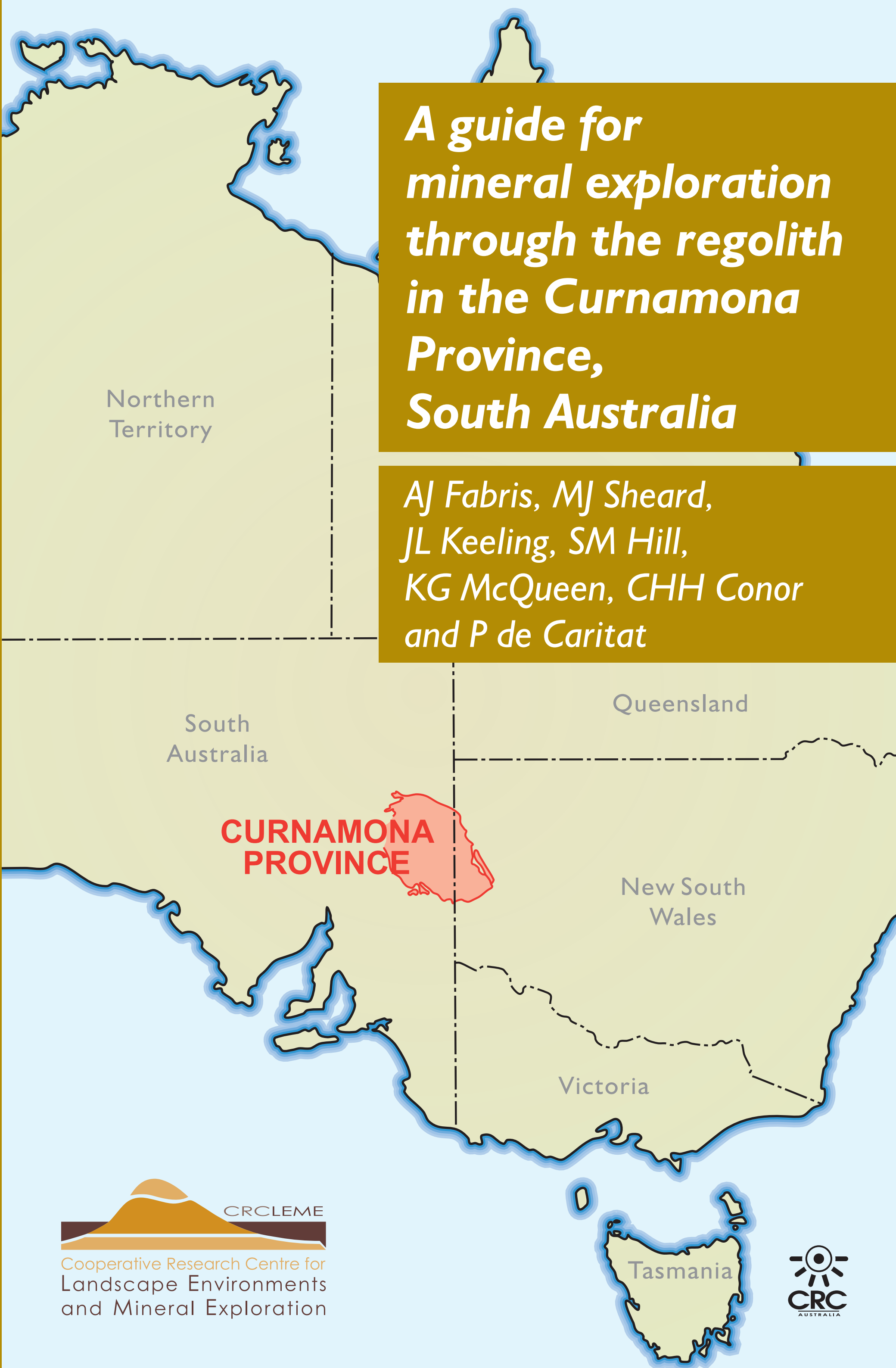
A guide for mineral exploration through the regolith in the Curnamona Province, South Australia

AJ Fabris, MJ Sheard, JL Keeling, SM Hill, KG McQueen, CHH Conor and P de Caritat



CRCLEME
Cooperative Research Centre for Landscape Environments and Mineral Exploration

A GUIDE FOR MINERAL EXPLORATION THROUGH THE REGOLITH IN THE CURNAMONA PROVINCE, SOUTH AUSTRALIA

AJ Fabris, MJ Sheard, JL Keeling, SM Hill, KG McQueen, CHH Conor and P de Caritat

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1. INTRODUCTION

1.1 Purpose of the guide

This Guide is designed to assist mineral explorers working in regolith-dominated regions of the Curnamona Province (*Figure 1*). Although the information presented may be applied across the Curnamona region, the focus is on the southern Curnamona Province where there has been the greatest number of regolith studies.

Figure 1. Location of the Curnamona region and surrounding Cenozoic sedimentary basins.

The Guide provides an introduction to the regolith and landscape history of the area, as well as advice on appropriate exploration strategies and techniques for exploring through, and within, the regolith. The information presented here is based on current knowledge and best practice, but the Guide is not meant to be a foolproof manual for exploration success.

1.2 Exploration context and general challenges

The Curnamona Province has a long history of exploration following on from the discovery of the world-class Broken Hill Pb–Zn–Ag deposit in 1883. Numerous mineral occurrences have been located throughout the district. The majority of exploration and subsequent discoveries, however, have been made in and around bedrock exposures, which account for less than 10% of the landscape. The major challenge facing exploration in the region is exploring effectively through thick transported regolith. Although large areas are beyond explorable depths–with more than 1 kilometre in thickness of sediment cover–there are extensive areas where predicted depth to bedrock is less than 100 metres. Around bedrock inliers, sediment thickness may decrease to less than 1 metre, but, even here, the thin cover is usually comprised of distally transported deposits. Mineral exploration approaches need to be able to penetrate sediment cover and weathered bedrock to effectively explore within, or through, the regolith.

2. PHYSICAL SETTING

2.1 Location

The Curnamona Province straddles the South Australia–New South Wales (SA–NSW) border. The region forms part of an internally draining basin bounded by the Flinders Ranges to the west, Olary Ranges in the south and Barrier Ranges in the east (*Figure 2*).

2.2 Climate

The Curnamona region covers part of Australia's arid core, where a warm temperate, dominantly dry, climate has persisted since the Pleistocene (White 1994). Temperatures commonly exceed 40°C in summer, with average monthly maxima ranging from 16°C in July to 35°C in January. Evaporation potential ranges–between about 2600 millimetres per annum in the south to more than 3200 millimetres per annum in the north–both far exceed average annual rainfall of less than 200 millimetres. The area around Lake Callabonna has the lowest annual rainfall in Australia at about 100 millimetres. A significant orographic affect around the Flinders Ranges produces locally higher annual rainfall of more than 250 millimetres (Allen 1990).

2.3 Vegetation

There are four broad vegetation types in the Curnamona Province, each with close geobotanical associations with regolith-landform settings:

1. Open woodlands on sandplains and in dunefield swales. Includes mulga (*Acacia aneura*) trees, sandhill wattle (*Acacia ligulata*) shrubs and a rich diversity of ephemeral herbs. White cypress pine (*Callitris glaucophylla*)-dominated woodlands or isolated individuals extend across some aeolian dunes and sandplains, particularly within the Strzelecki Desert north of Teilta. Mallee woodlands (including *Eucalyptus socialis*) become more dominant within the dunefields towards the south of the region, such as within the margins of the Murray Basin.

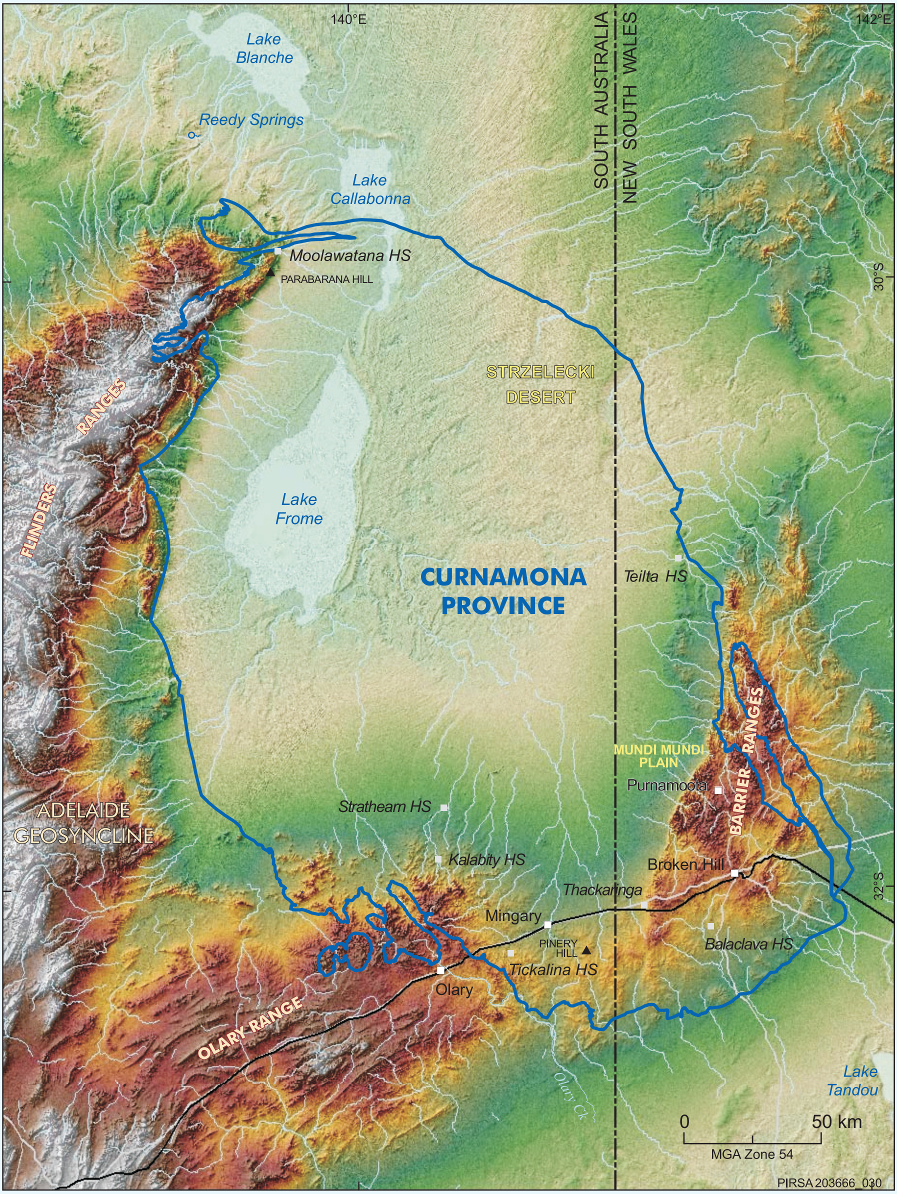


Figure 2. Outline of the Curnamona Province over a digital elevation model.

2. Chenopod shrublands on sheetflow plains and rises. These have a co-dominance of saltbush (*Atriplex spp.*) and bluebush (*Maireana spp.*) with copper-burrs (*Sclerolaena spp.*). The most widespread and abundant shrubs include bladder saltbush (*Atriplex vesicaria*), cotton bush (*Maireana aphylla*), black bluebush (*Maireana pyramidata*), and pearl bluebush (*Maireana sedifolia*). Open woodlands with chenopod understorey typically include trees of black oak (*Casuarina pauper*), rosewood (*Alectryon oleifolius*) and mulga (*Acacia aneura*). Chenopod shrublands also colonise the margins of saline lakes, where samphires (*Halosarcia spp.*) tend to prevail.

3. Riparian woodlands. Major channels and their banks are typically colonised by river red gum (*Eucalyptus camaldulensis*) grading downstream to depressions and floodplains dominated by black box (*Eucalyptus largiflorens*). Smaller channels may be colonised by prickly wattle (*Acacia victoriae*) and western boobialla (*Myoporum montanum*) and, in northeastern Curnamona, inland teatree (*Melaleuca glomerata*).

4. Open mixed woodlands on erosional hills and rises of weathered bedrock. Widely dominated by mulga (*Acacia aneura*) trees, with gum-barked coolibah (*Eucalyptus intertexta*) becoming abundant in the northern Flinders Ranges. Shrubs are mixed and variable, but typically include saltbushes (*Atriplex spp.*), bluebushes (*Maireana spp.*), dead finish (*Acacia tetragonophylla*), hopbushes (*Dodonaea spp.*), cassias (e.g. *Senna artemisioides*), emu bushes (*Eremophila spp.*), velvet potato-bush (*Solanum ellipticum*) and, within the northern Flinders Ranges, spinifex (*Triodia spp.*).

Despite local variations, these four broad vegetation types dominate the region. Further details and subdivisions can be found in Keith (2004), Beadle (1948) and Pickard and Norris (1994). As discussed later, their recognition has important implications for using biogeochemical sampling programs. Excellent botanical field guides for the region include Cunningham *et al.* (1992), Rutsche and Lay (2003), and Moore (2005).

Since the late 1800s, the vegetation cover has been greatly modified due to increased herbivore grazing – resulting from the introduction of rabbits, sheep, cattle and goats, together with increased kangaroo populations–as well as localised tree clearance for fuel and construction (Kenny 1936; Beadle 1948; Lord 1999).

2.4 Physiography

The topography of the Curnamona Province can be categorised broadly into low relief Quaternary plains that include longitudinal dunefields, expansive claypan areas and evaporitic playas–dominated by Lakes Frome and Callabonna in the northwest. The plains are bordered by low ranges to the east and south, and low to high ranges to the west (*Figure 2*). The terrain generally has less than 100 metres relief, but overall its surface rises from –15 metres in Lake Frome to 951 metres AHD atop Freeling Heights (Mount Painter Inlier). A number of small inliers such as the Mooleulooloo Hills and Nancatee Hill project as low isolated pinnacles.

2.5 Groundwater

Shepherd (1978, 1982) and Drexel and Preiss (1995) provide useful overviews of the regional groundwater resources, potential aquifers, expected salinity and bore water yields.

In the northern Curnamona, groundwater is dominantly exploited either from a series of Cenozoic aquifers (watertable) or from a few Mesozoic aquifers (sub-artesian to artesian). Aquifer water chemistry and salinity are highly variable: expected ranges from less than 1000 to more than 14000 mg/L TDS (Cenozoic, watertable) and from about 1000 to more than 3000 mg/L TDS (Mesozoic, artesian, typically 40–60°C–may carry hydrocarbon gases). Near the Flinders Ranges, localised surface run-off may recharge adjacent sedimentary aquifers, forming small areas of much lower salinity groundwater (< 100–600 mg/L TDS). Depths to water tables are highly variable: ranging from less than 25 to more than 130 metres. Artesian groundwater intersections range in depth from about 150 metres near rangelands and uplifted strata to more than 400 metres around the large ephemeral lakes.

There has been very little exploitation of fractured-rock-hosted groundwater in the northern Flinders Ranges, owing mostly to low yields and commonly brackish salinities (use > 95% for stock).

In the southern Curnamona region, groundwaters are dominantly brackish, of the Na–Cl–SO_4 and Na–Cl types: their pH is around neutral, and Eh mildly oxidising to strongly reducing (de Caritat *et al.* 2005). They show general trends of increasing temperature, electroconductivity, Fe^{2+} and S^{2-}, and decreasing Eh, dissolved oxygen and alkalinity from the outcrop margins of the Broken Hill and Olary Domains towards the deeper Callabonna Sub-basin.

Groundwater occurs within fracture zones in Palaeoproterozoic and Neoproterozoic rocks and above saprock developed in basement, with the primary aquifer within Mesozoic Eromanga Basin sediments (Great Artesian Basin). Smaller localised aquifers occur in alluvial and fluvial sands within Cenozoic sediments. Depths to the water table–where measured by de Caritat and Kirste (2005)–vary from 4 to 133 metres, with a median depth of 25 metres below surface.

Overall, the high salinities and minimal groundwater in the region reflect low rainfall, high evaporation and limited recharge during the Quaternary. Recharge occurs during rare high rainfall events and in areas where ponding of significant run-off coincides with effective connection to aquifers or the water table. Groundwater flow is assumed to be generally towards Lakes Frome, Callabonna and Blanche.

3. GEOLOGY AND MINERALISATION

3.1 Geological framework

The Curnamona Province is visible in airborne geophysical imagery as an oval feature spanning the SA–NSW border. Basement rocks crop out in the Olary and Broken Hill regions in the south and the Mount Painter region in the northwest. The Benagerie Ridge–a horst of basement rocks–is a dominant basement feature through the centre of the Curnamona Province and is outlined by thick Neoproterozoic–Cambrian sediment within and underlying the Moorowie and Yalkalpo sub-basins (*Figure 3*).

Southern Curnamona Province

The Curnamona Province basement is represented by rocks ranging from late Palaeoproterozoic to Mesoproterozoic that can be divided into two groups. The older group comprises the late Palaeoproterozoic metasedimentary and partly metavolcanic Willyama Supergroup. Neither the base nor top of the Willyama Supergroup have been identified. The varied distribution and thickness of the observed lithostratigraphy provides evidence that deposition across the basin was not uniform. Currently available information supports the concept of a rift setting, with the Broken Hill Domain representing a portion of the main rift, the Olary Domain the western flanking shelf, and the Mulyungarie Domain the transitional region. It is significant that the Pb–Zn–Ag fertile Broken Hill Group is best developed in the Broken Hill Domain, but the older auriferous oxidised volcano-sedimentary Curnamona Group is limited to the Olary Domain. The intervening Mulyungarie Domain is characterised by the thick sulphidic Portia Formation that hosts epigenetic Cu–Au–Mo mineralisation currently under investigation at the Kalkaroo and Portia prospects (*Figure 4*).

The younger group comprises early Mesoproterozoic igneous rocks that are of equivalent age to the around 1600–1575 Ma Hiltaba Suite in the Gawler Craton. Included are the S-type granite-dominated intrusions of the Ninnerie Supersuite in the Olary, Mulyungarie and Broken Hill Domains, and the bi-modal mafic and felsic A and I-type volcanics and sediments of the Mudguard Domain.

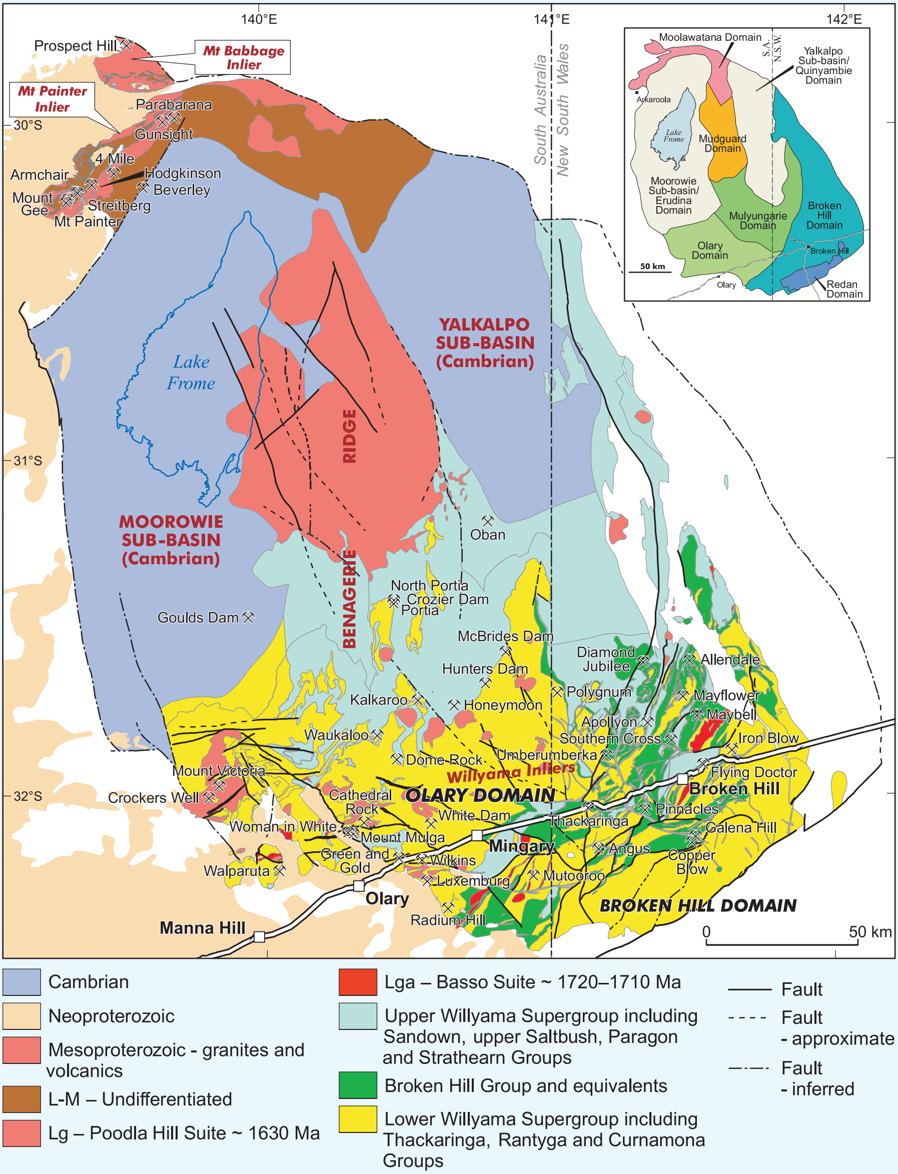


Figure 3. Geology and mineralisation of the Curnamona Province over a map showing generalised solid geology and selected mines and prospects. Geological domains of the Curnamona Province are shown on the top right (after Conor 2006).

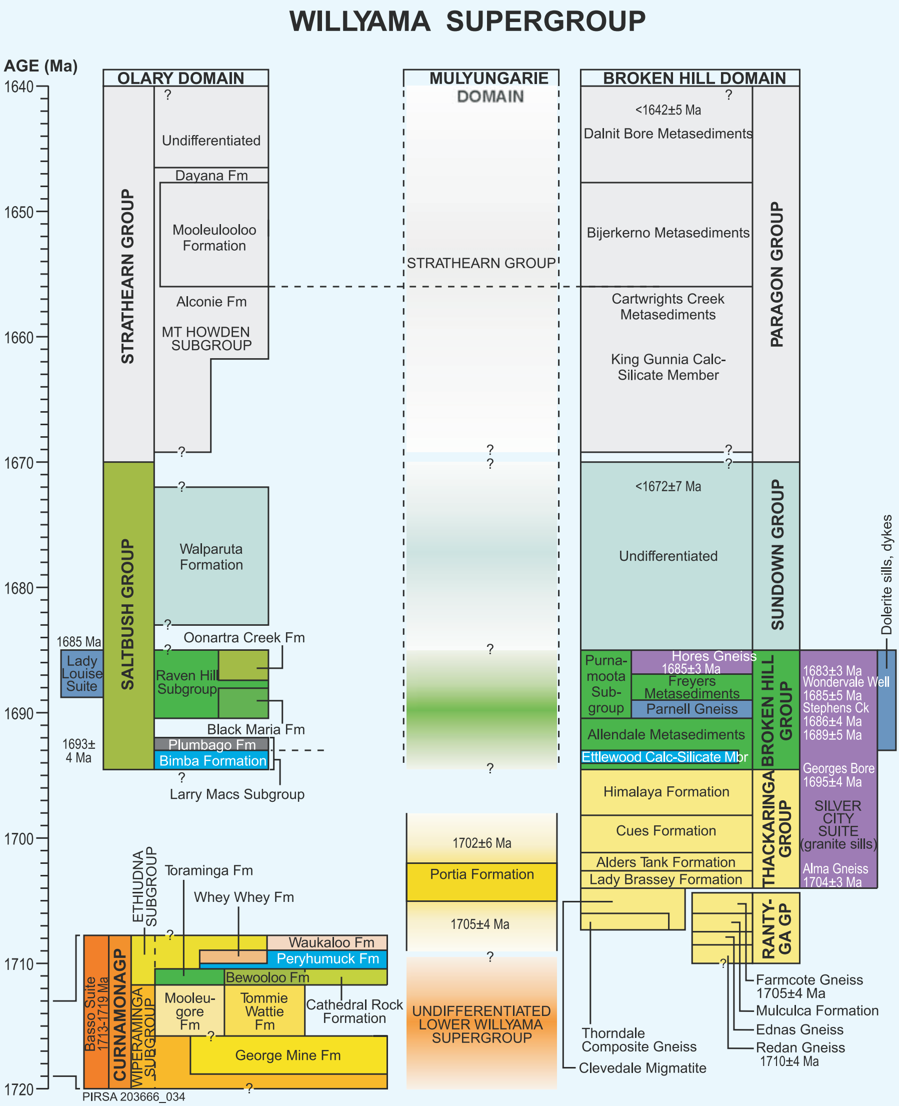


Figure 4. Lithostratigraphy of the Olary Domain compared with the Mulyungarie and Broken Hill Domains. The highly prospective Portia Formation has only been recognised in the Mulyungarie Domain (Conor 2006).

The Curnamona Province was affected by the around 1610–1680 Ma Olarian Orogen, with metamorphic grade varying northwestwards from granulite to lower greenschist facies. The Mesoproterozoic rocks of the Mudguard Domain, which dominate the central and northern Benagerie Ridge, are relatively unmetamorphosed and apparently overlie folded Willyama Supergroup.

Concurrent with the latter stages of the Olarian Orogeny was pervasive alkali–iron–calcsilicate alteration of the lower part of the succession, resulting in widespread replacement of silicate minerals by alkali-feldspar, mainly albite. Hydrothermal calcsilicate-matrix breccias are extensively developed in the Ethiudna Subgroup.

Northwestern Curnamona Province

Broadly, the geology of the Mount Painter and Babbage Inliers at the northwestern limit of the Curnamona Province appear similar to the southern part of the Province, with metapelites, schists, calcsilicates and quartzites (Radium Creek Metamorphics of Coats and Blissett 1971) being intruded by later granites. Teale (1993a) equated the metasediments with the Willyama Supergroup based on lithological similarities, but this has not been supported by geochronology. In addition, the history of intrusion varies, with most granites tending to be younger than the around 1600–1580 Ma Ninnerie Supersuite in the south.

Two anorogenic volcano-plutonic events occurred in the Mesoproterozoic: a high crustal level intrusion, (the Mount Neill Granite) and extrusive equivalent (the Pepegoona Porphyry) that has been dated around 1580 Ma. A similar age has been determined for rhyolite at the Gunsight copper prospect. The second event (1560–1555 Ma) mainly affected the northern end of Mount Painter Inlier and most of Mount Babbage Inlier. Units involved include the Petermorra Volcanics (~1560 Ma) and the Moolawatanna Suite of felsic intrusives (1555 Ma: Box Bore Granite, Yerila Granite, Wattleowie Granite, Terrapinna Granite, White Well Granite, Golden Pole Granites and Con Bore Granite; Sheard *et al.* 1992; Teale 1993b; Sheard and Callen 2000). As in the south, the rocks of the Moolawatana Domain (Mount Painter and Mount

Baggage Inliers, and their easterly extension undercover) are extensively alkali-feldspar–iron-oxide-altered, although at least some of this alteration is Palaeozoic in age.

Deformation and differential rotation of the two inliers during the Delamerian Orogeny (~500 Ma) has overprinted pre-existing fabrics and added intense foliations to the post-Olarian Orogeny rocks. Ordovician granitoids were emplaced towards the end of the Delamerian deformation and include British Empire Granite (~ 444 Ma; Elburg *et al.* 2003), Gordon Springs Granodiorite and Mudnawatana Tonalite (Rb–Sr 427±133 Ma [IR=0.07056] Farrand and Preiss 1995; Teale 1979).

In the Mount Painter–Mount Gee area, bodies of granitic and hematitic breccia (Radium Ridge Breccias) have been developed over a distance of 11 kilometres, which are associated with a major fault system within Mesoproterozoic granitic rocks. In places the matrix is infused by uraniferous hematite and chlorite. Overlying and intruding the breccias is a layered quartz–hematite rock (Mount Gee Sinter), which originates from a post-Delamerian epithermal system: possibly late Ordovician to Silurian, or Cenozoic, age.

Palaeo-Mesoproterozoic basement rocks are overlain by sedimentary basins containing Neoproterozoic, Cambrian, Mesozoic and Cenozoic sediments. A major period of rifting during the Neoproterozoic resulted in the formation of the rift complex of the Adelaide Geosyncline (i.e. ~820–520 Ma). This forms the western margin of the Curnamona Province and extends into the province as a series of grabens that host thick Neoproterozoic and Cambrian meta-sediments. Neoproterozoic to Early Cambrian marine sediments–dominated by meta-siltstone, sandstone and meta-glaciogene sediments (referred to as 'Adelaidean rocks')–exceed 3000 metres in thickness in the Moorowie Sub-basin. Elsewhere, Adelaidean sediments partially fill the Yalkalpo Sub-basin, form a thin veneer over parts of the Benagerie Ridge and Mingary region, and infill north-westerly-trending half-grabens in the south of the Province. Cambrian sedimentation overlying the Curnamona Province forms part of the Arrowie Basin and is mainly confined to the Moorowie and Yalkalpo Sub-basins. Sediment fill consists of carbonates and siliclastics up to 2200 metres in thickness in the Moorowie Sub-basin. Deformation and low to moderate grade metamorphism during the Delamerian Orogeny has imparted a fabric of variable intensity on both Adelaidean and Cambrian rocks in the south, but does not affect equivalent units in the central Curnamona Province.

A marine incursion in the Early Cretaceous resulted in sediment deposition extending over the Province's central and northern portion (Eromanga Basin). Widespread deposition of terrigenous sediments across much of the Curnamona Province followed in the Palaeogene (Lake Eyre Basin). Together with Neogene alluvial and aeolian sediments, these form a sediment blanket ranging in thickness from less than a few metres close to the ranges to over 250 metres in the northwest. Unmetamorphosed units (Mesozoic to Holocene) within the Curnamona Province will be discussed in more detail in the section on Regolith (Section 5).

For further detail on the geology, stratigraphy and tectonic history of the Curnamona Province, refer to reviews by Callen (1975), Callen (1990), Forbes (1991), Flint and Parker (1993), Ashley *et al.* (1995), Robertson *et al.* (1998) and Conor (2006). A geological summary with emphasis on the Broken Hill Domain can be found in Stevens and Stroud (1983).

