Geochemical signature of mineralization in weathered sediments and bedrock, Thunderdome prospect, Broken Hill region, western New South Wales, Australia: implications for mineral exploration under cover

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ABSTRACT: The stratiform Pb–Ag–Zn and stratabound Cu–Au mineralization of the Thunderdome prospect, located in the Mundi Mundi Plain 50 km NW of Broken Hill, NSW, is covered by c. 200 m of sediments. A downhole mineralogical and geochemical dispersion study was carried out on 245 regolith samples from six exploration drillholes to establish if geochemical dispersion from the mineralization could be identified in the overlying cover. This was achieved using a combination of qualitative and quantitative XRD, Portable Infrared Mineral Analyzer (PIMA) and XRF techniques. The stratigraphy is defined by a variable thickness of diagenetically modified and weathered Cenozoic sediments (and soil) overlying the weathered Proterozoic basement, which hosts the mineralization. The composition of the sediments and saprolite appears to have been influenced by chemical dispersion from underlying mineralization, as shown by anomalous concentrations of Cu (up to c. 13 times above background), Ni (c. 9 times), As, Zn, Pb and Co (all c. 3 times) among others. Some of these anomalies are widespread and may be either clastic or related to adsorption on clay minerals, Fe-oxides and neoformed, poorly crystalline mineral phases. The precise transport mechanisms from the underlying mineralization need to be tested in order to gain further insights into geochemical dispersion processes under cover.

KEYWORDS: basin cover, weathering, regolith, geochemical dispersion, blind mineralization

The Broken Hill region (Fig. 1) has been the focus of considerable mineral exploration activity since the end of the 19th century because of the presence of the world-class Broken Hill Pb–Ag–Zn ore deposit, and the widespread occurrence of mineralization in areas of bedrock outcrop. Current ore reserves for the Broken Hill deposit are forecast to run out in the near future. This has brought a new focus to the regolith- and sediment-covered margins of the Broken Hill Domain. However, limited knowledge about the origin, provenance and post-depositional history of the cover materials has precluded major discoveries being made here to date.

Over 70% of Australia consists of intensely weathered rock, transported overburden, and/or cover of basin sediments that may conceal (or host) mineralization. The greatest potential for future world-class ore deposit discoveries lies in areas of substantial cover on the (under- or un-explored) margins of established mineralized provinces (Butt et al. 1998). They have complex subsurface relationships, which include intricate facies variations, stratigraphy and basin architecture. In addition, the sediments and underlying bedrock have also typically been subjected to prolonged periods of diagenesis and weathering. Many of these interrelationships are poorly understood and hence exploration work is tedious, highly expensive and frequently unsuccessful. New methods need to be developed to increase the success rate of drillhole targeting under cover.

Although the challenge of exploring through thick sedimentary cover has been tackled on numerous occasions in various places worldwide, very few detailed case studies have been reported in the mainstream scientific literature (e.g. Wang et al. 1999).

The Thunderdome prospect occurs within the Mundi Mundi Plain, which is situated immediately west of the Broken Hill Domain (Fig. 1). The Mundi Mundi Plain has evolved through
extensive Cenozoic sedimentation covering the Proterozoic basement (e.g. Hill 2000). This paper aims to:

(1) elucidate the mineralogical and geochemical characteristics of the diagenetically modified and weathered sediments and bedrock overlying the Thunderdome prospect;
(2) examine the distribution of ore-related chemical elements and their dispersion within the regolith cover; and
(3) make recommendations for exploration under cover based on these dispersion patterns.

REGIONAL GEOLOGY, SEDIMENTARY HISTORY AND EXPLORATION TARGETS

The Mundi Mundi Plain is predominantly underlain by a sequence of Broken Hill equivalent rocks (including complexly deformed high-grade metamorphic rocks of the Early Proterozoic Willyama Supergroup) and Adelaidean rocks (more gently folded, mostly lower greenschist-grade Late Proterozoic sediments with minor volcanic rocks). This basement is covered by Cenozoic (and, further north, Mesozoic) sediments. Detailed accounts of the geology of the Broken Hill Domain have been reported in a number of studies (e.g. Stevens 1980, 1986; Willis et al. 1983; Page & Laing 1992; Stevens & Corbett 1993).

The Willyama Supergroup comprises aluminous metasedimentary gneisses, plus locally abundant albite-rich rocks, basic gneisses (amphibolites), lesser quartzo-feldspathic gneisses and substantial bodies of deformed pegmatite and leucocratic quartzo-feldspathic rocks. The Willyama Supergroup can be found within the Broken Hill Domain, where it includes the Thackaringa and Broken Hill Groups, the Olary Domain, and the Redan Geophysical Zone, which both contain abundant albite and calc-albite (Stevens & Corbett 1993). The Adelaidean sequence unconformably overlies the Willyama Supergroup and can be correlated with the more extensive occurrence of Adelaidean rocks in South Australia (Cooper et al. 1978; Preiss 2000). It consists of a sequence of quartzite, quartzite conglomerate, limestone, siltstone, sandstone, shale, dolomite and diamicite forming various groups (Willis et al. 1983; Stevens et al. 1988; Stevens & Corbett 1993). Downthrown Proterozoic rocks west of the Mundi Mundi Fault are overlain by a thick fluvo-lacustrine sedimentary succession belonging to the Cenozoic Lake Eyre Basin, which extends across a vast area of central Australia. This basin is interpreted to have formed by tectonic subsidence in northeastern South Australia during the Late Palaeocene (Callen et al. 1995). The Lake Eyre Basin comprises a number of sub-basins, including the Callabonna Sub-basin within which the Mundi Mundi Plain occurs. Quaternary sediments and soils commonly cover Tertiary units. Deposition in the Lake Eyre Basin occurred in three phases, described below (Callen et al. 1995).

(i) In the first phase, sandstone, carbonaceous clastics and conglomerate of the Eyre Formation were deposited during the latest Palaeocene to Middle Eocene.

(ii) The second phase includes deposition of grey, green and white clay, fine-grained sand and carbonate, with minor conglomerate of the Namba Formation during the Oligocene to Pliocene. It is informally divided into a lower member characterized by smectite and cyclic deposition, and an upper member with illite and kaolinite. The Namba Formation was deposited in low-energy lacustrine environments (Callen 1990).

(iii) The third phase was characterized by the deposition of red and yellow-brown sand and sandy clay, and the development of gypsum and carbonate palaeosols during the Pliocene to Quaternary.

This stratigraphic scheme is not always easily identifiable in drillholes, especially far away from the type sections (as here), where varying provenance and depositional facies give rise to heterogeneous sedimentary packages. Therefore, we shall differentiate the various sedimentary units on the basis of their textural properties, rather than attempt to ascribe them to stratigraphic Formations, which have age connotations.

