Ore Geology Reviews 73 (2016) 451–474

Contents lists available at ScienceDirect

Ore Geology Reviews

journal homepage: www.elsevier.com/locate/oregeorev

Regolith-landform processes and geochemical exploration for base metal deposits in regolith-dominated terrains of the Mt Isa region, northwest Queensland, Australia

Ravi R. Anand

CSIRO, Minerals Resources Flagship, 26 Dick Perry Avenue, Kensington, WA 6151, Australia

A R T I C L E I N F O

Article history:
Received 6 May 2015
Accepted 19 August 2015
Available online 22 August 2015

Keywords:
Mount Isa
Regolith-landforms
Exploration geochemistry
Geochemical dispersion
Models

A B S T R A C T

The regolith in the Mt Isa region of Queensland consists of a variety of saprolites and duricrusts developed on Proterozoic basement rocks and fresh to weathered Mesozoic, Tertiary and Quaternary cover, all of which has impeded base metals exploration. This paper presents an overview of some of the regolith-geochemical work conducted in the Mt Isa region as part of an industry-supported three year CRC LEME/AMIRA Project. A complex weathering and landscape history has produced a landscape of (a) continuously exposed and exhumed basement rocks that have undergone varying intensities of weathering and partial stripping; (b) weathered and locally eroded Mesozoic cover sequences and (c) areas with younger transported cover concealing basement and Mesozoic cover. Various regolith sample media have been evaluated at a number of prospects and deposits which represent different regolith-landform terrains and landscape history. Geochemical dispersion processes and models are presented and false anomalies explained.

Where ferruginous duricrust or ferruginous nodular gravel are preserved on weathered bedrock on an eroded plateau, they exhibit large (>500 m) multi-element (As, Pb, Sb) dispersion haloes and are useful sampling media. Dispersion haloes in truncated profiles on weathered bedrock covered with colluvium are restricted, are limited to tens of metres from subcrop of the source, and contrast to the extensive anomalies in ferruginous duricrust and nodules. Geochemical exploration in covered areas depends on the possible presence of dispersion through the sediments or leakage along faults or fractures, but may be complicated by high metal backgrounds in the sediments themselves. Some of the most prominent anomalies occur in ferruginous materials and soils representing emergent residual terrain developed on Mesozoic sediments. These are largely due to weathering of sulfide mineralization that continued during submergence in a marine environment, with hydromorphic dispersion into the sediments as they accumulated. Multi-element (Cu, As, Zn, Sb, Au) anomalies occur in basal sediments and at the unconformity, due to a combination of clastic and hydromorphic dispersion and represent a useful sample target. Metal-rich horizons in weathered sediments, higher in the sequence, can also be targeted, particularly by specifically sampling ferruginous units and fragments. However, these are less certainly related to mineralization. Zinc and Cu, concentrated in Fe (and Mn) oxides at redox fronts, may be derived by leaching from the sediments with concentration in the sesquioxides, and be unrelated to any proximal basement mineralization. In all these regolith-dominated terrains, a clear understanding of local geomorphology, regolith framework, topography of unconformities and the origins of ferruginous materials is essential to sample medium selection and data interpretation.

1. Introduction

Most sulfide-rich base metal deposits in the tropics and sub-tropics have been found by discovery of outcropping gossans or through recognition of the geochemical signature of gossan fragments in soil, lag and stream sediments (Butt and Zeegers, 1992). Many discoveries were made in the semi-arid and arid terrains of Australia, mostly in erosional terrains where gossans, or gossan remnants, are exposed at surface (Butt, 1995). There have been few discoveries in areas of extensive, thick and complex regolith and low relief, such as in the Mt Isa region. The Mount Isa region has a complex regolith, reflecting weathering from the Late Cretaceous to the present (Vasconcelos, 1998) and has been variably eroded, covered with sediments and exhumed. It is blanketed by ferruginous duricrusts, silcretes, gossans and other undifferentiated weathering profiles (Grimes, 1979; Day et al., 1983; Scott, 1987; Anand et al., 1996). Mesozoic marine sedimentary cover is particularly challenging (Grimes, 1972; Anand et al., 1996). Relief inversion adds complexity. The Mt Isa region hosts numerous base metal, Au and U deposits discovered by mapping and sampling of outcropping

---

E-mail address: ravi.anand@csiro.au.

http://dx.doi.org/10.1016/j.oregeorev.2015.08.014
0169-1368/

bedrock and gossans, stream sediment geochemistry, shallow drilling, soil sampling and geophysics. An extensive and generally thick *in situ* and transported regolith of variable composition impedes discovery of further deposits where geochemical models, used successfully in areas lacking this cover, are less effective. Most geological studies have focussed on the bedrock of the Mt Isa region. It is now necessary to better understand regolith materials and the influences of landscape evolution and weathering on element dispersion to guide geochemical exploration programs. There has been little consideration of the regolith except for Twidale (1966), Connah and Hubble (1960), Senior et al. (1978), Grimes (1979), Day et al. (1983), Taylor and Scott (1982).

In 1997, CRC LEME/AMIRA completed a research project in regolith geology and geochemistry in North Queensland, supported by 11 mining companies, through the Australian Mineral Industries Research Association (AMIRA International). This project “Geochemical Exploration in Regolith-Dominated Terrains, North Queensland” aimed to substantially improve geochemical exploration for base metals and gold under transported cover or obscured by deep weathering within the Mt Isa region. The activities of the project ranged from regional through district to local-scale regolith-landform studies (Fig. 1; Robertson et al., 1995; Anand et al., 1996, 1997; Wilford, 1997a,b, Li Shu and Robertson, 1997; Robertson et al., 1997; Phang et al., 1997a,b; Wildman, 1997; Jones, 1997; Dell, 1997; Vasconcelos, 1998). Recommendations for exploration procedures for some typical regolith environments were developed, regolith materials were evaluated as sample media and attempts were made to explain false anomalies. A number of sites were studied to relate surface geochemical dispersion to underlying mineralization, within well-controlled regolith-landform frameworks. The regolith was characterized, mapped and examined in detail. Some sites contained unexplained anomalies and a few had small to significant mineralization.