3.2 Mineralisation

The Curnamona Province is most notable as host to the Broken Hill deposit: the largest Pb+Zn deposit by contained tonnes in the world (Large *et al.* 2002). In addition, anomalous concentrations of Cu, Au, Mo and U are widely reported across the region.

Summary descriptions of mineralisation and exploration in the Curnamona Province include those of Campana and King (1958), Barnes (1980), Stevens *et al.* (1990), Yates (1992), Yates and Randell (1994), Robertson *et al.* (1998), McCallum (1998a, b), Ashley (2000), McKay and Miezitis (2001), Conor (2006) and Robertson *et al.* (2005). Selected mineral occurrences are shown in *Figure 3*. Mineralisation styles and exploration potential differ between domains of the Curnamona Province (*Figure 3 insert*) and are summarised below.

Broken Hill Domain

The Broken Hill Domain contains the huge ore body of the Broken Hill deposit as well as several hundred small to very small Pb–Ag–Zn occurrences (Barnes 1980). The most abundant and well-known deposit types are the Broken Hill-type stratiform Pb–Ag–Zn (operating Broken Hill and Pinnacles mines) and Thackaringa-type Ag–Pb–Zn vein deposits (well-defined groups of deposits occur at Thackaringa, Umberumberka and in the Apollyon Valley). The Mutooroo Cu–Co deposit is currently at pre-feasibility stage. A number of smaller mines were worked between 1880 and 1890. Other deposits are numerous and include Cu, W, Sn, platinoids, Ni, Co and Au, and industrial mineral deposits of feldspar, beryl and mica (Barnes 1980; Lishmund 1975). Most economic mineralisation is within the Broken Hill Group and underlying Thackaringa Group.

Redan Domain

The Redan Domain occupies a relatively small area in the southeast of the Curnamona Province. Only a few minor occurrences are known. These include 'Sisters-type' quartz-magnetite +/- iron sulphide associated with Cu and Co and pyrite (+/-Au) hydrothermal quartz veins.

Mulyungarie Domain

The Portia Formation is an around 250 metre thick sulphidic unit and, together with overlying graphitic metasediments, occupies a complex syncline that is buried by sediment cover throughout much of the Mulyungarie Domain. Syngenetic zinc-dominated mineralisation is known from prospects such as Hunters Dam and Dayana. Current exploration is focused on epigenetic Cu–Au–Mo mineralisation. Projects in an advanced stage of exploration through to pre-feasibility include Kalkaroo Cu–Au (Mo) and Portia Au. There is potential for Cu–Au in the oxidised stratigraphic package of the Curnamona Group, Pb–Zn–Ag Broken Hill-type mineralisation where the Broken Hill Group exists, and Mount Isa-style Pb–Zn–Ag in the overlying Strathearn Group (*Figure 4*).

In addition, U is being extracted by *in situ* leach of sandstone hosted mineralisation in Palaeogene channel sands at the Honeymoon Mine.

Olary Domain

Known mineral occurrences and workings for Cu, U (and Th), Au, Pb, Zn and industrial minerals (feldspar, beryl and barite) are widespread in the Willyama Inliers, although production has been small. An early Mesoproterozoic pegmatite has been a source of feldspar for several years at the Antro feldspar mine. The Bimba Formation shows anomalous Cu, Au and Mo and has been targeted by exploration companies, along with the Ettlewood Calcsilicate Member of the lower Broken Hill Group. The Bimba Formation is possibly equivalent to part of the Portia Formation of the Mulyungarie Domain. The volcanic units of the Basso Suite of the Curnamona Group are pyritic and Fe-rich. Small historic workings, such as the Woman-in-White mine, indicate the potential for Cu–Au, as do volcanogenic barite deposits near the base of the Ethiudna Subgroup, such as the Mount Mulga Barite mine. Epigenetic mineralisation styles appear to be dominant in the Olary Domain. The most significant current example is the White Dam Au (Cu, Mo) deposit, which is at an advanced stage of feasibility.

The Mesoproterozoic thermal event produced granites that are U enriched. For example, between 1954 and 1961, davidite was mined at the Radium Hill Mine. Exploration at the Crocker Well U (historic mine) prospect has outlined an inferred resource of 12.5 Mt @ 0.05% U_3O_8 at a cut-off grade of 0.03% U_3O_8.

Mudguard Domain

The central to northern portion of the Benagerie Ridge horst is prospective for Olympic Dam-style Fe oxide Cu–Au–U (IOCGU) mineralisation. The geology has similarities to the Olympic Domain–host to the Olympic Dam deposit–and includes a sheet of extensive coeval, possibly co-magmatic, felsic and mafic volcanics (similar in age and composition to the Gawler Range Volcanics) and high-level intrusions (equivalent to the Hiltaba Suite) (Burtt *et al.* 2004). The setting provides the opportunity for the mixing of magmatic-derived and meteoric fluids–analogous to Olympic Dam (Haynes 2000; Reeve *et al.* 1990).

Moolawatana Domain

The Moolawatana Domain includes the Mount Painter region, which is host to mineralisation of Cu, U, REE, Th, Zn, Au, Ag, W, Ga, Sn, Co, Bi and Mo: mostly as minor occurrences (Teale 1993a; Sheard, in prep.). Copper mineralisation has been exploited since the late 1800s, and 110 mines and minor prospects are known (Coats and Blissett 1971). Of more recent significance is U, which is present in over 40 historic mines and prospects. Sedimentary U mineralisation occurs to the east of the ranges.

The Beverley Mine, 12 kilometres east of the Mount Painter Inlier, is the largest and most recently constructed *in situ* leach mine in the western world–with an annual production of 1000 tonnes of U_3O_8. Together with the emerging Four Mile prospect, this region represents a world-class sedimentary U province. In the Mount Painter–Mount Gee area, the Radium Ridge Breccias are host to U resources at Armchair, Streitberg, Mount Gee and Hodgkinson prospects.

There is noteworthy Cu mineralisation in the region. The Parabarana Cu–As–Mo prospect–located in the northern Mount Painter Inlier–is hosted by calcareous metasediments and, to a lesser extent, metapelite and quartz–albite rocks of presumed Palaeoproterozoic age (Teale 1993a). Mineralisation occurs in veins and fractures, and may be related to the Mount Neill Granite intrusion (Brewer 1978), although Every (1975) suggested a volcanogenic–sedimentary origin. At the Gunsight prospect, which is 5 kilometres southwest of Parabarana Hill, Cu–U–Co–REE mineralisation is hosted by sulphide-rich schist and Fe formation associated with calcsilicate and Mesoproterozoic volcanics. Mineralisation comprises chalcopyrite, pyrite, uraninite, monazite, allanite and cobaltian sulphides (Teale 1993b).

At Prospect Hill–northern Mount Babbage Inlier–Sn mineralisation, as cassiterite, occurs within a narrow, quartz–biotite–gahnite–garnet–fluorite ± magnetite horizon within deformed Mesoproterozoic Petermorra Volcanics (Brewer and Teale 2007; Teale, 1993a). The mineralisation is associated with anomalous Cu, Zn, Pb, Ag, W, Y, Bi and U. Elsewhere, Sn can be located in tourmaline-rich, 'Greisen-like' high-strain zones (Brewer and Teale 2007).

Heavy mineral sands have been observed on the shores of Lake Callabonna, with analyses indicating the presence of titaniferous hematite, zircon, rutile, ilmenite, magnetite, monazite and silicates in varying proportions (Sheard, in prep.).

Erudina and Quinyambie Domain

Known mineral occurrences within these domains are within cover units. Of most significance is sedimentary U, such as at the Goulds Dam prospect. Due to the extensive thickness of cover in these regions, little is known about the mineral potential of basement rock units.

Key mineralisation styles

- ***Pb–Ag–Zn mineralisation***–stratiform. Hosted in metasediments (generally psammite to psammopelite, but occasionally pelite) of the Broken Hill Group. Specifically in quartz–gahnite and/or garnet–quartz-rich horizons. Mineralisation within these horizons is present as disseminations or pods of galena, Fe-rich sphalerite and other minor sulphides. Deposits are also in amphibolite and quartz–feldspar–biotite–garnet gneiss ('Potosi' type; Barnes 1980). Examples include Broken Hill, Pinnacles, Allendale, Southern Cross, Little Broken Hill and Galena Hill.

- ***Ag–Pb Thackaringa-type vein deposits***–hosted by siderite–quartz±calcite veins of 0.1 to 1.0 metre width within fault zones or retrograde shear zones (Barnes 1980). Ore minerals include argentiferous galena and minor sphalerite, chalcopyrite, pyrite, tetrahedrite and arsenopyrite. Mineralisation was formed probably by remobilisation of pre-existing base metals within the Willyama sediments and commonly has a spatial relationship to Broken Hill-type mineralisation. The lack of deformation of the veins indicates that they were formed late in the geological history. Most have undergone only minor strain but those in shear zones can be strongly sheared. Examples include Thackaringa, Umberumberka and within the Apollyon Valley, Mayflower and the Maybell areas.

- ***Zn–Pb–Ag mineralisation***–stratiform and stratabound in reduced pelitic and psammopelitic metasediments. Syngenetic–diagenetic or 'early' replacement origin: possibly structurally controlled by early rift faults to form sulphide mineralisation that is layered, disseminated or partly remobilised into veins within the Ethiudna Subgroup, Portia Formation and Saltbush and Strathearn Groups. Models of mineralisation have been equated to those at Mount Isa, McArthur River and Century. Examples include Hunters Dam, McBrides Dam and Polygonum prospects.

- ***Cu–Au (±Mo) mineralisation***–stratabound or discordant. Mineralisation occurs in veins, stockworks, breccia matrices, as disseminations and replacement along compositional layering. Present predominantly in non-pelitic rocks. Regionally Cu–Au mineralisation appears to be concentrated near a redox boundary situated between the magnetite-bearing lower part of the stratigraphy and the more-reduced upper part. Mineralisation is probably related to regional sodic-, potassic-, calcic-, Fe-oxide alteration, similar to many other Fe oxide–Cu–Au districts, including the Cloncurry District. The origin of mineralisation is likely to be related to fluid movement during the Olarian Orogeny. This resulted in epigenetic mineralisation and, in some cases, enrichment of primary mineralisation within structural and sedimentary traps. As a consequence, styles of mineralisation will vary across the different stratigraphic levels, lithologies and metamorphic facies. Copper-gold mineralisation styles include:
  - stratabound replacement of pyrite in calcareous beds and nodules, and within veins and breccias in the Portia Formation; e.g. Kalkaroo, Portia and North Portia prospects
  - Cu–Au mineralisation in the quartz–magnetite±barite horizon of the Cathedral Rock Formation; e.g. Cathedral Rock prospect
  - fracture-fill; e.g. Waukaloo Mine
  - those in a biotite–magnetite matrix; e.g. Walparuta Mine (Ethiudna Subgroup)
  - those in graphitic metasediments at the base of the Strathearn Group; e.g. Dome Rock mine
  - those associated with epigenetic ironstone (magnetite) bodies; e.g. Wilkins, Green and Gold, (Wiperaminga Subgroup)

- – Cu–Au mineralisation associated with leucosome development within gneiss and migmatite in the lower part of the sequence; e.g. White Dam deposit and Diamond Jubilee Mine
- – Cu (Au) mineralisation with higher Cu grades identified in magnetite-rich bodies below the Broken Hill Group and within the Thackaringa Group; e.g. Copper Blow, Iron Blow (magnetite-rich bodies) and The Sisters (quartz-rich bodies).

- ***Fe-oxide–Cu–Au–U*** mineralisation in high-level, possible Palaeozoic hydrothermal breccias of the Olympic Dam style. Examples include Mount Painter–Mount Gee deposits.
- ***Cu mineralisation*** as supergene enriched zones near the base of weathered profiles in basement rocks, such as is prevalent at the Kalkaroo deposit.
- ***U, Th, REE mineralisation*** in veins, shears, stockworks and breccias. Hosted by S-type granitoid of unusual sodic, leucocratic character at Crocker Well, shear zones in migmatite and S-type granite at Mount Victoria, pegmatite in shear zones at Radium Hill and Fe-rich breccias at Mount Painter–Mount Gee area.
- ***Au mineralisation*** as eluvial-alluvial deposits at the base of Cenozoic sediments. Sediments must be reducing to prevent the dissolution of the Au (Tan 2001). An example is the Portia prospect.
- ***U mineralisation*** in Cenozoic sedimentary cover ('roll front', redox controlled). Hosted in Eocene palaeochannel sediments (Eyre Formation) north of Willyama Inliers of the Olary region and in Eocene (Eyre Formation) and Miocene (Namba Formation) alluvial sediments east of the Mount Painter Inlier (*Figure 5*). Known world-class deposits demonstrate this region's prospectivity. Examples include the Beverley, Honeymoon, Goulds Dam, Four Mile and Oban deposits.

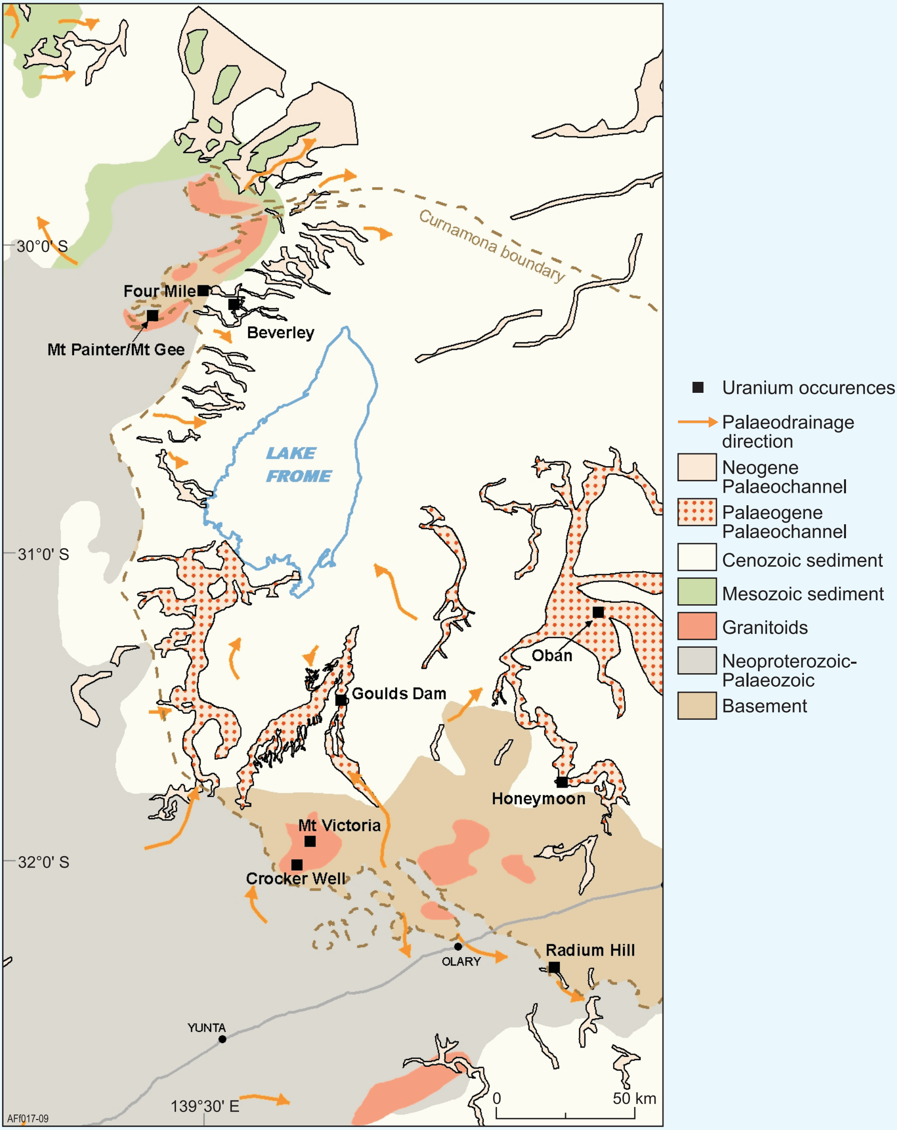


Figure 5. Palaeochannel map of the Curnamona Province showing major sedimentary U occurrences. Palaeodrainage directions are regional trends and may differ locally (after Hou et al. 2007).

4. LANDSCAPE EVOLUTION

4.1 Landscape history

Key references and ideas on the landscape history of the Curnamona Province are drawn from: Alley and Frakes (2003), Alley and Lindsay (1995), Belperio (1995), Benbow *et al.* (1995), Callen (1975, 1981, 1990), Callen and Tedford (1976), Krieg (1995), Sheard (1990), Sheard and Callen (2000), Sheard (in prep.), White (1994).

Palaeozoic

After a hiatus in sedimentation in the Adelaide Geosyncline at the end of the Neoproterozoic, renewed rifting and a late Early Cambrian marine incursion resulted in the deposition of marine carbonates and dominantly marginal marine redbed clastics within the Moorowie and Yalkalpo Sub-basins (Gravestock and Cowley 1995; Zang 2002). The absence of Cambrian strata over the Benagerie Ridge indicates it was either a topographic high at the beginning of Cambrian sedimentation, or that it was subsequently removed by erosion. The Moorowie Sub-basin was bisected by a northerly trending wrench fault system–sub-parallel to the Benagerie Ridge–referred to as the Poontana Fracture Zone (Adams 1987). This fault system affects Cambrian to Cenozoic sediments and appears to have been an important control in U distribution east of Mount Painter. Cambrian sedimentation was eventually terminated with onset of the Cambrian Delamerian Orogeny (i.e. ~500 Ma) that resulted in uplift of the Adelaide Geosyncline (e.g. Flinders Ranges) and widespread erosion.

Two periods of depositional hiatus exist in the region. The first is from Ordovician to Devonian, where erosional surfaces and some deep weathering profiles have been observed (Gravestock *et al.* 1995). A second major depositional hiatus resulted from continental scale glaciation over most of remnant Gondwana during the Permian. It is inferred that during this glaciation the deep weathering profiles developed during the Ordovician to the Devonian were largely removed. Exposed Palaeozoic sediments were either reduced in extent or thickness. Permian sedimentation in this region is known only from the Cooper Basin (north of the Curnamona Province, underlying the Eromanga Basin). From the very Late Permian onwards, the exposed Curnamona Province landscape was open to weathering processes.

Mesozoic

A series of climate excursions during the Triassic and Jurassic promoted deep weathering in exposed rocks. Sesquioxides-hydroxides and mobile elements were stripped during cyclic episodes of weathering to give leached (pallid) saprolite profiles up to 20 metres in thickness (Drexel and Preiss 1995).

In the Early Jurassic, rifting within the remnant Gondwana began to form two separate continental masses (Australia and Antarctica): this led to rift and intracratonic basin formation along the southern edge of the Australian landmass. From the Late Jurassic to Early Cretaceous, Australia was situated at about 70–60º S and the climate was seasonally periglacial to glacial, punctuated by numerous warmer phases. Coniferous forests covered large parts of the landscape.

During the Early Jurassic, tectonic movement resulted in the formation of the Eromanga Basin. The Frome Embayment is a southern extension to the Eromanga Basin that overlies much of the central and northern Curnamona Province.

Early Jurassic to Early Cretaceous deposition was dominated by braided fluvial systems (Algebuckina Sandstone) that drained centripetally into lowland lakes and swamps. Aeolian sands also form a significant portion of the same sequence. Subsequently, a marine transgression during the earliest Cretaceous resulted firstly in coastal plains terrigenous to back-barrier to estuarine sand and silt deposition (Cadna-owie Formation, Parabarana Sandstone), then secondly in deposition of thick high-stand mudstones, with thin transgressive shore-face sandstone units (Marree Subgroup: Bulldog Shale, Coorikiana Sandstone and Oodnadatta Formation). In the Late Cretaceous the sea regressed, leaving the marginal marine Mackunda Formation shale-siltstone. Deposition shifted to non-marine, terrigenous, meandering fluvial system dominated by sand (Winton Formation). However, this later phase of deposition has left little or no sedimentary evidence over the Curnamona Province, which may reflect subsequent uplift and erosion.

Cenozoic

As Australia gradually drifted northwards (> 63º S to < 40º S over a period of 45 million years (Pillans 2006), the climate warmed and rainfall increased: promoting more rapid rock weathering and fluvial erosion. Deeper weathering developed over chemically or physically unstable rock units, such as sulphidic, albititic, carbonaceous and fractured lithologies. Major river systems drained and incised into the Curnamona Province in a northerly direction from the Olary Ranges and north-westerly from the Barrier Ranges. A basement high between the Callabonna and Murray Basins through Pinery Hill marked the drainage divide, as it does today (Crooks 2002). Drainage sediments are represented mostly by sands of the Eyre Formation within channels (southern Curnamona) and as a sand sheet in lower energy streams, and as alluvial plains in the remaining part of the Basin. Eocene channel sands can host U mineralisation. Kaolinite derived from the eroding, deeply weathered–leached terrain, forms a trace to major component of the Eyre Formation–especially within lacustrine and billabong facies. The deep erosional channelling seen in southern Curnamona Province suggests contemporaneous uplift of the Olary Ranges. Chert pebbles within the Eyre Formation to the north are interpreted as being derived from Jurassic and Cretaceous sediments (Wopfner *et al.* 1974), whereas silcrete pebbles to granules within the Mulligan Dam Regolith and lower Eyre Formation, as reported by Sheard and Callen (2000), imply a pre-Eocene (Palaeocene or possibly latest Cretaceous) siliceous duricrust. This indicates a period, or periods, of relative landscape stability within a more dynamic tectonic regime.

By the end of the Eocene, relief was subdued and basins were partially filled by the Eyre Formation. Vegetation cover was extensive. During Late Eocene–Oligocene, another episode of siliceous duricrust development occurred, mostly in areas marginal to the ranges. On the basis of dissolved and re-precipitated kaolin within the Eyre Formation, Callen (1975) suggests the prevalence of acidic groundwater conditions. This is supported by Simon-Coincon *et al.* (1996) who suggested silicification occurred in the

Lake Eyre Basin under acidic groundwater conditions in a hot palaeoclimate with alternating wet and dry periods.

By the Middle Miocene, the Poontana Trough (proto-Lake Frome) began forming west of the current Lake Frome shoreline, and was the depocentre for clays of the lower Namba Formation within a permanent lacustrine setting. Sedimentation had changed to fine-grained smectite-rich fluvio-lacustrine deposition as a result of a change to a climate with a higher rainfall. Palynological evidence suggests temperatures cooled from Eocene times, which has been attributed to a change in the ocean currents after Australia separated from Antarctica, although temperatures remained relatively warm (Crook 1981). The proto-Lake Frome continued to develop as a relatively deep and permanent lake that changed from fresh to saline water with time. Large aquatic vertebrates, such as crocodiles, lungfish and turtles, inhabited the lake. Gallery forests grew on the lake shores. Callen (1975) suggests that rainfall exceeded the rate of evaporation to an extent that may have been sufficient for the lake to overflow into the sea to the north. The subsequent shallowing of the lake due to increased evaporation in seasonal periods of aridity led to carbonate deposition and, with fluctuations in alkaline groundwaters, to dolomite precipitation. The middle and upper units of the Namba Formation were deposited over most of the Benagerie Ridge.

By Late Miocene times, a carbonate forming lacustrine environment was replaced by a predominately floodplain environment with interspersed lakes and swamps. Sedimentation became illite-rich. The basin margins were host to fluvial and lacustrine offshore bar deposition, particularly in the Poontana Trough. A period of extensive ferruginisation and silicification in the late Neogene followed the deposition of the Namba Formation.

The uplift of the Flinders Ranges continued throughout the late Neogene, and sedimentation along the western Curnamona became dominated by fluvial/colluvial regimes (Willawortina Formation). Deposition at this time developed in oxidising conditions, as sediments accumulated above the water table in a more arid climate. This contrasts with the sub-water-table reducing environment present during deposition of the Namba Formation. Elsewhere in the basin, lacustrine environments were replaced by alluvial, floodplain and aeolian environments. The palaeodrainage is closely aligned with present day drainage. As Lake Frome dried out, Fe oxides/hydroxides and carbonate precipitated–particularly in areas close to the ranges. Erosion during the ?Pliocene to Quaternary cut into the landscape, from the exposed less-competent saprolitic lowlands towards the generally siliceous or ferruginous duricrust armoured upland surfaces. This process has formed terraces in elevated bedrock-dominated regions and escarpments, mesas and plateaus towards the plains standing less than 2 to more than 20 metres (Brown 2006). The terraces commonly expose softer pallid saprolite zones. The landscape lowering removed much of the thick weathering profiles now only preserved in the Curnamona's south-east, Kalabity, Strathearn and southern Benagerie Ridge regions, and left duricrust fragments (siliceous and ferruginous lags) on many plains and colluvial slopes.

In the late Pleistocene to Holocene, extensive dune and lunette systems developed during glacial maxima in response to the arid and windy conditions of the ice age (Sheard *et al.* 2006). Aeolian carbonate dust–primarily sourced from marine calcium carbonate from exposed marine shelves to the south–progressively accumulated in these sediments (the remobilisation of these is continuing today; Dart *et al.* 2007; Lintern *et al.* 2006). Later pedogenic and biotic processes–along with infiltrating meteoric water–have transformed those aeolian carbonate dusts into recrystallised 'regolith carbonate accumulations' or 'calcretes'.

Regional vegetation adapted to the increasing aridity by becoming sclerophyll dominant (e.g. toughened leaf cuticles and fewer leaf pores), sparse, tolerant of sodic high pH soils, and by becoming of moderate to low stature (Urban 1993; Northcote and Skene 1972; Stace *et al.* 1968; Rutsche and Lay 2003).

4.2 Regolith profile development

Regolith profiles across the region are the result of many episodes of weathering, erosion and deposition over an extended period. Over 90% of the Curnamona Province is covered by sediment, with areas of bedrock outcrop restricted to the Olary, Barrier and Flinders Ranges. Regolith profiles throughout the Curnamona are therefore highly variable and dominated by thick transported deposits in basinal areas.

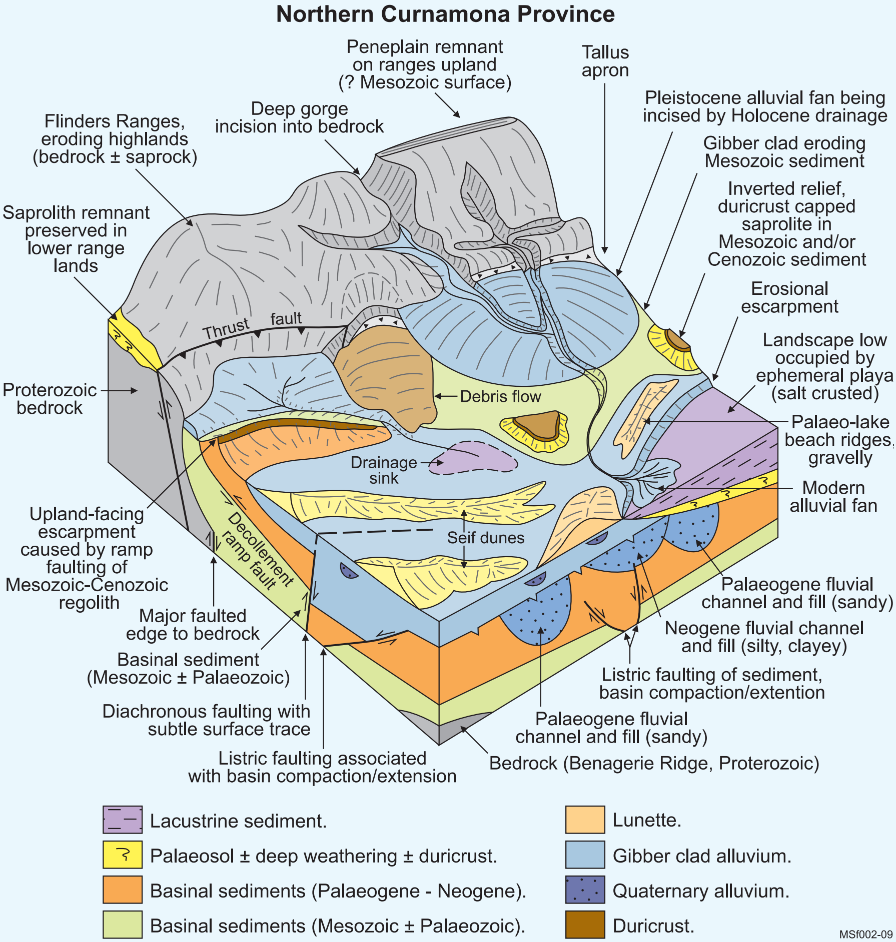


Figure 6. Block diagram summarising the main regolith-landform components of the northwestern Curnamona Province-northeastern Flinders Ranges.

In situ profiles show great variability of internal structure and thickness (typically < 1 m to ~80 m), with major controls including landscape position, rock type and availability of water. Thick *in situ* profiles have developed in areas that are not covered by pre-Cenozoic sediments (southern Benagerie Ridge, Olary Domain and parts of the Broken Hill Domain). Outcrop of this weathered basement is rare except in the Mingary and Kalabity-Strathearn region where duricrusts and lags have been an effective armour to erosion (*Appendix 2*).

Major landscape and palaeolandscape components and associated regolith materials are summarised in *Figures 6* and *7*. Typical regolith profiles are illustrated in *Figure 8*. These include sites from various landscape and palaeolandscape settings, and with different histories of erosion and deposition. A common feature of many *in situ* weathered profiles within the Curnamona is their truncation by erosion leaving little or no pedolith and an unroofed or truncated pallid saprolite.