The regional regolith and landscape features of the Broken Hill region are now being extensively studied. Recent works include those of Hill et al. (2000), Hill (2000), Gibson (2000) and Caritat et al. (2000a, b, 2001). Depth to fresh bedrock in the region varies from minimal in bedrock-dominated terrains up to c. 200 m under basin cover (Caritat et al. 2000a). The dominant regolith materials in the region include saprolite, sediments, soils, ferricretes, silicretes, siliceous and/or ferruginous lags and carbonate accumulations (e.g. Hill 2000; Hill et al. 2000). Areas of deepest weathering occur in areas of high preservation potential, including down-titled fault block margins, under dune or lag-strewn surfaces, and in localized areas isolated from regional erosion or base-level lowering (Hill 2000).
Current exploration work within the Mundi Mundi Plain involves the search for a wide range of mineralization styles. The principal target models are early stratiform to stratabound iron formation/calc-silicate-related and/or sediment-hosted Cu–Au through to Pb–Ag–Zn deposits plus later Fe-oxide replacement deposits (Leyh & Conor 2000). These include Portia/Selwyn/Ernest Henry style (Cu–Au/p5 Ag–Mo–Co), polymetallic 'Bimba style' (Zn–Ag–Pb–Cu/p5 Co–Au–W), Broken Hill style (Pb–Ag–Zn) and McArthur River/Mt Isa distal sedimentary (Pb–Ag–Zn) systems (Fig. 2). Mineralization occurs mostly within specific stratigraphic intervals, including within and below the Thackaringa Group, within the Broken Hill Group and within the Sundown-Paragon Groups.

Aeromagnetic, gravity and company drillhole data generated as a result of the Broken Hill Exploration Initiative (BHEI) are continuing to provide explorers with high-quality targets. Recent correlation of stratigraphy and mineralization by Primary Industries and Resources South Australia (PIRSA) using information from existing prospect drillholes in the Mundi Mundi Plain plus extensive solid geology interpretation across the New South Wales–South Australia state border, has contributed to a stratigraphically based metallogenic model (Leyh & Conor 2000). This has facilitated a more detailed understanding of prospective, stratigraphically controlled target zones within the upper and lower Willyama Supergroup and the relationships between mineralization and stratigraphy of the Broken Hill Domain as defined by Stevens et al. (1983).

The highest prospectivity within the Mundi Mundi Plain so far has been obtained from the Thunderdome prospect.

Aeromagnetic data have delineated a number of domal structures where the prospective lithologies have been elevated by folding or faulting into semi-circular domes, which vary in geometry from broad or 'open' (Dome 1) to much tighter (Dome 5) to the north (Fig. 3). Attention has been directed at these domal environments because they have a thick sequence of metal-rich rocks and an anomalous structure, which may have led to thickening in the prospective horizons and/or remobilisation and concentration of ore forming fluids (Richardson 1997). The most encouraging drilling results have been encountered at Dome 5 (Fig. 4). This sequence includes highly prospective rocks of the Thackaringa and Broken Hill Groups.

A comprehensive comparison with Pb–Zn–Ag ores on a worldwide basis, and more significantly with the Broken Hill and Cannington deposits, strongly suggests an intersection of a proximal-to-ore host rock package (Richardson 1997). This paper examines the expression of this mineralization within the overlying sedimentary cover at Dome 5 and at three other locations within the Thunderdome prospect area.

**METHODS**

Rotary air blast drill chips were collected from six exploration holes DD96P1 (on Dome 3), DD96P3 (Dome 6), DD96P2,
Fig. 3. Filtered high-resolution aeromagnetics of the exploration targets around the Thunderdome prospect, Broken Hill [Reproduced with permission from Platsearch N.L.].

DD97P4, DD97P5 (all Dome 5) and SR5 (hereafter P1, P3, P2, P4, P5 and SR5, respectively) drilled by exploration companies Plutonic and Savage Resources. The location of these drillholes is shown in Figure 2. A total of 245 samples were selected for geochemical analysis (XRF). Samples for bulk XRD were prepared by crushing 50 g in a ball-mill for 10 seconds and mounting the resultant powder on a sample holder following the back-pack method. The sample was then run from 2–70° 2θ at steps of 0.02° and a counting time of 1.2 second/step on a Siemens D501, 0–20 powder diffractometer utilizing CuKa radiation and a graphite post-sample monochromator, collimated by 1° divergence slits. The Rietveld-based computer software SIROQUANT™ (Taylor & Clapp 1992) was used to obtain quantitative mineralogy results from bulk XRD data. These were then constrained by comparing mineral abundances, mineral chemistries and bulk chemistry using linear programming analysis implemented by the computer code LPNORM (Caritat et al. 1994). The two methods yielded broadly similar results showing that they are complementary, but inclusion of the normative analysis procedure allows elimination of chemically impossible results. Portable Infrared Mineral Analyzer (PIMA; Pontual et al. 1997) was also used to identify minerals from characteristic spectral signatures. Major and trace element geochemistry was determined using PW 1400 XRF spectrometers at the Australian National University and Geoscience Australia using the methods of Norrish & Chappel (1977) and Chappel (1991). Data quality was monitored by replicate analysis introduced at a rate of one control per 5 unknowns. Statistical analysis, boxplots and scatterplots were produced using DAS® (Dutter et al. 1995). Downhole plots were produced using Logplot98™ (RockWare 1998). Colour codes of the dry samples were recorded from the Munsell colour chart (Munsell Color Company 1975).

REGOLITH STRATIGRAPHY

The stratigraphy of the six drillholes is presented in Figure 5. The distribution and mineralogical characteristics of the sediments and bedrock have been comprehensively described in Tonui & Caritat (2003). In the following, the diagenetically modified and weathered sediments will collectively be referred to as the ‘transported regolith’ and the weathered bedrock (i.e. saprolitic and saprock) as the ‘in-situ regolith’ or ‘residual regolith’. Thickness of the weathered sediments ranges from 160 m from top to bottom in SR5 to 210 m in P3. The regolith stratigraphy comprises the units described hereafter.

Transported regolith

Soil. The most common soil type in the area is red to reddish brown sandy loam. It contains carbonates, which occur as soft, friable, white to creamy stains within the clay matrix. Rhizomorphic calcrete is common. The soil also contains coarse to fine grained detrital rock and quartz fragments and gypsum, which is present as near-transparent to translucent crystals. The thickness of the soil ranges from 1 to 3 m.

Sandy clay unit. The sandy clay unit is the most common and diverse regolith unit. It shows variable texture and colour, and ranges in thickness from c. 50 to 110 m. The two most common varieties are red/reddish brown and reddish brown/grey sandy clay units. The red/reddish brown variety overlies the reddish brown/grey variety. Intermediates between these two types occur and range from reddish brown to yellow. The sandy clay unit is coarse to medium grained and contains abundant detrital quartz and rock fragments. Nodular calcrete is also present in small amounts especially in the upper parts. The matrix is composed of fine silt-sized quartz grains and clay minerals. The clays are dense and bleached in parts and commonly display random cracking fracture surfaces. The grains are poorly sorted indicating an immature sediment. Post-depositional processes have obliterated most of the secondary structures and fabrics.

