral and magnetic techniques can be used to map mineral alteration associated with hydrothermal fluid activity in the central Gawler Craton. An association between intensity of sericite alteration and Au distribution in Mesoproterozoic

Au occurrences of the CGGP is confirmed by spectral logging of drill core. Zones of strong sericite alteration in areas of exposed bedrock and saprolite can be mapped using airborne hyperspectral survey–as demonstrated over the Tarcoola Goldfield. Available satellite spectral data (Hyperion, ASTER) do not have the spatial or spectral resolution to map the level of detail required, but are useful in assessing the suitability of an area for airborne spectral survey.

PART 3. EXPLORATION CHALLENGES AND STRATEGIES (pp. 83–127)

A mineral-systems model approach to mineral exploration in the central Gawler Craton has been successful in targeting similar styles of mineralisation in areas of cover. The approach brings together those factors required to form a deposit based on known mineral systems in the region, and targets areas where many of the key factors appear to be present.

Key questions for exploration include (pp. 83–84)

- Are current mineralisation models the most applicable to the region?
- What additional data are needed to assess the fertility of the region for a particular commodity?
- What is the evidence for element mobilisation?
- What are the physical and chemical requirements for trapping or concentrating elements to make ore grade?
- What techniques are available to identify potential traps?
- How do we identify and rank anomalous data?
- Can we refine anomalies to improve targeting?
- What are the most cost effective techniques to test anomalous sites?

Integrating regolith knowledge and exploration programs (pp. 84–86)

- Regolith knowledge is simply another mineral exploration tool focused on surface materials, which are most accessible to sample and study.

- The factors that limit or facilitate the movement of ions through the unsaturated zone and cover sediments under arid conditions remain poorly understood. Regardless, regolith mineral associations have been identified that can be applied in effective geochemical sampling programs.
- In arid environments, where groundwater is tens of metres below the surface, deeply rooted vegetation and soil biota play a role in cycling elements through the unsaturated zone to the surface. When the potential for evaporation is well in excess of precipitation, elements accumulate in zones of high evaporation/transpiration.
- Regolith studies–supported by dating techniques–underpin landscape evolution models and assist with interpretation of past climate, eustacy and neotectonics. This information is fundamental to developing models for U and heavy mineral accumulation in the regolith.

Targeting mineral deposits within in the regolith (pp. 86–91; Figures 42–45)

Widespread palaeochannel sediments and extensive palaeo-coastal barrier systems are highly prospective for U and heavy minerals, respectively.

- Identifying targets at the reconnaissance stage of exploration can be done at relatively low cost by combining topographic data with remotely-sensed imagery such as Landsat or night-time thermal infrared. 2D reconstruction of sediment distribution will highlight potential targets. Geophysical techniques such as EM or gravity can refine the extent of sediments and indicate their thickness.
- Test drilling is required to confirm channel sediment or barrier sands, to refine and update exploration models and to collect samples for logging and analysis. Sample spectral logging has proved useful as a consistent independent technique for regolith logging. Downhole geophysical logs (e.g. gamma, electric and neutron) are now commonly used in U exploration to identify prospective host units and to estimate *in situ* U grade.
- Sedimentological analysis and interpretation–when combined with knowledge of local landscape evolution and geophysical information–

are useful tools in reconstruction of the palaeochannel architecture and history.

- 3D computer modelling is a powerful tool where sufficient data are available to input into 3D visualisation models of the palaeo-valley landform and sediment fills. Such models can provide insights into landscape evolution and controls on the dynamics of palaeo-rivers that influence target zones for mineralisation.

Sampling the regolith (pp. 91–108; Figures 22, 24, 26, 29, 46-48)

An understanding of local and regional regolith landform processes, sample provenance and transport history will assist in choice of sampling medium. Pedogenic calcrete is widespread in the region and is a preferred regional sampling medium reflecting an 'evaporative' concentration of elements. A lack of widespread ferruginous materials from bedrock weathering makes this medium problematic for regional surveys.

- Calcrete developed in *in situ* regolith and thin transported cover is useful for Au and other elements (e.g. Ag, Ni, Zn and Pb) at regional and local scale. Knowledge of the host material is important in determining threshold and anomalous values.
- Soils are useful in some areas of *in situ* regolith and thin transported regolith, where calcrete is absent or discontinuous. Soils may contain an appreciable aeolian component that can act as a variable dilutant.
- Lag distribution is uneven, and of variable mineralogy, and can have a complex history of formation and reworking. If the provenance is from local bedrock, then this can be a useful sample medium.
- Siliceous materials derived from pedogenic silcrete are widespread and more common than ferruginous materials. Silcrete can restrict dispersion of ore minerals in weathered bedrock outcrop and, in this situation, can be a useful sample medium. Groundwater silcrete is typically barren.
- Ferruginous materials are not abundant or widespread on the Gawler Craton but can be useful at the local scale for Au, Ag, Cr, Cu, Ni, Pb, V, and Zn where derived from nearby weathered bedrock.