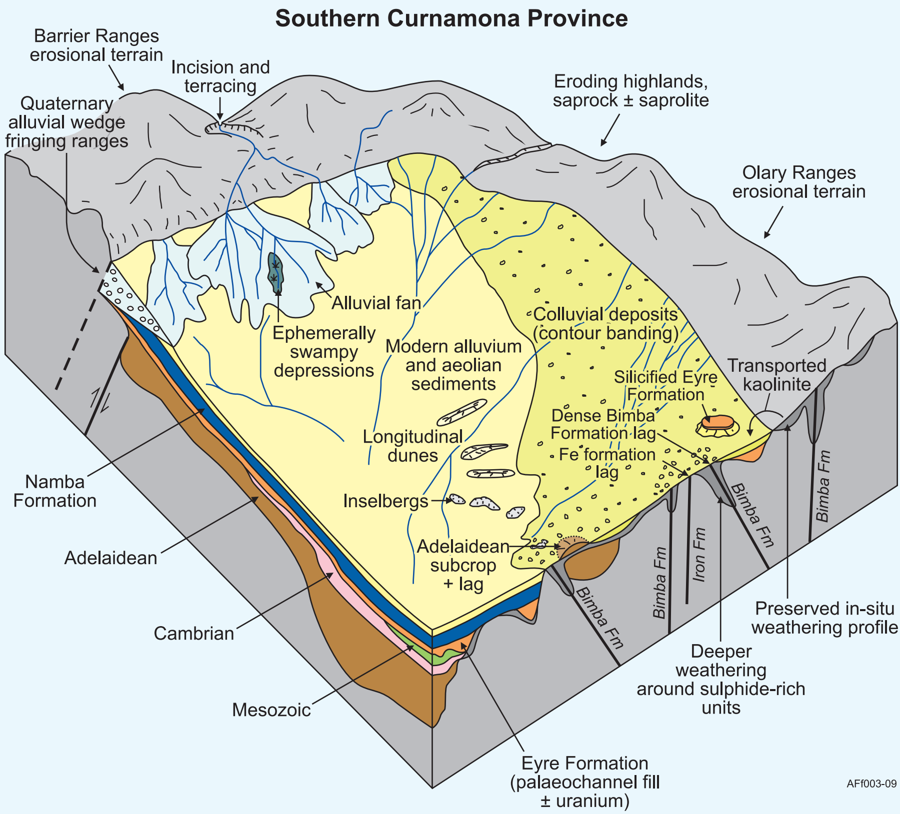


Figure 7. Block diagram summarising the main regolith-landform components of the Olary and southern Barrier Ranges. Extensive lag deposits north of the Olary Ranges have a close relationship to the basement rock-type.

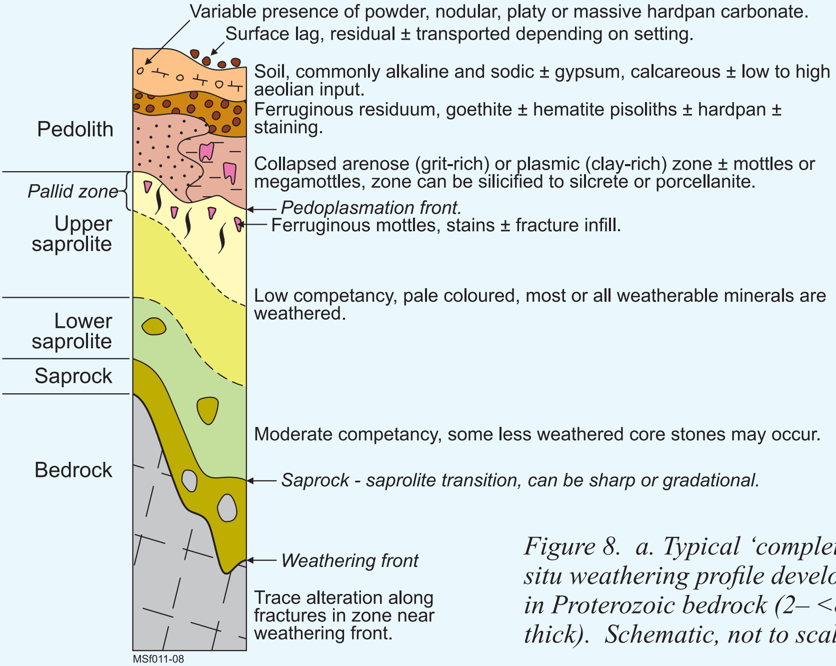
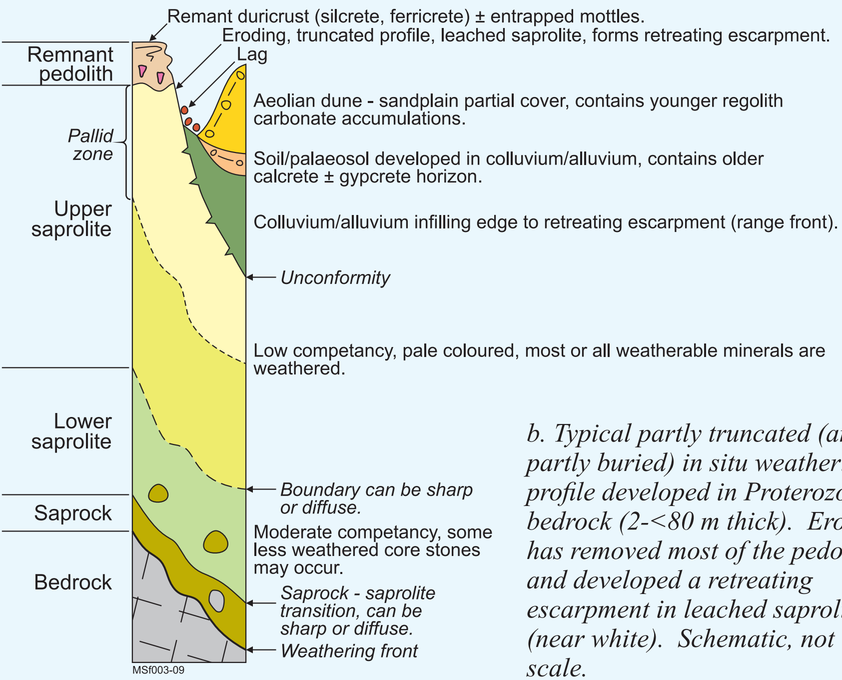
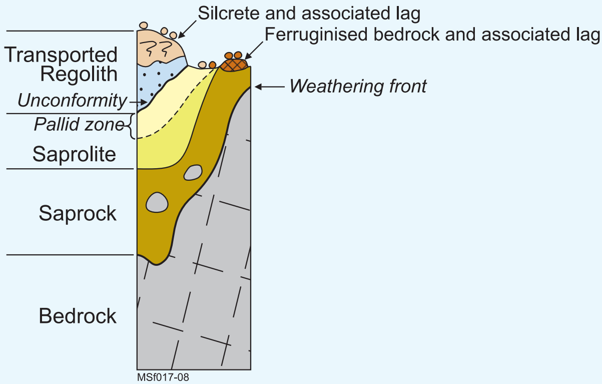


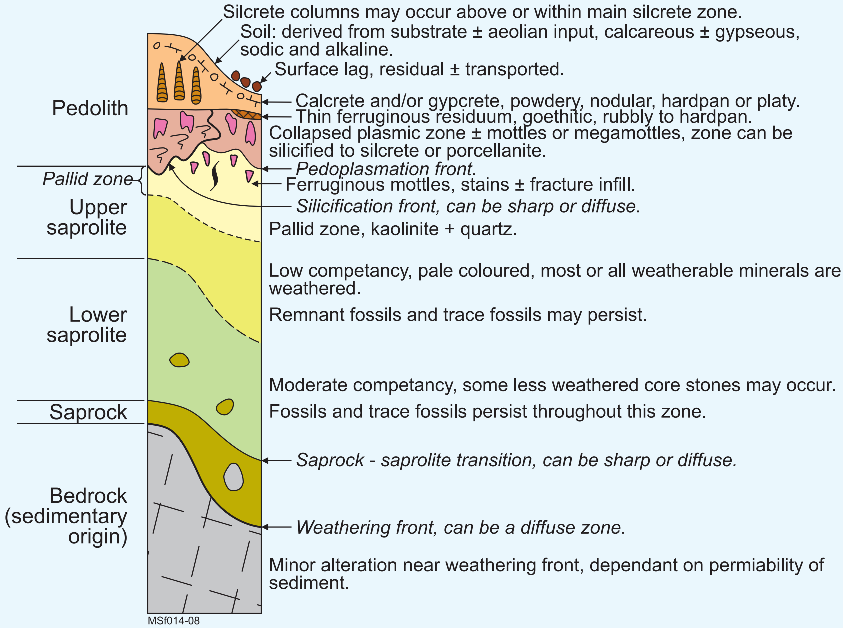
Figure 8. a. Typical 'complete' in situ weathering profile developed in Proterozoic bedrock (2– <80 m thick). Schematic, not to scale.



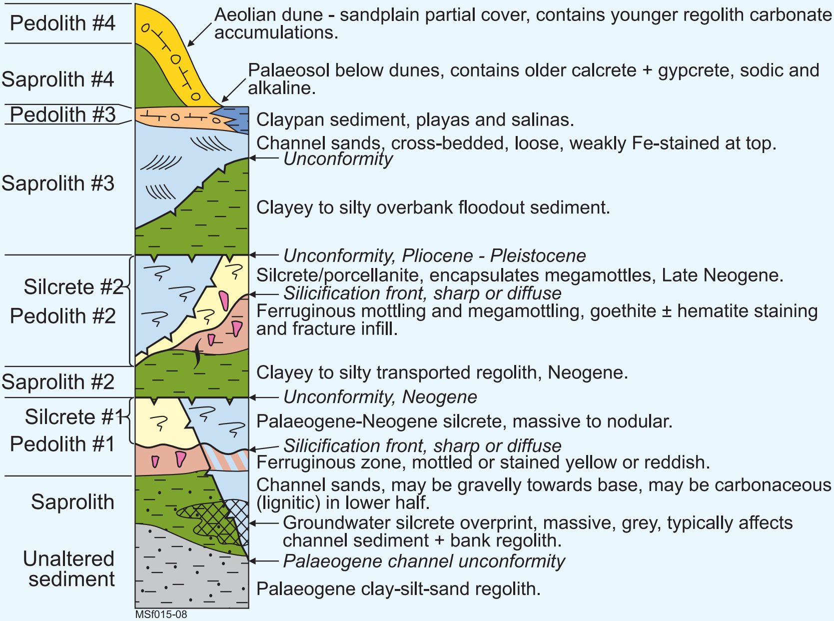
b. Typical partly truncated (and partly buried) in situ weathering profile developed in Proterozoic bedrock (2-<80 m thick). Erosion has removed most of the pedolith and developed a retreating escarpment in leached saprolite (near white). Schematic, not to scale.



c. Truncated in situ weathering profile developed in Proterozoic bedrock where a ferruginous zone has formed at the palaeo-weathering front (not typical of the entire Curnamona region). Sediment deposited in fluvial channels is similar in character to that which it truncates. Schematic, not to scale.



d. Typical 'complete' residual in situ weathering profile developed in Mesozoic–Paleocene sediment (5– >60 m thick). Schematic, not to scale.



e. Cenozoic transported regolith: the complexity of repeated weathering cycles imposed on a sedimentary basin where sediment influx episodically overwhelms deep weathering cycles. Four cycles are displayed, but more are likely in many locations. Schematic, not to scale.

5. REGOLITH

5.1 Regolith materials

The regolith is defined as 'everything between fresh rock and fresh air'. It can be divided into five broad types of material:

- *in situ* regolith
- transported regolith (sediments)
- indurated regolith (duricrusts and pans)
- lag materials
- soils.

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

In situ regolith

In situ regolith refers to weathered basement that has not undergone physical transport. In the Curnamona, the *in situ* regolith is principally weathered Willyama Supergroup. In a well-developed weathering profile, there is a progression of increasing alteration to the weatherable minerals, from fresh rock (trace altered < 5%) to saprock (minor alteration > 5 to < 20%) to saprolite (significantly to highly altered > 20%). This progression develops vertically, but may be quite uneven laterally, with less weathered corestones in some cases persisting to the surface.

Within the saprolith (saprock + saprolite), the primary rock fabric remains largely preserved (i.e. weathering alteration has essentially been isovolumetric). Saprock may have gradational boundaries with either or both bedrock and saprolite–a feature enhanced by rock fracturing and shearing. Saprock commonly contains bedrock corestones and variable competence intervals. If erosion is slow relative to the rate of weathering, a thicker saprolite evolves. Sufficient weathering can lead to the development of pedolith that includes either a plasmic zone if the parent rock is clay-rich, or an arenose zone if it is quartz-rich. Iron mottles may form due to Fe remobilisation during the weathering process (*Figure 9*).

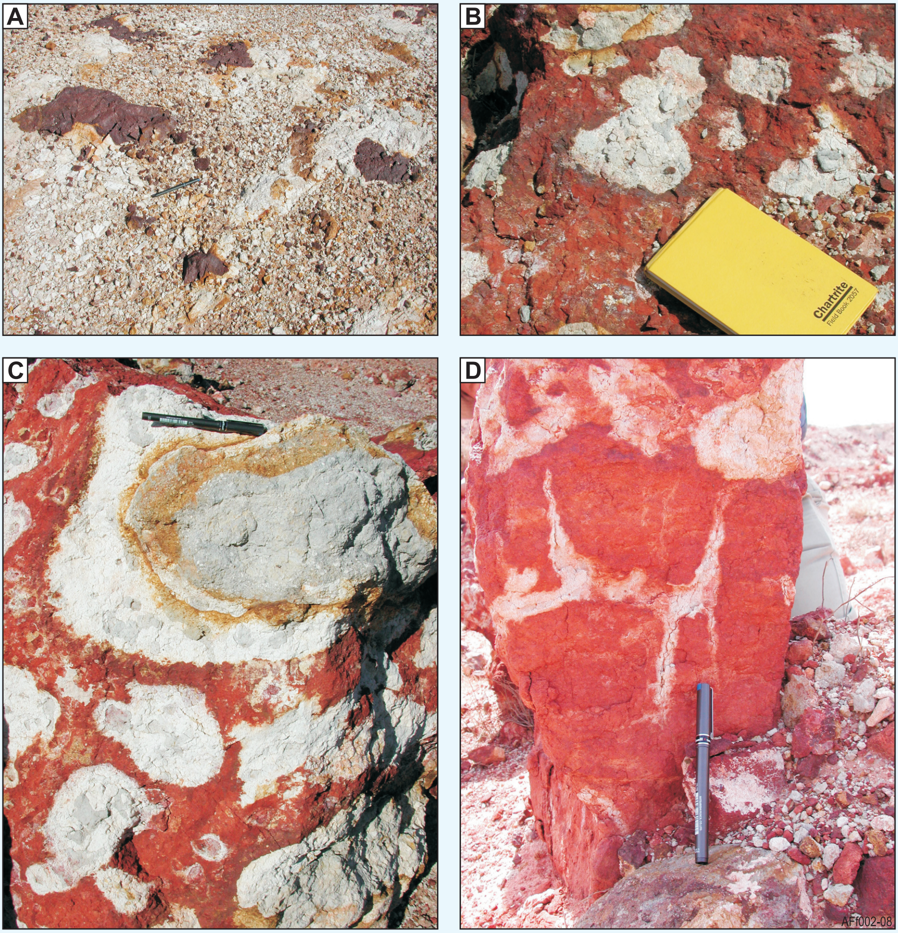


Figure 9. Mottling within upper saprolite, Mingary Pit (483500mE, 6446955mN, WGS84/MGA54). (A) Iron mottles. (B) Leached mottles. (C) Porcellanite formed in leached mottle within a ferruginised matrix. Tree roots exploit porous mottles and are replaced by porcellanite after the organic matter decays. Goethite rims represent Fe precipitation at redox boundaries. (D) Root-like shapes within the mottle zone suggest that roots may influence Fe mobilisation.

Discrimination of saprolith/pedolith from overlying transported material can be difficult in areas where both are composed primarily of kaolinite. This situation is not uncommon in the Curnamona Province, where the kaolinite-rich basal units of the Eyre Formation sit directly on highly weathered Palaeoproterozoic basement or Adelaidean rocks. Where core is available, primary rock fabrics may be identifiable in saprolith, but this is much more difficult with cuttings. Measuring the decrease in kaolin crystallinity associated with the transported material using XRD or PIMA has been used in these situations (Lawie 2001; Dawson 2000).

Most basement outcrop in upland areas of the Curnamona is considered saprock; however, the degree of weathering is locally influenced by rock type. Highly weathered rocks are generally restricted to covered or tableland regions. Outcrop of the upper saprolite (typically pallid) is most commonly found in retreating escarpments, mesas and buttes, but can also be found in erosional terrains around Mingary and north of Kalabity, where it is covered by a thin veneer of lag (*Figure 10*).

Figure 10. Exposed upper saprolite developed from Willyama Supergroup on the main track, 1 kilometre south of Strathearn Homestead.

Transported regolith

Transported regolith includes alluvium, lacustrine and marine sediments, colluvium and aeolian deposits. Dominance of any one of these varies from one location to another, but all are significant in their own right in the Curnamona Province.

Alluvial sediments and palaeodrainage

A wide range of alluvial sediments have been deposited within the region during the Mesozoic and throughout the Cenozoic. Variations in climate and tectonic activity affecting the Curnamona region led to a diverse and evolving landscape, and one which varied significantly from the present. During the Palaeogene and Neogene, widespread sands and clays were deposited over the Curnamona as a response to erosion of the Olary, Barrier and northern Flinders Ranges. Within the southern Curnamona, channels tens of metres deep were incised into weathered bedrock and into sediments of the Eromanga and Arrowie Basins. These channels were filled with carbonaceous, very coarse to fine sands and clays of the Late Paleocene to Late Eocene Eyre Formation. Uranium mineralisation is hosted within these fluvial sediments. In the northern Curnamona, alluvial/fluvial sediments within the Namba Formation were developed during Late Oligocene to Miocene and host the Beverley U deposit.

Some modern stream valleys preserve channel deposits that may be intermediate in age between Palaeogene and the modern channel deposits. On the surface, they form broad terraces within modern creek systems, with a scattering of exotic cobbles (*Figure 11*). Rare sections expose well-rounded, lithic cobble conglomerates cemented by calcium carbonate and gypsum (e.g. near 'Mutooroo' homestead and south of Radium Hill; Crooks 2002). The change to a more arid environment in the Quaternary has resulted in areas that were dominated by widespread alluvial sedimentation being dominated by aeolian deposition.

Colluvial sediments

Colluvial sediments are widespread across the region: partly as local creep,

Figure 11. Terraced fan remnants abutting the Mundi Mundi range front immediately north of Umberumberka Creek. The land surface in the foreground is within the main part of the Umberumberka fan (518600mE, 6481500mN, WGS84/ MGA54).

fall, slide and flow deposits flanking steep-sloped weathered bedrock exposures in the region (significant fan-apron deposits off the Flinders and Barrier Ranges), but most importantly as sheetflow deposits that extend across most hills, rises and plains in the region (*Figure 12*). These deposits are typically characterised by distinctive 'contour banding' or 'tiger stripe' surface patterns, which are defined by alternating bands of sparsely vegetated, dominantly quartz and ferruginous surface lags alternating with finer grained fine sand- and silt-dominated bands that are more densely colonised by chenopod shrubs (*Figure 13*; Wakelin-King 1999).

Debris-flow deposits are known from the northern Flinders Ranges east flanks and beyond. These have involved significant mass-slides of loosened, partly weathered bedrock out onto a lower surface, where gravity, together with a lubricant (typically water), plus a trigger (earth tremor or over-steepened slope), induced a down-slope flow of mud and rock fragments. The largest of these–which occurs east of Parabarana Hill and has flowed

Figure 12. Sheetflow deposit extending across a colluvial erosional rise.

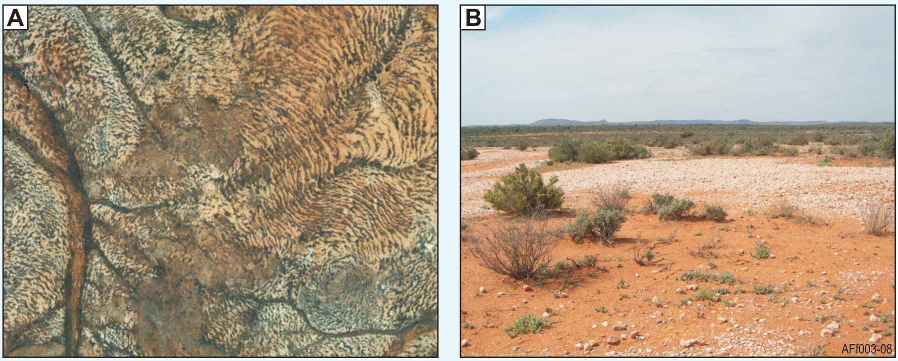


Figure 13. Contour banding is typically formed close to areas of outcrop in colluvial settings subject to sheetflow. Striping is a result of alternating bands of dense lag with silt-dominated, more vegetated sediment. (A) Aerial view of contour banding, 12 kilometres northeast of Kalabity Homestead (ortho-image), (B) field view of quartz-rich contour banding.

about 4 kilometres east (~3 km wide) and is 2–6 metres thick–is a matrix- to clast-supported conglomerate (angular to semi-rounded clasts ~75%, sandy-clayey matrix ~25%; Sheard and Callen 2000; Sheard, in prep.). Such materials over-run regolith of different geochemistry and landscape history, and can give a misleading geochemical signature if not recognised. Many more debris flows undoubtedly exist in this region.

Aeolian sediments

These form a component of most surficial regolith across the region. Landforms dominated by aeolian processes occur in the far north (Strzelecki Desert, lunettes around Lakes Callabonna and Frome) and to the south, where the influence of surface run-off from erosional terrains of the Olary Ranges is diminished. There, aeolian landforms, such as dunefields and sandplains, are preserved in the landscape (*Figure 14*). These materials can pose a major challenge to surficial geochemical sampling programs because they have the potential to mask, dilute and disperse bedrock chemical signatures. In practice, orientation programs determining the optimum sample size fraction have found the finer fractions (typically considered the most exotic in aeolian regolith) best express the underlying mineralisation signatures in areas of known mineralisation (Brown and Hill 2003; Law 2003; Skwarnecki *et al.* 2001).

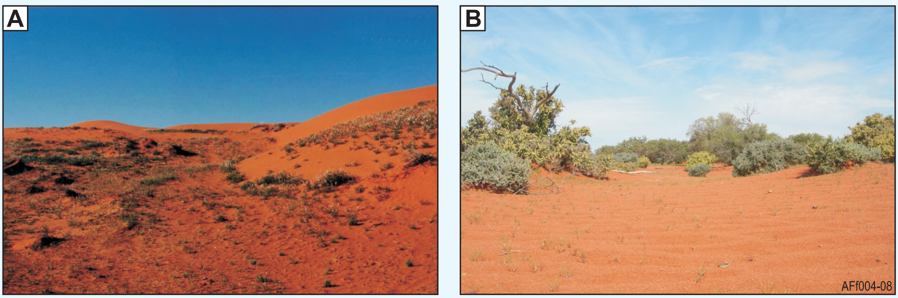


Figure 14. Aeolian dunefields cover the central Curnamona Province within the Strzelecki Desert, while aeolian sandplains extend into outcropping regions. (A) Iron-rich siliceous sand dunes of the Strzelecki Desert. (B) Sandplain on Bimbowrie Station (415146mE, 6463754mN, WGS84/MGA54).

Lacustrine sediments

Today, lacustrine sediments are restricted to Lakes Callabonna and Frome and many smaller playas and pans over the Curnamona that have inflows infrequently in times of extreme rainfall. In the Miocene, clay, sandy clay and silt (also carbonate and dolomite within the Poontana Trough) of the Namba Formation filled widespread saline to freshwater lakes covering a large portion of the Curnamona. Key sections can be found in Yalkalop 1 bore and Wooltana 1 bore. The Namba Formation is exposed north of Mount Painter, but elsewhere is largely restricted to dry lake edges and in creeks, east and southeast of Lake Frome (Curnamona, Frome, Callabonna 1:250k map sheets).

Indurated regolith (duricrusts, pans and cements)

Indurated regolith, formed by the introduction and precipitation of silica, iron oxide, carbonate or sulphate in pre-existing regolith, is present as distinctive cemented horizons termed duricrusts and pans.

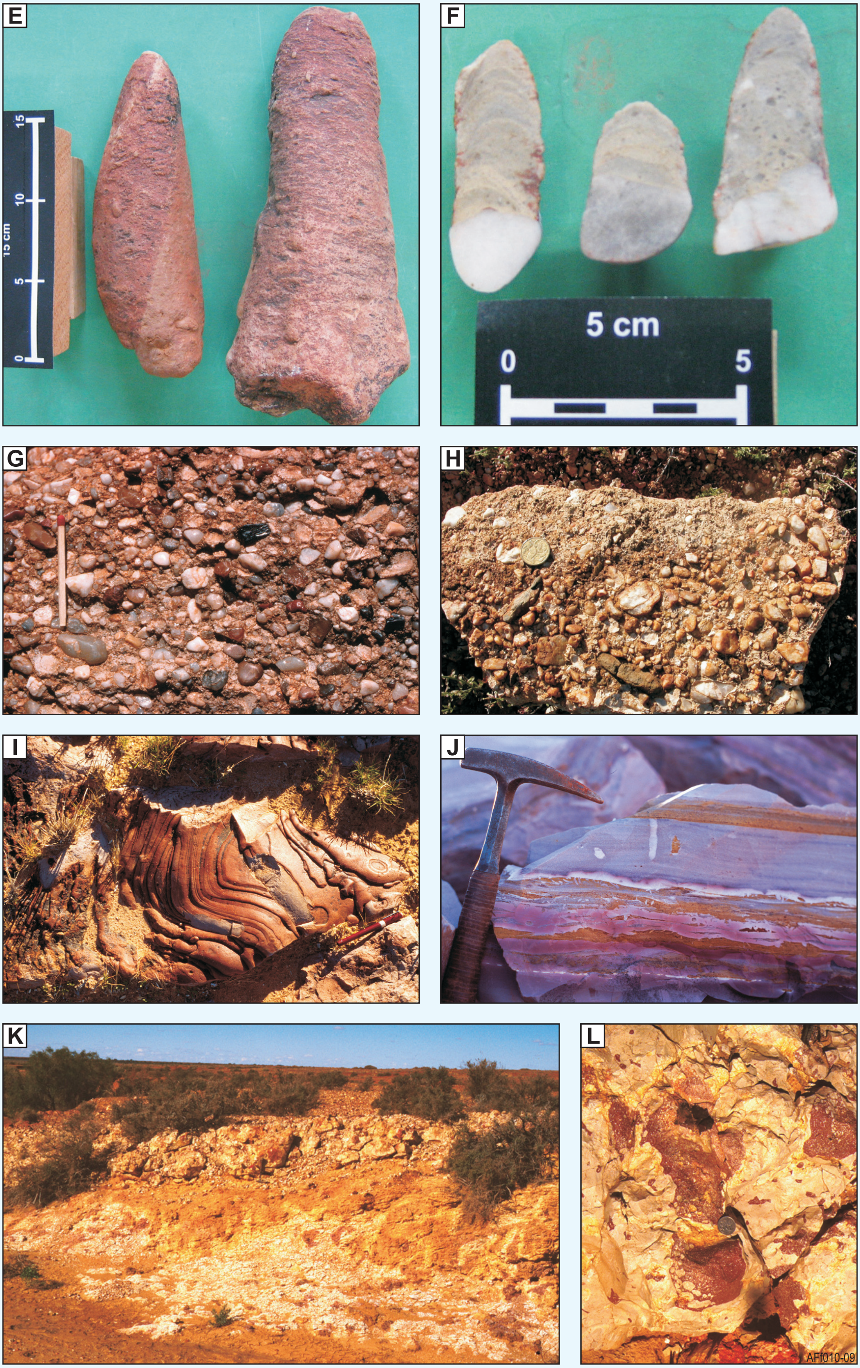
Silicified regolith

Siliceous regolith (see *Figures 15 and 16*) occurs in a variety of forms in this region, including: silcrete, porcellanite, chalcedony and common opal. Silicification occurs when silica saturation in a host medium is exceeded. Some of the major factors affecting silica mobility and precipitation include: pH/Eh; organic complexing biological activity; temperature and pressure; salt and cation content; redox reactions; and nucleation. Of the siliceous regolith types, silcrete is the most abundant; however, this can be derived from two distinct processes: pedogenic and groundwater. Common siliceous materials are listed below.

1. Pedogenic silcrete is a secondary siliceous cementation developed in porous regolith–at or near the surface–by pedogenic processes. It can form a durable armouring to many palaeo-surfaces. Silcrete is widespread across the Curnamona in both transported and *in situ* weathered units. Pedogenic silcrete consists of cryptocrystalline silica ± titania cements–replacing most, or all, fines–and infilling intergrain voids to yield a hard-brittle grey to brown rock. Where the host

regolith is strongly coloured, silcrete can be red, brown or yellow. Silcrete tends to break across entrapped grains rather than around them. Silicification entraps resistate mineral grains, such as quartz, which may display etch pits and embayed edges, ± ilmenite ± zircon ± hematite ± graphite ± Au. Silicified horizons range from less than 0.3 to more than 3 metres in thickness, but may also have an underlying incipiently silicified zone of less than 0.1 to about 1 metre thick.

Figure 15. Various Curnamona Province silcretes. (A) Steeply dipping pedogenic silcrete (~5 m thick) developed in ramp faulted Eyre Formation (dip ~ 60° SE, towards right-hand side). Groundwater silcrete crops out on the left-hand side (out of view) deeper in the section, west of Prospect Hill. (B) 'Ants nest' pedogenic silcrete spheroid aggregate (~2 m thick), north of Mount Babbage. (C) Pedogenic silcrete breccia developed in weathered Bulldog Shale, north of Mount Babbage (pen scale is 140 mm long). (D) 'Canon-ball' pedogenic silcrete (~1 m thick) developed below massive silcrete in steeply dipping Eyre Formation, east of Parabarana Hill.