Mottled clay unit. The mottled clay unit ranges in thickness from 25 to 40 m. It is fine to medium grained and red to reddish grey or pinkish grey in colour. The mottles (Fe-rich segregations) are dull to earthy in appearance and exhibit sharp boundaries with the surrounding, intensely bleached ‘cracking’ grey clay. The matrix is composed of very fine sand granules and detrital rock fragments. Like the sandy clay unit, the mottled clay unit contains no discernible secondary structures.

Grey clay unit. Two main types of grey clay units occur, i.e. the light grey to dark grey clay and olive or greenish grey clay units. The light grey to dark grey clay unit overlies the olive grey and greenish grey clay unit or, in SR5, the saprolite-derived light grey clay unit. This unit consists of fine grained, poorly sorted, angular to subangular sand, silt and clay and ranges in thickness from 10 to 70 m. The clay is dense and massive and displays slickenslide fracture surfaces. The olive and greenish grey clay unit consists of fine to very fine grained, poorly sorted, angular to sub-angular sand, silt and clay. It ranges in thickness from 50 to 70 m and, like the light grey to dark grey clay unit, is dense, massive and displays slickenslide fracture surfaces. The light grey clay commonly occurs as intercalations within the olive grey or greenish grey clay unit. Like the sandy and mottled clay units, the grey clay units contain no discernible secondary structures.
**In-situ regolith**

Saprolite. The saprolite is soft, highly friable and displays textures and fabrics of the underlying fresh rock. The two most common types are the white/whitish grey and light grey saprolite. The white/whitish grey saprolite overlies the light grey saprolite. Remnant primary high-grade gneissosity is still conspicuous in the white/whitish grey saprolite indicating that it is derived from Willyama gneisses and schists. In some instances, remnant quartz veins are expressed by the presence of gritty grains within the matrix. These could also be associated with weathered intrusive granites or pegmatites. The light grey saprolite is thought to be derived from Adelaidean siltstone and shale or underlying granite-bearing diamictite, which unconformably overlie Willyama meta-feldspathic gneiss grading to granitoid and pegmatite.

Saprock. The saprock is slightly weathered and, like the saprolite, displays textures and fabrics of underlying fresh rock. It occurs as white/whitish grey and light grey types, similar to the saprolite, reflecting the composition of the underlying rock.

**Unweathered bedrock**

The fresh basement consists of Willyama Supergroup gneiss and schist and Adelaidean siltstone and shale. The lithostratigraphy and mineralization is summarized in Figure 2.

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**RESULTS**

**Mineralogy**

The mineralogical distribution in drillhole P5 (Fig. 6) is representative of most of the drillholes. The boxplot distribution of the minerals in the transported and in-situ regolith is shown in Figure 7. The median values give a good estimate of the mineral abundance in each regolith group. Mineralogical characteristics of the regolith are described in the following.

**Quartz.** Quartz is present in all units and is more abundant within the in-situ regolith than in the transported regolith. It occurs mainly as a coarse to fine grained detrital constituent and as fine sand grains in the transported regolith. Some of the quartz is present as grit (probably remnants of quartz veins) within the saprolite. The highest amounts of quartz occur within the saprolite, followed by the sandy clay and the grey clay units.

**Kaolinite.** Kaolinite is the major secondary product and is more abundant within the transported regolith than in the in-situ regolith. The highest contents occur within the mottled and grey clay units, followed by the saprolite and the sandy clay unit.

**Feldspar.** Feldspar (plagioclase and K-feldspar) is generally more abundant within the transported regolith than in the in-situ regolith.
It occurs mainly as detrital rock fragments, which are most abundant within the sandy clay unit. The overall trend is one of a downward decrease in feldspar content as older sediments have had the potential to experience a more protracted weathering history. Feldspar is present in appreciable amounts (up to 10%) within the saprolite.

Fe-oxides. Fe-oxides (hematite and goethite) are present in low amounts (<5%) in most of the units and are generally more abundant within the transported regolith than in the in-situ regolith. These contents are low despite the highly Fe-stained nature of some of the units, e.g. the sandy clay unit. The geochemical data show higher amounts of Fe$_2$O$_3$ (5–10%) in these units. SEM micromorphology (Tonui & Caritat 2003) shows the Fe-oxide to be present as stains on the surface of clay minerals without any discernible crystal morphology. This suggests that the oxides occur as poorly crystalline 'mineral' phases (or poorly diffracting material, PDM), which are

![fig5](image)

**Fig. 5.** Thunderdome prospect drillhole logs of the regolith intersections.

![fig6](image)

**Fig. 6.** Mineralogy of regolith in drillhole P5 (SIROQUANT$^{TM}$ and PIMA) [PDM: poorly diffracting material; H$_2$O: water absorption peaks corresponding to presence of smectite; Al-OH: Al hydroxyl absorption peak corresponding to the presence of Al-bearing minerals such as kaolinite; KaolXT: kaolinite crystallinity based on sharpness of absorption peaks; Fe$^{2+}$: spectral response of Fe-bearing minerals].

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abundant within these units (Fig. 6). The Fe is allochthonous and was probably mobilized from Fe-rich lithologies in the Broken Hill Block.

**Muscovite.** Muscovite (or illite) is slightly more abundant within the in-situ regolith than in the transported regolith in all drillholes. Highest contents in P5 occur within the sandy clay unit, where it occurs in detrital rock fragments. Moderate amounts are present within the mottled clay unit, grey clay unit and saprolite. Muscovite is generally more abundant than feldspar in most of the units as a result of its slightly greater resistance to weathering.

**Smectite.** Smectite is more abundant within the transported regolith than in the in-situ regolith. The highest amounts occur within the soil and upper levels of the sandy clay unit, where it is present as pedogenic carbonate. Very low amounts occur within the grey clay unit and saprolite.

**Poorly Diffraacting Material (PDM).** PDM is more abundant within the transported regolith than in the in-situ regolith. Highest contents occur within the sandy clay and grey clay units. The actual nature of these materials could not be determined within the scope of this study, although the micromorphological and geochemical data suggest that at least some are present as poorly crystalline Fe- and Mn-oxides.

**Minor phases.** These phases occur in very small amounts (<5%) and hence cannot be satisfactorily quantified by SIROQUANT™. Rutile, zircon and anatase occur as minor phases within the bulk fractions of the transported regolith. Minor amounts of ferromagnesian silicates (diopside and hornblende) and barite occur within the in-situ regolith.

**Spectral signatures.** PIMA spectral data interpretation is based on characteristic mineral absorption features in the Short Wave-length Infrared (SWIR) electromagnetic spectrum (Pontual et al. 2003).
The spectral parameters shown in Figure 5 are measured as numeric values ranging from 0 to 1, where 1 indicates strong reflectance characteristics. The dominant bonds giving rise to SWIR absorption are hydroxyl-Al, −Mg or −Fe bonds and water, which occur between 1400 nm and 1900 nm. The absorption strength of Al–OH and H$_2$O bonds is related to the abundance of kaolinite and smectite, respectively. The Fe$^{2+}$ response in the spectra allows Fe-bearing minerals to be distinguished from non-Fe-bearing equivalents. KaolXT is a measure of crystallinity of kaolinite based on the shapes of the diagnostic absorption features. Downhole compositional variations in the samples are typically represented by shifts in the wavelength positions of diagnostic absorption features, with the overall characteristic spectral signature of the sample remaining unchanged (Tonui & Caritat 2003).