2. Regional geological settings

The geological framework outlined here draws particularly on work completed by the Geoscience Australia and the Geological Survey of Queensland. Detailed summaries of the geology of the Mt Isa region are given by Blake (1987), Blake et al. (1990), Blake and Stewart (1992), the Geological Survey of Queensland (2011) and Withnall and Hutton (2013). The Mt Isa Inlier is an area of exposed early and middle Proterozoic rocks, covering more than 50 000 km^2 in northwest Queensland, roughly centred on the township of Mount Isa (Blake, 1987). It is bounded by younger basins, namely the Proterozoic South Nicholson Basin to the west and south, the Mesozoic Eromanga Basin to the south and southeast, and the Mesozoic Carpentaria Basin to the northeast. Three broad tectonic divisions are distinguished within the Mount Isa Inlier: the Western Fold Belt, Kalkadoon-Leichhardt Belt, and Eastern Fold Belt (Fig. 2). Early Paleoproterozoic basement forms the Kalkadoon–Leichhardt Subprovince, a meridional belt dividing the younger domains that comprise the Eastern and Western fold belt sub provinces (Withnall and Hutton, 2013). Recent work by the Geological Survey of Queensland (2011) has divided the Mount Isa Province into 15 domains. The Kalkadoon–Leichhardt Subprovince corresponds to the Kalkadoon–Leichhardt Domain, the Western Fold Belt Sub province comprises the Century, Mount Oxide, Sybella and Leichhardt River domains, and the Eastern Fold belt Province comprises the Mary Kathleen, Mitakoodi, Tommy Creek, Marimo–Staveley, Doherty – Fig Tree, Kuridala – Selwyn, Soldiers Cap and Canobie domains. In the northwest, the Camooweal–Murphy Domain includes rocks of the Murphy Province, McArthur Basin and South Nicholson Basin.

The precise age and context of the Kalkadoon–Leichhardt Sub province remains unresolved (Withnall and Hutton, 2013). Its rock assemblages registered deformation and metamorphism, generally to amphibolite grade, during the Barramundi Orogeny, which was widespread in the North Australian Craton at 1900–1870 Ma (Etheridge et al., 1987; Betts et al., 2006). For the Mount Isa Inlier, this episode of orogenesis reflects east–west contraction (Blake and Stewart, 1992). In the northwest an east-trending basement high separates the McArthur Basin to the north from the South Nicholson Basin to the south. It is sometimes referred to as the Murphy Tectonic Ridge and was described by Ahmad and Wygralak (1990). It comprises the comagmatic 1860–1850 Ma Cliffdale Volcanics and Nicholson Granite Complex.

Protoliths of late Paleoproterozoic metasedimentary rocks of the Eastern and Western fold belts were generally marine sediments

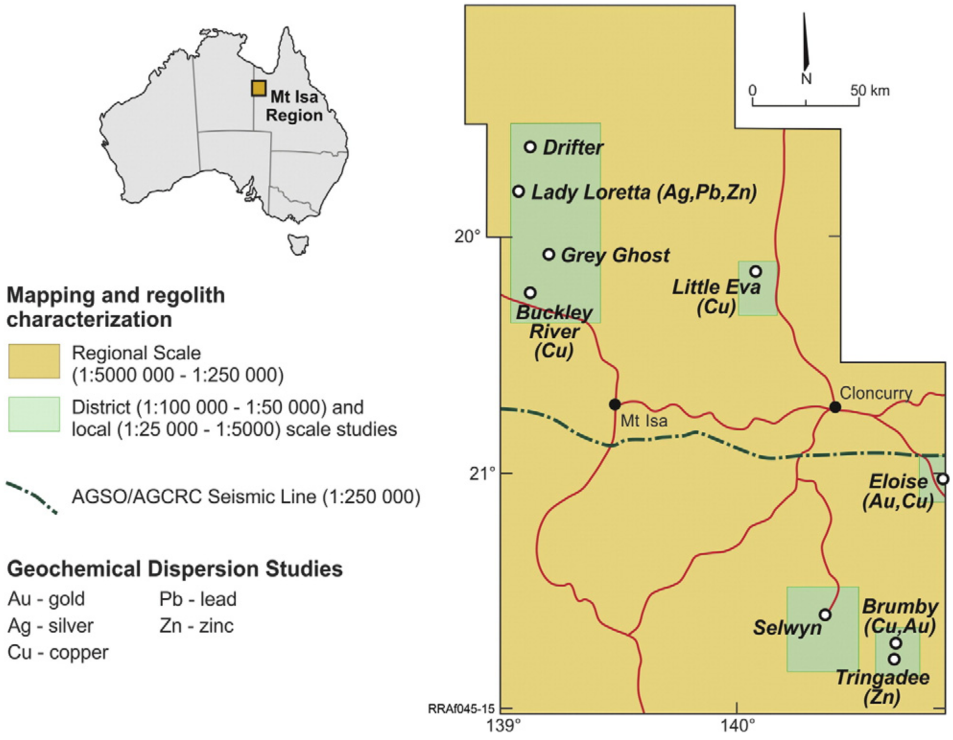

Fig. 1. Location of study areas in the Mt Isa Region.