E
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10
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Figure 15. Curnamona Province silcretes continued:
(E) Pedogenic silcrete columns, Mulligan Dam Regolith type section, northeast of Mount Babbage.
(F) Sectioned pedogenic silcrete mini columns displaying basal pebble growth-nuclei, and internal convex curved draped banding; from the same location as 'E'.
(G) Well-rounded and polished gravel (quartz + chalcedony + agate + jasper + petrified wood) upper Eyre Formation, enclosed within pedogenic silcrete, Mount Yerila (match scale is 43 mm).
(H) Silicified cobble beds of probable Palaeocene age are exposed within the Olary Creek to the southwest of the Radium Hill Mine (465747mE, 6421207mN, WGS84/MGA54).
(I) Groundwater silcrete with typical ropy top (Fe-stained), west of Prospect Hill (pen scale is 130 mm long).
(J) Porcellanite developed in highly weathered Mackunda Formation shale-siltstone, west of Prospect Hill.
(K) Silcrete duricrust (~1.4 m thick) on-in megamottled highly weathered Namba Formation. Silicification has encapsulated some megamottles (see 'L'), northeast of Blanchewater Ruins.
(L) Silcreted lower pedolith (enlargement from 'K'), silcrete encapsulated ferruginous megamottles (coin at centre, is 28 mm diameter).

Pedogenic silcrete exhibits similar morphologies to pedogenic calcrete in that it may be in the form of pisoliths, nodules, pebbles, boulders, laminated forms, columns or 'ant's nest' aggregated spheroids. Columnar silcrete is present in a number of areas, such as Mulligan Dam Regolith in the northern Curnamona (*Appendix 2*). The columns appear to 'grow' upwards as additional silica is deposited on an initiating nucleus–usually a clast–and they are characterised by draped concentric banding. Columns in this region may reach 0.5 metres in height and have a basal diameter of about 100 millimetres. Pedogenic silcrete in the Curnamona is known to affect the following units: Cadna-owie Formation; Parabarana Sandstone; Bulldog Shale; Marree Subgroup; Eyre Formation; and Namba Formation. Some of the best exposures within the Cenozoic units occur along the arcuate ramp fault running from Parabarana Hill (northern Mount Painter Inlier) north through Moolawatana pastoral station aerodrome, and then west to Mount Hopeless and Blanchewater Springs. This Cenozoic sequence has been locally upturned (< 75 to ~90º) and is incised by several creek lines. More regionally, surface exposures are best found

Figure 16. Mount Yerila—an isolated narrow north–south trending mesa-butte about 6.5 kilometres north of Mount Babbage Inlier and about 13 kilometres north northwest of Moolawatana Homestead. A pedogenic silcrete (~2 m thick) caps terrigenous Palaeogene Eyre Formation gravelly sand (~65 m thick), that unconformably rests upon Cretaceous marine Marree Subgroup shale. Erosion has removed between 100 and 150 metres of profile from the surrounding lower plain, leaving a let-down lag of silcrete gibber on weathering Marree Subgroup shale. View is westward.

around the edges of bedrock-dominated terrains (Mount Painter and Mount Babbage Inliers, and Moolawatana Domain) and as more-isolated occurrences (Olary and Broken Hill Domains). Episodes of pedogenic silcrete development in this region have–in numerous locations–been interleaved with basin onlap sediments that have been dated. Earlier workers argued for only two main silcrete formation episodes, although more-recent studies have demonstrated a third, older episode. The main episodes recognised so far include: pre-Eocene, Late Eocene, and Miocene to Pliocene. Silcrete has enclosed ferruginous megamottling within the Miocene Namba Formation, thereby indicating silcrete development there since megamottle development.

2. Groundwater silcrete is formed by precipitation of silica dissolved in groundwater: typically as a massive overprint at the margins of palaeochannels. Groundwater silcrete may display a distinctive ropy upper surface and a uniformly grey interior, with no banding or cloudy silica. It has lower trace element content, with very low Fe, Ti, V, Y and Zr compared with pedogenic silcrete. Examples of groundwater silcrete can be observed in exposed channel cross-sections along the ramp fault mentioned above. Silicified ?Palaeogene gravels are exposed in the Olary Creek near Tickalina Homestead.

3. Porcellanite forms by silicification of clayey to silty regolith–yielding a form of silica overprint that resembles unglazed porcelain. This can be as hard and brittle as massive silcrete, or quite friable when only incipiently developed. Porcellanite horizons may include veins/bands of chalcedony and hyaline opal. Porcellanite can form a duricrust cap to deeply weathered Bulldog Shale, Marree Subgroup and Namba Formation in the northern Curnamona.

4. Chalcedony is known from this area as rounded gravel-sized clasts (commonly highly polished) within the Palaeogene Eyre Formation. These can comprise 5–15% of some gravel bands and they also occur randomly throughout the Eyre Formation. Forms include: black chert-chalcedony; green, brown, yellow and red jasper; multi coloured agate; and silicified wood (the latter is not strictly chalcedony, but does have a micro- to crypto-crystalline silica structure). Sources for these granules are uncertain because they are not known from local outcrop and they may have been reworked from distal Mesozoic sediments during the Palaeogene. Some of these chalcedonic granules are probably alteration products developed within volcanic rocks, while others may have formed within weathering profiles. Importantly, these granules become concentrated in surface lags surrounding eroding Eyre Formation highlands. The flanks and surrounds of Mount Yerila (~13 km north-northwest of the Moolawatana Homestead) are a good example, but there are many others in the northern Curnamona Province.

5. Common opal occurs as hyaline silica–predominantly within the leached (pallid) saprolite zones in deeply weathered Mesozoic marine

shales (Bulldog Shale, Marree Subgroup and Mackunda Formation). Forms include fracture and remnant bedding parting infill, or as rare blebs within porcellanite caps on saprolite, and occasionally as shelly fossil replacement. Petrographic examination of thin-sectioned silicification zones below silcrete and within porcellanite indicates variable quantities of amorphous opaline silica infilling inter-grain voids. No evidence for precious opal has been reported from this region, but the formational processes for common opal are expected to resemble those observed and reported for Coober Pedy and Andamooka Opal Fields further west and northwest.

The resistance of silcrete to weathering and erosion means that it is commonly preserved in sites of topographic inversion: atop ridges and as mesa cappings on erosional plains. In erosional regimes, silcrete can form a conspicuous gibber lag that may temporarily armour a surface against more rapid erosive loss.

In general, their diverse form, common stratigraphically isolated occurrence and genesis suggest it is unwise to use silcrete horizon(s) alone as morpho-stratigraphic markers–other than at quite localised sites.

Useful references on silicified regolith, with particular relevance to the Curnamona Province, include: Wopfner *et al.* 1974; Thiry and Milnes 1991; Firman 1994; Benbow *et al.* 1995; Sheard 1996; Hill 2000; Sheard and Callen 2000; Sheard *et al.* 2000, White *et al.* 2000; Lintern 2004; and Sheard, in prep.

Ferruginised regolith

Ferruginised materials within the southern Curnamona have been studied in detail by Lawie (2001) and are also reported in Ashley *et al.* (1997). A number of ferruginous materials occur within the region (see *Appendix 2*). These include the ferruginous products of Willyama rocks, Adelaidean rocks, Mesozoic and Cenozoic sediments–with some being derived from deep weathering, whereas others have formed as a result of lateral movement of Fe at the near surface or within groundwaters. Details for mechanisms of ferruginisation can be found in Anand and de Broekert (2005); Butt *et al.* (2005); Taylor and Eggleton (2001) and Hill (2005). The combination of host rocks and modes of formation means their use as a sample medium can be problematic. Common ferruginous materials are listed below.

1. ***Gossans*** (no economic connotation) are derived from the weathering of sulphide-bearing rocks (commonly related to the Bimba and Portia Formation). Gossans are commonly goethite-rich. They follow underlying geological units or structures and may exhibit a boxwork fabric derived from their sulphidic precursor (*Figure 17A, B*).
2. ***Ferruginised Willyama Supergroup*** can be recognised by the presence of unstable remnant minerals, such as andalusite, and this suggest formation at a weathering front and not at the top of a weathered profile (*Figure 17C, D*). They commonly follow geological units.
3. ***Ferruginised Adelaidean rocks*** are common in the Strathearn Station region. The presence of unstable remnant minerals such as albite suggests formation at a weathering front and not at the top of a weathered profile (*Figure 17E*). They commonly follow geological units.
4. ***Ferruginised Mesozoic sediments (ferricrete)*** are generally restricted to around the Mount Painter and Mount Babbage Inliers and the northern Barrier Ranges. Ferruginisation is related to groundwater-derived Fe sesquioxide- and hydroxide-cementation of Mesozoic sediments that onlap crystalline basement (Sheard, in prep.).
5. ***Ferruginised Cenozoic sediments (ferricrete)*** occur as massive and pisolitic Fe accumulations developed in transported regolith derived from the lateral movement of Fe in the landscape. Pisoliths typically have broken or missing cutans. Tends to occupy high topographic positions owing to inversion of relief.
6. ***Ferruginous lags*** are predominantly transported fragments of (2) and (3), but also derived from exposed mottled zones (e.g. Mingary region; *Figure 17F*). Lags often retain primary rock fabric. In the northern Curnamona, ubiquitous ferruginous lags are commonly derived from eroding Mesozoic strata, rather than bedrock. Lawie (2001) noted that most ferruginised lags in the southern Curnamona are derived from pelitic rocks of the Strathearn and Saltbush Group.

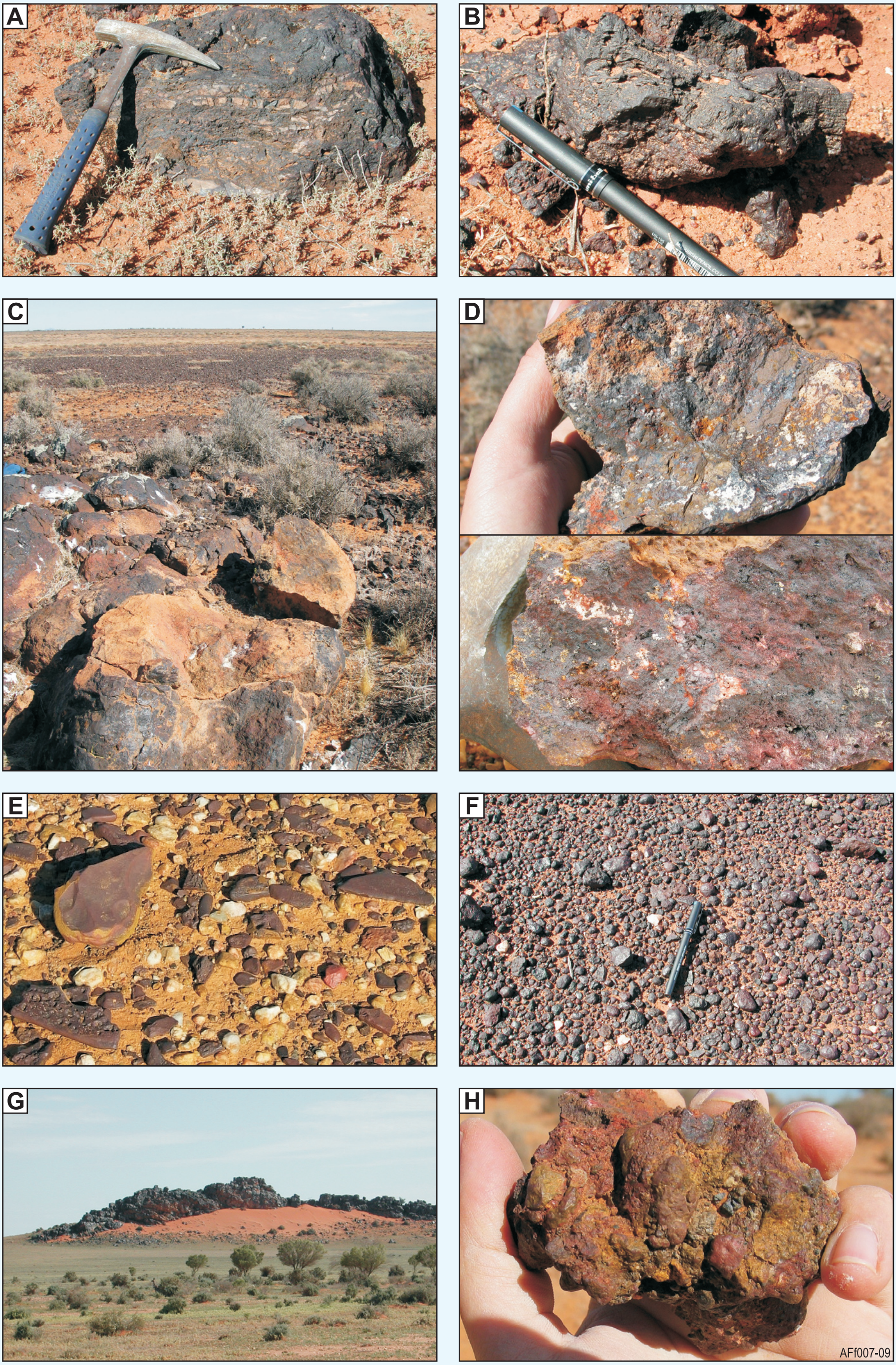
In similar landscape positions–and over quartzo-feldspathic rocks, pegmatites and quartz veins of the Curnamona Group–an angular quartz lag dominates.

7. ***Iron formations*** form prominent, steeply dipping outcrops and associated lag deposits (*Figure 17G*). These ferruginous materials encompass syngenetic, finely laminated Fe formations and massive epigenetic replacement ironstones and are predominantly composed of magnetite.
8. ***Mottles*** are developed over basement rock. Pedogenic processes commonly destroy primary rock fabrics, but kaolinite crystallinity can be used to demonstrate their basement origin (*Figure 9*). Degradation and erosion of mottles can result in extensive lag.
9. ***Ferruginised river gravels*** are a conglomerate of ferruginised rock fragments of different origins that have been cemented together (*Figure 17H*). Ferruginised river gravels occupy low topographic positions, which suggest a younger age of formation than (5).

Figure 17. Various Curnamona Province ferruginous materials.
(A) Ferruginous outcrop (probable Bimba Formation), 9 kilometres northeast of Strathearn Homestead.
(B) Gossan displaying bedrock/boxwork texture.
(C) Outcrop of ferruginised Willyama Supergroup, 15 kilometres southeast of Strathearn Homestead.
(D) Hand specimens of ferruginised Willyama Supergroup displaying bedrock textures such as quartz veining and remnant feldspar.
(E) Ferruginised Adelaidean siltstone lag, 2.5 kilometres east northeast of Strathearn Homestead.
(F) Blocky, nodular and pisolitic ferruginous lag.
(G) Outcropping iron formations, Ironstone Well.
(H) Conglomerate of ferruginised rock fragments (445569mE, 6482690mN, WGS84/ MGA54).

Regolith carbonates

Regolith carbonate accumulations–or calcrete–are generally widespread throughout the region, although their presence decreases northwards and away from outcropping regions (*Figure 18*; Dart *et al.* 2007). The word calcrete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is traditionally used in reference to regolith carbonate, although this tends to be misleading as the 'crete' implies complete induration, which is only occasionally present. Regolith carbonates are composed largely of calcium carbonate, but dolomitic or magnesitic carbonates are not excluded (Eggleton 2001). Regolith carbonates occur in semi-arid regions around the world and are widely distributed in southern Australia. Dart *et al.* (2007) has shown a dominantly marine source of carbonate throughout the Curnamona, where its contribution has swamped that related to Ca leached from bedrock.

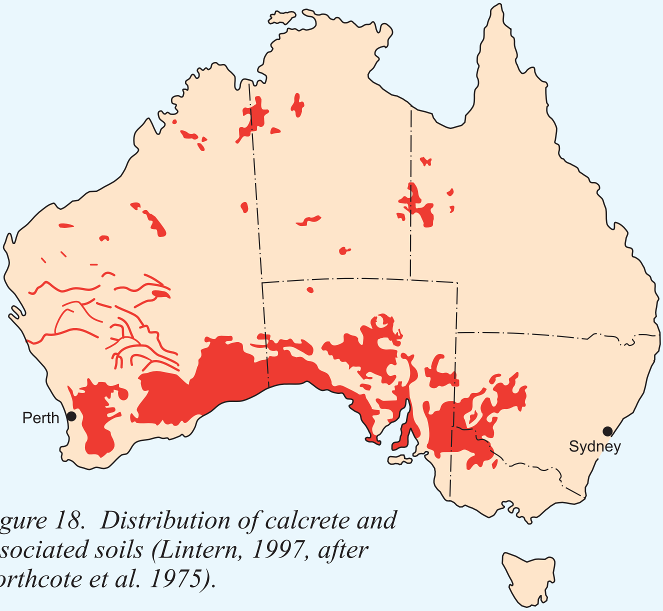

Figure 18. Distribution of calcrete and associated soils (Lintern, 1997, after Northcote et al. 1975).

Thick carbonate profiles are generally restricted to valley systems and flanking upland regions (*Figure 19A*). Within thicker profiles, a wide variation in carbonate morphology–with no strict chronological relationship–is common and includes: loose and aggregated nodules and pisoliths; earthy vermiform segregations and powders; and laminated and massive forms (*Figure 19*). These are developed within substrates of saprolite, pedolith, duricrusts, residual soils, fluvial and aeolian sediments. Many of the indurated forms have complex internal fabrics and structures: indicating cyclic carbonate deposition, dissolution, disruption, redistribution and re-cementation. The

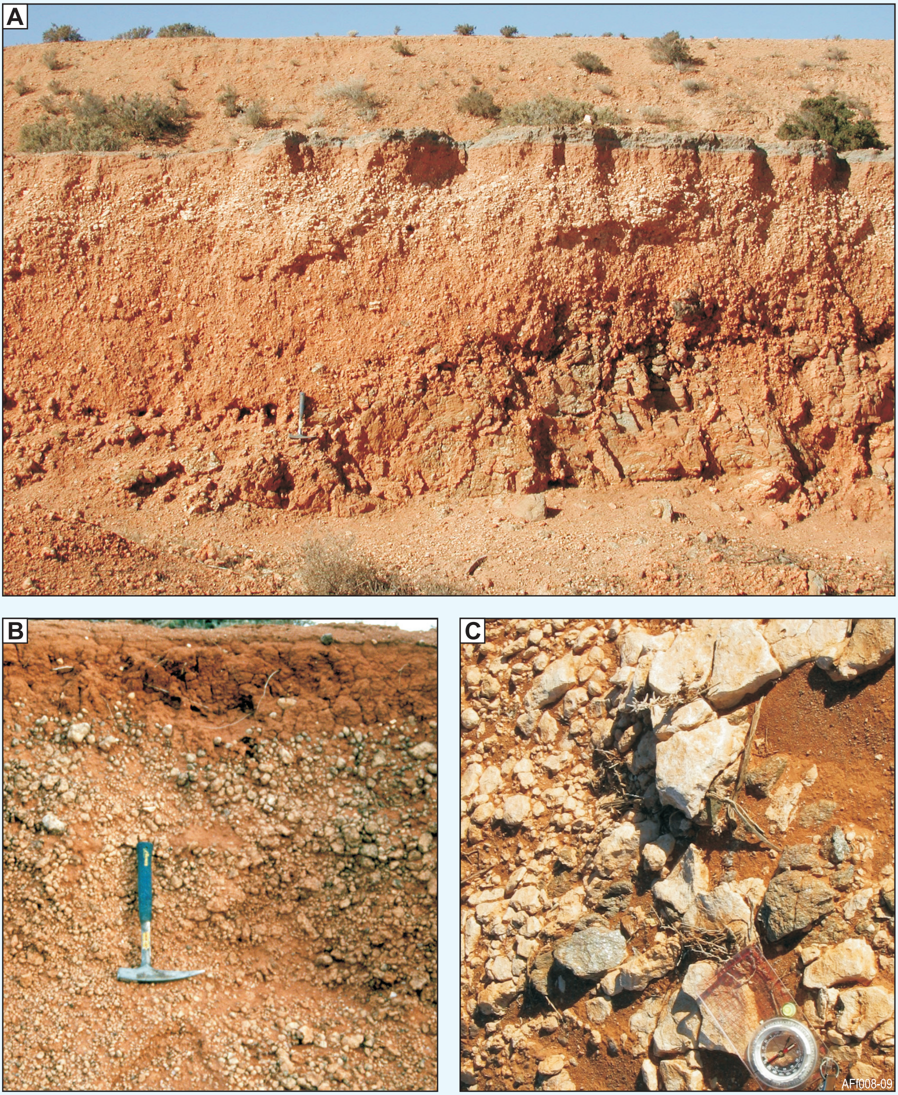

Figure 19. Typical calcrete occurrences and morphologies from the Curnamona Province.
(A) Calcrete horizon developed in alluvial sediments over weathered bedrock, Radium Hill Mine. Hammer for scale.
(B) Costean exposure showing well-developed nodular morphological facies, Pinnacles.
(C) Hardpan calcrete.

partially rounded cores of many nodules may be evidence of a transported origin (Wittwer 2004). Regolith carbonate accumulations commonly contain millimetre- to centimetre-sized fragments of saprolite, hardpan, silcrete, ferricrete and lags. Colours vary from cream to pale pink and pale grey to rich red and brown. Most indurated regolith carbonate is found towards the base of soil profiles. Commonly, the thicker units have horizontal partings and vertical fractures, which are exploited by plant roots.

Regolith carbonate accumulations also occur in modern ephemeral creek sediments as massive horizons less than 1 to more than 3 metres thick (colloquially called 'creekite'). This form of carbonate is related to lateral water movement to low areas in the landscape, rather than to pedogenic processes.

Gypseous regolith

Gypseous regolith is a component of many regolith types–either as disseminated crystals or polycrystalline aggregates–particularly in low-lying landscape settings (Hill 2005). The main settings include:

- near ephemeral playas containing evaporitic gypsum in the lake bed and accumulated in fringing lunettes where gypcrete pans can develop
- within the evaporative zone of the soil profile as small crystals (can easily be mis-identified in the profile as pedogenic carbonate)
- in saprolite on erosional rises; e.g. near Broken Hill at Balaclava
- within outcrop of Eyre Formation–commonly having polycrystalline morphology.

The addition of gypsum to transported regolith is predominantly via aeolian dust fallout, followed by dissolution and recrystallisation (Chivas *et al.* 1991; Watson 1985). Gypsum can also develop owing to weathering of sulphides or where sulphate bearing groundwaters are concentrated by evapotranspiration (Shirtliff 1998; Hill 2000). Gypcrete can also coincide with calcrete to form a mixed induration zone or horizon, and this phenomenon is widespread in arid South Australia (SA). Gypsum can also act as a significant geochemical dilutant within regolith (Lintern 2004).

Other indurations

Manganiferous accumulations are related to weathering of primary Mn-rich minerals. Associated lags are characteristically black. Anomalous geochemistry compared with other ferruginous materials is commonly a result of the highly absorbent property of Mn-oxides (e.g. for Cu, Co, Ni, U, W and Zn).

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) or a distant source (overlying alluvium e.g. Mundi Mundi Plain) (*Figure 20*). Lag is dominated by chemically and physically resistant minerals and rocks. Field observations indicate that lags containing metamorphic minerals within Willyama rocks rarely extend further than 100 metres from outcrop unless indurated. Lags derived from Mesozoic and Cenozoic sediments and duricrusts may extend many hundreds of metres to tens of kilometres from the source.

Pelitic lags are generally derived from the Strathearn and Saltbush Group, and angular quartz lag is developed over quartzo-feldspathic rocks, pegmatites and quartz veins, of and within the Curnamona Group (Lawie 2001).

Lag is dominated by chemically and physically resistant minerals and rocks. It includes a macroscopic component, commonly of quartz, lithic fragments, and indurated regolith of various size fractions. There is also a micro-lag component of resistate minerals including: zircon, rutile, ilmenite and other heavy minerals.

Soils

Soils are formed by the destruction of the fabric of the parent material by pedogenic processes related to climate, macro- and micro-organisms and topography (Eggleton 2001). As such, soils differ from the material from which they are derived in many physical, chemical, biological and morphological properties, and characteristics.

Figure 20. Various Curnamona Province Lags.
(A) Dense ferruginous lag spread related to nearby subcropping bedrock, 6 km SE of Strathearn Homestead.
(B) Ferruginised Willyama Supergroup lag in the foreground reflects underlying bedrock while quartz lag in the midground is related to regional colluvium.
(C) Quartz and silcrete pebble lag atop a highland-fringing Quaternary alluvial fan, S of Parabarana Hill.
(D) Quartz pebble lag east of Mt Babbage resting on weathering crystalline basement – but this lag is actually derived from eroding Cadna owie Formation (Cretaceous). This type of lag may have a very different history to nearby basement derived lag

The discussion on soils in the Curnamona Province that follows draws on: Lintern (2004), Lintern *et al.* (2006), Northcote *et al.* (1960-68) Northcote and Skene (1972), Sheard (1995), Sheard and Callen (2000) and Sheard, in prep.

There are numerous soil types in this region and those that dominate are listed and grouped in *Table 1*. Most have regolith carbonate developed within B_{Ca} horizons and, when relatively near the large playas, may also contain gypcrete horizons. Soils can incorporate surface lags (e.g. quartz, Fe-rich granules, quartz-rich lithics, silcrete and calcrete). Palaeosols are present in the area, but these are usually thin and generally difficult to recognise in drill cuttings.

Table 1. Dominant soils of the Curnamona Province.

Soil name[1]	Soil key[2]	General locality
Lithosols	Uc 1.43, 6.11, 6.13 Um 1.4, 5.11, 5.41, 5.51, 6.24	Flinders and Olary Ranges + on and near basement outcrop
Siliceous sands	Uc 1.21, 1.23	Strzelecki Desert + east of Lake Frome
Desert loams	Dr 1.13, 1.31, 1.33	Fringing the Flinders and Olary Ranges, alluvial fans
Grey, brown and red clays, dark soils	Ug 5.11, 5.17, 5.2, 5.3, 5.4, Uf 5.31, 6.32, 6.61 Um 6.12, 6.21	East and north of Lakes Blanche and Callabonna
Solonised brown soils	Gc 1.12, 1.22, 1.11	Central Curnamona Province, plains west and south of Lake Frome

[1] Wright and Northcote (1969); [2] Northcote *et al*. (1960-68) and Northcote (1979).
U = uniform texture; c = coarse-grained, m = medium-grained, f = fine-grained, g = gleyed fine-grained.
G = gradational texture; c = calcareous throughout.
D = duplex texture (contrasting horizons); r = red B horizon.
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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, whereas 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 obvious from a high proportion of calcrete and gypcrete in B horizons.

Curnamona Province clayey soils (medium- to heavy-textured) are predominantly of Late Quaternary age, although some may be considerably older. Some are uniformly textured, while others are gradational or even strongly duplex textured (i.e. sandy on clayey or loamy on clayey). The more pedogenically organised soils are developed on or near clayey substrates. In the arid zone, these tend to be sodic and alkaline. Clayey soils–away from dunefields, and near retreating escarpments or eroding uplands–are typically gibber-clad, lack horizon development and are 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 in the region's north and have only a small to moderate vertical texture contrast, minimal pedogenic differentiation, and tend to occur mostly within sandplains and dunefields. Luminescence dating of dune quartz grains gives ages ranging from about 243 ka to less than 4 ka (Gardner *et al.* 1987; Lomax *et al.* 2003; Sheard *et al.* 2006).

5.2 Distribution of regolith materials

Basin architecture

The depth to basement and 3D distribution of regolith over the Curnamona is critical in defining exploration risk and aiding drill hole interpretation. The subsurface mapping of regolith materials has been carried out using drill hole information and interpreted aeromagnetic and seismic data (Burtt *et al.* 2005a). Considerable mis-interpretation of drill hole cuttings has in part been resolved by palynological dating. These data have been combined to develop models of depth to basement, base of Cambrian, Mesozoic and Cenozoic (*Figure 21*; see 3D model in *Appendix 3*).