The absorption features typically increase in sharpness with increasing crystallinity. Transported regolith generally exhibits poor kaolinite crystallinity and vice versa for the in-situ regolith. Smectite is abundant within the mottled and grey clay units as shown by pronounced H$_2$O peak intensities. Kaolinite is more abundant within mottled clay as shown by pronounced Al–OH absorption peaks. The distribution of kaolinite inferred from spectral reflectance is similar to that expressed by SIROQUANT$^\text{TM}$. The Fe$^{2+}$ response reflects the presence of reducing clay notably smectite in the mottled and grey clay units. The crystallinity of kaolinite increases towards the saprolite and saprock.

**MAJOR AND TRACE ELEMENT GEOCHEMISTRY**

**Regolith distribution**

Most of the elements are more abundant within the transported regolith than in the in-situ regolith (Figs. 7 & 8). Highest maximum concentrations of SiO$_2$ occur within the saprock, light grey and greenish-grey clay units associated with the primary rock-forming silicates. The distribution of K$_2$O is similar within the transported and in-situ regolith (Fig. 8) with the highest maximum contents within the sandy clay unit, mottled clay unit and saprolite associated with the K-feldspars and muscovite. The distribution of Al$_2$O$_3$ reflects the presence of kaolinite, while high contents of Fe$_2$O$_3$ occur within the mottled clay and grey clay units associated with hematite, goethite and smectite. Highest maximum concentrations of Na$_2$O occur in the sandy clay unit and soil associated with plagioclase in detrital rock fragments, while high contents of MgO occur within the grey clay unit and soil corresponding to the abundance of smectite. Highest concentrations of CaO occur within the soil and upper levels of the sandy clay unit associated with calcite and gypsum. One sample from a calcrite horizon (P4 drillhole) contained a high value of 31.2% CaO.

Among the trace elements, median As, Ni, Pb, Ba and Zn concentrations are higher within the transported regolith than within the in-situ regolith. Highest maximum concentrations of As occur in the saprolite, soil, sandy clay and dark grey clay.
units. Copper shows more or less similar abundance (median concentration values) in the transported and in-situ regolith with a few outliers occurring within the saprolite. Median and highest maximum concentrations of Ni occur within the dark grey clay unit suggesting association with smectite. Median Zn and Pb concentrations are highest within the sandy, mottled and grey clay units.

Geochemical associations

Table 1 shows the background values of geochemical elements of interest in sediments and saprolite currently utilized by the exploration industry in the Mundi Mundi area. A summary of actual bedrock data from P2, P4 and P5 from depths of 610–720, 295–915 and 265–825 m, respectively, is presented in Table 2 (courtesy of BHPB Ltd.). Table 3 shows the statistical data for the regolith intersected in those six drillholes (upper 200 m). The correlation coefficients (r) for selected elements from the regolith intersections are presented in Table 4. Downhole distribution graphs of the trace elements are presented in Figures 10 to 12.

Silicon shows an antipathetic relationship with most of the elements especially in the in-situ regolith. This reflects the breakdown of silicates accompanied by progressive enrichment of Fe₂O₃ and Al₂O₃ in Fe-oxides and clay minerals (as well as closure). The positive associations between MgO, Ni and Fe₂O₃ (Fig. 13) reflect secondary accumulation within smectite.

A strong association exists between K₂O and Rb (Fig. 13), as is often observed in geological materials (e.g. Reimann & Caritat 1998; Butt 2001). Cesium also shows a strong association and distribution similar to these two elements. High concentrations

<table>
<thead>
<tr>
<th>Element</th>
<th>Background</th>
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<tr>
<td>Ag</td>
<td>≤ 0.1</td>
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<tr>
<td>As</td>
<td>10</td>
</tr>
<tr>
<td>Au</td>
<td>0.001</td>
</tr>
<tr>
<td>Ba</td>
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</tr>
<tr>
<td>W</td>
<td>20</td>
</tr>
<tr>
<td>Zn</td>
<td>70</td>
</tr>
</tbody>
</table>

Fig. 9. Boxplots of selected trace elements for all drillholes and units (see Fig. 7 for key to abbreviations). Stippled: below background values from Table 1.
of TiO₂ and rare earth elements (REEs; here specifically Zr and Nb) occur within the transported regolith, reflecting the occurrence of resistate mineral phases (zircon and rutile) and their relative accumulation as more soluble components are lost during weathering. This is related to the stability of these minerals and ability to survive many cycles of weathering, transport, diagenesis, metamorphism and anatexis (Milnes & Fitzpatrick 1989). It appears from the distribution and clustering of the REEs that there was little fractionation suggesting a common source.

Strongest indicators of mineralization are shown by strong correlations between Ag, Bi, Cu, As, Pb and S in the bedrock (Table 2). This is expressed in the regolith by strong correlations between Ba and Bi, Cu and Bi and Ba and Cu (Table 3). Other associations that are indicators of mineralization include Zn with Cu, As, Ni and Pb in both transported and in-situ regoliths.

### Table 2: Concentration of selected trace elements in bedrock at the Thunderdome prospect (P2, P4 and P5) and significant correlations (in ppm; N=241, except As for which N=179 [P2 & P5 only], and Mo for which N=62 [P4 only]). Data provided by BHPB Ltd.

<table>
<thead>
<tr>
<th>Element</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>Median</th>
<th>Correlation (r ≥ 0.5)</th>
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</thead>
<tbody>
<tr>
<td>Ag</td>
<td>≤ 0.5</td>
<td>10000</td>
<td>314</td>
<td>2</td>
<td>Cu and Ni (P2 and P5); As, Co and Zn (P2)</td>
</tr>
<tr>
<td>As</td>
<td>≤ 0.5</td>
<td>73600</td>
<td>3037</td>
<td>18</td>
<td>Ag, Co, Cu, Ni and Zn (P2)</td>
</tr>
<tr>
<td>Co</td>
<td>≤ 0.5</td>
<td>119</td>
<td>13.4</td>
<td>13</td>
<td>Ag, As, Cu, Ni and Zn (P2)</td>
</tr>
<tr>
<td>Ca</td>
<td>≤ 0.5</td>
<td>2050</td>
<td>79.7</td>
<td>8</td>
<td>Ag and Ni (P2 and P5); As, Co and Zn (P2); Pb (P4); S (P5)</td>
</tr>
<tr>
<td>Mo</td>
<td>≤ 0.5</td>
<td>320</td>
<td>9.6</td>
<td>2.3</td>
<td>—</td>
</tr>
<tr>
<td>Ni</td>
<td>2</td>
<td>290</td>
<td>49.8</td>
<td>40</td>
<td>Ag and Cu (P2 and P5); As, Co and Zn (P2)</td>
</tr>
<tr>
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<td>2780</td>
<td>191</td>
<td>75</td>
<td>Cu and S (P4)</td>
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<tr>
<td>S</td>
<td>≤ 0.5</td>
<td>31000</td>
<td>2252</td>
<td>550</td>
<td>Pb (P4); Cu (P5)</td>
</tr>
<tr>
<td>Zn</td>
<td>≤ 0.5</td>
<td>35550</td>
<td>763</td>
<td>130</td>
<td>Ag, As, Co, Cu and Ni (P2)</td>
</tr>
</tbody>
</table>