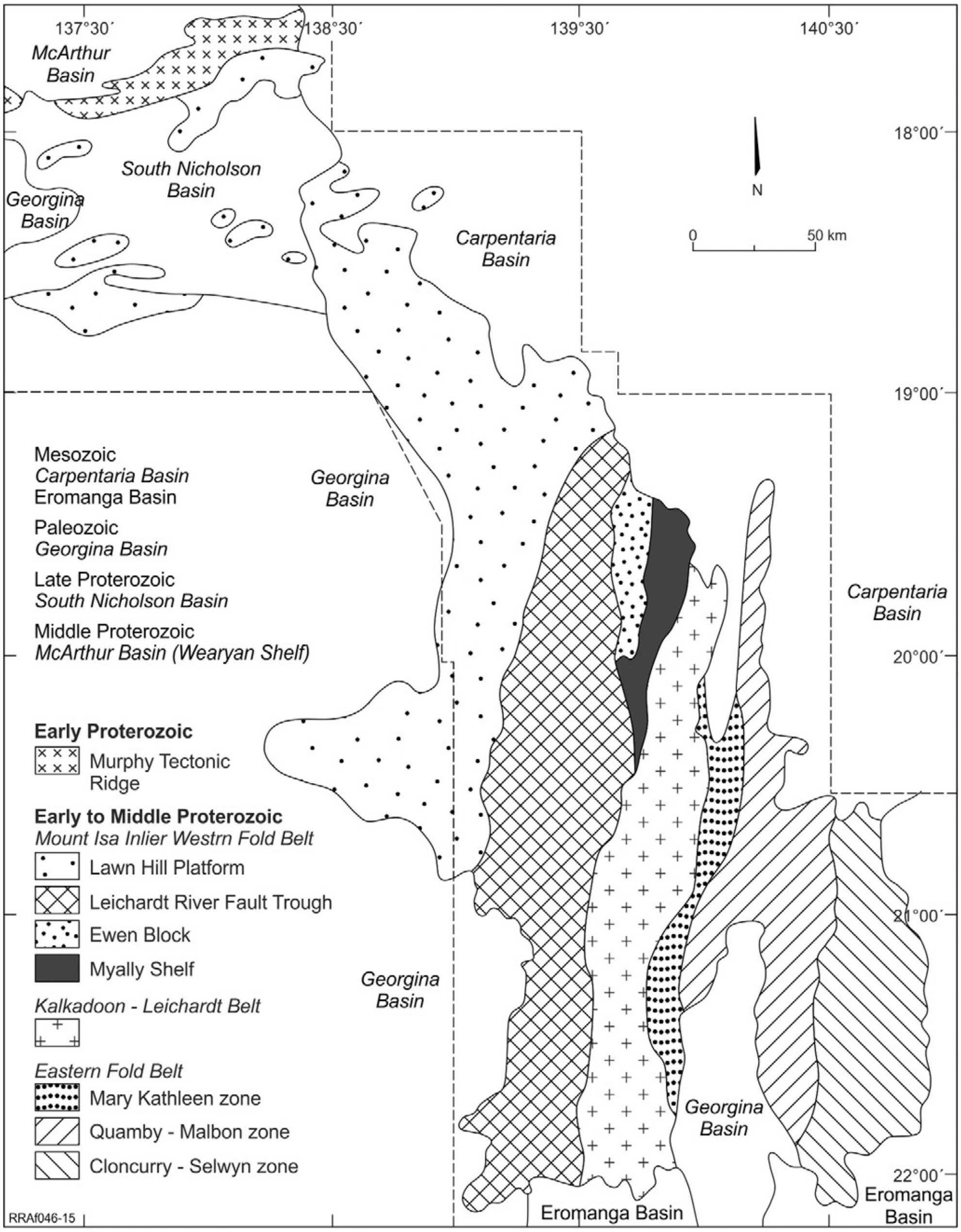

Fig. 2. Tectonic zones, Mt Isa region.
(After Blake, 1987).

deposited during three discrete episodes of basin formation (Jackson et al., 2000; Betts et al., 2006). The Leichhardt Superbasin (1790–1730 Ma) is best represented in the Western Fold Belt, along the north–south Leichhardt Rift (Derrick, 1982) at the western margin of the Kalkadoon–Leichhardt Domain. Its basin fill includes the products of bimodal volcanism. Granites and mafic intrusions were emplaced at various times before ~1100 Ma. Granites older than 1550 Ma are metamorphosed and generally deformed. From west to east the main batholiths exposed are the Sybella (1670 Ma) in the Western Fold Belt Province, the Kalkadoon and Ewen (1870–1850 Ma) in the Kalkadoon–Leichhardt Domain, the Wonga (1750–1725 Ma) in the Mary Kathleen Domain, and the post-orogenic Williams and Naraku Batholiths in the domains to the east. Intrusives of the Williams and Naraku Batholiths have been shown to be of at least three different ages (1750–1730 Ma, 1545–1530 Ma and 1520–1490 Ma).

The Mt Isa region has had a complex history of deformation, which has been dominated at different periods by extension, shortening and transcurrent faulting (Blake and Stewart, 1992). The earliest deformation is recorded in basement units that were tightly folded and in places partially melted before the onset of volcanism of the Leichhardt Superbasin. This early shortening is attributed to the Barramundi Orogeny. The Barramundi compressional event was followed by extension, leading to basin formation and deposition of rocks of the Leichhardt Superbasin (Withnall and Hutton, 2013).

At ~1620 Ma an early phase of thrusting and folding resulting from north to south compression took place and was followed between 1550 Ma and 1520 Ma by the east–west compression of the Isan Orogeny. This event formed the major north-trending upright folds that characterise much of the Mount Isa Province. A period of later extension is implied by the intrusion of the Williams and Naraku Batholiths at ~1500 Ma. The main faults in the Mount Isa Province have kilometre-scale, predominantly strike-slip displacements. These faults were active during the Proterozoic, and some may have been active also during the Phanerozoic (Withnall and Hutton, 2013).