- Bedrock/saprock/saprolite. Bedrock and saprock are generally poorly exposed in the region and are usually sampled by drilling to target mineralisation, primary dispersion halos or supergene dispersion. Saprolite is typically highly leached of trace metals, but ferruginous segregations and resistate minerals may preferentially retain metals or pathfinder trace elements and may be suitable for lag sampling.
- Sediments include Cenozoic palaeodrainage sediments, which are widespread in the region and are a conduit for groundwater and dissolved metals. They are prospective for chemically precipitated U and Au, with potential for placer Au and diamonds. Coarser fractions, or heavy mineral fractions, are most useful, although anomalous metal values in calcrete are usually displaced anomalies from nearby bedrock source areas. Dunes are widespread on *in situ* and transported regolith. Regolith carbonate accumulations in dunes may contain detectable metal signatures above mineralisation, but anomalies are likely to be one to two orders lower than in underlying saprolite. Eucla Basin coastal barrier dunes contain heavy minerals and are generally sampled by drilling. Marine sediments are extensive on the margins of the region and are typically barren, as are glaciogene sediments found mostly in the north of the region. Access to lacustrine sediments in dry salt lakes of Lakes Gairdner, Everard, Harris, and Acraman is restricted and sampling information is limited.
- Vegetation is potentially a useful sampling medium in areas of *in situ* and transported regolith (< 20 m thick). Preliminary surveys have identified regolith-landform context, seasonality, and species and plant organ differentiation as variables that need to be constrained to use this approach successfully. Sampling protocols are provided in *Appendix A6* (on CD).
- Groundwater in the region is generally saline and found at between 20 and more than 100 metres depth, with few water bores available across the region. The small number of hydrogeochemical surveys indicate that groundwater sampling is less attractive in bedrock areas than surface geochemistry and drilling. Groundwater in palaeodrainage sediments may be a suitable sampling medium to detect areas of U accumulation.

Drilling, sampling, modelling (pp. 108-120; Figures 38, 49-51)

- Drilling and drill hole sampling, diligence and cautions. Drill sampling should extend to the base of oxidation and ideally into fresh rock. Sampling the full regolith profile with analysis at 1 metre sample intervals in selected drill holes in a project area is usually required to establish the most appropriate regolith zone and materials to sample. At least one fully cored regolith profile is recommended for each prospect to assist and refine regolith interpretation. Practices need to be put in place to minimise possible drill sample contamination between holes. Potential drill contaminants from drill bits (W, Ag and Cu) and greases (Mo, Cu and S) need to be considered. Choice of regolith sample interval for analysis usually requires some orientation sampling. Be aware of hardness variation in regolith materials that may result in premature termination of drilling and influence interpretation of analytical results.
- What to look for in drilled samples. Regolith features observable in drill cuttings will vary with material provenance (*in situ* versus transported), degree of weathering and profile preservation. The transition from weathered rock to fresh rock is not always obvious from cuttings, but is usually marked by a change from pale or moderate yellow, brown or orange hues to grey, green-grey, dark grey-brown or near black colours. Spectral analysis (e.g. PIMA or ASD AgriSpec) may give a more reliable estimate of the relative abundance of regolith minerals and assist with identifying redox boundaries where trace elements can be concentrated. Calcrete within *in situ* and transported regolith mark evaporative horizons. Gold and other elements (e.g. Cu, Ni, Pb and Zn) can accumulate in this zone. Unconformities may also provide permeability barriers or contain lag materials that concentrate mobile elements.
- Logging. Regolith logging should be systematic and consistent. Information is available to assist with describing regolith materials. Dry and washed cuttings are ideally described on site as drilling proceeds. Representative subsamples of dry raw cuttings and washed chips should be retained for later reference. Entry of all logging information into a digital database is an essential exploration management process

and forward planning tool. Good visual, textural and spectral logs of regolith from all drill holes in a prospect are essential for developing 3D knowledge of the regolith.