### Table 3: Concentration of selected trace elements in transported and in-situ regolith at the Thunderdome prospect for all units (in ppm; N=162, except Co for which N=50)

<table>
<thead>
<tr>
<th>Element</th>
<th>Min</th>
<th>Med</th>
<th>Max</th>
<th>Mean</th>
<th>Med/Bkgd(a)</th>
<th>Max/Bkgd(b)</th>
<th>Med (Reg/BR)(c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>As</td>
<td>1.9</td>
<td>8.55</td>
<td>33.5</td>
<td>9.22</td>
<td>0.86</td>
<td>3.35</td>
<td>0.48</td>
</tr>
<tr>
<td>Ba</td>
<td>123</td>
<td>412.5</td>
<td>2733.4</td>
<td>446.34</td>
<td>1.38</td>
<td>9.11</td>
<td>—</td>
</tr>
<tr>
<td>Bi</td>
<td>&lt;0.1</td>
<td>0.1</td>
<td>68</td>
<td>0.84</td>
<td>0.02</td>
<td>13.60</td>
<td>—</td>
</tr>
<tr>
<td>Co</td>
<td>9.1</td>
<td>22.55</td>
<td>55.9</td>
<td>24.33</td>
<td>1.13</td>
<td>2.80</td>
<td>1.73</td>
</tr>
<tr>
<td>Cu</td>
<td>8</td>
<td>24.5</td>
<td>545</td>
<td>34.72</td>
<td>0.64</td>
<td>13.63</td>
<td>3.06</td>
</tr>
<tr>
<td>Mo</td>
<td>&lt;0.1</td>
<td>2.5</td>
<td>5.9</td>
<td>2.64</td>
<td>0.50</td>
<td>1.18</td>
<td>1.11</td>
</tr>
<tr>
<td>Ni</td>
<td>7</td>
<td>24</td>
<td>141</td>
<td>25.14</td>
<td>1.60</td>
<td>9.40</td>
<td>0.60</td>
</tr>
<tr>
<td>Pb</td>
<td>5.5</td>
<td>22.35</td>
<td>147.5</td>
<td>26.79</td>
<td>0.45</td>
<td>2.95</td>
<td>0.30</td>
</tr>
<tr>
<td>S</td>
<td>120</td>
<td>355</td>
<td>11710</td>
<td>978.21</td>
<td>1.78</td>
<td>58.53</td>
<td>0.65</td>
</tr>
<tr>
<td>Zn</td>
<td>13</td>
<td>60.5</td>
<td>228</td>
<td>69.36</td>
<td>0.86</td>
<td>3.26</td>
<td>0.47</td>
</tr>
</tbody>
</table>

(a) Med/Bkgd is the ratio of the median regolith value over background; (b) Max/Bkgd is the ratio of the maximum regolith value over background; (c) Med (Reg/BR) is the ratio of the median values for regolith over bedrock.

### Table 4: Correlation coefficients (r) of selected oxides and trace elements in transported and in-situ regolith at the Thunderdome prospect for all units (in ppm; N=162, except Co for which N=50)

<table>
<thead>
<tr>
<th></th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>MgO</th>
<th>K₂O</th>
<th>As</th>
<th>Ba</th>
<th>Bi</th>
<th>Cu</th>
<th>Ni</th>
<th>Pb</th>
<th>Rb</th>
<th>Sn</th>
<th>U</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al₂O₃</td>
<td>-0.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>-0.66</td>
<td>0.52</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>MgO</td>
<td>-0.52</td>
<td>0.13</td>
<td>0.60</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K₂O</td>
<td>-0.29</td>
<td>0.43</td>
<td>0.17</td>
<td>0.23</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>As</td>
<td>-0.29</td>
<td>0.19</td>
<td>0.50</td>
<td>0.25</td>
<td>0.21</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Ba</td>
<td>-0.14</td>
<td>0.16</td>
<td>0.18</td>
<td>0.15</td>
<td>0.45</td>
<td>0.15</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bi</td>
<td>-0.03</td>
<td>0.08</td>
<td>0.01</td>
<td>0.01</td>
<td>0.21</td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cu</td>
<td>-0.14</td>
<td>0.17</td>
<td>0.15</td>
<td>0.04</td>
<td>0.21</td>
<td>0.02</td>
<td>0.63</td>
<td>0.76</td>
<td></td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Ni</td>
<td>-0.42</td>
<td>0.30</td>
<td>0.72</td>
<td>0.54</td>
<td>0.09</td>
<td>0.40</td>
<td>0.13</td>
<td>0.10</td>
<td>0.24</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pb</td>
<td>-0.17</td>
<td>0.27</td>
<td>0.10</td>
<td>-0.05</td>
<td>0.19</td>
<td>0.31</td>
<td>0.15</td>
<td>0.03</td>
<td>0.14</td>
<td>0.06</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Rb</td>
<td>-0.50</td>
<td>0.66</td>
<td>0.41</td>
<td>0.30</td>
<td>0.90</td>
<td>0.30</td>
<td>0.40</td>
<td>0.20</td>
<td>0.23</td>
<td>0.29</td>
<td>0.26</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sn</td>
<td>0.04</td>
<td>-0.08</td>
<td>-0.04</td>
<td>-0.11</td>
<td>0.05</td>
<td>0.10</td>
<td>0.21</td>
<td>0.16</td>
<td>0.16</td>
<td>0.04</td>
<td>0.09</td>
<td>0.05</td>
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<td></td>
</tr>
<tr>
<td>U</td>
<td>-0.02</td>
<td>0.06</td>
<td>0.03</td>
<td>-0.10</td>
<td>0.13</td>
<td>0.05</td>
<td>0.32</td>
<td>0.35</td>
<td>0.35</td>
<td>0.09</td>
<td>0.22</td>
<td>0.14</td>
<td>0.78</td>
<td></td>
</tr>
<tr>
<td>Zn</td>
<td>-0.21</td>
<td>0.08</td>
<td>0.50</td>
<td>0.28</td>
<td>0.05</td>
<td>0.57</td>
<td>0.18</td>
<td>0.08</td>
<td>0.27</td>
<td>0.51</td>
<td>0.52</td>
<td>0.17</td>
<td>0.24</td>
<td>0.29</td>
</tr>
</tbody>
</table>

* Bold values where |r| ≥ 0.5 (p>0.001 for |r| >0.3).
Cobalt does not correlate with any of the other elements. However, it is present in anomalous concentrations (>20 ppm) in most of the regolith units and shows a broadly similar distribution pattern to As, Ba, Cu, Ni, Pb and Zn. A surprisingly strong correlation exists between U and Sn in both transported and in-situ regolith (Fig. 13). Uranium, like the base metals, shows anomalous concentrations (>20 ppm) within the saprolite (Figs. 11 & 12). Molybdenum shows no association with any of the other elements and is present in low concentrations in the transported and in-situ regolith and in slightly higher concentrations in the bedrock.