The rocks of the Mount Isa Province have been significant producers of Cu, Pb, Zn and Ag (Geological Survey of Queensland, 2011; Withnall and Hutton, 2013). Four main styles of mineralization account for the majority of the mineral resources within the rocks of the Mount Isa region. Sediment-hosted Ag–Pb-Zn accounts for the majority of Pb-Zn and a high proportion of the Ag resources within Queensland. These deposits occur mainly within the fine-grained sedimentary rocks of the Isa Superbasin in the Western Fold Belt Sub province and include the Black Star (Mt Isa Pb-Zn), Century, George Fisher North, George Fisher South (Hilton) and Lady Loretta deposits. Sediment-hosted base metal mineralization also occurs within Isa Superbasin equivalents at Dugald River in the Eastern Fold Belt Province. Brecciated sediment-hosted copper deposits occur predominantly within rocks of the Leichhardt, Calvert and Isa Superbasin of the Western Fold Belt Sub province. These Cu deposits include the Mt Isa Cu orebodies and the Esperanza/Mammoth mineralization. Mineralization is commonly hosted by brecciated dolomitic, pyritic and carbonaceous sedimentary rocks or brecciated sandstone proximal to regional fault/shear zones. Iron oxide-Cu–Au deposits consist predominantly of chalcopyrite–pyrite–magnetite/hematite mineralization that occurs within high-grade metamorphic rocks in the Eastern Fold Belt Sub province. Deposits of this style include Ernest Henry, Osborne and Selwyn. The Ernest Henry deposit is breccia-hosted, and thus is distinctly different from the strata-bound Osborne and Selwyn deposits. Broken Hill type Ag–Pb–Zn deposits occur within high-grade metamorphic rocks in the Eastern Fold Belt Province. Cannington is the major example, but several smaller currently subeconomic deposits such as Pegmont are known. Gold has been produced mainly as a by-product of copper from the iron oxide–Cu–Au deposits of the Eastern Fold Belt Subprovince.

3. Physical features

The geomorphology of the Mt Isa region has been described by Stewart (1954), Twidale (1966) and Blake et al. (1984). The topography of the region is dominated by a central spine of hills flanked by a series of rolling, undulating and flat plains together with isolated mesas. The maximum elevation is about 550 m above mean sea level near Mount Guide in the southwest, and the lowest is about 60 m in the northeast. A low divide separates drainages north to the Gulf of Carpentaria from south flowing streams of the Georgia-Diamantina inland drainage system. Local relief is generally less than 100 m. Both regionally and in detail, the relief of the Mt Isa region directly reflects underlying structures and lithologies (Birot, 1956; Twidale, 1966). Metamorphosed sandstones (mainly quartz arenite) typically form prominent north-trending strike-ridges (Blake et al., 1984). Calc-silicate rocks, especially where they are metamorphosed to amphibolite facies, give rise to rugged hilly terrain. Mafic igneous rocks generally form flat to gently undulating terrain. Mafic dykes are mostly less resistant to erosion than the rocks they intrude, and tend to form depressions (Blake et al., 1984). Felsic volcanic rocks are less recessive, and mainly form low hills and tors. Granitic rocks are exposed as steep-sided hills and mesas (especially in the east) capped by much weathered granite, ferruginous duricrust, or flat-lying Mesozoic and Cambrian sediments; as tors and boulder-covered hills, and as undulating terrain and plains (Twidale, 1966). The lower Paleozoic rocks in the western parts of the region form broad treeless plains.

The region has a semi-arid, tropical, monsoonal climate with hot, wet season from October to March and a mild to warm, dry season from April to September. Most of the summer rainfall (300–500 mm) occurs between October and March but it is unpredictable and droughts are common. Mean temperature ranges are from 25–35 °C in December with corresponding winter temperatures some 10 to 15° cooler. The vegetation reflects the semi-arid climate, consisting mainly of *Eucalyptus* and *Acacia* shrub with Spinifex (*Triodia pungens*) and ephemeral grasses. Outcrops of Proterozoic rocks typically have a cover of shrubs and Spinifex. Mesozoic sediments are typically densely covered by *Acacia Shirleyi* (lancewood). Several species show strong association to soils with high Cu concentration including *Polycarpaea glabra*, *Eriachne mucronata* and *Tephrosia* sp. are associated with mineralization at Lady Loretta and Drifter. A detailed account of vegetation types is given by Perry and Christian (1954).

4. Study areas and methods

A wide range of areas were selected, based on the nature and importance of residual and transported regolith, thickness of transported cover, styles of mineralization and their perceived exploration significance (Fig. 1). Regolith mapping at a local to district scale was by aerial photography and remote sensing, checked by extensive field traverses. Regolith stratigraphy was established from drill cuttings, core and field exposures. Samples were characterized for mineralogy and petrography. The district and local-scale regolith-landform studies formed the essential building blocks of the project and the resultant knowledge was applied to a broader, regional perspective that has resulted in an improved understanding of weathering and landscape history of the region. Using this regolith-landform framework, opportunities for using geochemistry in this difficult environment were investigated in a variety of sites. The sites investigated were Buckley River (Cu), Lady Loretta (Ag-Pb-Zn), Little Eva (Cu), Eloise (Cu–Au), Brumby (Cu, Au) and Tringadee (Zn). Transported cover at these sites ranges in thickness from 0 m to 70 m (Table 1).

Each sample (I kg) for geochemical analysis was split on a PVC riffle. Aliquots of 100 g were pulped to a nominal <75 μm. Mineralogy of pulped samples was determined by Philips PW1050 diffractometer, using monochromated Cu Kα radiation generated at 50 kV and 20 mA. Optical microscopy was followed by scanning electron microscopy (SEM). Scanning electron microscope (SEM) imaging and analyses were performed using a back-scattered electron (BSE) detector on a Philips XL40 controlled pressure SEM fitted with an EDAX energy dispersive spectrometer (EDS). *In situ* geochemical analyses of selected samples were performed on polished thin sections by electron microprobe to determine mineral element associations in transported and *in situ* regolith.