Sediment cover reaches a thickness of over 1 kilometre within the Moorowie and Yalkalpo Sub-basins and can be almost 6 kilometres nearer the Adelaide Geosyncline. These sediments are contained in a series of overlapping basins of varying lateral extent (*Figure 21a*). Adelaidean sediments are

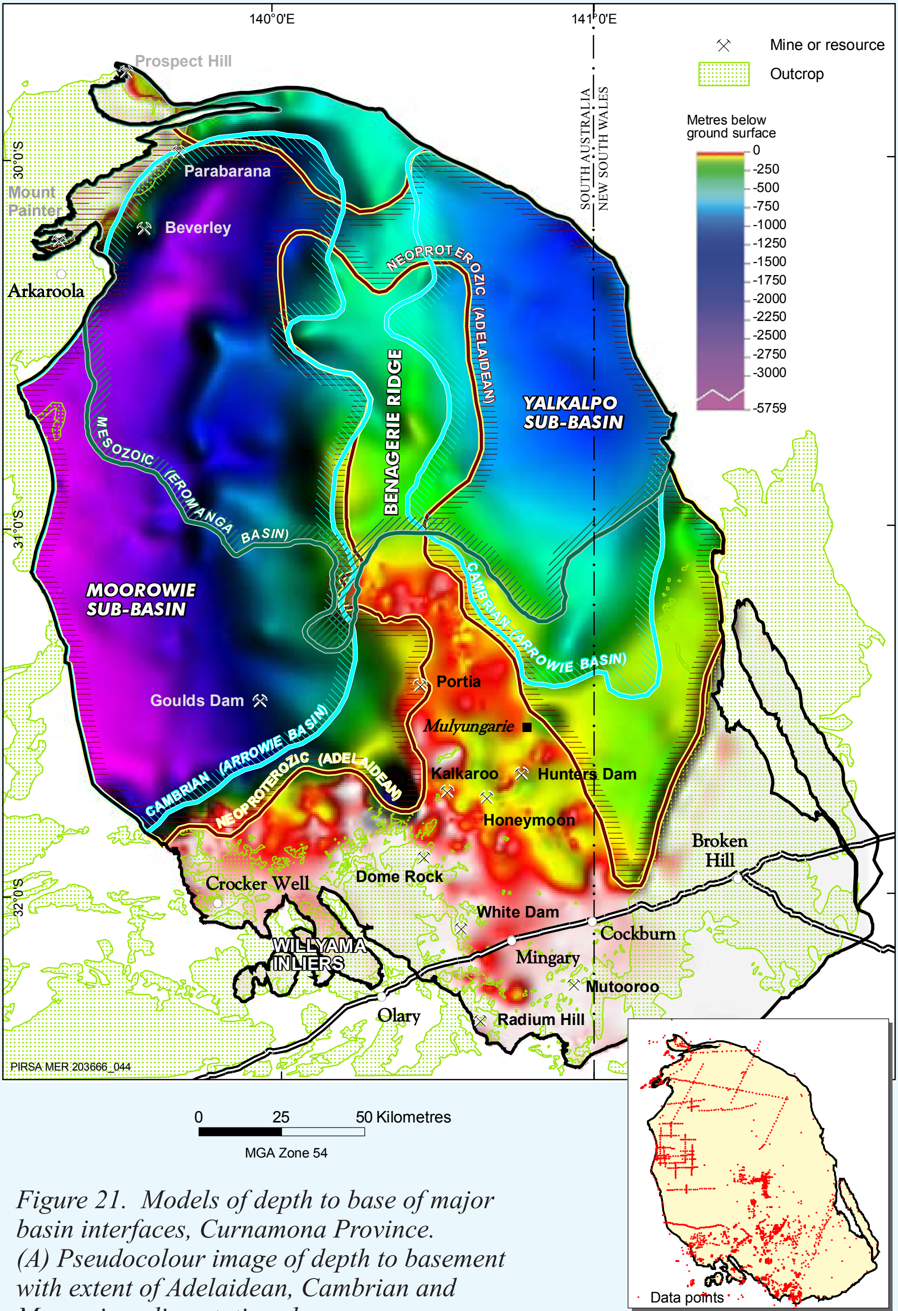
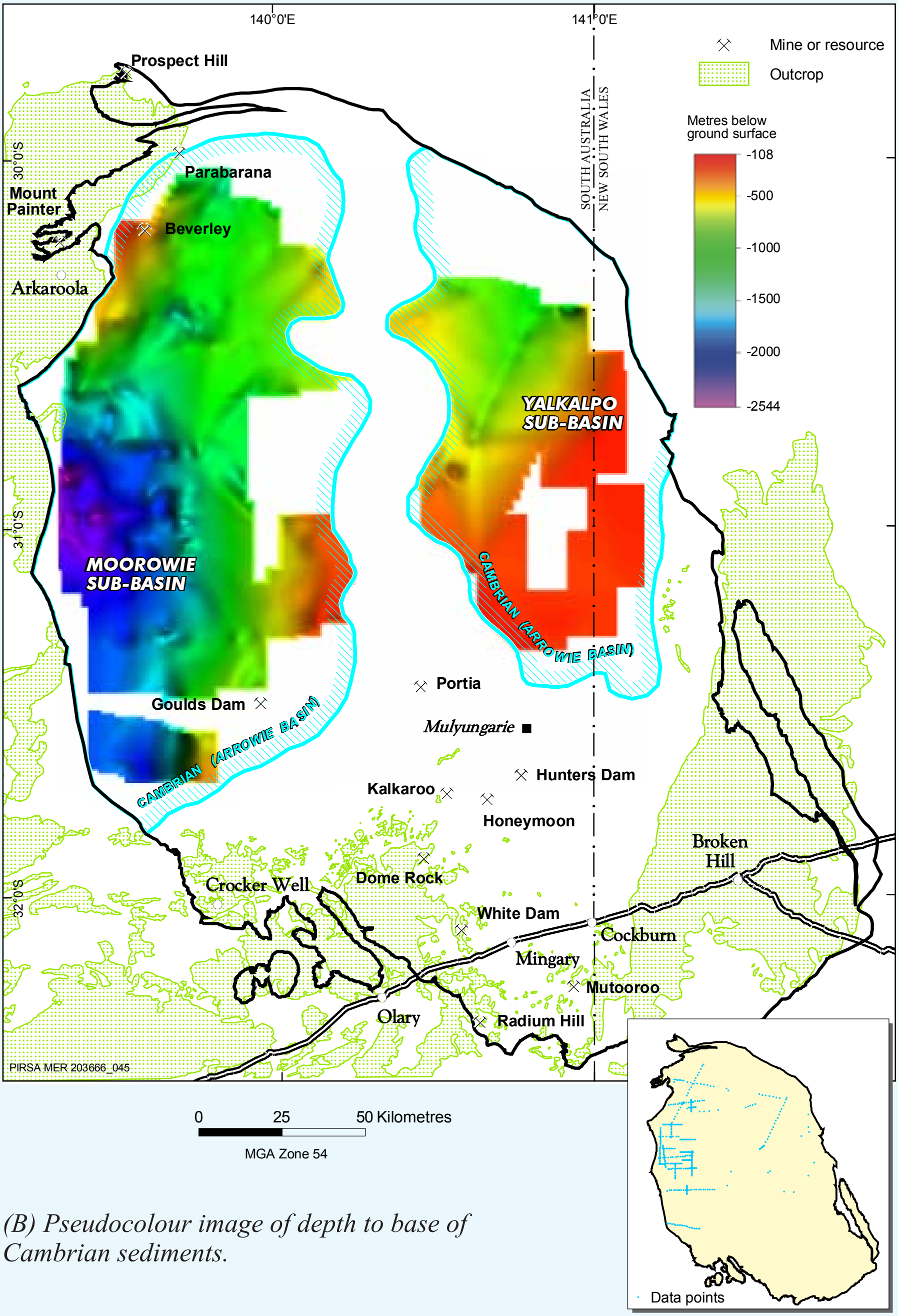
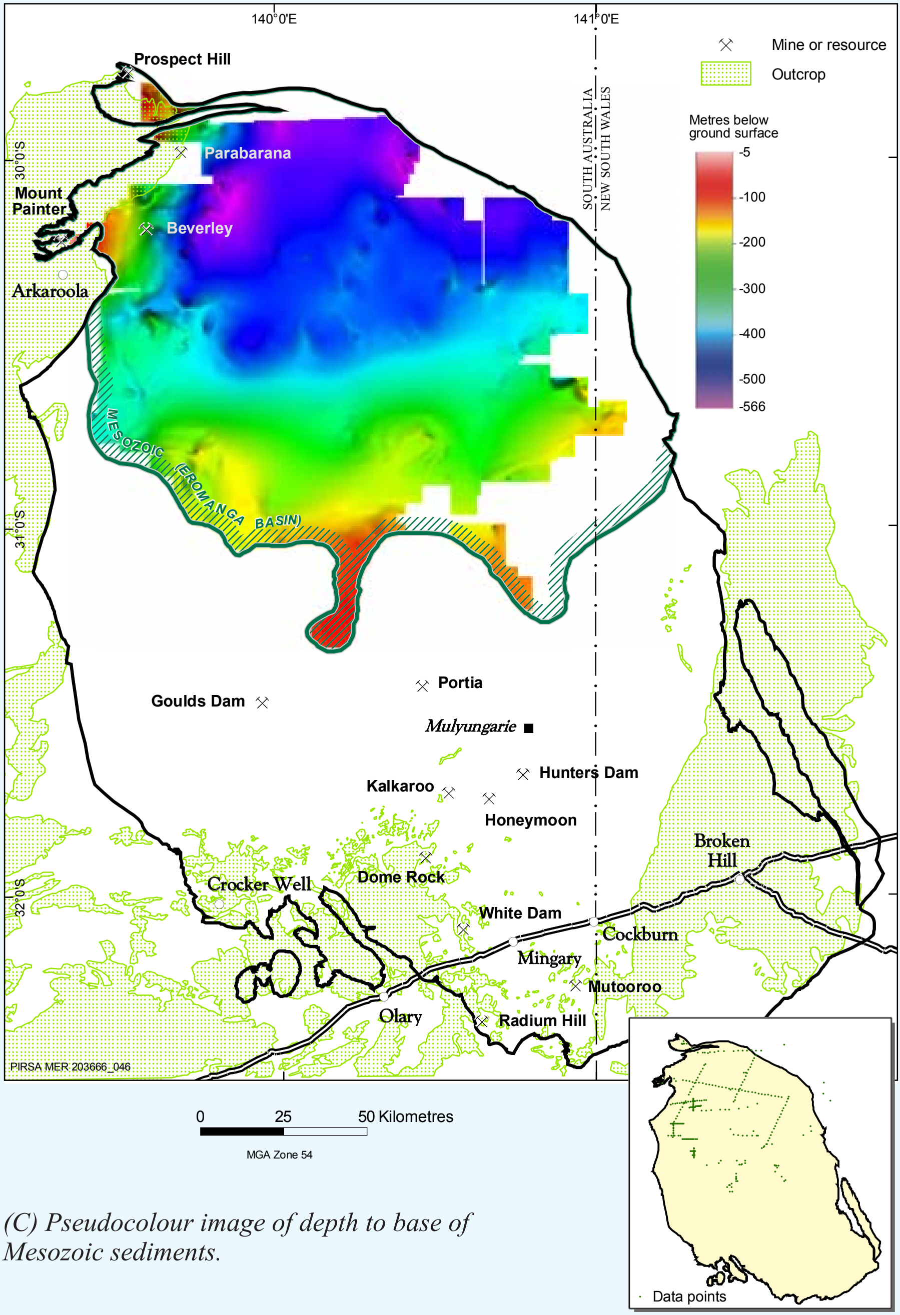


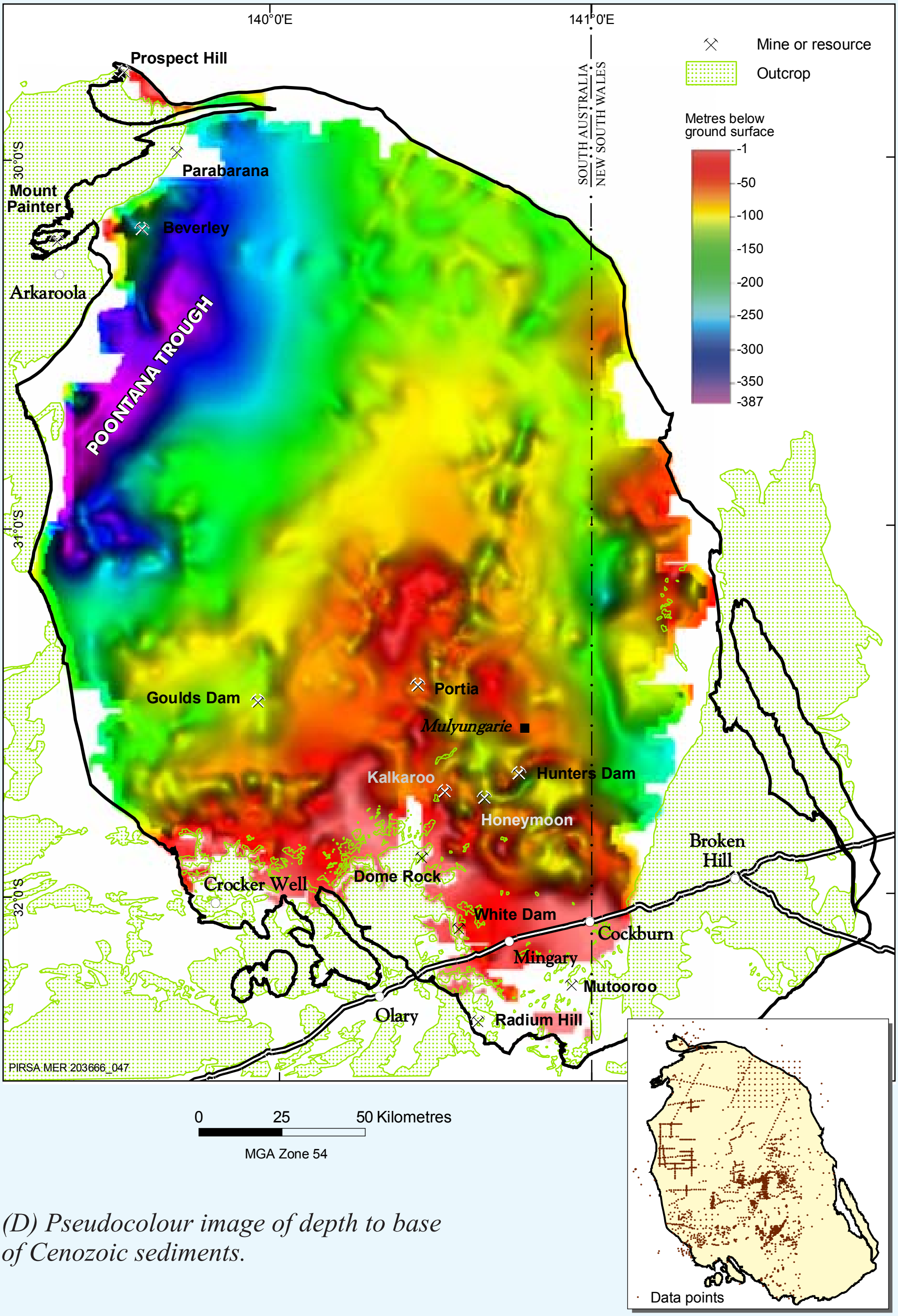
Figure 21. Models of depth to base of major basin interfaces, Curnamona Province. (A) Pseudocolour image of depth to basement with extent of Adelaidean, Cambrian and Mesozoic sedimentation shown.



(B) Pseudocolour image of depth to base of Cambrian sediments.



(C) Pseudocolour image of depth to base of Mesozoic sediments.



(D) Pseudocolour image of depth to base of Cenozoic sediments.

widely distributed, but are isolated to absent over the Benagerie Ridge and southern Curnamona Province. Cambrian sediments of the Arrowie Basin reach a thickness of at least 1923 metres within the Moorowie Sub-basin (Moorowie-1 drill hole), but thin towards the Benagerie Ridge, over which Cambrian sediments are generally absent. Mesozoic sediments range in thickness from over 300 metres in the north of the province to a few metres towards its margin in the central Curnamona Province. Cenozoic sediment cover is widespread and thickens from a few metres around the ranges, to over 300 metres within the Poontana Trough. Areas surrounding the Olary and Barrier Ranges are covered by thin to moderate, mainly Quaternary to recent, sediments. Where valleys were cut into basement rocks during the Palaeogene, subsequent sediment infill significantly increases cover thickness (e.g. sediment-fill within the Yarramba Palaeochannel can exceed 80 metres).

Regolith landform mapping

Regolith maps are constructed to provide context for exploration in regolith-dominated terrains. Specifically, regolith maps are used:

- as a first step to understanding the landscape evolution of an area and to provide a framework to interpret geochemical provenance and dispersion
- to show the distribution and abundance of various regolith materials available for geochemical sampling
- to aid design of geochemical sampling surveys and interpretation of results
- to provide a foundation for derivative maps that highlight attributes of the regolith or features for special purpose applications such as mineral exploration (e.g. *in situ* versus transported regolith, types of sample media).

Regolith-landform maps show the surface distribution of weathered products in context of the landform in which they reside. There is commonly a strong correlation between regolith type and particular landforms: therefore the two features are best mapped together. Features such as vegetation and

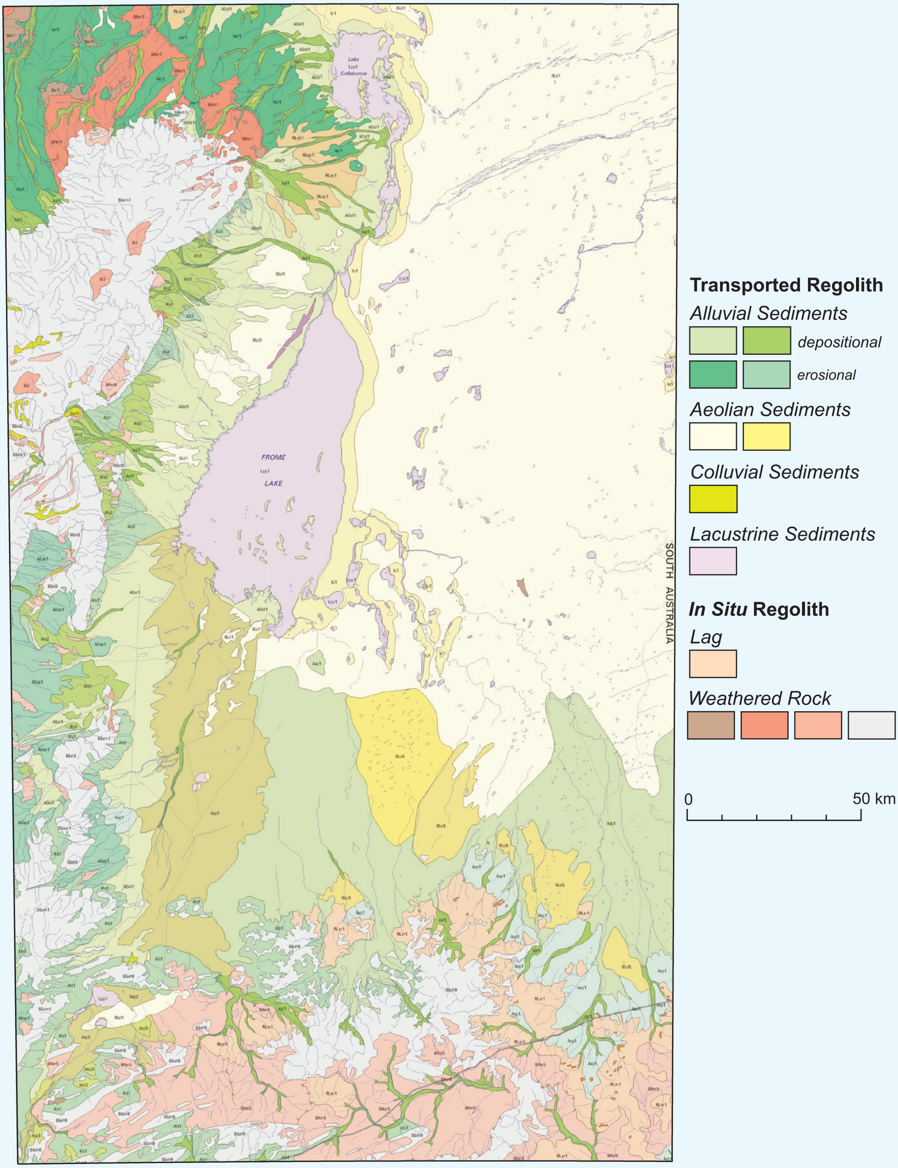


Figure 22. Regolith landform map of the South Australian portion of the Curnamona Province showing the distribution of major in situ and transported regolith units (RTMAP system from Gibson 1999). (see Appendix 4 for a digital copy of the map and detailed legend).

lag composition can be incorporated into map units as modifiers, and may be useful for further segregation of regolith units. 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. Of those, the RTMAP system (described in *Appendix 4*) and the RED scheme (and modified versions, see Crooks 2002) are the most commonly used (*Figures 22 and 23*).

As for all maps, the scale of mapping depends upon the purpose and use. For regional exploration, a scale of 1:25 000 is optimal in many situations, but more detailed mapping may be helpful at the prospect scale (1:10,000 or 1:5,000; Brown and Hill 2003). A list of regolith maps for the Curnamona is included in *Appendix 4*.

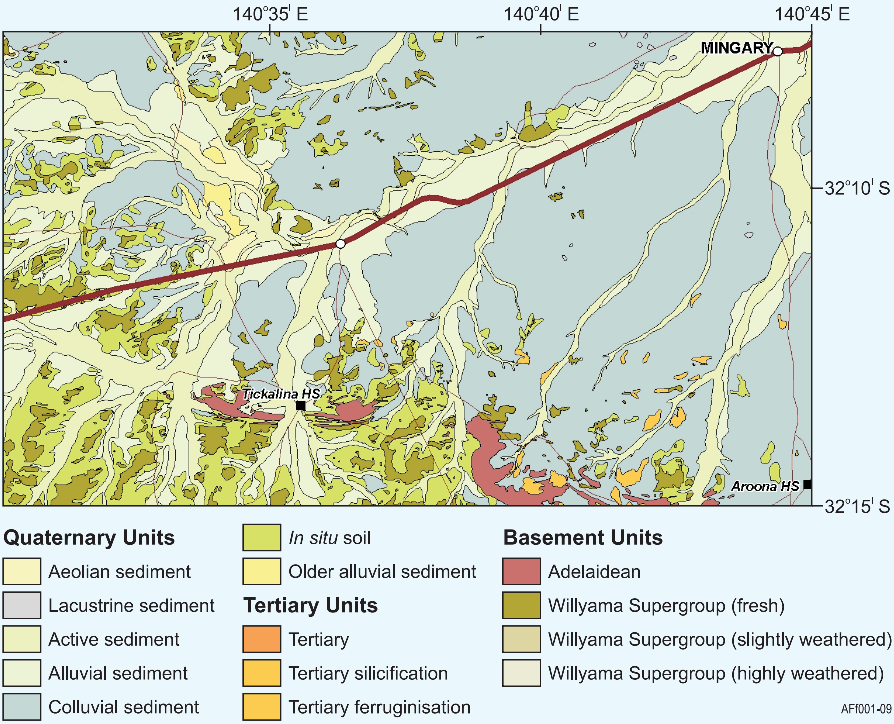


Figure 23. Excerpt from regolith landform map of the Mingary 1:100 000 map sheet using a modified version of the RED regolith mapping scheme (see Appendix 4 for a digital copy of the map).

Regolith mapping tools

Regolith maps are typically constructed using a combination of remotely sensed data and field observation (Papp 2002). Typical techniques and their uses include the following.

Surface mapping

- ***aerial photographs*** have the advantage of having high resolution and true colours, but a lack of contrast can make distinguishing regolith unit boundaries difficult. Orthoimagery (georectified aerial imagery) is readily available over the southern Curnamona and Quickbird over the Mount Painter Inlier.
- ***digital elevation models (DEM)*** are useful in defining landscape setting–particularly areas of drainage. The Curnamona is covered by shuttle radar tomography mission DEM (SRTM) at 90-metre resolution. The southern Curnamona also has a 50-metre resolution DEM acquired during collection of orthoimagery.
- ***Landsat imagery*** is widely available and easy to process with the appropriate software (e.g. ERMapper or ENVI). Data processing techniques such as ratioing and principle component analysis are effective ways of distinguishing a range of surface regolith materials (Wilford and Creasey 2002). Landsat is generally limited to mapping at 1:50 000 scale and mineral identification is quite basic.
- ***ASTER (Advanced space-borne thermal emission and reflection radiometer)*** has 14 bands: three from visible-near infrared (VNIR), six from shortwave infrared (SWIR) and five of which are in the thermal infrared, which, after processing, can map spatial distribution of clay, carbonate, Fe oxide and silicate. The spatial resolution varies from 15 metres (VNIR) to 90 metres (TIR) and is useful for mapping surface regolith at scales as high as 1:25 000. An investigation of ASTER for depicting abundances of mineral groups associated with either the composition of geological units, regolith material or possible overprinted alteration produced mixed results (Hewson *et al.* 2005). Maps were generated that qualitatively represent the abundance of mineral groups, including AlOH, MgOH/carbonate and quartz, over the southern Curnamona Province; however, their reliability was limited in

areas of low illumination or low albedo (i.e. reflectance). Additionally, cross-talk effects (band leakage) generated significant noise to SWIR bands and complicate interpretation.

- ***ASTER thermal bands*** measure the surface radiant temperature, which is controlled by the ability of near-surface bodies to adsorb and radiate thermal energy. Night time acquisition gives maximum thermal contrast (Tapley 1989) and can potentially detect temperature variation in subsurface sediments. This may be useful in mapping palaeodrainage, where higher moisture content may relate to shallow channel deposits. In the Curnamona, palaeodrainage that attracts economic interest is deeply buried and so spectral methods generally have limited function. Thermal imagery may, however, have some application around the Mount Painter and Mount Babbage Inliers (Stamoulis 2006) where there are shallower palaeodrainage systems, but this method remains to be tested.

- ***Hyperspectral sensors*** have tens of continuous spectral sensors across a wavelength width that enables the identification of many hydrous silicates, carbonates, Fe oxides, clays, micas, chlorites, amphiboles, talc, serpentine carbonates, pyroxenes, feldspars and sulphates (Papp and Cudahy 2002). The HyMap system has excellent spatial resolution (3–10 m), which enables it to be used at prospect scales. Hyperspectral techniques can potentially identify large alteration systems related to mineralisation, thereby increasing the size of the exploration target. Hyperspectral techniques–both airborne (HyMap) and proximal instruments (PIMA, ASD and Hylogger™)–have been used to map the character and mineralogy of regolith materials. In the White Dam area, processed HyMap imagery was used to identify *in situ* soils (comparatively high in goethite and kaolinite of various crystallinity) and weathering halos around bedrock exposures (comparatively high in white micas) (Lau 2004). Information of this type can guide effective soil-sampling programs.

- ***Airborne radiometrics surveys*** measure gamma radiation from a number of radioactive isotopes that may be linked to the abundances of K, Th and U in the top 30 centimetres of the regolith (given that U and Th are in equilibrium with their relevant daughter isotopes).

Radiometric methods are useful for identifying areas of outcrop, source regions in U exploration and for surface regolith mapping (*Figure 24*). Areas of thick vegetation cover and strongly leached *in situ* and transported regolith show a low response for all three elements (they appear dark in RGB combination). Active colluvial/alluvial systems typically have a gamma-ray signature similar to the bedrock from which they have been derived. Playa lake systems are relatively enriched in U and consequently appear blue.

- ***Magnetic imagery*** can be used to map regolith materials directly –typically relying on the accumulation of maghemite and magnetite within transported materials or weathering products. Although this has application to mapping drainage and palaeodrainage, it has not generally been effective in the Curnamona due to limited availability of magnetic minerals.

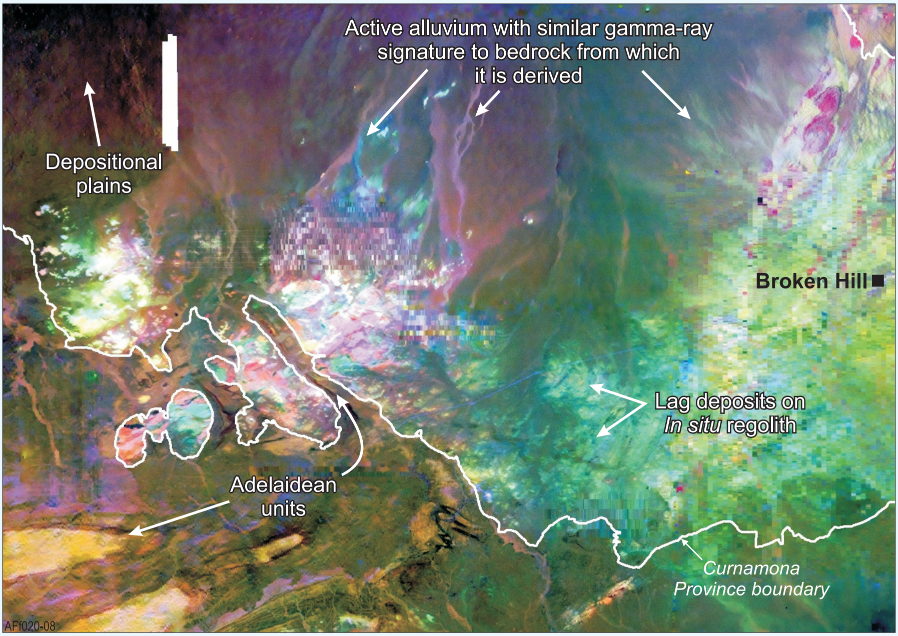


Figure 24. Ternary RGB radiometric image of the southern Curnamona Province. Brightly coloured regions highlight mostly residual regolith. Adelaidean rock units appear blander and of darker tones than Willyama rock units. Areas of transported regolith show a low response for all three elements (appear dark). Active colluvial/ alluvial systems typically have a gamma-ray signature similar to the bedrock from which they have been derived.

Subsurface mapping

- ***Electrical (AEM and TEM) methods*** measure the electrical conductivity of the ground both laterally and vertically. Data can be processed to show ground conductivity as a function of depth, and can potentially be an ideal means of mapping the regolith in 3D. The electrical properties of regolith materials may vary depending on their porosity, moisture content and the conductivity of saline groundwater within them. High salt content within transported regolith throughout the Curnamona severely decreases the effective depth of electrical methods and may mask bedrock features (conductivity values are typically 1–5 ohm-m; Baker 2007; Godsmark *et al.* 2003). This is important when designing surveys to be used in the region e.g. a TEM transmitter loop size of at least 100 metres is necessary to gain a response from basement below 60–80 metres of transported cover in the Kalkaroo region. The direct detection of mineralisation using electrical methods in areas of thick cover has generally been unsuccessful because of the thick and conductive overburden, although chargeability mapping using the MIMDAS system gave moderate success over the Kalkaroo deposit (Busuttill and Law 2003).

  Electrical methods have successfully been used to map the thickness and distribution of palaeochannel sediments, depth to basement, thickness of weathered bedrock, shallow faulting, groundwater and salinity (Baker 2007; Busuttill and Bargman 2003; Davey 2003; Lane 2002). The technique has been widely adopted by U explorers in the Curnamona to gather data on the distribution and thickness of palaeochannel sediments, where few other surface techniques have been successful. The fixed-wing, time-domain airborne system, TEMPEST, is typically used and is preferred for large areas and deep ground penetration to around 150 metres (Dentith and Randell 2003; *Figure 25*). Ground transient electromagnetic surveys (TEM) have been shown to map subsurface features within the regolith at a range of depths (several metres to hundreds of metres; Baker 2007; Davey 2003). Data can be used to produce 2D and even 3D maps showing the electrical properties of the regolith (*Figure 26*).

- Most ***seismic surveys*** in the Curnamona have been conducted in relation

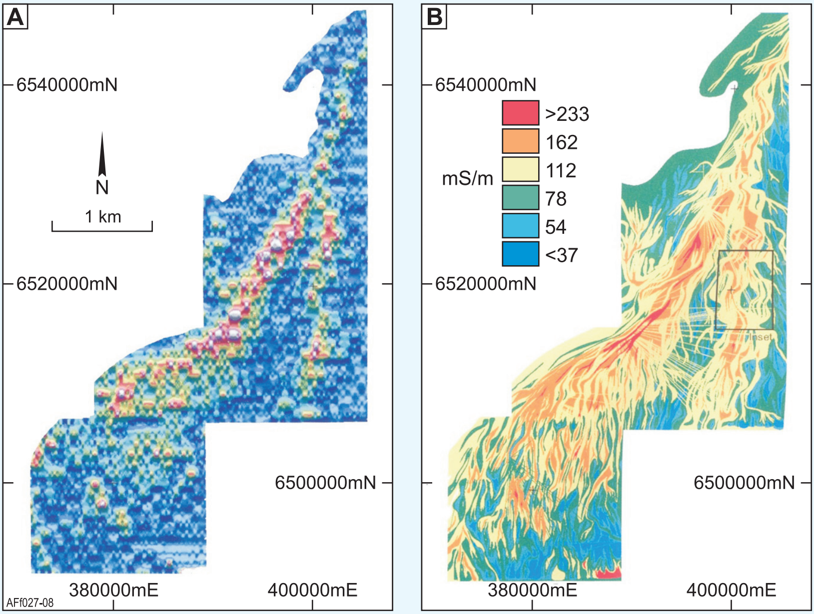


Figure 25. (A) TEMPEST 25 Hz airborne EM data from across the Curnamona and Billeroo palaeochannels. The data are the conductivity–depth slice for 100 metres. (B) Interpretation of (A). (after Dentith and Randell 2003).