Factor analysis (Table 5) reflects the dominance of weathering and diagenetic processes. The elements associated with mineralization, i.e. Cu, Zn and Pb, are weakly expressed in Factor 5 in both transported and in-situ regolith. This expression is weak mainly because of the masking effect of secondary processes involving clay minerals and Fe-oxides. This is expressed by the clustering of Al2O3, Fe2O3, TiO2, Ga, Ce, Nb, Pb and Cr accompanied by a negative correlation with SiO2. Some of the REEs (La, Nd, Pr and Y) are likely to be incorporated into carbonates (Factor 2; transported regolith). The occurrence of K2O with Rb and Cs in Factor 1 in the in-situ regolith is largely due to their presence in K-feldspar and muscovite. The clustering of U and Sn with Al2O3 (in-situ regolith) and K2O and Na2O (transported regolith) suggests secondary concentration within clay or primary mineral phases such as muscovite or plagioclase. The occurrence of Ba within the transported regolith (notably the sandy clay unit) appears to be strongly influenced by these primary minerals. The associations between As and Fe2O3 (transported and in-situ regoliths) and between As, S and Ba (in-situ regolith) are due to adsorption onto Fe-oxide minerals (notably goethite) and possible occurrence within sulphides (as arsenopyrite) in the underlying mineralization.

**DISCUSSION**

**Geochemical distribution and dispersion patterns**

A number of inferences can be drawn regarding geochemical dispersion at the Thunderdome prospect based on distribution patterns and geochemical associations.

*Major elements – Al, Fe and Si.* As in most regolith-dominated terrains, the oxides (e.g. goethite, hematite and quartz) or aluminosilicate (e.g. kaolinite) hosts of these elements are the predominant products of chemical weathering at the Thunderdome prospect. Their abundances and distributions are generally negatively correlated due to closure. Aluminium is present in the transported and in-situ regolith within feldspar, kaolin and muscovite. Strong positive correlation exists between Al2O3 and Fe2O3, associated with the common occurrence of dominant weathering products. Associations with trace elements, e.g. Pb, reflect the secondary properties of clay minerals, (specifically their ability to adsorb trace elements within their complex chemical structures or adsorbed onto their mineral surfaces, e.g. Paquet et al. 1987), and Fe-oxyhydroxides (McKenzie 1980).

Iron is enriched within the mottled and sandy clay units, where it occurs as hematite and goethite. The high contents of Fe2O3 (2–14%) within the grey clay units are associated with the occurrence of undetermined ‘poorly diffracting’ secondary phases. The high concentrations of As, Bi, Cu, Pb and Zn within the mottled and grey clay units may be due to the strong chemical reactivity and adsorption capacities of these poorly crystalline Fe-oxides (e.g. Jenne 1968).

Silicon occurs principally within ferromagnesian and aluminosilicate minerals in the unweathered rocks. Most of the regolith units have high contents of SiO2, which occurs mainly as detrital quartz fragments in the transported regolith. Silicon...
shows an antipathetic correlation with most of the other elements as a result of closure and the breakdown of silicates during weathering.

**Alkaline earth elements** - Ba, Ca and Mg. Concentrations of Ba above background (300 ppm) occur within all regolith units, but especially high values are found within the sandy clay and mottled clay units and saprolite (notably grey saprolite). A few samples from these units contain very high concentrations of Ba (1300–2733 ppm), with the maximum concentration being 9 times above the regional background. Even the median Ba concentration in the regolith (413 ppm) exceeds the regional exploration background value. Barium shows strong correlations with Bi and Cu and similar downhole distribution patterns to Co, Cs, Pb and Ni suggesting an association with mineralization. It is mainly incorporated into Fe-oxides, carbonates and clay minerals in the regolith. In the bedrock, Ba is hosted by feldspar, probably K-feldspar, which appears to show an association with the alteration zone. Barite is also present in very small amounts within the saprock.

Calcium occurs predominantly as calcite in most of the units. It occurs within the soil at concentrations of up to 31.2% CaO, hosted in calcite, dolomite and gypsum. Apart from a weak association with Ba and REEs (in P4), CaO does not show any association with the other elements.

Magnesium is abundant within the soil, grey clay and sandy clay units corresponding to its occurrence in pedogenic carbonate and smectite. Ferromagnesian silicates (diopside or hornblende) are the probable hosts for Mg in the fresh rock. Magnesium shows strong association with Ni, mainly as a component of smectite.

**Alkali metals** - Cs, K, Na and Rb. A strong association exists between K, Cs and Rb in the regolith. This association results from the occurrence of these elements within muscovite and K-feldspar. Potassium is most abundant (>2.5% K2O) within the saprolite, sandy clay and mottled clay units. Muscovite occurs in almost all the regolith units; of the major primary minerals present here it is the second most resistant to weathering (after quartz). The strong associations between K2O and Cu, Ba and Pb in the regolith may partly be due to potassic alteration associated with mineralization in the underlying bedrock (e.g. SR5, Fig. 2).

High contents of Cs (>12 ppm) occur within the saprolite, sandy clay and mottled clay units. Rubidium and Cs shows strong association with K2O with highest concentrations of Rb (>110 ppm) occurring within the saprolite, sandy clay and mottled clay units. Both Rb and Cs generally are hosted in K-bearing minerals because K, Rb and Cs have similar ionic radii, allowing substitution. Adsorption plays an important role in the concentration of Rb relative to K in the later stages of weathering, as Rb is more firmly adsorbed than K because it has a more similar ionic radius to H3O+ (Heier & Billings 1978).

Sodium is strongly associated with plagioclase and, apart from its occurrence within the sandy clay unit, it appears to have been leached from much of the regolith.

**Base and transition metals** - As, Bi, Co, Cu, Ni, Mo, Pb and Zn. The base metals (As, Bi and Pb) are associated with inferred mineralization at the Thunderdome Prospect and have similar chemical behaviour with the transition metals (Co, Cu, Ni, Mo and Zn) in the regolith. Arsenic shows strong positive correlations with Ag and Pb in the bedrock and with Zn in the

**Fig. 11.** Trace element geochemistry of regolith in drillhole SR5. Thin vertical lines: background values from Table 1.
regolith. Concentrations of As above background (10 ppm) occur within most regolith units, particularly the sandy clay, mottled clay and dark grey clay units and the saprolite, where they can exceed 15 ppm. Arsenic shows widespread distribution within the regolith and hence has the potential to be a useful pathfinder element for underlying mineralization. Maximum concentrations of As are 3.4 times above the regional background. Arsenic is strongly associated with the Fe-oxides within the transported regolith. In solution, As is normally present in its oxidized form as arsenate oxyanions, which tend to be strongly adsorbed by goethite because of its excess of positive charges at pH values below 8 (Hingston et al. 1972). In the bedrock, As appears to be present as arsenopyrite, which occurs in mineralized Bimba Formation and upper and lower Broken Hill Group lithologies within the district (Barnes 1988).