All samples were analysed by XRF (CSIRO) and by INAA (Becquerel Laboratories), as follows:

> INAA
>
> Aliquots of 10 or 30 g (depending upon availability) were encapsulated at CSIRO and sent to Becquerel Laboratories for INAA analysis. Elements analysed were K, Fe, Zn, Ba, Na, Rb, Ag, Se, Cr, Mo, W, Ce, Br, U, As, Co, Cs, Ta, La, Eu, Yb, Hf, Th, Sb, Sm, Lu, Sc, Ir and Au.
>
> XRF
>
> X-ray fluorescence analysis was performed at CSIRO on fused discs (0.7 g sample and 6.4 g Li borate) using a Philips PW 1080 instrument. Elements analysed were Si, Al, Mg, Na, Fe, Ti, Mn, P, Ca, K, Ba, Ce, Cl, Cr, Co, Cu, La, Ni, S, Pb, Rb, Sr, V, Y, Zn, Zr, Nb and Ga.
>
> Standards and duplicates analysed at the same time were in good agreement (error <10%)

5. Regolith-landform provinces

As weathering occurs, some material is eroded and transported away from its original site, whereas other material may be altered, but still remain at its parental material's site; that is, as a landscape develops, both transported and residual regolith form. Several mechanical, chemical and biological processes have operated on each assemblage of bedrocks and sediments to produce a particular landscape and regolith. Thus, the processes that lead to regolith formation in the landscape are complex and they will vary from place to place. In the Mt Isa region, mapping of an area of 84,000 km^2 at a scale of 1:500,000 has shown the broad distribution of regolith materials and landforms (Anand et al., 1996). For convenience, three typical regolith-landform provinces

Table 1
Characteristics of deposits/prospects.

Deposit/prospect	Type of deposit	Discovery	Regolith environment	Transported cover (m)
Lady Loretta	Ag–Pb–Zn	Soil sampling	'Complete' ferruginous profile on Proterozoic basement	0
Buckley River	Cu	Drilling	'Complete' ferruginous profile on Proterozoic basement	2
Little Eva	Cu	Lag	Truncated profile on Proterozoic basement	<2
Osborne	Cu–Au	Geophysics/drilling	'Complete' ferruginous profile on Mesozoic sediments	30–60
Brumby	Cu–Au	Geophysics/drilling	Truncated profile on Mesozoic sediments	70
Tringadee	Zn	Geophysics/drilling	Truncated profile on Mesozoic sediments	20–30
Eloise	Au–Cu	Geophysics/drilling	Younger transported cover overlying Mesozoic sediments	50–70

are recognised, each with its unique regolith and landscape (Fig. 3). These are:

- Hill belts
- Dissected paleolandsurfaces. These can be divided on the basis of their dominant geology into:
  (a) Those largely on Proterozoic basement
  (b) Those largely on Mesozoic sediments

- Plains which may be divided on the basis of topography into:
  (a) gently undulating plains
  (b) undulating to rolling plains
  (c) Flat plains

5.1. Hill belts

The hill belts occupy the deeply incised central portion of the region (Fig. 3, A) which consists prominently of north trending flat-top hills and ridges that average between 320 and 480 m above mean sea level but in places exceed 520 m. Hill belts are devoid of thick regolith and consist of Proterozoic metamorphic and igneous rocks (granite, quartzite, gneiss, schist, amphibolites, limestone and shale) that form deeply incised landscapes. The detailed sculpture of the landsurface is intimately related to differential weathering and erosion of various rock types. Quartzite, for instance, commonly forms upstanding masses, whereas siltstone and shale are eroded relatively easily to form lowlands and valleys. The plateau surfaces are best preserved on resistant quartzite and bevel various Proterozoic strata. Mesozoic sediments are sporadically distributed in the hill belts, particularly over the Cloncurry district. They rest unconformably on Proterozoic rocks as small, isolated mesas.

Not all rocks in the hill belts are fresh; many show signs of former and present weathering, including superficial secondary silicification; basalt, schist, amphibolites and siltstone are kaolinized to 5–20 m depth and the weathered rocks are generally Fe stained. In general, the regolith thickens away from the hills, but there is no strict correlation between surface elevation and thickness of regolith. The degree of truncation increases with relief and it is also dependent on bedrock