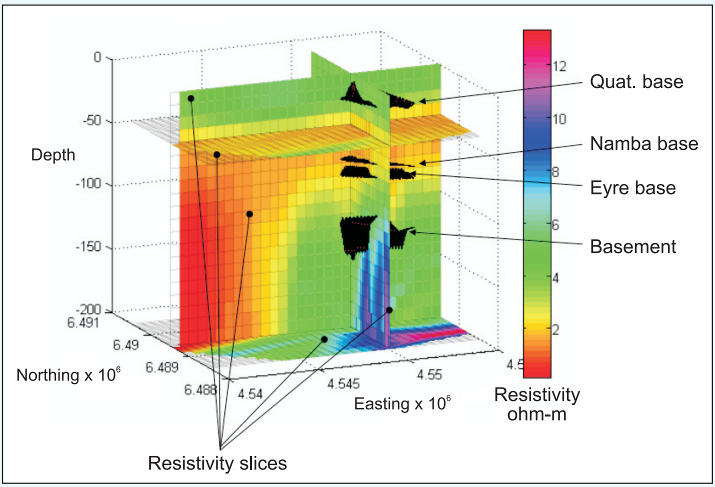


Figure 26. Example of the process of compiling 2D resistivity slices to create a 3D resistivity volume. The profiles highlight a horizontal layer with low resistivity (mapping Cenozoic sediments) and variation in bedrock (low resistive region in the west and highly resistive region towards the east; from Baker 2007).

to petroleum exploration. The majority of surveys were conducted in the 1960s to 1980s. Data definition in the near-surface region (< 100 m) is poor; however, the seismic profiles can be used to distinguish basinal features, including stratigraphy, major unconformities and faulting. Deep palaeodrainage can be interpreted from subtle features within a more recent seismic survey (03GA-CU1); however, specialised surveys with increased resolution in the top few hundred metres is regarded as a requirement for detailed palaeochannel mapping.

- ***Down-hole spectral methods,*** such as the PIMA, can be used in the discrimination of *in situ* from transported regolith based on kaolin crystallinity (Dawson 2000; Lawie 2001; Tan 2001). Hyperspectral mapping is not only a powerful tool for surface mapping, but instruments such as HyLogger™ and HyChips™ can be used for down-hole mineral mapping.
- ***Geophysical well logging*** offers the opportunity of determining the composition, variability and physical properties of the regolith around a drill hole. A number of geophysical tools are available (Chopra *et al.* 2002). Geophysical well logging is routinely used in sedimentary U exploration because of its application to detailed sedimentological analysis and natural radiation determination (potentially related to U mineralisation). Electrical logs can be used to ground-truth airborne EM data.
- ***Gravity surveys*** map density contrasts which are conventionally used to map basement rocks and structure. The generally lower density of the regolith may have a considerable effect on the interpretation of gravity data. For example, Paleoproterozic basement topography is the dominant factor affecting the gravity response over the Moorowie and Yalkalpo Sub-basins because of the low density of the thick sedimentary fill. Considerable processing and modelling are required to distinguish subtle features that may relate to ore deposits.

  Detailed gravity surveys can be used to map zones of intense weathering, such as those related to oxidation of sulphide mineralisation. Residual negative gravity anomalies (amplitudes of 1 to 2 mGal) from detailed gravity measurements (50 m intervals on 200 m spaced lines) over the Benagerie Ridge Magnetic Complex have been used to identify numerous prospects based on enhanced deep weathering of sulphide-rich zones (Godsmark *et al.* 2003; *Figure 27*).

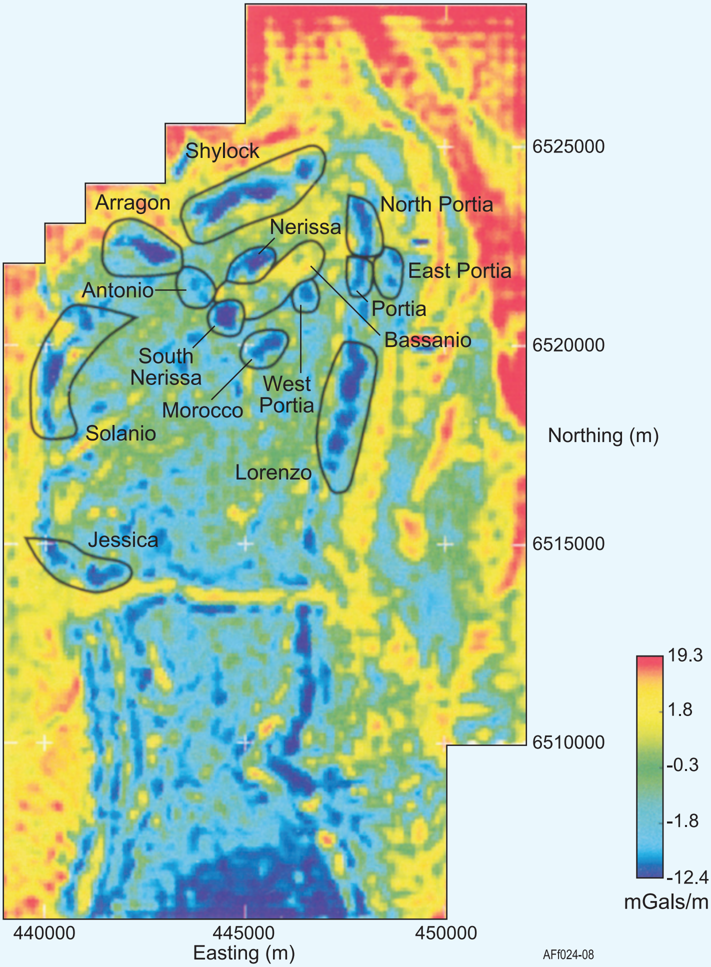


Figure 27. Bouguer gravity 1st vertical derivative of the Benagerie area with the trace of Portia mineral prospects. Prospects from the Portia region are associated with gravity lows (after Godsmark et al. 2003)

Gravity surveys can also be used to explore within the regolith, such as for palaeochannel-hosted deposits. Gravity has been used in conjunction with AEM surveys to explore for U in the region (Dentith and Randell 2003). Provided there is sufficient density contrast between the channel-fill and incised bedrock, processed residual gravity data can indicate the thickness and extent of palaeochannels. Station spacing will depend on channel width (commonly 100 m).

- ***Magnetic data*** are critical to the mapping of basement rocks and structures in areas covered by transported regolith. Detailed surveys allow mapping of particular stratigraphic units–based on their magnetic response. This information has been used extensively to target stratiform and stratabound mineralisation in the district (Busuttill and Law 2003). Magnetic minerals, such as maghemite, are not common in the cover sediments in the region and generally do not interfere with basement magnetic signals.

5.3 Regolith geochemical fundamentals

Element dispersion during weathering

Weathering of primary rock-forming minerals ultimately leads to residual profiles dominated by quartz, kaolinite ± Fe and Al oxides/oxyhydroxides. 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 (McQueen and Munro 2003). Goethite, hematite, alunite-jarosite group minerals, Mn minerals, and regolith carbonates are important trace element hosts with widespread occurrence. Smectite group clays–and possibly also vermiculite–can incorporate a wide range of trace elements in their crystal structure (Taylor and Eggleton 2001). Smectite group clay minerals also have a high cation-exchange capacity. Depending on pH (acidity), 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.

The process of sulphide weathering

The majority of mineralisation styles relevant to the Curnamona involve sulphide as part of their ore mineralogy, and so an understanding of sulphide weathering is paramount. The following is a summary of more comprehensive reviews in Thornber and Taylor (1992), Blain and Andrew (1983) and Lawie (2001).

As sulphide bodies are progressively exhumed, their contained sulphide minerals gradually became chemically unstable. Weathering agents within groundwater–particularly water, dissolved oxygen, carbon dioxide and ionic species–cause the sulphide body to chemically re-equilibrate. Sulphide minerals oxidise, where bacteria may play an important role in catalysing the reactions (Nordstrom and Southam 1997), releasing electrons that are consumed elsewhere by complementary cathodic reduction reactions. The migration of anions and cations take place between mineral grains of different reactivity and, where there is electrical conductivity, between the near-surface oxidative environment and relatively reduced base of the water table (Taylor and Eggleton 2001). The resultant current flow means that during weathering, large sulphide bodies act as very large electrochemical corrosion cells (Andrew 1980). Where sulphides are disseminated, chemical interaction with wall-rock minerals is significant: leading to intense leaching due to the low pH generated and the formation of kaolinite at a more rapid rate than where sulphide is absent.

In some instances, corroding sulphides are then transformed to stable oxidate phases at the top of the profile to form gossans. The influx or residual enrichment of Fe and silica lead to the formation of stable secondary minerals (predominantly Fe-oxides and hydroxides) that incorporate or adsorb soluble metal ions. However, depending on the chemical environment of gossan formation, leached ore metals may be lost to the system completely. They may also react with primary sulphides to further enhance the development of supergene enrichment zones. These are typically broader than the primary mineralisation.

The mineralogy, geochemistry and texture of the resultant gossan differ considerably from that of the primary sulphides from which it was derived

(Lawie 2001).

Controls on element dispersion

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). These are particularly important where there are significant changes or boundaries, such as the sediment cover/weathered bedrock interface and regolith carbonate horizons (pH > 8.6)
- ***availability of complexing and oxidising agents*** (e.g. O_2, CO_2, SO_4^{2-}, NO_3^-, halides and organic compounds)
- ***biogeochemical processes*** including element uptake and recycling by roots, bioturbation by burrowing animals (both invertebrates and vertebrates), tree throws and the significant role of microbiota (bacteria and fungi) in mineral weathering, biochemical dissolution and fixation (Milnes 1992; Reith and Rogers 2004)
- ***evaporation***, which causes precipitation of solutes in the near-surface environment
- ***physical processes*** (water, wind and gravity), which cause mechanical dispersion. 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) become strongly bound to hematite, which may be widely dispersed into colluvium, alluvium and soil by mechanical processes (McQueen 2008).

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

Effect of climate on weathering regimes

Chemical conditions in the regolith of the Curnamona Province have changed significantly through time, particularly in response to climatic changes. Warm and wet conditions, with high water tables, dominated from Paleocene to Late Miocene times (McPhail 2007). These conditions generally favoured hydration–hydrolysis reactions–aiding 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 particularly where sulphides were oxidising or decaying vegetation occurred (e.g. swamps). There is widespread evidence of high organic levels in soils, swamps and lakes (lignitic beds and carbonaceous horizons); their presence would favour organo-complexing of many elements.

A shift towards more regional arid conditions occurred after the Mid Miocene (McPhail 2007). 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, whereas other elements–especially Pb, Ba and Hg–would have been relatively fixed as insoluble chlorides, sulphates or carbonates. Marked pH gradients around sulphide deposits that continued to weather resulted in dispersion of some elements (e.g. As, Cu and Zn) to form broader anomalies.

Element transport in covered terrains

Lateral dispersion is an important component of element transport in areas of transported cover (e.g. surface process and groundwater flow). However, there are many mechanisms that can potentially result in vertical element mobility through transported cover (*Figure 28*; Govett 1976; Goldberg 1998; Hamilton 1998; Smee 1998; Aspandiar 2004; Mann *et al.* 2005; Cameron *et al.* 2004). Those that may be relevant to upward metal transport through thick cover sediments in the Curnamona region include:

- ***fluctuating groundwater***–groundwater is the main agent of dispersion of metal ions from an ore body. Furthermore, heat produced by the weathering of sulphides can lead to the upward migration of metal ions within the saturated zone driven by convection. Fluctuation in groundwater levels can mobilise mineralising elements from bedrock into transported sediments

- ***capillary rise and evaporation***–ions can be concentrated above the water table by the effect of capillary rise and evaporation. Capillary rise within the soil profile in conjunction with evaporation at the surface provides an advective mechanism to pump metal ions in solution to the near-surface (Mann *et al.* 2005)
- ***water flux***–in semiarid and arid conditions, where evaporation far exceeds precipitation, water (liquid and vapour) flux in fine-grained sediment can be in the upward direction throughout up to 100 metres of unsaturated sediment (Scanlon *et al.* 2003). This provides a possible advective mechanism to link the water table at depth to the near-surface
- ***electrochemical***–the redox differential between the oxidising environment towards the surface and reduced conditions at depth is the basis behind electrochemical movement. In saturated conditions, an oxidising sulphide body will become a conductor within this field, causing an excess in cation concentration around the top (cathode) of the conductor and positive potential around the bottom (anode) of the conductor and subsequently promotes upward ionic movement (Govett 1976; Smee 1983, 1998; Hamilton 1998)
- ***deep-rooted vegetation***–the potential for plant-assisted metal transfer is based on the plant's ability to source elements from groundwater. Many plant species have dimorphic root systems: with lateral and vertical (taproot) roots. Taproots can potentially extend for metres to tens of metres (Canadell *et al.* 1996). The depth of penetration of the taproot is critical in determining whether the target plant species is obtaining elements from the subsurface or just recycling a soil anomaly. In areas of thick sediment cover in the Curnamona, vegetation tends to be relatively sparse and dominated by shallow-rooted species. Vegetation–groundwater interaction was possibly more significant in the past when climatic conditions were much wetter. Fossil soil anomalies that reflect

underlying mineralisation may therefore be buried in the profile and may have potential to be remobilised

- ***gas migration***–gases are generated during the oxidation of an ore body and/or groundwater and can migrate upwards by molecular diffusion, advection, barometric pressure changes and gas streaming (Hale 2000). In the process of gas streaming, gases evolved during weathering ore bodies, such as CO_2, COS, H_2S, SO_2 and various hydrocarbons, can carry metal ions to the surface where changing pressure can cause instability of the gas 'bubble' and subsequent release of the metal at the near-surface. Although most gases that reach the surface are lost to the atmosphere, some are adsorbed onto the surface of soil particles. The role of bacteria in ore-body weathering is believed to be important in the generation of ore-related gases
- ***seismic pumping***–earthquake activity compresses faults and fractures, which may result in the effusion of groundwater or gases associated with mineralisation to the surface. This process is particularly relevant on the margins of the Flinders Ranges where earth movements are common.

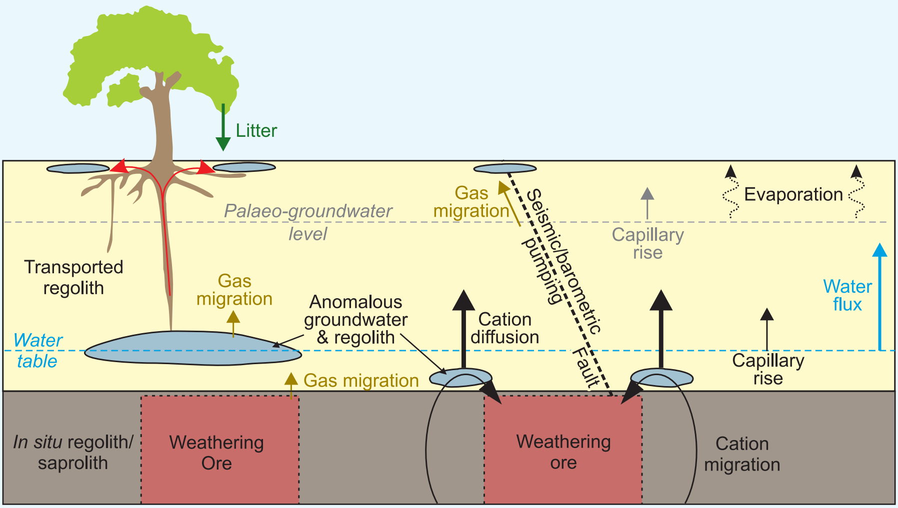


Figure 28. Some potential mechanisms for vertical dispersion through the regolith. Any one or combination of these mechanisms can result in near-surface geochemical anomalies.

Regolith element associations

Some useful points and regolith-related element associations relevant to exploration in the Curnamona Province are set out below. These are drawn from: Fabris (2007), Lawie (2001), Skwarnecki *et al.* (2001), Tan (2001) and Wittwer (2004).

- Namba Formation clays tend to have elevated Zn levels compared with overlying Quaternary and underlying Eyre Formation sediments.
- Mineralising elements (Au and Cu) have been mobilised into the overlying Eyre Formation and in its absence, into the Namba Formation (elevated concentrations are noticeable for only a few metres vertically from the *in situ*-transported regolith contact as determined at Portia and Kalkaroo.
- Across the region there are 'evapotranspirative' zones in the near-surface regolith marked by the deposition of Ca and Mg carbonate in particular, but also other salts. These have been found to be useful sampling media for Au, Cu, Zn, Pb, and As.
- Surface soil sampling has shown some degree of success in both residual and transported regolith regimes. Elements that have discriminated underlying mineralisation within surface samples include Ag, Au, As, Bi, Cd, Co, Cu, Mo, Pb, U, W and Zn.
- Iron oxides and oxy-hydroxides may incorporate Au, Cu and other trace elements (As, Bi, Sb, Se, Zn and W) and be useful locally. Tan (2001) reported that ferruginous zones in the saprolite over the Portia and North Portia prospects act as host for Cu, Pb, As and Mo. Ferruginous saprolite derived from barren albitite and carbonaceous pelite does not host significant chalcophile elements and oxyanions. Lawie (2001) found that ferruginous materials derived from the weathering of sulphide-bearing rocks are goethitic, and non sulphide-derived ferruginous materials are dominantly hematitic. The only significant goethite detected in non-gossanous rocks was in pisolitic ferricrete.
- Most anomalous elements within gossanous materials in the Curnamona are held within goethite, and locally within secondary Mn minerals such as lithiophorite, hollandite and cryptomelane (Lawie 2001). An

exception was Cu, which was present in all secondary iron phases.

- Pisolitic ferricrete contains a Zn–Cu–U–Co–Ag association indicative of a 'fossilised' groundwater signature. This association may be related to groundwater transport responsible for 'roll-front' U mineralisation that flanks the Benagerie Ridge. From an exploration point of view, the pisolitic ferricrete and its associated chemistry does not have any 'connection' to basement.

Behaviour of selected elements in the regolith

Lawie (2001) summarised the behaviour of elements during weathering, and the following section is a modified version.

Iron (oxide)

Iron activity during weathering is important because of its particular Fe^{2+} (soluble) and Fe^{3+} (insoluble) oxidation states which have an important influence on the pH and consequently on the mobility of other elements (Thornber 1985). Minor elements (e.g. Cu) are also often co-precipitated with, or adsorbed onto, secondary Fe minerals.

Aluminium (oxide)

The solution chemistry of Al is dominated by Al^{3+}. Its solubility is significant below pH 5 (as Al^{3+} in solution) and above pH 9 (as the soluble anion $Al(OH)_4^-$; Thornber 1985). Aluminium is commonly precipitated in the form of clay minerals or, where sulphate and K^+ is readily available, as minerals of the alunite–jarosite group (Nickel and Daniels 1985).

Manganese (oxide, cation)

The solubility of Mn exceeds that of Fe by six or seven orders of magnitude at any given Eh and acid pH (Nickel and Daniels 1985). Manganese oxides are effective scavengers of some of the important ore-forming elements and may influence sample media geochemistry.

Copper (cation, metal)

The behaviour of Cu is complex as it possesses two oxidation states (Cu^+,

Cu^{2+}) that transition in the middle of the Eh range that is typical during the weathering of sulphide-rich bedrock (Thornber 1985). Where Cu is abundant, significant amounts can go into solution and be transported if the pH is below 5 (Thornber 1985). The result can be the formation of secondary Cu minerals where more alkaline conditions are encountered. The most widespread mineral–malachite–is precipitated at near neutral pH in the presence of carbonate, and is highly stable (Nickel and Daniels 1985). Where SO_4^{2-} and Cl^- are readily available, Cu^{2+} can be immobilised under low pH conditions in compounds such as atacamite, $Cu_2(OH)_3Cl$, and brochantite, $Cu_4(OH)_6SO_4$ (Thornber 1985). Chrysocolla–a stable mineral–is precipitated under conditions of high silicon activity (Nickel and Daniels 1985). At pH values less than 6, where Cu^+ and Cu^{2+} can exist with Fe^{2+} in solution, the weathering of Cu sulphides, such as covellite or chalcocite can result in the precipitation of native Cu.

Lead (cation)

Pb^{2+} is relatively insoluble: forming compounds with phosphate, sulphate, chloride and carbonate (Thornber 1985). Lead in solution also adsorbs very strongly onto Fe oxyhydroxide surfaces.

Zinc and Nickel (cations)

Zinc and Ni are mobile in acid solutions (Thornber 1985). At neutral and higher pH, Zn and Ni are readily co-precipitated with Fe-oxides, or adsorbed by them, and can be retained in the regolith where subject to limited weathering. At low pH, adsorption onto Fe-oxides is less than that for other base metals. Secondary Zn minerals, such as the carbonates, smithsonite and hydrozincite, and the silicate, hemimorphite, are readily precipitated at neutral or higher pH. Secondary Ni minerals also precipitate at higher pH values, but these tend to be dissolved during subsequent weathering.

Gold (metal, cation)

Gold may be retained as a primary mineral in the weathering environment. However, on exposure to weathering it is generally relatively depleted in Ag which Mann (1984) took to indicate that Au and Ag have been dissolved, transported and redeposited. More recent work by Butt and Hough (2006) suggest that it is just a result of the Ag being leached. Solutions capable of dissolving Au alloys can occur under neutral to alkaline conditions or very acidic, oxidising conditions (Mann 1998). At neutral to alkaline pH, the oxidation of sulphides, such as pyrite, can generate thiosulphate capable of dissolving Au/Ag alloys (Webster and Mann 1984). Oxidising sulphide ores also produce bisulphide complexes, which are also able to mobilise Au (Vlassopoulos and Wood 1990).

In low pH conditions, Cl^- is able to corrode Au alloys via acid chloride- or thiosulphate-bearing solutions. Although both are stable under different pH and Eh conditions, both environments are possible in a single weathering profile at the same time: i.e. acid oxidising conditions above the water table; and neutral less-oxidising conditions below the water table.

Cyanide and organic complexes may also be important in Au mobility. Their role is partly or extensively influenced by biological factors, such as bacteria, fungi or plants (Gray *et al.* 1992).

The particle size of elemental gold in the secondary environment is dependent not only on primary mineralisation, but also on mechanisms of supergene dispersion and reprecipitation (*Table 2*). Coarse primary Au tends to be unevenly distributed or ‘nuggetty’ in the regolith, whereas very fine-grained gold is more evenly distributed (Lintern and Sheard 1998, 1999a, b).

Table 2: Some potentially important gold species (modified from Gray et al. 1992).

Species	Solubility Conditions	Product
$AuCl_2^-/AuCl_4^-$	Oxidised-saline-acid	High-fineness gold
AuI_2^-	I- released from organic matter	High-fineness gold
$Au(HS)_2^-$	Reduced-neutral	Medium-high-fineness gold
$Au(S_2O_3)_2^{3-}$	Alkaline-mildly acid	Medium-fineness gold
$Au(CN)_2^-$	Cyanide present	Low-fineness gold

Silver (metal, cation)

Silver is associated with many of the mineralisation types across the

Curnamona region. Silver metal is fairly unreactive. When sulphides are oxidised, native Ag is commonly precipitated, but, during prolonged weathering, or in the presence of thiosulphate, can be taken into solution. If the halogens chlorine, bromine and/or iodine are present, silver will form complexes. Chloride is the most soluble of the halides, so the formation of Ag chloride complexes will tend to deplete Ag in the upper parts of a gossan forming profile (Mann 1984). Fabris *et al.* (2007) noted a general shift in background values of Ag in near-surface soils over thickly covered bedrock at the Kalkaroo and Polygonum prospects, and demonstrated these shifts in background concentration may reflect changes in underlying lithologies. This suggests that Ag may be mobile within regolith of the Curnamona and be useful in discriminating bedrock stratigraphy in covered regions.

Molybdenum (oxyanion)

Molybdenum is associated with sulphide mineralisation as molybdenite. On weathering, Mo can be released into solution and is readily precipitated–often as the hydrated secondary mineral, ferrimolybdite, $Fe_2(MoO_4)_3.8H_2O$ (Nickel and Daniels 1985). Molybdenum may also go into solution as the anionic species molybdate, MoO_4^{2-}. At low pH, this anionic species may be adsorbed onto goethite.

Uranium (cation)

Uranium has two common oxidation states under natural conditions: the reduced form U^{4+} and the oxidised form U^{6+}. In its oxidised form, U is highly mobile as the uranyl ion (UO_2^{2+}) or may form soluble complexes with CO_3^{2-}, HPO_4^{2-}, OH^-, F^- and other anions (Langmuir 1978). During weathering, U has a similar mobility to Mo and As, and together, these commonly form groundwater anomalies (Rose 1994). Once mobile as the uranyl ion, U may be immobilised via adsorption onto secondary Fe and Mn minerals or organic matter. Uranium may also be immobilised via reduction. The reduction and precipitation of U from groundwater may occur to the extent of accumulating economic concentrations of U in 'roll-front' deposits. Reductants within channel sediments typically include decomposed organic matter, sulphide and carbonaceous clay.

6. EXPLORATION STRATEGIES IN REGOLITH-DOMINATED TERRAINS

It is widely believed that all of the significant mineral deposits in areas of outcrop in the Curnamona Province have been discovered. In the last few decades, exploration for basement-hosted mineralisation has ventured into more deeply covered regions. The Kalkaroo and Portia prospects are examples of success in such terrains (> 50 m transported cover). Despite this success, the failure of conventional soil sampling techniques to delineate the mineralised zone under less than 4 metres of transported cover at White Dam (Brown and Hill 2007) suggests that deposits are still being overlooked.

Large tracts of prospective terrain remain both in deeply and thinly covered depositional settings. These areas are not only prospective for basement-hosted mineralisation, where the regolith acts as a mask, but for mineralisation within the sedimentary cover such as U (e.g. Honeymoon, Beverley) and placer Au (e.g. Portia). The challenge is to explore these areas effectively.

The ultimate aim of understanding the regolith is to reduce the risk associated with exploring in covered areas. Furthermore, understanding what can be sampled–and the origin of what is being sampled can help in knowing how to assess and rank data and, subsequently, a region's prospectivity. Regolith information should be seen as another knowledge layer to be integrated with geological, geochemical and geophysical data and direct 3D information from drilling.

6.1 Key questions

Key questions for mineral exploration in the Curnamona Province include:

- What is the depth to *in situ* regolith?
- Where is the *in situ* regolith and where is the transported regolith?
- What are the dispersion pathways for target and pathfinder elements and what is their form or host minerals in the regolith?
- Does transported regolith completely mask the geochemical signature of underlying mineralisation?

- What exploration techniques have been effective in regolith-dominated terrains?
- What is the best material to sample in drill holes?
- What is a significant anomaly and how do we rank anomalous data?

The answers to these questions lie in understanding the regolith.

6.2 Exploration approach

The initial stage of exploration involves establishing the nature of the regolith: its thickness, its character (*in situ* or transported), the degree of weathering and, if transported, its origin. This information can be derived from a combination of surface and subsurface mapping techniques including drilling and geophysics (see Section 5.2). The information can be used to select appropriate exploration methods and sampling techniques for particular areas (e.g. surface versus drill sampling, media type, type of geophysical methods; *Figure 29*). It can also help plan orientation studies that take into account the variety of regolith-landform units and materials. Areas that have been surface sampled or drilled to shallow depth in previous exploration programs may have included transported regolith or strongly leached saprolite. Regolith-landform mapping can identify these areas, which might be re-examined using more appropriate sampling methods or deeper drilling. As exploration proceeds, the regolith database should be extended and refined by addition of new information (e.g. from drilling and geochemical data). This information can be used to develop regolith dispersion models that will further guide sampling (*Figure 30*). Well-developed models will describe palaeo-landscape evolution and dispersion trends. Dispersion is an evolving process. For example, rising or falling water tables brought about by climatic change and/or tectonic movement can impose a different set of chemical conditions on a previously formed dispersion pattern and further modify it (Lawie 2001). In areas of thick transported regolith, gossanous weathering profiles may be buried. Groundwater flowing through the weathered ore zone, which may be significantly different to that that initially formed the gossan, could mobilise metals and transport them into the overlying and younger rocks (*Figure 31*). Later erosion can expose any level of a dispersion system and may enlarge geochemical haloes by mechanical dispersion.