Bismuth is present at relatively low concentrations in the regolith and shows a very strong association with Cu and a distribution similar to Pb and Ba. The Bi content of the ore at Broken Hill is low, averaging between 8 and 22 ppm, but high Bi concentrations occur locally in some prospects especially in pyritic to pyrrhotitic sulfide mineralization of the Lower Broken Hill Group, particularly in the Bimba/Ettlewood calc-silicate members. This mineralization occurs in association with polymetallic Zn, Cu, Pb, Ag, Mo, W, Ni, Co, As and Ba. This probably explains the high concentrations of Bi in the saprolite in SR5 (Fig. 11), where it reaches 14 times regional background values, and its association with underlying mineralization. The association with Cu, Pb and Ba is particularly strong within the in-situ regolith.

Cobalt shows similar distribution patterns to the other metals and is present in concentrations above background (20 ppm) in most of the regolith units. Hence, Co is one of the strongest indicators of mineralization within the Thunderdome prospect. Mobile Metal Ion (MMI) analysis within the soil B- horizon had revealed the presence of this mineralization and association with Co within SR5 drillhole prior to bedrock drilling by BHPB Ltd. (R. Richardson, pers. comm. 2001). The highest concentrations of Co (>25 ppm) occur within the saprolite and sandy clay unit. Median Co concentration in the regolith (22.6 ppm) is 1.7 times that in the bedrock (13 ppm), and even exceeds the regional exploration background value (20 ppm). The host mineral for Co is unclear but, like Cu, it may be hosted in silicates and sulphides, is leached into solution during weathering and subsequently is incorporated into or adsorbed onto the Fe-oxides and secondary clay minerals, notably smectite.

Sulphides appear to be the main hosts of Cu, as shown by the positive correlation between Cu and S in the bedrock (e.g. r=0.51 for P5). Ferromagnesian silicates may also be important Cu hosts. Copper concentrations above background (40 ppm) occur particularly within the sandy clay, mottled clay, dark grey clay and olive grey clay units and in the saprolite. Copper is strongly associated with Bi and Ba in the transported and in-situ regolith (Table 4). The persistence of this association (e.g. Cu–Bi in in-situ regolith: r=0.74) within the transported regolith (r=0.57) is strong evidence for a chemical or mechanical expression of the underlying mineralization. Enrichments in Cu up to 14 times above background (Table 3) are found in the regolith. The highest median regolith to median bedrock concentrations ratio found in this study is for Cu (MedReg/MedBR=3.1).

Nickel in the bedrock shows strong positive correlations with Cu and Ag (especially over Cu–Au targets) suggesting a
common source, most probably sulfide minerals. The highest Ni concentrations (>25 ppm) occur within the mottled clay and the various grey clay units. The highest Ni concentration in the regolith (141 ppm) is 9.4 times above the regional exploration background level (15 ppm). In the regolith, Ni has strong positive correlations with MgO, Fe₂O₃, and Zn (Table 4). This suggests an association with mineralization with later incorporation into or adsorption onto Fe-oxides and smectite. Nickel is usually released by weathering of silicates into solution as Ni²⁺ and subsequently incorporated into secondary Fe–Mg
regolith

In-situ

Variance 26.6 15.2 12.1 9.3 6.2 70.4

Molybdenum is not abundant in the regolith despite displaying some high but localized concentrations in the bedrock. This distribution within the bedrock tends to be extremely irregular, and it occurs here mostly as molybdenite (MoS$_2$). Molybdenum is associated with Cu–Au mineralization in the Thackaringa Group, i.e. Upper Albite/Himalaya Formations/Olary to Broken Hill stratigraphic equivalents. The style of mineralization is closely associated with albitic metasedimentary units rich in magnetite as well as BIF similar to those seen in SR5 and P1 and expressed by the clear association between Cu, Au, Co and Mo. Localized enrichment (>5 ppm) is expressed in P1 within the dark grey clay unit probably associated with poorly crystalline Fe–oxides (Tonui & Caritat 2003).

Lead in the bedrock shows strong positive correlations with Cu and S (Table 2). High concentrations of Pb (>30 ppm) occur within the sandy clay, mottled clay and dark grey clay units and, especially, in the saprolite (Fig. 9). The maximum Pb concentration in the regolith is 2.95 times above the regional background (Table 3). In the regolith, Pb shows the strongest correlation with Zn, which appears to express underlying mineralization. The association patterns suggest that K-feldspar, mica and sulphides host Pb in the Thunderdome prospect, whilst its behavior in the weathering environment is largely controlled by adsorption onto clay minerals and Fe-oxides.

Zinc tends to be more widely dispersed in the bedrock and hence the apparent lack of correlation with the other metals. However, it shows similar distribution patterns to Cu, Pb, As and Ni. Highest concentrations in the regolith (>60 ppm) occur in the mottled clay and grey clay units. Zinc concentration in the regolith reaches up to 3.3 times above the regional exploration background level. Like Cu, sulphide minerals and ferromagnesian silicate minerals appear to host Zn in the unweathered rock. Zinc cations (Zn$^{2+}$) may substitute for Fe$^{2+}$ and Mg$^{2+}$ in silicates and oxides (e.g. Wedepohl 1978) and hence its occurrence in the regolith may be both structural and adsorption related.

Other significant elements – S and U. Sulphur shows a positive correlation with Cu in the bedrock, which relates to the occurrence of pyrite and chalcopyrite. High concentrations of S (>1000 ppm) in the regolith occur within the soil, sandy clay and grey clay units. It is strongly associated with gypsum within the soil and upper levels of the sandy clay unit. Median S concentration in the regolith (355 ppm) is greater than the regional background value. The Bimba Formation is the most pyritic unit with the sulfi ed occurring as massive pyrite and pyrrhotite. The upper Albite/Himalaya Formations are less pyritic with the sulfi ed occurring mostly as disseminated pyrite hosting Cu-Au below the Bimba Formation (Fig. 2). Sulphide minerals are very susceptible to weathering and are rapidly broken down. Subsequently sulphur re-concentrates within clay bearing units as sulfi tes, notably jarosite, gypsum and barite. Sulfur isotope studies, such as currently underway on ground-water sulfate and regolith gypsum deposits (Caritat et al. 2002), can help in differentiating the origin of the regolith S between a seawater meteoric source and a mineralization (primary) source.

High concentrations of U (>20 ppm) in the regolith occur within the saprolite of holes P3 and SR5. Uranium shows a distribution pattern similar to the base metals in the in-situ regolith (Figs. 11 & 12) and in bedrock, especially within Cu-Au targets of the Bimba Formation and upper Albite/Himalaya Formations. A strong correlation (r=0.69) exists between U and Sn in the regolith (Fig. 13). Tin is present in the Broken Hill district in the form of cassiterite in non-uraniferous pegmatite veins with no apparent association with U. The latter element occurs mainly as uraniumiferous ilmenite or davidite in different pegmatites in the region (Lishmund 1982; Barnes 1988). Unlike Sn, leaching and sorption of U is pH-dependent with enhanced mobility at pH values between 8 and 9. This is mainly attributed to carbonate complexation and formation of stable complexes at high pH values (Watte et al. 1994). This has been demonstrated within the soil and sandy clay unit of the Mundi Mundi Plain with secondary mineralogy (notably illite and kaolinite) and water chemistry playing important roles (Harries et al. 1998). This association between U and Sn is hence not related to their mobility in the weathering environment but to possible re-concentration within secondary mineral phases such as kaolinite and illite.