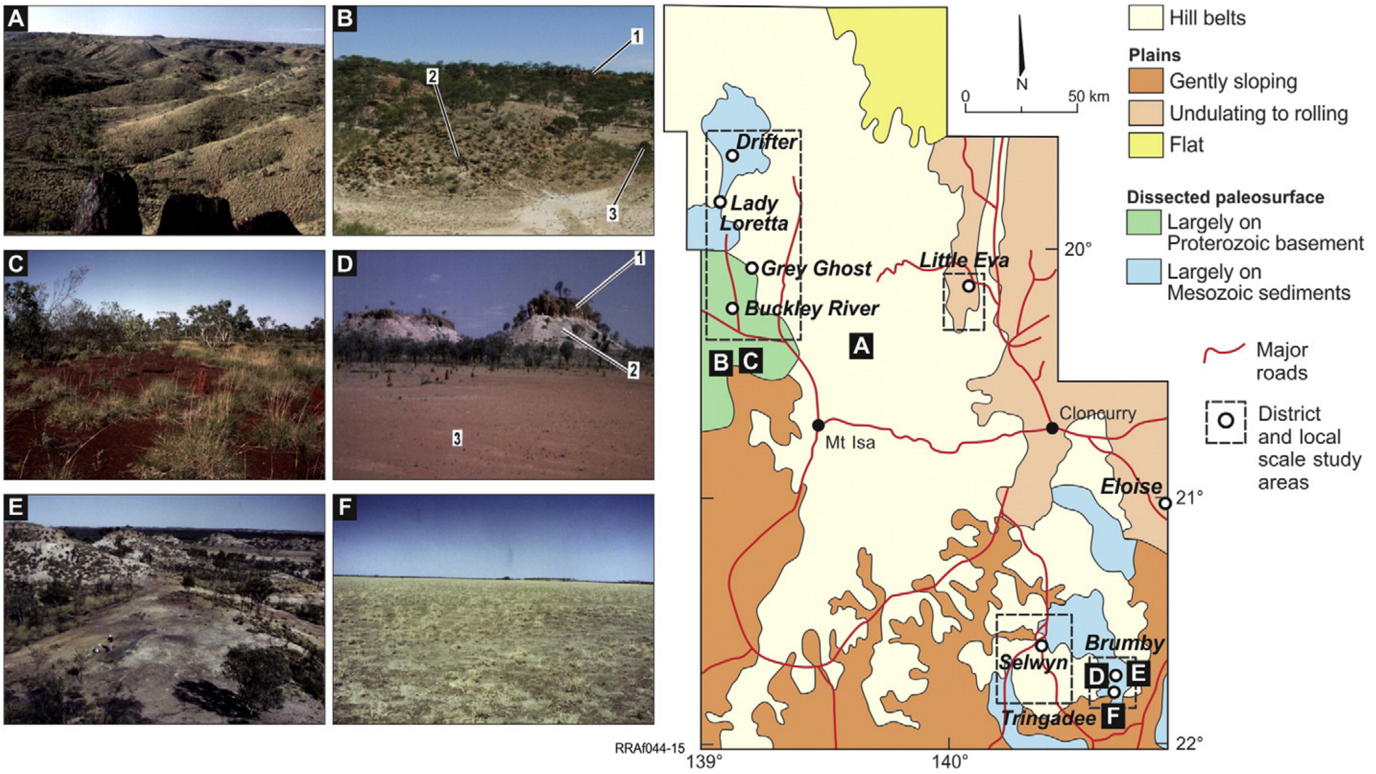

Fig. 3. Generalized regolith-landform provinces of the Mt Isa region (*Modified after* *Anand et al., 1996*). Location of photos is shown in Figure. (A) Hill belt showing the characteristic irregular terrain with little or no weathering. Little of the erosional plateau surface remains. Location: 441810 mE, 759040 mN, Selwyn area. (B) Dissected paleosurface showing mesa and pediments developed on Proterozoic bedrock. Well-developed ferruginous-duricrust capped 'complete' weathering profile on mesa (1) and truncated profile showing saprolite exposed on low hill (2) and pediments (3). Location:309581 mE, 7777178 mN, Buckley River area (Photo by Ian Robertson) (C) Paleoplains mantled with hematite-rich ferruginous nodules and pisoliths. Location: 308170 mE, 7747656 mN, Buckley River–Lady Loretta area. (D) Dissected paleosurface showing remnants of Mesozoic sediments as mesa, capped with ferruginous duricrust on Mesozoic sediments (1) unconformably overlies granitic saprolite (2) and shallow soil on saprolite (3) on erosional plain. Location: 478380 mE, 7590800 mN, Tringadee area (Photo by Cajetan Phang). (E) Truncated profile showing saprolite on Mesozoic sediments and low hills. Location: 47540 mE, 7584430 mN, Brumby area. (F) Gently sloping plain mantled with smectitic soil. Location 481900 mE, 7584840 mN, Tringadee area.

lithology, so that even where the relief is low, saprolite is adjacent to almost unweathered rocks of contrasting lithology. Much of regolith is residual with generally shallow 1–2 m of colluvium and alluvium on hill slopes and in the valley. Lithosols are associated with resistant rocks and areas of high relief and steeper slopes. Ferruginous nodules in the colluvium may imply derivation from a deep regolith formed under earlier humid climates, whereas calcite, dolomite and smectite in saprock and soils suggest formation under conditions of impeded drainage and mild leaching, characteristic of a semi-arid climate. These features were observed along the 26 km AGSO/AGCRC Seismic line (Drummond, 1996) that passes through the hill belts of Proterozoic assemblages (Fig. 1; Anand et al., 1996; Dell, 1997).

5.2. Dissected paleolandsurface largely on Proterozoic basement

This province occupies the Buckley River–Lady Loretta area in the Western Succession and forms a complex of mesas and plains (Fig. 3, B, C). These areas are part of a dissected plateau on which the original surface forms a significant component of the landscape. Here, regolith is dominated by weathering of Proterozoic bedrocks. Generally, Mesozoic sediments are thin or absent which suggests that they were never deposited or have been removed (Wilford, 1997a). An erosional scarp separates old landforms and deep regolith over a paleolandsurface on the western side, from younger landforms and shallow regolith on the east (Figs. 4, 5). Exploration drilling beneath paleoplains on the western side, typically record weathering depths of up to 150 m. The eastern side of the scarp is dominated by erosional processes and consists mainly of saprolite and saprock. However, exceptions to this are isolated mesas that preserve older remnant surfaces of the paleoplain that once extended further east (Wilford, 1997a).

The mesas are flat to gently sloping, commonly reaching 20–30 m above their surroundings, up to 2 km wide and are separated by pediments and plains (Fig. 5). Mesas can be capped either with ferruginous or siliceous duricrusts. The surrounding landforms consist of pediments and erosional plains covered with locally-derived ferruginous gravel and much younger thin (<2 m) residual soils formed from *in situ* weathering of saprolite. Below the mesa, saprolite or mottled clay zones have been exposed on pediments by erosion of a pre-existing weathered material, or may represent the most weathered form of the parent rock, which had never been capped with a ferruginous duricrust or silcrete. Incomplete removal of detritus, eroded from the weathered mantle, has left a widespread sedimentary cover in adjacent colluvial–alluvial plains and valleys.

On mesas, ferruginous or siliceous duricrusts have formed both in residual and transported materials. Where transported, they were developed in sand and gravel in valleys which have subsequently indurated and now form high points in the topography, due to relief inversion. It is possible to form two ferruginous or siliceous duricrusts at the same level at very similar times, although they cement very different regolith materials. The lithological control on the distributions of silcrete and ferruginous duricrust is marked (Anand et al., 1996; Wilford, 1997a). They may occur within a few hundreds of metres of each other, with silcrete developed instead of a ferruginous duricrust where the underlying Proterozoic bedrock is siliceous (siltstone, claystone). Ferruginous duricusts have two end members, lateritic residuum (residual) and ferricrete (transported). Lateritic residuum (massive and nodular duricrusts; nodular gravel) has formed by accumulation of ferruginous material from the mottled saprolite by down-wasting due to the loss of matrix minerals. The nodules lack complex multiple cortices, a simplicity interpreted to reflect a short weathering history and little to no transportation (Bourman, 1993; Anand and Paine, 2002). However, because of the vulnerability of the upper horizons to erosion and the lateral transport of dissolved Fe during weathering, there may be an apparent imbalance between the relative thicknesses of the ferruginous horizons and the underlying regolith. An example of this residual duricrust is sited from south of the Buckley River (324605 E, 7755409 N; Fig. 6) where the mesa consists of hematite-rich massive to nodular duricrust over 3–4 m of mottled saprolite and saprolite formed from the weathering of metabasalt. Preservation of quartz veins throughout the whole profile suggests *in situ* regolith formation. Ferricretes are ferruginized sediments (slabby duricrust; Fig. 5) that have no direct relationship with the underlying lithology. At the Buckley River prospect, goethite-rich slabby duricrust occurs on plateau margins and forms massive, horizontal plates of sub-rounded to rounded quartz-rich material, impregnated by goethite but lacking quartz pebbles. It is suggested that this slabby duricrust was formed in a low position and the topography has been inverted since induration.