- 2D and 3D interpretation of the regolith. Regolith cross-sections, fence diagrams, landscape catena sections, stacked plan slices and block models, should be constructed using well-established geological and geomorphological principles. All vertical exaggerations, distortions or approximations need to be noted. Incorporation of additional data–such as digital terrain data, radiometrics, magnetics, thermal imagery, high resolution seismic, geochemistry, mineralogy, alteration halos and standard colours (Munsell)–into a block model can provide additional dimensional perspectives for interpretation.

Analytical approach and methods (pp. 121–123)

- A multi-element approach is recommended using: Ag, As, Au, Cr, Cu, Ni, Pb, Zn, and U, with the variable inclusion of Cd, In, Mo, PGE, Rb, REE, S, Sb, Se, Sr, Th, Ti, V, W and Zr–depending on the target mineralisation.
- Major and minor elements (e.g. Al, Ca, Fe, K, Mg, Mn and Si) can be used to monitor the host for trace elements in the regolith and help to identify different regolith materials.
- Multi-acid or strong acid (aqua-regia) digest followed by analysis using ICP OES/MS are good 'first pass' methods for geochemical exploration over the Gawler Craton.
- Partial leach methods may be useful where the element dispersion controls and regolith host sites are well understood.
- Total analytical methods (e.g. XRF, INAA and fusion ICP OES/MS) are recommended to interpret parent rock type or detect primary alteration patterns.
- Some elements (e.g. Au and PGE) may require specific analytical techniques or sampling procedures.

Quality assurance and quality control (pp. 123–124)

- Aspects to consider for quality assessment and assurance include

sampling procedure, sample preparation, and analytical precision and accuracy.

- Duplicate or replicate samples from bulk samples can assess the reproducibility of the sampling procedure.
- Duplicate or replicate splits of prepared and homogenised samples from each sample batch can be used to assess analytical precision.
- Standard reference samples can be submitted for analysis to assess analytical accuracy.
- Some elements (e.g. Au and PGE) should be 'cross checked' using alternate sampling and analytical methods.

Identifying anomalies (pp. 124–126)

- Trace elements do not have a common background level for all regolith materials across the Gawler region.
- Orientation surveys and case studies that compare typical background materials and sites with materials from areas of known mineralisation can be used to establish thresholds.
- It is critical to examine the spatial distribution of element abundances and element associations.
- Exploratory data analysis (EDA) is a useful first step in understanding the distribution of analytical data and highlighting values for more detailed statistical and spatial analysis.
- Templates showing typical element variability for specific regolith materials can be used to identify anomalous outliers.

Illustrative field sites

- Selected regolith benchmarks– 33 sites from 16 case study summaries– are set out in Sheard (2008), which is included in the *Appendix A2* (on CD). These include consistent logs, suggested sample media, assay data and regolith landscape histories for sites across the Gawler Craton.

CRC LEME EXPLORERS' GUIDE SERIES

Objective: This series is about regolith; the layer of weathered material between fresh rock and fresh air that blankets much of Australia. More specifically, it is about using regolith indicators to help identify mineral deposits in regolith-dominated terrains.

Mineral exploration is unpredictable at best. Of the thousands of prospective sites evaluated each year only a very small percentage are promising enough to justify follow-up work, and of those only a handful will yield economically viable mineral deposits. Intelligent and informed exploration – incorporating a comprehensive understanding of regolith types and processes - shortens the odds in favour of the explorer and increases the chances of success.

The **central Gawler Craton Guide** highlights the latest regolith information and implications for mineral exploration in this most significant metallogenic province of South Australia.

The guide has three parts:

- An introduction to the setting, geology and exploration potential of the central Gawler Craton
- The regolith: including the landscape history, regolith features, geochemical and geophysical aspects
- Exploration challenges and strategies.

The guide also contains an easy reference guide summary and key. The accompanying CD includes a regolith benchmark atlas, to illustrate sites on the central Gawler Craton, and regolith mapping information. Sampling methods are also included in digital appendices on the accompanying CD.

The CRC LEME Explorer's Guides include:

A guide for mineral exploration through the regolith in the Cobar region, Lachlan Orogen New South Wales

A guide for mineral exploration through the regolith in the Curnamona Province, South Australia

A guide for mineral exploration through the regolith of the central Gawler Craton, South Australia

A guide for mineral exploration through and within the regolith in the southwestern Thomson Orogen, New South Wales

A guide for mineral exploration through the regolith in the Yilgarn Craton

A guide for mineral exploration through the regolith in the Tanami Desert region, North Australia

Series Editors: D Garnett, G Govett and L Worrall.