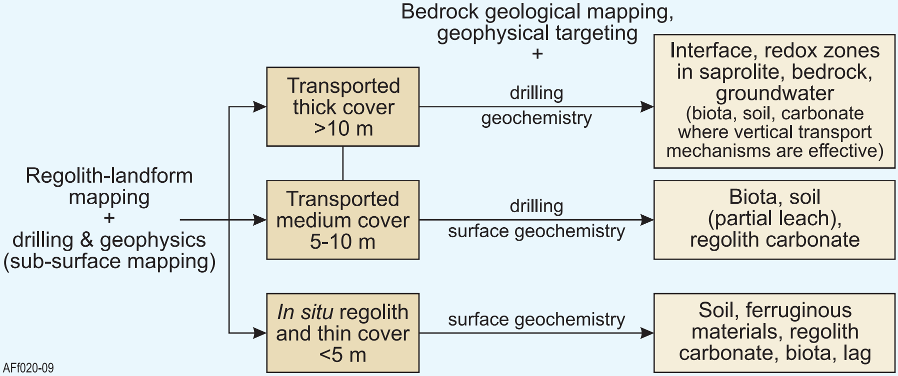


Figure 29. An approach to exploration in regolith-dominated terrains

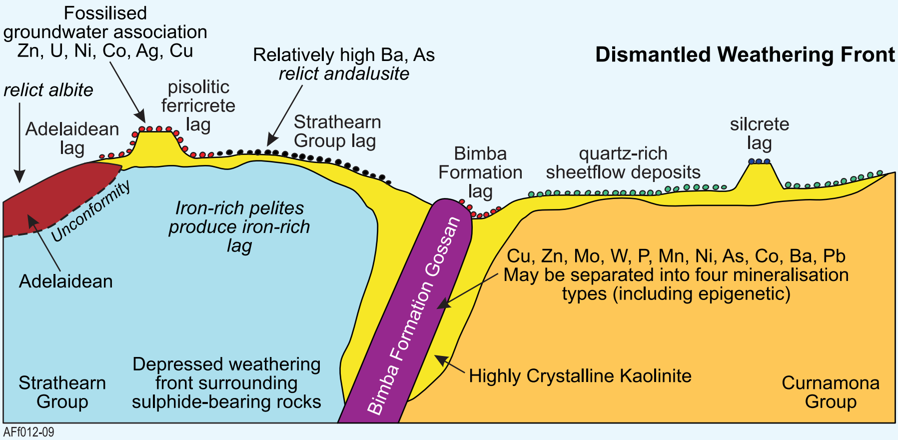


Figure 30. An example of a regolith dispersion model for the southern Curnamona Province. Chemical dispersion during weathering forms ferruginous material containing multi-element patterns related to styles of mineralisation at the weathering front. Later erosion causes the physical dispersion of these materials—enlarging the exploration target. Surface sampling including soils, lags and auger samples should be effective (after Lawie 2001).

At the interpretation stage, regolith knowledge can be used to categorise geochemical data into populations with similar regolith-related geochemical backgrounds. This allows appropriate normalisation procedures to be applied. Different orders of anomalies can be identified and examined in their regolith context (e.g. weathering regime, likely mineral hosts and degree of leaching). Where anomalies are detected in transported regolith, knowledge of the landscape history and transport vectors can help to locate source areas.

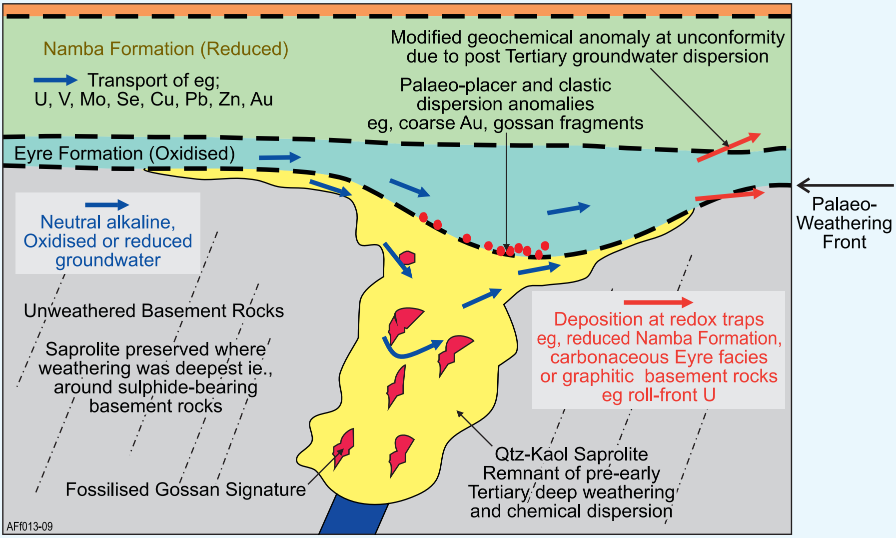


Figure 31. An example of a dispersion model involving thick transported cover. Dispersion is initially similar to that shown in Figure 30, but is subsequently covered by transported sediments (Eyre and Namba Formation). Eroded material is deposited predominately in channel sediments of the Eyre Formation. Later groundwater flow may enlarge pre-existing geochemical dispersion. In this situation, interface sampling (between transported Cenozoic sediments and Willyama rocks), groundwater and saprolite samples should be effective (after Lawie 2001).

6.3 Sampling options

The appropriate sampling medium is determined by factors such as the scale of exploration (regional to prospect; *Table 3*), availability, landscape evolution and mode of secondary dispersion–combined with previous sampling experience. The following section summarises useful techniques and approaches based on case studies and company experience in the region (some of which are included in *Appendix 5*). A comprehensive summary of approaches to sampling regolith materials can be found in Butt *et al.* (2005).

Table 3. Sampling options for regional or prospect-scale exploration. The type of sample taken and sampling approach is influenced by the scale of exploration.

Regional-scale exploration	Prospect-scale exploration
- Drainage/overbank sediments - Groundwater - Biota along drainage systems, e.g. river red gums - Regional grid/opportunistic ferruginous, carbonate, soil, lag sample	- Soil, carbonate, biota, ferruginous material, siliceous material - Lag in erosional settings - Drilling (interface, redox zones within saprolite, groundwater)

Lag

Surface lags vary in distribution and density over the Curnamona Province. High density lags in erosional settings north of the Olary Ranges usually reflect a local source and can therefore make a good bulk-sample medium. Lag sampling is widely used, particularly at reconnaissance phases of exploration (generally the > 2 mm fraction is used, although this may vary where a specific material is targeted).

Particular care must be taken in depositional settings where a lag may have a complex transport history and a highly variable mineralogy that can affect its usefulness. Due to the resistate nature of lags, they can have a long history of reworking in the landscape. An understanding of lag provenance and transport history is essential before using any lag as sample media. Careful examination of lag morphology (size, degree of rounding or roughness), as well as its landscape and palaeolandscape setting, give clues to transport history.

Bulk lag samples containing lithic and ferruginous fractions are most useful where they can be shown to be locally derived from *in situ* regolith. Selective sorting of lag into specific types or provenance can be a useful orientation refinement. However, no advantage in using the magnetic fraction has been found around the Olary Domain (Skwarnecki *et al.* 2001). Lag transported directly from *in situ* regolith is useful for regional anomaly detection (similar to stream sediment sampling in other terrains).

Ferruginous lags will be dealt with in more detail under 'ferruginous regolith' sampling media.

Soil

Soil can be an appropriate and convenient sampling medium where it overlies *in situ* regolith, or shallow transported regolith (< 5 m), or contains significant bedrock-derived components (via bioturbation or down-slope processes). In areas of moderate to thick transported cover (> 5 m), caution is required because studies in the region are inconclusive and show both poor (Skwarnecki *et al.* 2001) and potentially useful results (Fabris *et al.* 2007; Hedger and Dugmore 2001; Leyh and Corbett 2001). Soil surveys can be meaningful at a range of scales, but it is important that soil results are interpreted in context of their regolith-landform setting–where regolith mapping can assist with the interpretation of anomalous values (Brown and Hill 2003). Different regolith units commonly have different geochemical thresholds.

Most soils in the region contain a variable aeolian content as fines (silt-size dust) or a 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. The effect of this dilution can be reduced by sampling from deeper in the soil profile (at least deeper than 100 mm). Surface debris should be removed regardless of aeolian influence to reduce the likelihood of surface contamination and avoid surface organic matter that is not the target of a conventional soil sample.

In many situations–particularly those where the substrate being sampled is transported–the collection of as fine a fraction as practical is recommended (ideally < 75 µm). A fine particle size provides a large surface area available to chemical attack during partial digestion, and therefore greater access to target elements adsorbed or attached to the surface of mineral grains (e.g. clay minerals and iron-oxides-oxyhydroxides). Surveys in the region that compared size fractions have found the smaller than 180 µm fraction adequate–and smaller than 75 µm optimal–over residual, thinly and thickly covered deposits (Skwarnecki *et al.* 2001; Law 2003). The target depth of any sampling program should be determined by an orientation survey, and can differ depending on the landscape setting. Where the landscape setting is variable over a survey line, adhering to a particular target depth can lead to sampling inconsistencies.

The White Dam Au deposit was discovered through regional soil sampling at one sample per square kilometre and an *aqua regia* digest on a smaller than 200 µm fraction by Aberfoyle Resources (McGeough and Anderson 1998). Soil anomalies outlined subcropping mineralisation only (threshold of 15 ppb, peak of 53 ppb). Follow-up sampling on a 400 metre × 400 metre grid, and subsequently 100 metre × 100 metre grid, produced additional anomalous assays, but did not delineate the main body of mineralisation and, furthermore, gave transported anomalies with no underlying mineralised zone. High-grade mineralisation was masked by only 1 metre of transported regolith.

Soil sampling by LEME at the White Dam deposit using 50 metre spacing, 1–2 centimetre depth and the smaller than 75 µm fraction, resulted in improved delineation of the mineralised zone (Brown and Hill 2005; multi-acid digest for most elements except Au, which was determined by graphite furnace AAS and *aqua regia*). Critically, detailed regolith-landform mapping at 1:2,000 scale and surface dispersion vectors were used to rank anomalous values and identify transported anomalies (Brown and Hill 2003).

In areas of moderate to thick transported cover, partial leach techniques are generally preferred. Samples for partial extraction are commonly taken at depths between 10 and 25 centimetres (Mann *et al.* 2005). Partial leach methods are designed to target loosely bound ions on the surface of mineral grains, rather than dissolving the entire mineral grain. The effect is to increase the exotic metal ion contribution that may reflect underlying mineralisation and to limit the contribution of the transported regolith components that are not related to mineralisation. However, partial leach methods are also more sensitive to contamination, minor changes in analytical practice and subtle regolith-landform variations.

Although there have been a number of reports describing equivocal results from partial leach methods, a few studies have shown the potential application of soil sampling in areas with moderate to thick transported cover (Hedger and Dugmore 2001; Leyh and Corbett 2001; Fabris *et al.* 2007). Soil geochemical surveys on the Mundi Mundi Plain near the NSW–SA border, reported Ag anomalies (> 44 ppb) and a pattern of elevated metal values (also Zn, Cd, Mn, Cu and Au) from bulk cyanide leach analysis of soils containing minor carbonate and overlying Pb–Zn–Ag mineralisation buried by over 130 metres of transported regolith (Hedger and Dugmore 2001). Similar results, were reported in a subsequent survey using a shallower sample depth (10–25 cm compared with 40–60 cm; Fabris *et al.* 2007). Investigations in the same area, sampling the regolith carbonate horizon in soil profiles, also reported anomalous concentrations for Ag (> 100 ppb) and other metals (Co, Zn, Cu, Au and Mo; using a weak cyanide leach and ICP-MS) that showed spatial correspondence with known mineralised zones within the bedrock. The results were distinctly different however, from those for samples taken at shallower depths (Leyh and Corbett 2001; Fabris *et al.* 2007). Although it was concluded that soil geochemistry showed a spatial relationship to underlying trace metal content in bedrock, questions remained as to the mechanism responsible for dispersion of metal ions through thick cover and the possibility that the anomalies are coincidental and the result of metal dispersion in outwash fans from the Barrier Ranges, some 25 kilometres to the east.

Investigations have been conducted at the Kalkaroo Cu–Au–Mo deposit into the use of soil sampling to detect mineralisation below thick cover (> 50 m). These include comparative tests of several partial leaches (Fabris and Fidler 2005). Fabris *et al.* (2007) concluded that despite thick transported overburden at the Kalkaroo deposit, results from shallow soil samples (10–25 cm) using partial leaches showed a relationship to bedrock. This was particularly true for Mo and Ag determined using a cyanide-based leach.

Regolith carbonate

The successful use of regolith carbonate (or 'calcrete') as a sampling medium has been demonstrated in the Curnamona Province, predominantly for detecting Au mineralisation, but also for pathfinder elements associated with Cu–Au and polymetallic deposits. The association of Au with regolith carbonate reflects an evaporative environment within transported or *in situ* regolith that is conducive to precipitation of carbonate and Au–rather than direct control on Au fixation by calcrete. Sampling experience in the Gawler Craton has shown that calcrete morphology is probably irrelevant with 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 chose the sample depth. It is important, however, to maintain a consistent sampling position within the carbonate horizon (typically, the calcrete top) and to sample similar calcrete morphology because this will give more consistent assay results. Background values for both the target and pathfinder elements need to be established before deciding on what is truly anomalous. 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, and often are, offset from source mineralisation. Causes can include lateral displacement through down-slope colluvial and fluvial processes and down-slope water movement through the regolith. A regolith carbonate anomaly may be present in transported regolith and laterally displaced by hundreds to thousands of metres from the source of mineralisation. In this situation, a regolith carbonate anomaly should be treated in a similar way to a stream sediment anomaly.

There is a misconception in the Curnamona that regolith carbonate has a restricted distribution and is therefore not a viable sampling medium. Recent studies have shown that regolith carbonate is widespread (although not typically abundant) and is useful in detecting mineralisation (Dart *et al.* 2007; Fabris *et al.* 2007; McQueen *et al.* 1999; Skwarnecki *et al.* 2001; Senior and Hill 2002; Burtt *et al.* 2005b; Wittwer *et al.* 2004).

Wittwer (2004) and Wittwer *et al.* (2004) characterised regolith carbonate accumulations in the shallow cover region of White Dam–Luxemberg, east of Olary. They found that regolith carbonate in areas of known mineralisation (e.g. White Dam, Wilkins, Green and Gold, and Luxemburg deposits) had elevated Au contents of several tens of ppb to over 100 ppb. Microprobe analysis showed that Au was present as rare submicron grains, which were randomly dispersed in the regolith carbonate. The polymetallic nature of much of the mineralisation in the district is reflected in elevated metal contents in regolith carbonate (including As, W, Bi and Mo). Multi-element analyses are recommended and will help to identify anomalous areas by the pattern of pathfinder element distribution. Landscape setting influences Au assay results both at the regional and prospect scale (i.e. the magnitude of anomalous values increases as the landscape relief decreases). Therefore, anomalous element values need to be evaluated in the context of the regolith-landform setting.

In transported terrains, experience from other parts of southern Australia suggests that surface carbonate sampling is effective only where mineralisation is covered by less than 10 metres of transported sediment, and preferably less than 5 metres. An investigation at four prospects in the bedrock-dominated region of the Olary Domain found that anything more that 6 metres of transported regolith was sufficient to mask any geochemical signature related to bedrock mineralisation (Skwarnecki *et al.* 2001). In contrast, Leyh and Corbett (2001) reported Ag anomalies (up to 1305 ppb in a BLEG sample) over underlying mineralisation through more than 100 metres of transported regolith on the Mundi Mundi Plain. The results were repeated by Fabris *et al.* (2007). Further work is required to prove the link between surface anomalies and bedrock mineralisation in this case.

Ferruginous materials

Ferruginous regolith is widespread in areas of subcrop and associated colluvial terrains–particularly in the southern Curnamona Province. Where related to sulphide weathering (gossans), ferruginised regolith is an effective sampling medium. As outlined earlier under regolith materials (section 5.1), sampling of ferruginous materials in the Curnamona region is not straightforward because of the different origin of ferruginous materials. Although textural features, such as boxwork and primary rock fabrics, identify samples from *in situ* regolith and are preferred for geochemical sampling, these are not always present. Analysis of ferruginous materials of unknown origin can lead to misinterpretation because of element scavenging by hematite, goethite and manganese oxides. For example, pisolitic ferricrete in the region has high levels of Zn–Cu–Co–Ag. Although this may initially provoke some interest, this element association has been shown to reflect fossil groundwater conditions and is not associated with nearby mineralisation (Lawie 2001).

On the basis of 429 ferruginous samples collected across the Olary and Mulyungarie Domains, Lawie (2001) developed geochemical discriminators using multivariate analysis that effectively separate gossan samples from non-gossan samples despite element fractionation associated with weathering (limited fractionation occurs because gossans are interpreted as forming at weathering fronts, rather than at the top of a deeply weathered profile). Ferruginous weathering products were analysed for Cu, Pb, Zn, Fe, Mn, As, K, P, Co, Ni, Sb, Bi, Mo, W, U, Ag, Se, Sn, Ba and Au. Gossanous samples were normalised to background, which was determined as the average of non-gossanous, ferruginised basement rocks and lags (*Table 4*). Gossanous samples were subdivided into four groups that reflect four broad styles of mineralisation within the Curnamona Province. These are categorised as 'high Bimba', 'stratiform', 'stratabound' and 'epigenetic' styles (*Figure 32*). The high Bimba group is related to syn-depositional mineralisation within the Bimba Formation. The stratiform group reflects massive to disseminated Zn–Pb–Ag mineralisation that is commonly associated with marble, calcsilicate and pelite (e.g. Hunters Dam prospect). The stratabound group represents disseminated, locally remobilised Cu and Zn sulphide mineralisation. The epigenetic group is associated with Fe–Cu–Au (±Mo) mineralisation and is linked with post-peak metamorphic, high temperature, hydrothermal fluids (e.g. Kalkaroo deposit). Although there is likely to be overlap between the groups, geochemical rules (using analysis of 19 elements) derived from discriminant analysis were established and used to assign samples into the identified groups with 98.6% correctly classified (Lawie 2001).

The geochemical discriminators developed by Lawie (2001) can be applied to ferruginous saprock to assess mineral potential and identify the most likely style of mineralisation. This has particular relevance to drill hole samples from below transported cover where the geological setting is poorly understood.

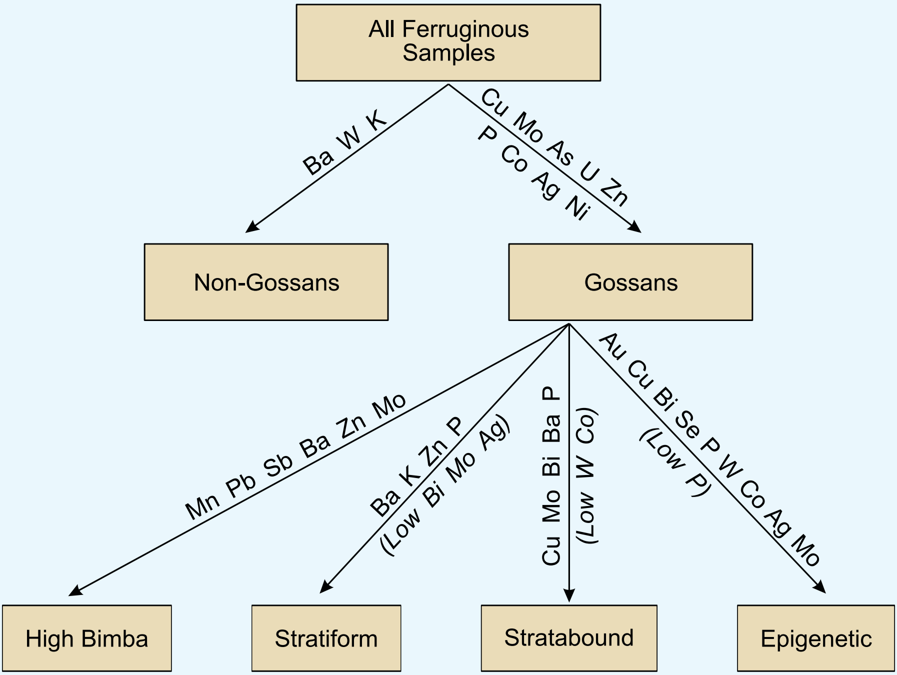


Figure 32. Summary of allocation rules for sorting ferruginous materials within the Curnamona Province. Elements important in allocating samples into each group are shown (where low, element lists are in brackets and italicised) (Lawie 2001).

Table 4. Average values of ferruginised non-mineralised basement rocks and lags. All values are in ppm (Ashley et al. 1997.)

Cu	Zn	Co	Pb	As	Mn	Ba	Mo	P	U	Ni	Se	Ag	W	Bi	Sb
35	34	5	50	87	275	4050	11	635	4	13	5	0.3	3	3	3

Siliceous materials

Pedogenic silcrete is widespread across the Curnamona and affects both transported and some *in situ* regolith. 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 (Au particles, graphite, ferruginous mottling and metamorphic foliation; Lintern and Sheard 1998). Where Au mineralisation subcrops, pedogenic silcrete might be a preferred sample medium to trace the source of Au in bedrock, especially where calcrete is absent or intermittent (Lintern and Sheard 1998).

Groundwater silcrete is common in Palaeogene sandy deposits and is not a suitable mineral exploration sample medium (purely silica, barren of trace elements; Thiry and Milnes 1991).

Vegetation

The basic principle of using plant biogeochemistry for mineral exploration is that the roots of plants take up trace elements, including metals, 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 extreme cases, these substrates may include mineralisation, and plant uptake of metals and trace elements from this, can lead to an expression of buried mineralisation in plant tissues.

Biochemical surveys can be conducted at a regional through to prospect scale. Some of the advantages of this technique include:

- sample media widespread and, in some places, abundant across the landscape
- easy access to samples that in many cases are convenient to take
- an ability of plant organs to penetrate through the transported cover and provide chemical expression of buried mineralisation (*Figure 33*)
- the ability to selectively extract and concentrate some elements (e.g. hyper-accumulators)
- a potential ability to amalgamate a chemical signature from an enlarged and potentially heterogeneous substrate
- environmentally passive exploration approach, with minimal site disturbance and need for remediation
- numerous examples where buried mineralisation have been delineated.

Figure 33: Partial exposure of the root system of a bluebush (Maireana spp.). Bluebush tap-roots have been known to exceed 3 m depth.

Table 5 describes some of the common plant species for the Curnamona region and provides details of their biochemistry where available. A more comprehensive description and details regarding sampling and sample preparation can be found in *Appendix 6*. An overview of results from earlier studies in the NSW part of the Curnamona is given in Hill and Hill (2003).

The main biogeochemical studies from the region have been designed to target a range of commodities, as well as the four main regolith-landform settings for vegetation communities. The latter is used as the basis for this overview.

Open woodlands on aeolian sandplains and dunes

Although these settings are widespread in the region, they have not been extensively biogeochemically characterised. White cypress pines (*Callitris glaucophylla*), which are common across some dunefields and sandplains of the Strzelecki Desert, have been sampled at a regional scale in the Teilta area. Results were inconclusive because the underlying geology was not well defined (Hill 2005). However, the species has given positive results in other regions (Cohen *et al.* 1998). Mulgas and other acacias have been tested in this regolith-landform setting in nearby northwestern NSW within the Thomson Orogen region (Hill *et al.* 2008).

Chenopod shrublands on sheetflow plains and rises

The chenopod shrubs–mostly including bluebushes and saltbushes–have been widely and successfully used to biogeochemically express buried mineralisation. An early study by Morris (1974) at Anabama Hill found elevated Cu in older branches and leaves of black bluebush (*Maireana pyramidata*; 8.4–25.5 ppm Cu) and bluebush (*Maireana sedifolia*; 8.5–17.5 ppm Cu) over Cu-mineralisation buried by 1.5 metres of transported cover, although the anomaly over mineralisation was more subtle than using soil samples. More recent studies at the Flying Doctor prospect found that black bluebush effectively expressed buried Broken Hill-type mineralisation–particularly for Pb, Zn and Cu (Hill *et al.* 2005). Low *et al.* (2005) found higher metal concentrations in leaves, including higher Cd concentrations in leaves than soils from the same site. Black bluebush samples from a 25-metre grid across a low-order stream catchment south of the Pinnacles effectively expressed a buried quartz–gahnite lode, whereas other media, such as soils, showed marked landscape dispersion and reworking (Senior and Hill 2002).

Approximately 80 bladder saltbush (*Atriplex versicaria*) samples and accompanying soil samples were collected across the White Dam Cu–Au deposit before extensive excavation and surface disturbance (Brown and Hill 2005; 2007). This study clearly showed that the bladder saltbush could provide a biogeochemical expression of mineralisation through 5–10 metres

Species	 *Eucalyptus camaldulensis* River red gum	 *Acacia aneura* Mulga
Description and Biochemistry	• Up to 30 m tall. • Long-lived with deep and spreading roots. • Abundant along major watercourses. • Up to 1.03 ppb Au in twigs and 0.65 ppb Au in leaves near Teilta. • 108-256 ppm Zn, 1.9-3.7 ppm Cd in leaves over the Broken Hill Line of Lode and > 300 ppm Pb over the Perseverance Lode.	• Up to 14 m tall, but also forms bushy shrubs 3-5 m tall. • Long lived and deep-rooted. • Widespread and locally abundant on hills and dunes. • Up to 445 ppm Zn in phyllodes from trees over the Broken Hill Line of Lode. • Up to 12 ppm Cu, 14 ppm Pb, 63 ppm Zn in phyllodes at Flying Doctor Prospect.
Species	 *Acacia victoriae* Prickly wattle	 *Casuarina pauper* Black oak
Description and Biochemistry	• Up to 20 m tall. • Long-lived with deep roots along rock fractures. • Widespread across hills and rises of weathered bedrock. • Up to 349 ppm Zn in phyllodes over the Broken Hill Line of Lode. • Up to 221 ppm Zn, 49 ppm Pb, 9 ppm Cu from phyllodes overlying Flying Doctor prospect.	• Variably shaped, bushy to upright tree up to 15 m tall. • Long lived and deep-rooted. • Widespread and locally abundant. • Used successfully to detect serpentinites at Thackaringa,exhibiting a markedly higher concentration of Cu compared to over adjacent pegmatite.

Table 5. Common plant species for the Curnamona region. Specific case studies in this table include Teilta region (Hulme and Hill 2003), Broken Hill Line of Lode

Species	 *Callitris glaucophylla* White cypress pine	 *Maireana sedifolia* Pearl bluebush
Description and Biochemistry	• Erect pine-like tree up to 15 m tall. • Long lived (100-200 years) and deep rooted. • Widespread on southeast slopes and on some dunes.	• Bright blue-white, multi-branched shrub to 1.5 m tall. • Succulent, egg-shaped leaves. • Long lived (at least 150-300 years) and relatively deep tap-root system (up to 3 m). • Common, chiefly around fractured bedrock or sites with regolith carbonate within 60 cm depth.
Species	 *Maireana pyramidata* Black bluebush	 *Atriplex vesicaria* Bladder saltbush
Description and Biochemistry	• Dark blue-green to grey, multi-branched shrub to 1.5 m tall. • Succulent, egg-shaped leaves. • Live for several decades. • Common on sheetwash-dominated erosional landforms. • Up to 55 ppm Cu overlying quartz gahnite lode. • Up to 7 ppm Cu, 44 ppm Pb, 178 ppm Zn at Flying Doctor.	• Erect to spreading shrub up to 70 cm tall. • Leaves rigid, elliptical. • Long-lived to 30 years. • Mostly shallow rooted but may extend to 5 m. • Widespread. • >0.5 ppb Au, >20 ppm Cu in twigs overlying buried Cu-Au mineralisation at White Dam.

and Perserverance Lode (Hill 2004), Flying Doctor prospect (Hill et al. 2005), Thackaringa serpentinite mine (Hill 1998), White Dam deposit (Brown and Hill 2005).

of transported cover, whereas the use of soils was only effective with less than one metre of transported cover, and otherwise gave transported/false/misleading anomalies.

Riparian woodlands

The greatest biogeochemical success from the region has been associated with river red gums (*Eucalyptus camaldulensis*) along the Pine Creek drainage channel near the Pinnacles (Hill and Hill 2003; Hulme and Hill 2003, 2004, 2005a, b; Hill 2004; Hulme 2008). An initial orientation sampling program at approximately 200-metre spacing detected elevated Pb, Zn, Cd, Ag and Sb concentrations in leaf samples near the Pinnacles Mine (Hill 2004). This was further investigated with sampling of all trees along a several kilometre stretch of the creek in this area (Hulme 2008). This not only repeated the original elevated responses, but also found other anomalies immediately upstream of the mine. Scanning electron microscope (SEM) studies of the leaves showed minimal detrital additions to the samples, so a small excavation was made in the creek bed near one of the trees with elevated metal contents. This helped to discover one end of the Perseverance Lode that is to be evaluated for development. In this case, the trees were able to penetrate alluvial sediments that contain signatures from the local Pinnacles Mine and express a buried mineralised system.

River red gum leaves have also been recently sampled along Four Mile Creek and tributaries near the Four Mile U mineralisation (Neimanis *et al.* 2007). Broadly, these results show decreasing U contents with distance away from where the channels leave the U-rich bedrock of the northern Flinders Ranges. However, where lineaments (mostly neotectonically active faults) cross the channels and the underlying mineralisation, the trees show highly anomalous U contents (5–6 ppm U). This suggests that these trees are accessing groundwater moving along fracture systems that intersect mineralisation. Inland tea-tree samples from the same channels tended to have U contents that more closely reflect the U content in the stream sediment–supporting observations that they are more shallow rooted (Neimanis *et al.* 2007).

Prickly wattle (*Acacia victoriae*) from alluvial systems at the Flying Doctor prospect not only biogeochemically expresses buried mineralisation, but also has low metal contents overlying non-mineralised bedrock overlain by transported soil anomalies (Hill *et al.* 2005). This demonstrates the preferential use of the large tap-root by this species to penetrate the transported cover and obtain biogeochemical signatures largely from groundwater at the sediment–bedrock interface.

Open mixed woodlands on erosional hills and rises

Cole (1965) reports elevated Pb levels within jockeys caps (*Prostanthera striatiflora*) and silvertails (*Ptilotus obovatum*) near mineralisation at Little Broken Hill, Angus and Thackaringa mines. However, the mineralisation at these sites is near surface and the distribution of these two species is restricted to bedrock exposure, therefore limiting their application for mineral exploration under cover. A wide range of species–including black oak (*Casuarina pauper*) and curly mallee (*Eucalyptus gillii*)–were sampled over the Thackaringa serpentinite mine (west of Broken Hill), and were found to provide strong biogeochemical expression of the shallow underlying bedrock (Hill 1998).

Shallow buried U mineralisation in the northern Flinders Ranges in the Mount Painter–Mount Gee area, and further north at the Gunsight prospect, typically have strong biogeochemical expressions for elements such as U, Cu, Ag and Th (Neimanis and Hill 2006). Most notable has been the U content in leaves from curly mallees and gum-barked coolibahs (*Eucalyptus intertexta*) growing on mineralised hematite breccias at Radium Ridge that contain over 6 ppm U, whereas from nearby background settings the U contents are less than 0.1 ppm (Neimanis and Hill 2006). Emu bushes, such as the rock fuchsia-bush (*Eremophila freelingii*), can have elevated Ag contents near U mineralisation, such as 70 ppb at the Armchair prospect (Neimanis and Hill 2006). This may prove to be a useful species for close-spaced sampling not only because of its local abundance, but also because of its widespread distribution in the ranges and on the flanking plains - such as in the Four Mile prospect (Gallasch and Hill 2007).