Some estimates of the rates of long term geomorphic process have been made for mesa-dominated terrains by Vasconcelos (1998) and Vasconcelos et al. (2008) who, by dating Mn oxides, has shown that ferruginized weathering profiles in the Mt Isa region may be as old as 66.9 + 0.1 Ma. They also showed that sites at higher elevations (>400 m) contain older (67–30 Ma) supergene minerals; weathering profiles located at intermediate elevations (350–270 m) yield ages in the 21–12 Ma range. Samples collected from lower elevation sites (<200 m) yield results younger than 10 Ma. Thus, there appears to be a strong topographic control on weathering ages.

Siliceous weathering on Proterozoic bedrock consists, from top to base, of silcrete, silicified saprolite, saprolite and saprock (Fig. 6B). Residual silcretes may have floating quartz grains in a matrix of cryptocrystalline silica and anatase, formed from secondarily mobilized Ti. Over granitic rocks, they may also contain significant concentrations of relict zircons and aluminosilicates in the cement (Butt, 1985). Other silcretes consist of quartz pebbles, gravels and sand that suggest that the original material was either a river channel or sheetwash deposit that has been silicified (Anand et al., 1997; Wilford, 1997a; Vasconcelos, 1998). Ferruginization of the silcrete is widespread and ranges from minor mottling to Fe oxide-cementation of siliceous nodules. Vasconcelos (1998) observed that pediments to the silcrete-capped mesas in the Tick Hill area in the Mt Isa region are draped by strongly ferruginized silcrete breccias. These apparent paleopediments may suggest a past large-scale erosion of the silcrete mesas, possibly due to increasing relief and tectonic reactivation of regional faults. If silicification and ferruginization are evidence for arid and humid conditions, respectively, then a humid climatic period must have post-dated silcrete formation (Vasconcelos, 1998). The age of Mn oxides replacing silcretes places numerical constraints on the minimum age of silcrete formation in the area. The silcretes of the Tick Hill area are at least 38 Ma old, indicating that these silcretes are not associated with a postulated transition towards arid conditions in the Miocene. If they represent arid conditions, these conditions must have occurred in the Paleocene or Mesozoic (Vasconcelos, 1998).

5.3. Dissected paleolandsurface largely on Mesozoic sediments

Unconformably overlying the Proterozoic rocks are mesas and buttes of consolidated Mesozoic sediments in the southeast (e.g., Tringadee, Selwyn) and northwest (e.g., Drifter) (Figs. 3D,E; 7). The Mesozoic sediments (sandstone, greywacke, shale, claystone, siltstone, limestone and conglomerate) of the inland basins are mostly fluvial and shallow marine, and were deposited over a large part of the Mt Isa region (Grimes, 1972).

These Mesozoic sediments retain evidence for prolonged deep weathering; the upper ferruginized and silicified saprolite contains a well-developed ferruginous duricrust or silcrete (Fig. 6C, D). Ferruginized or silicified Mesozoic sediments occur at several levels. Most are lower than adjacent areas of Proterozoic rocks but, in some places, they rise to the same elevation. The differences in elevation of the weathered surface suggest that the pre-Mesozoic landsurface had significant relief. The irregular thicknesses of sediments and an undulating Proterozoic-Mesozoic unconformity can be best explained by infilling of valleys. A paleosurface then formed across the infilled valleys, as at Drifter, Selwyn and Tringadee (Anand et al., 1996; Wilford, 1997a, b; Phang et al., 1997a). Such landscapes imply differential erosion,