**IMPLICATIONS AND RECOMMENDATIONS FOR EXPLORATION UNDER COVER**

This study attempts to unravel the specific and complex challenges of exploring through the regolith in areas of significant sedimentary cover in the Broken Hill region. Because studies of this type are in their infancy here and elsewhere in Australia, we have endeavoured to address implications for exploration under such cover, and make generalized recommendations in this section that can be applied to other areas with similar thick cover.

The geochemical expression of any concealed mineralization is a function of the ore type, preservation of the underlying in-situ regolith and the post-depositional history of the
sedimentary cover. The highly weathered, well-preserved and chemically enriched nature of the in-situ regolith beneath the Mundi Mundi Plain presents an ideal situation for chemical dispersion to occur into the overlying transported regolith over long periods of time. Despite the masking effect of depositional processes and subsequent diagenetic and weathering processes, the presence of anomalous concentrations of base metals in the cover is potentially a good indication of mineralization. Correct interpretation of these dispersion patterns is essential as it leads to the choice of suitable sampling media and hence increases the likelihood of exploration success.

Accurate differentiation of transported and in-situ regolith components is central to understanding and interpreting the processes that occurred during regolith development, and in determining the most probable dispersion models. Contemporary mineralogical techniques, like PIMA, are particularly useful for ‘probing’ extensive cover for they facilitate a quick delineation of the boundary between transported and in-situ regolith and between individual units based on their spectral signatures. Combining mineralogical and geochemical techniques optimizes the interpretation of primary and secondary characteristics of the ore-forming elements and assists in the determination of possible host minerals for these elements. This translates into a better understanding of the overall geochemical dispersion pathways and hence improved exploration models.

The dispersion patterns at the Thunderdome prospect have several implications for exploration for the dominant commodities, i.e. Cu, Pb, Ag and Zn. The presence of mineralization is reflected in the bedrock composition by strong associations between Cu, Ni, Pb, Ag, As and S (Table 1). Some elements such as As show a widespread distribution in most of the regolith units and for many styles of mineralization within the basement, implying that they can be useful as pathfinder elements. The strongest indicators of mineralization within the transported and in-situ regoliths include Cu, Bi, Ni, Ba, As, Zn, Pb, Co and Mo (in order of decreasing $\text{M}_{\text{regolith}}/\text{Bkgd}$). Nickel and Co (and S) show systematic enrichments, as shown by the median regolith values being greater than the background, thus >50% of the regolith samples collected were above the regional exploration background value. These elements may be quite reliable exploration pathfinders here and perhaps also in other environments.

The events that accompanied the erosion, deposition and subsequent secondary processes in the sediments have undoubtedly affected the geochemical expression of these elements. Difficulties arise when trying to ascertain whether these anomalies are the result of mechanical dispersion from the adjacent mineralized Broken Hill Domain or if they relate to any underlying mineralization, especially in the absence of drillholes through to bedrock. Regolith anomalies may have been weakened or smoothed out by post-depositional processes and reworking over long periods of time, but they still clearly exist over the Thunderdome prospect. In general, however, the superimposition of multiple weathering events and the intensity of chemical dispersion during post-depositional weathering and diagenesis may in some cases completely obliterate any secondary geochemical halo in the overlying sediments.

Chemical dispersion, however, is often, as is the case here, indicated by enrichments in both the in-situ and transported regolith, commonly with an enhancement close to their contact, which represents a pathway for groundwater. Element enrichments and associations existing both in the in-situ regolith and the sediments are an indication that geochemical anomalies are not caused by mechanical deposition of sediment carrying an allochthonous geochemical signature. This is the case for a number of trace elements at the Thunderdome prospect (e.g. Zn, Cu, Ni, As and Pb). When this is observed, careful close-spaced sampling across the contact and laterally can help determine the extent of possible hydromorphic dispersion haloes. The presence of such dispersion haloes, however, cannot be guaranteed; hence drilling should at first be carried out deep into the saprolite to intersect the mineralization itself or any alteration zone, secondary dispersion halo or depletion zone associated with it. Closely spaced sampling is particularly effective because subcropping weathered mineralization may be disseminated or non-economic and the size of the dispersion haloes may be restricted, presenting small exploration targets. Available data show that most exploration groups in the Mundi Mundi region have not adequately addressed this practice to date.

Detailed investigation of carbonates and base metals should also be carried out in the future to determine their genetic relationship. This investigation was hampered by the scarcity of samples from the soil horizon. However, calcrete sampling over the adjoining Polygonum prospect has just been completed (Hedger & Dugmore 2001). The results show a potentially useful relationship between a number of metals and known Pb-Zn-Ag mineralization. Of particular interest is an area, untested by previous drilling, where Ag values in calcrete exceed 100 ppb with a maximum of 1,500 ppb. Detailed geological mapping, ground magnetics and rock-chip sampling has also been completed over the Great Goulburn Mine prospect (Platsearch 2001), c. 60 km south of the Thunderdome prospect. Trial calcrete sampling on two lines across this prospect gave anomalous Au results up to 50 ppb. An earlier plant and soil (several horizons) geochemical study, using total and selective leach methods, has shown the existence of secondary dispersion haloes at the Great Goulburn prospect (Jones 1999; Hill et al. 2000).

The interpretation of secondary dispersion haloes within the regolith can also be difficult especially when discriminating between actual dispersion haloes and subtle secondary processes attributed to adsorption onto and co-precipitation with clay minerals and Fe-oxides. These processes mainly govern the distribution of most of the trace elements within the Thunderdome prospect. The distribution of many trace metals appears to be associated with non-crystalline ‘amorphous’ phases within the transported material (as shown by high poorly diffracting material contents) and subsequent hydromorphic processes. Biogenic controls on these chemical processes are also likely to be very important. Vegetation, including mulga and saltbush, has been growing on these plains for long periods of time generating rhizomorphic calcrete accumulations, which appear to be useful for exploration in the region. Indeed, mulga and casuarina trees have been observed to penetrate the regolith down to depths of 40 m over old mine workings in the region, implying that they might also be responsible for mobilizing some of these elements from depth. The enrichment of the overlying sedimentary cover depends heavily on physical dispersion during erosion and deposition and on post-depositional mechanical mixing associated with shrink-swell characteristics of clay minerals. All these processes need to be ‘probed’ in order to explain the precise mechanisms of mobilization of ore elements from depth.

The subjects of mineral-element hosts and the precise mechanisms of possible transport of elements from underlying mineralization are poorly understood. We recommend that partial or selective leaching be carried out in future investigations to determine the nature of labile ions. Isotope geochemistry, especially of S, Sr and Pb, should also be attempted to trace the movement of chemical elements within the
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