As with most sampling techniques, careful consideration must be given to sampling consistency: particularly in terms of plant species and plant organ sampled. Further detail on sampling protocol and considerations can be found in *Appendix 6*.

Drainage sediments

Stream sediment sampling is used for regional-scale geochemical reconnaissance, where sampling near stream junctions is effective in identifying mineralised source areas. Surveys have been mainly conducted in the Mount Painter and Mount Babbage Inliers, Barrier and Olary Ranges. Although these have shown some success (particularly around Mount Painter), the widespread occurrence of sub-economic sulphide mineralisation throughout the Curnamona Province is a challenge to effective exploration.

In areas of low relief, channels are poorly defined and commonly choked with silt from deflation of the surrounding soils. These contain a substantial aeolian component and are generally not a useful sampling medium. However, the coarser sediments that include rock fragments, and the fine fractions from the base of the channel, are more suitable for geochemical sampling (McQueen 2008).

Interfaces

'Interface' sampling refers to sampling across an unconformity: generally that between weathered basement and cover. Samples of transported overburden are taken directly above the unconformity and may include quartz granules, lithic fragments and ferruginous lag derived from the underlying weathering profile. This material will retain dispersed elements that may have been leached from the underlying saprolite. Trace element geochemistry of interface samples may simply represent detritus physically dispersed from *in situ* bedrock (e.g. fossil lag) or reflect addition of metal ions chemically dispersed by groundwater moving through the basal sediments (i.e. displaced anomaly; *Figure 31*). Interface sampling can be a useful prospect-scale technique in areas with extensive transported regolith.

At North Portia prospect, Mo, Au and Cu dispersed from bedrock Au mineralisation accumulate in the basal units of overlying sediment cover of around 50 metre thickness (Tan 2001). Coarse quartz sand of the Eyre Formation and smectitic clay of the Namba Formation that directly overlie mineralisation–and are within 10 metres of sediment-saprolite unconformity–contain anomalous trace element concentrations (Tan *et al.* 2005). Interface sampling from holes drilled at 200-metre spacing was sufficient to define the bedrock mineralised zones.

Interface sampling for Zn–Pb mineralisation has been shown to be effective at Crozier Dam and G17 prospects (unpublished company report). Anomalous Zn and Pb at the base of cover sediments indicate nearby bedrock mineralisation. At the Crozier Dam prospect, the Zn–Pb anomaly is displaced down-slope along the bedrock cover interface.

Placer-style Au deposits occur within basal Eyre Formation (e.g. Portia prospect) and interface sampling analyses for Au greater than 150 ppb are positive indicators of this style of mineralisation.

Saprolith

Redox zones within the saprolith are usually good targets for sampling during drilling (*Appendix 7*). Conversely, samples taken more generally within the upper saprolite tend to be leached of elements relating to mineralised zones, and so do not normally make good sampling media. Yellow-brown and orange zones appearing lower in the profile can indicate old redox fronts, which are generally related to palaeo or perched water tables. Goethite dominance is indicated by yellow and brown colours, whereas hematite dominance appears as purplish, red and pink shades. Mixtures typically result in different orange hues. Redox fronts are important chemical transition zones where metallic ions 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 in groundwater.

Where ferruginous zones are present, goethite and hematite will retain many target and pathfinder trace elements released and dispersed during weathering. Tan (2001) indicated that sampling the ferruginous zone in the saprolite intersected by shallow aircore drilling was sufficient to detect bedrock mineralisation in the area of the Portia prospects. In particular, a goethitic zone related to hydromorphic dispersion from weathering sulphide in bedrock provides a larger geochemical footprint of mineralisation than direct intersection of the ore zone. Element values generally need to be normalised to Fe content to account for higher background levels associated with hematite or goethite (McQueen 2008).

In areas where weathered bedrock is at, or close to, the surface, rock chip or lag sampling is generally recommended.

Groundwater

Groundwater interacts with the minerals that form or line the aquifer system through which it flows, and so it has the potential to be a direct sampling medium representative of the subsurface.

More than 350 groundwater samples have been collected from boreholes within the southern Curnamona region: both in areas of outcrop in the ranges and in areas of cover in the surrounding basins (de Caritat and Kirste 2005; de Caritat *et al.* 2005). Direct comparison of the concentration of target elements tends to be misleading because their concentration in groundwater is strongly affected by various processes–including pH, evaporation, evapotranspiration, mixing, precipitation–dissolution and oxidation/reduction–all of which take place during an often complex and, in some cases, long evolution.

To develop hydrogeochemistry into a useful tool for exploration for base-metal sulphides requires several steps in the analysis of the data. First, an index of 'sulphur excess' is calculated to identify which samples contain more S than can be accounted for by evaporation or mixing. Samples that show a 'sulphur excess' can be further sorted–using the stable isotopes of S and O in sulphate–into S from a meteoric source or from sulphide mineralisation. The multi-element analyses can then be used to determine those samples of economic significance.

Groundwater samples from the Curnamona region contain relatively anomalous concentrations of sulphur that originate mainly from the oxidation of sulphide mineralisation and dissolution of regolith gypsum (de Caritat *et al.* 2005). Dissolved sulphate from weathered sulphide–as identified from isotopic analysis–may have application in regional exploration for blind mineralisation. Reactive-transport modelling of the current groundwater system (de Caritat and Kirste 2005) indicates that anomalous concentrations of trace metals are not expected further than 100 metres from their source. Trace metal analysis of groundwater is therefore likely to be most useful in close proximity to mineralisation (*Figure 34*).

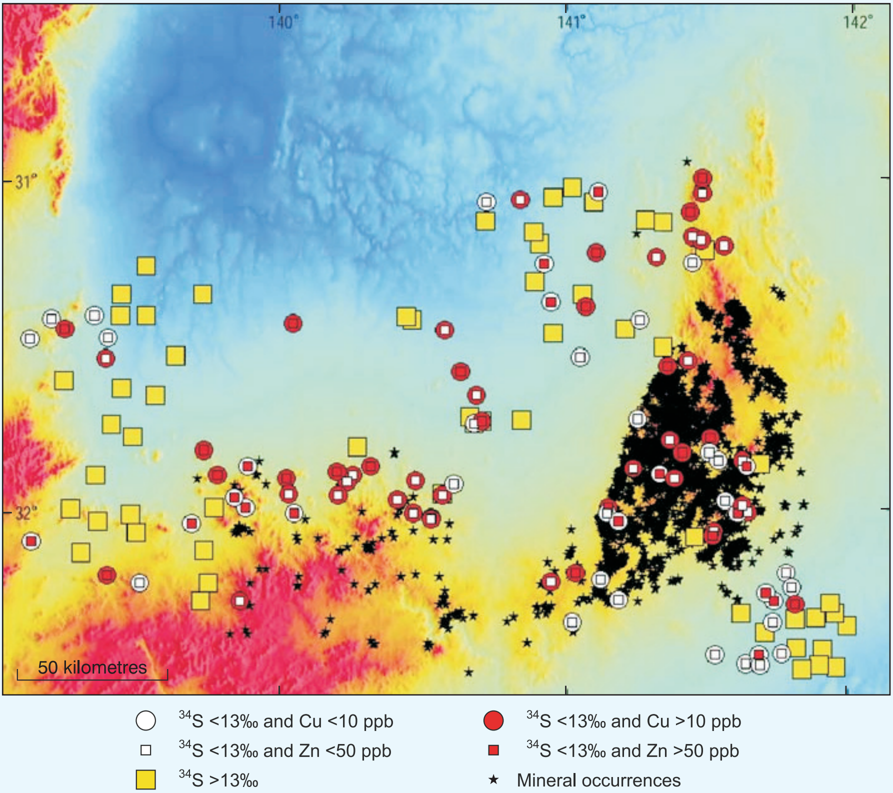


Figure 34. Distribution of groundwater samples in the southern Curnamona Province on an elevation model background. Symbols show groundwaters that have 'high' sulphur isotopic compositions as yellow squares, and 'low' sulphur isotopic compositions as circles; the latter are coloured red if Cu concentrations are greater than 10 parts per billion, or contain a red square if Zn concentrations are greater than 50 parts per billion. These symbols represent a gradation from probably unrelated to any mineralisation (yellow square), to distal (>2 km) to potential mineralisation (white circle and/or square), to more proximal to potential mineralisation (red circle and/or square). (After de Caritat and Kirste 2005.)

Groundwater sampling has potential application in the exploration for U. Uranium is mobile in oxidising groundwater and is precipitated upon reduction. The direct measure of U in solution is therefore a reflection of U solubility rather than proximity to ore. Full chemical analysis of groundwater–with major elements determined by ICP-AES and trace elements by ICP-MS–can be used to model the stability of U in solution. According to Dickson and Giblin (2007), when this information is combined with analyses of Pb isotopes in solution, groundwater offers a powerful tool to identify where U precipitation is favoured, together with evidence of U accumulation.

6.4 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 through minimising the potential for drill hole wall spall adding to the sample. Drill cuttings can provide only about 20% of the available regolith information compared with 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.

Where regolith information is limited, 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-metre 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 (*Appendix 8*). Bottom-of-hole mineralised cuttings can remain within drill rig airway/mud plumbing, sample cyclone separator and/or drill rods; the less oxidised bottom cuttings can contaminate the upper regolith samples of the next hole. The cyclone sample separator should be cleaned before drilling 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 and 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, Sn, Au 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.

Making sure a drill hole reaches its targeted termination level (fresh rock preferred) is a drilling supervision task. 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, cemented horizons, 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 certain 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.

Early in an exploration program it may not be clear which horizon is the best target (see *Appendix 7* for details on what to look for in drill holes). It is therefore advisable to sample and assay the entire drilled intersection–at least until the geochemical distribution patterns become clear.

6.5 Analytical approach and methods

The analytical approach used must employ an understanding of the sample media. In residual or very shallow cover, where the substrate being sampled includes a significant proportion of *in situ* rock fragments, a strong leach is appropriate to determine the near total composition of a sample. Strong acids employed include multi-acid ($HF–HNO_3–HCl–HClO_4$) or *aqua regia* ($HNO_3–HCl$) digests followed by analysis using inductively coupled plasma optical emission spectrometry and mass spectrometry (ICP-OES/MS). *Aqua regia* digest is preferred if Au and Ag are the targets metals. ICP-OES analysis is used for major and minor elements because it gives a detection range that covers their typical abundance. ICP-MS is preferred for trace element determination.

Where the sample contains a greater proportion of foreign material, a selective leach may be chosen to preferentially dissolve mineral phases that may host the elements of interest. If the sample is taken in areas with a significant thickness of transported cover (> 5 m), and is unlikely to contain fragments derived from underlying bedrock, using a weak leach that targets mobile metal ions of the surfaces of mineral grains is advisable. This method maximises the contribution of the analysis that may relate to vertical transport, rather than from the substrate itself. A choice of leach is dependent on several factors. These include the target elements, the mineralogy of the sample, the effective pH of the leach in relation to sample pH and which components of the sample are to be targeted. Cyanide-based leaches have generally been the most effective in the Curnamona region (Fabris *et al.* 2007; Leyh and Corbett 2001).

Analysis using partial leach methods and ICP-MS gives low detection limits, but the sensitivity and selectivity of the technique means careful field and laboratory handling are required, along with a good understanding of sample variability. If the sample medium is highly variable in the way it hosts dispersed elements, anomalies may be missed or interpreted incorrectly. Datasets that include Ca, Mg, Mn, Fe and organic matter (where significant in samples) can help to highlight this variability. Measurements of pH may also be useful in highlighting differences that affect soil chemistry and element mobility.

Where total analysis data are required–for example to assist with interpretation of parent rock type, or when applying 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.

Effective exploration geochemistry should involve a multi-element approach. The spatial association of anomalies with a number of key ore-related elements provides a more robust indicator of mineralisation than single element anomalies. For the Curnamona, these would typically include Ag, As, Au, Co, Cu, Mo, Pb, Zn and U, with the variable inclusion of Bi, Cd, Sn, Ti, W and Zr. Major/minor elements, such as Al, Ca, Cr, 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.

The appropriate method and sampling strategy to determine Au concentration is influenced by its particle size and distribution within a sample. For fine-grained evenly dispersed gold, 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' gold will require larger samples (3–5 kg) and methods such as bulk cyanide leach (BLEG) or screened fire assay.

6.6 Identifying anomalies

A geochemical anomaly is a feature having geochemistry different from that which is considered to be background for a particular site, prospect or region. Identifying what is anomalous, and what is not, therefore requires knowledge of 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 these 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 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, the 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. Obvious anomalies, the presence of multiple populations of data, and likely element associations can be identified by EDA. 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. Regolith mapping is crucial to this process and can often help clear up uncertainties about multiple populations and appropriate thresholds for defining anomalies.

6.7 Concluding comments

There has been a long history of mineral exploration and ore discovery in outcropping regions of the Curnamona. There are, however, vast regions below sediment cover that remain under-explored. More recent discoveries in areas of thick transported regolith have highlighted the region's further mineral potential. Future discoveries will be aided by extracting the maximum information from the regolith. Key benefits to exploration can come from the following:

- detection and interpretation of subtle geochemical anomalies in surface media over *in situ* and transported regolith
- drilling through cover and sampling of appropriate regolith zones in the underlying *in situ* regolith
- use of less-conventional techniques in areas of thicker transported cover, such as partial leach geochemistry, and groundwater and biota as sample media
- improved understanding of vertical metal ion transport within the regolith
- improved geophysical techniques
- improved drilling techniques.

All these approaches will require a good understanding of regolith materials, their setting and origin within the landscape and palaeo-landscapes of the region.

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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.

BLEG = Bulk leach extractable gold; 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.

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

DEM = Digital elevation model.

Duplex soil = Soil profiles 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).

Eh = A measure of the state of oxidation or reduction (activity of electrons in volts).

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 = Lag gravels to boulders of an arid region that are typically wind-polished or wind-sculpted.

Gypcrete = Duricrust cemented mainly by gypsum.

HyLogger = A device developed by CSIRO for automated spectroscopic logging of drill core and chips (HyChip).

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.

Lacustrine = Related to lakes.

Ma = Mega annum, a 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.

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).

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 = Front at which the lithic fabric is destroyed.

pH = A measure of the acidity or alkalinity (–log of the concentration of H+)

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.

Plasmic zone = Relatively homogeneous part of the weathering profile–predominantly composed of clay (plasma)–which has neither the lithic fabric of the saprolite nor the significant development of secondary entities such as nodules or pisoliths.

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

Porcellanite = A hard, dense, siliceous rock having the texture, dull lustre, hardness, fracture, or general appearance of unglazed porcelain. Commonly applied to silicified clay- or mud-stone.

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.

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 Fe2+ to oxidise to Fe^{3+}.

RED Scheme = Acronym for 'relict', 'erosional' and 'depositional'. A regolith mapping style for interpreting deeply weathered terrains with an emphasis on practicality for geochemical sampling.

REE = Rare earth elements; scandium, yttrium and fifteen lanthanide series elements in the Periodic Table.

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*).

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.

TDS = Total dissolved salt: 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.

GUIDE SUMMARY AND KEY

PART 1. INTRODUCTION (pp. 1-2; Figure 1)

- The majority of exploration and subsequent discoveries have been made in and around bedrock exposures, which account for more than 10% of the Curnamona landscape. The major challenge facing exploration in the region is exploring effectively through thick transported regolith.

PART 2. PHYSICAL SETTING (pp. 3-7; Figure 2)

- Straddles the SA–NSW border.
- Forms part of an internally draining basin bounded by low to high hills, and contains extensive plains and longitudinal dunefields and evaporitic playas–dominated by Lakes Frome and Callabonna.
- Semi arid to arid climate, hot dry summer, cool winter with average annual rainfall of < 200 mm.
- Sparse to moderate vegetation cover.
- Groundwaters in the southern Curnamona are dominantly brackish–of the $Na–Cl–SO_4$ and Na–Cl types–and their pH is around neutral, and Eh mildly oxidising to strongly reducing.

PART 3. GEOLOGY AND MINERALISATION (pp. 9-21; Figures 3-5)

Geological framework (pp. 9-14; Figures 3-4)

- Basement consists of late Palaeo- to Mesoproterozoic metasedimentary, metavolcanic and igneous rocks of the Willyama Supergroup. The rocks were affected by the Olarian Orogen, with metamorphic grade varying northwestwards from granulite to lower greenschist facies.
- The varied distribution and thickness of the observed lithostratigraphy provides evidence that deposition was not uniform, and so the geology can conveniently be described by geological domains: namely, Broken Hill, Redan, Mulyungarie, Olary, Mudguard, Moolawatana, Erudina and Quinyambie Domains.

- Palaeo-Mesoproterozoic basement rocks are overlain by sedimentary basins containing Neoproterozoic, Cambrian, Mesozoic and Cenozoic sediments. Neoproterozoic to Early Cambrian sediments deposited within the Adelaide Geosyncline form the western margin of the Curnamona Province and extend into the province as a series of grabens. Cambrian sediments form part of the Arrowie Basin and are mainly confined to the Moorowie and Yalkalpo Sub-basins. Mesozoic sediments of the Eromanga Basin extend over the Province's central and northern portion. Cenozoic sediments of the Lake Eyre Basin form a sediment blanket over the majority of the Province.

Key mineralisation styles (pp. 18-21; Figure 5)

The Curnamona Province is most notable as host to the Broken Hill deposit: the largest Pb+Zn deposit (by contained tonnes) in the world. In addition to Broken Hill-style deposits, the Curnamona is highly prospective for:

- Ag, Pb and Zn within fault and shear zones and as stratiform to stratabound mineralisation within reduced pelitic to psammopelitic metasediments
- epigenetic Cu, Au ±Mo, U in fractures, leucosomes, ironstones and near a redox boundary situated between the magnetite-bearing lower part of the Willyama Supergroup and the more reduced upper part
- Olympic Dam- style Fe-oxide Cu–Au–U within the Benagerie Ridge and Mount Painter and Mount Babbage Inliers
- U, Th and REE in veins, shears, stockworks and breccias within S-type granitoid, pegmatite and shear zones
- U within alluvial sediments of the Eocene Eyre Formation and Miocene Namba Formation.

PART 4. LANDSCAPE EVOLUTION (pp. 23-32; Figures 6-8)

Landscape history (pp. 23-26)

- Palaeozoic: renewed rifting and a late Early Cambrian marine incursion resulted in deposition within the Moorowie and Yalkalpo Sub-basins that continued until the onset of the Cambrian Delamerian Orogeny that produced uplift of the Adelaide Geosyncline and widespread erosion. The Poontana Fracture Zone developed within the Moorowie Sub-basin. Ordovician–Devonian and the Permian were major periods of depositional hiatus and erosion.

- Mesozoic: the Triassic and Jurassic were periods of deep weathering. Jurassic to Cretaceous non-marine and marine deposits extend to the central Curnamona as part of the Eromanga Basin to the north.
- Cenozoic: bedrock exposure included the southern Benagerie Ridge as far north as the present Lake Frome. A warmer climate and higher rainfall during the Palaeogene prompted widespread, rapid rock weathering and erosion. A fluvial channel network developed that deeply incised the landscape, particularly in the southern Curnamona. The drainage networks gradually filled with sediment and deposition within fluvio-lacustrine environments dominated (including the proto-Lake Frome) from the beginning of the Neogene. Associated deposition formed a blanket over much of Province. As the climate became drier towards the end of the Cenozoic, alluvial, floodplain and aeolian environments dominated. The direction of modern drainage commonly bears no relationship to that of earlier in the era.

Regolith profile development (pp. 27-32; Figures 6-8)

Regolith profiles across the region are the result of many episodes of weathering, *in situ* profile development, erosion and deposition over an extended period. Regolith profiles within the Curnamona are typically less than 1 metre to about 80 metres in thickness. Landscape models and profile variability are illustrated to assist with field interpretation of regolith units and to indicate factors that may influence geochemical sampling strategies.

PART 5. REGOLITH (pp. 33-81; Figures 9-28)

Regolith materials (pp. 33-56; Figures 9-20)

Regolith materials are conveniently grouped as, *in situ* regolith, transported regolith, indurated regolith (duricrusts, pans, 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.
- Highly weathered rocks are generally restricted to covered or tableland regions. Outcrop of the upper saprolite is typically found in retreating escarpments, mesas and buttes, but can also be found in erosional terrains covered by a thin veneer of lag.
- Transported regolith is widespread and variable in character. It includes alluvial, lacustrine, aeolian and colluvial deposits within a series of overlapping sedimentary basins.
- 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 may be recycled and widely dispersed across the landscape.
- Approximately five soil groups have been identified for the region. Most contain aeolian components as silt or sand fractions. Regolith carbonate and sulphates develop from aeolian inputs. Alkaline and sodic soils are common.

Distribution of regolith materials (pp. 56-70; Figures 21-27)

- *Basin architecture* – The depth to basement and 3D distribution of the regolith over the Curnamona is illustrated in a series of models based on drill hole information and interpreted aeromagnetic and seismic data. Basin sediments generally increase in thickness away from the ranges to more than 500 metres, except over the Benagerie Ridge where they are mostly less than 400 metres thick. A significant portion of the southern Curnamona is covered by less than 50 metres of transported cover.
- *Regolith landform mapping* – Regolith maps are constructed to provide context for exploration in regolith-dominated terrains. They are the first step to understanding the landscape evolution of an area and provide a framework to interpret geochemical provenance and dispersion, and distribution of potential sampling media, and can be used to design

geochemical sampling surveys.

- *Regolith mapping tools* – Regolith maps are typically constructed using a combination of remotely sensed data and field observations. Typical techniques used include aerial photography, digital elevation models, Landsat imagery, ASTER, Hyperspectral techniques, airborne radiometrics and magnetic imagery. Subsurface mapping can be achieved using electrical, gravity, magnetic and seismic methods, as well as down-hole spectral and geophysical tools.

Regolith geochemical fundamentals (pp. 71-81; Figure 28)

- *Element dispersion during weathering* – Target and pathfinder elements are fractionated with increasing degree of weathering and leaching, and are adsorbed or incorporated into new regolith minerals. These commonly include goethite, hematite, alunite–jarosite group minerals, manganese minerals, regolith carbonates and smectite group clays.
- *The process of sulphide weathering* – As sulphide bodies are progressively exhumed, their contained sulphide minerals gradually become chemically unstable. In some instances, corroding sulphides are then transformed to stable oxidate phases at the top of the profile to form gossans. The mineralogy, geochemistry and texture of the resultant gossan may differ considerably from that of the primary sulphides from which it was derived.
- *Controls on element dispersion* 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; biochemical processes; evaporation; and physical processes causing mechanical dispersion.
- *Effect of climate on weathering regimes* – Chemical conditions within regolith of the Curnamona region have changed significantly through time: particularly in response to climatic changes. Warm and wet conditions generally favoured hydration–hydrolysis reactions: aiding the mobility of reduced species (particularly Fe^{2+} and Mn^{2+}). Under arid conditions, falling and fluctuating water tables favour oxidation reactions and more complex regional groundwater compositions. The 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).

- *Element transport in covered terrains* can be in a vertical as well as lateral sense. Mechanisms that may be relevant to upward metal transport through thick cover sediments in the Curnamona region include: fluctuating groundwater; capillary rise and evaporation; electrochemical mobility; deep-rooted vegetation; gas migration; and seismic pumping.
- *Regolith element associations*
  - Mineralising elements (e.g. Au, or Cu) may be mobilised into overlying Eyre and Namba Formation.
  - Regolith carbonate ($CaCO_3$ ± Mg) is generally widespread in the Curnamona and has been found to be a useful sampling medium for Au, Cu, Zn, Pb, and As.
  - Surface soil sampling has been useful in discriminating underlying mineralisation using the following elements Ag, Au, As, Bi, Cd, Co, Cu, Mo, Pb, U, W, Zn.
  - Iron oxides and oxy-hydroxides may incorporate Au, Cu, As, Bi, Sb, Se, Zn and W and can be useful locally, however it is important to set appropriate threshold values.
  - Pisolitic ferricrete contains a Zn–Cu–U–Co–Ag association indicative of a 'fossilised' groundwater signature and so does not have any 'connection' to basement.
- *Behaviour of selected elements in the regolith* is described including Fe, Al, Mn, Cu, Pb, Zn, Ni, Au, Ag, Mo and U. Element behaviour is dependant on pH and Eh conditions and certain groups of elements may behave similarly.

PART 6. EXPLORATION STRATEGIES IN REGOLITH-DOMINATED TERRAINS (pp. 83-111; Figures 30-34)

The ultimate aim of understanding of the regolith is to reduce the risk associated with exploring in covered areas. Furthermore, understanding what can be sampled–and the origin of what is being sampled–can help to assess and rank data and, subsequently, a region's prospectivity.

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

- What is the depth to *in situ* regolith?
- Where is the *in situ* regolith and where is the transported regolith?
- What are the dispersion pathways for target and pathfinder elements and what are their form or host minerals in the regolith?
- Does transported regolith completely mask the geochemical signature of underlying mineralisation?
- What exploration techniques have been effective in regolith-dominated terrains?
- What is the best material to sample in drill holes?
- What is a significant anomaly and how do we rank anomalous data?

Exploration approach (pp. 84-86; Figures 30-31)

- The initial stage of exploration involves establishing the thickness and nature of the regolith. This can be achieved by a combination of surface regolith-landform mapping and subsurface information gained from previous drilling or geophysical methods.
- Regolith information can be used to select the best exploration methods and sampling techniques for particular areas and help plan orientation studies that incorporate the appropriate range of regolith-landform units and materials.
- Regolith data can be used to develop regolith dispersion models that will guide the sampling strategy.
- Regolith knowledge is essential for interpreting surface geochemical data. It can be used to categorise data into populations with similar regolith-related geochemical backgrounds.

Sampling options (pp. 86-105; Figs 32-34)

Appropriate sampling media are determined by factors such as the scale of exploration (regional to prospect), availability, landscape evolution and mode of secondary dispersion, combined with previous sampling experience.

- *Regional-scale techniques* include: drainage/overbank sediments, groundwater, biota along drainage systems, regional grid/opportunistic ferruginous, carbonate, soil and lag samples.
- P*rospect-scale techniques* include: soil, carbonate, biota, ferruginous material, siliceous material, lag in erosional settings and drilling (interface, redox zones within saprolite, groundwater samples).
- *Lag* is widespread around the ranges, but can have a complex history of formation and reworking. An understanding of lag provenance and transport history is essential before using any lag as sample media. High-density lags in erosional settings north of the Olary Ranges usually reflect a local source, and can therefore make a good bulk sample medium. Generally the larger than 2 millimetre fraction is used.
- *Soils* are useful in areas of *in situ* regolith and thin transported regolith, but are less reliable over moderate to thick transported cover. Soils may contain an appreciable aeolian component that can act as a variable dilutant.
- *Regolith carbonate* developed in weathered bedrock and thin transported cover is not only useful for Au, but other elements (e.g. Ag, As, W, Bi and Mo) at regional and local scales. Knowledge of host material is important in determining threshold and anomalous values.
- *Ferruginous materials* are useful where derived from nearby weathered bedrock. Gossanous samples can be geochemically subdivided to reflect local mineralisation styles.
- *Siliceous materials* are useful where silicification has prevented dispersion of ore minerals from weathered bedrock. Groundwater silcrete is typically barren.
- *Vegetation* is potentially a useful sampling medium in areas of *in situ* and transported regolith (< 20 m thick). Sampling consistent species and plant organs is a necessity.

- *Drainage sediments* are used in regional surveys to identify mineralised source areas.
- *Interface samples* may be taken at the base of transported cover (drill hole samples) and can be a useful prospect-scale technique in areas with extensive transported regolith.
- *Saprolith* is typically highly leached of trace metals, but ferruginous segregations and redox zones may preferentially retain metals or pathfinder trace elements and may be targeted in sampling.
- *Groundwater* interacts with the minerals that form or line an aquifer system through which it flows, and thus has the potential to be a direct sampling medium representative of the subsurface. Isotopic analysis should be used in conjunction with multi-element analysis. Groundwater in palaeodrainage sediments may be a suitable sampling medium to detect areas of U accumulation.

Drilling and drill hole sampling, diligence and cautions (pp. 105-108)

Regolith drilling should extend to the base of oxidation and ideally into fresh rock. Be aware of hardness variation in regolith materials that may result in premature termination of drilling and influence interpretation of analytical results. Sampling the full regolith profile, in selected drill holes for a particular project area, with analysis at 1-metre sample intervals is suggested 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 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.

Analytical approach and methods (pp. 108-109)

- In residual or very shallow cover, a multi-acid ('total') or strong acid (*aqua regia*) digest followed by analysis using ICP OES/MS is appropriate.
- A typical multi-element analytical suite within the Curnamona region

would include: Ag, As, Au, Co, Cu, Mo, Pb, Zn and U, with the variable inclusion of Bi, Cd, Sn, Ti, W and Zr–depending on the target mineralisation.

- Major and minor elements (e.g. Al, Ca, Cr, 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.
- Partial leach methods may be useful where the element dispersion controls and regolith host sites are well understood.
- True total analytical methods (e.g. XRF, INAA and fusion ICP OES/MS) are recommended to interpret parent rock type or detect primary alteration patterns.
- The appropriate analytical method to determine Au is influenced by its particle size and distribution within a sample.

Identifying anomalies (pp. 109-110)

- Trace elements do not have a common background level for all regolith materials across the Curnamona region.
- Orientation surveys and case studies that compare typical background materials with materials from areas of known mineralisation can be used to establish thresholds.
- 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.
- It is critical to examine the spatial distribution of element abundances and element associations and link this to their regolith and geological context.

Illustrative field sites

- Selected regolith field sites are described within two field guides (northern Curnamona and southern Curnamona) included in the Appendix CD.

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 **Curnamona Guide** has six parts:

- Introduction to the purpose of the guide and exploration challenges faced;
- Physical setting;
- The geology and exploration potential of the Curnamona Province;
- The landscape evolution of the region including regolith models;
- A description of regolith materials;
- Exploration challenges and strategies.

There is a guide summary and key at the back for quick reference to relevant sections.

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

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