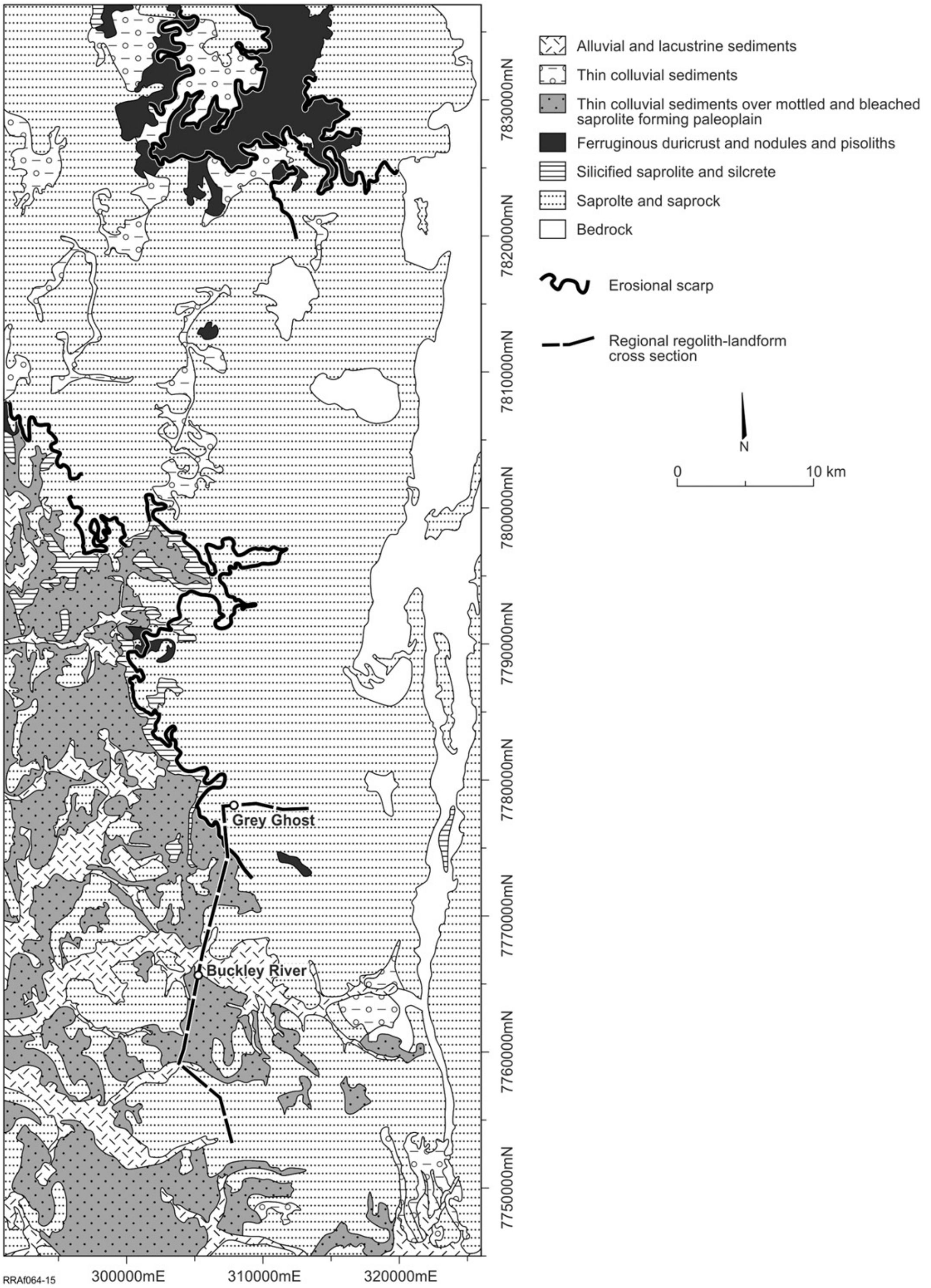

Fig. 4. Major erosional scarp separates old landforms and regolith over a paleolandsurface on the western side from the younger landforms and regolith on the east, Buckley River–Lady Loretta area.
(After Wilford, 1997a).

possibly with some relief inversion. Where the Mesozoic sediments have been removed, a thin veneer of cherty breccia or silcrete is revealed which is the base of an older sedimentary sequence (Cambrian) formed on silicified Proterozoic saprolite (e.g., Drifter). The erosion products of the Mesozoic sediments now occur in valley floors, ferruginized to goethite- and Mn-oxide-rich vesicular duricrusts.

Weathering profiles in Mesozoic sediments are variable and depend on the sediment type, with thicker (30–60 m) profiles developed on claystones and siltstones than on sandstones. Ferruginous duricrusts are developed on claystone and sandstone and closely resemble those developed on Proterozoic rocks (Anand et al., 1997). However, they are relatively enriched in Si due to the high quartz content of the sediment. The high Fe content (26.2%; N = 18) of the duricrusts compared to the sediments implies that they have largely resulted from absolute accumulation of Fe and they invariably contain more Fe than would readily have been derived from their Fe-poor parent rocks. The

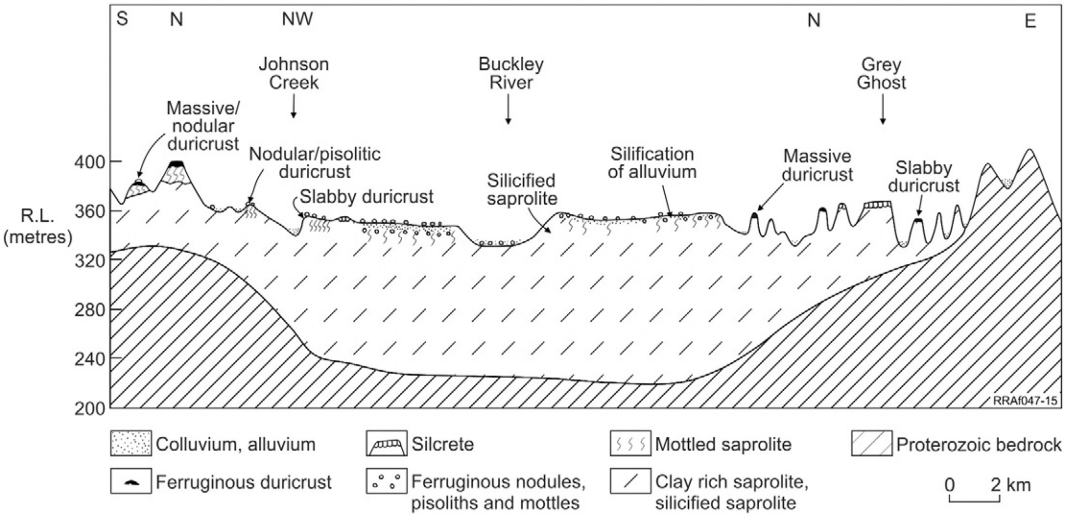

Fig. 5. A schematic cross section showing the relationship between the landforms and regolith for the regional traverse, Buckley River area (*After* Anand et al., 1997). See location of this traverse on Fig. 4.

ferruginous profile over claystones contains ferruginous nodules overlying patchy, massive or slabby duricrust that passes down into a mottled saprolite with blocky megamottles. Below the mottled saprolite, silicified collapsed ferruginous saprolite occurs and the boundary between them is uneven. The collapsed saprolite consists of a siliceous breccia in a yellowish brown clay matrix. This grades down into white, brown or purple saprolite clays. These clays are generally smectitic and contain some kaolinite, goethite and mica.

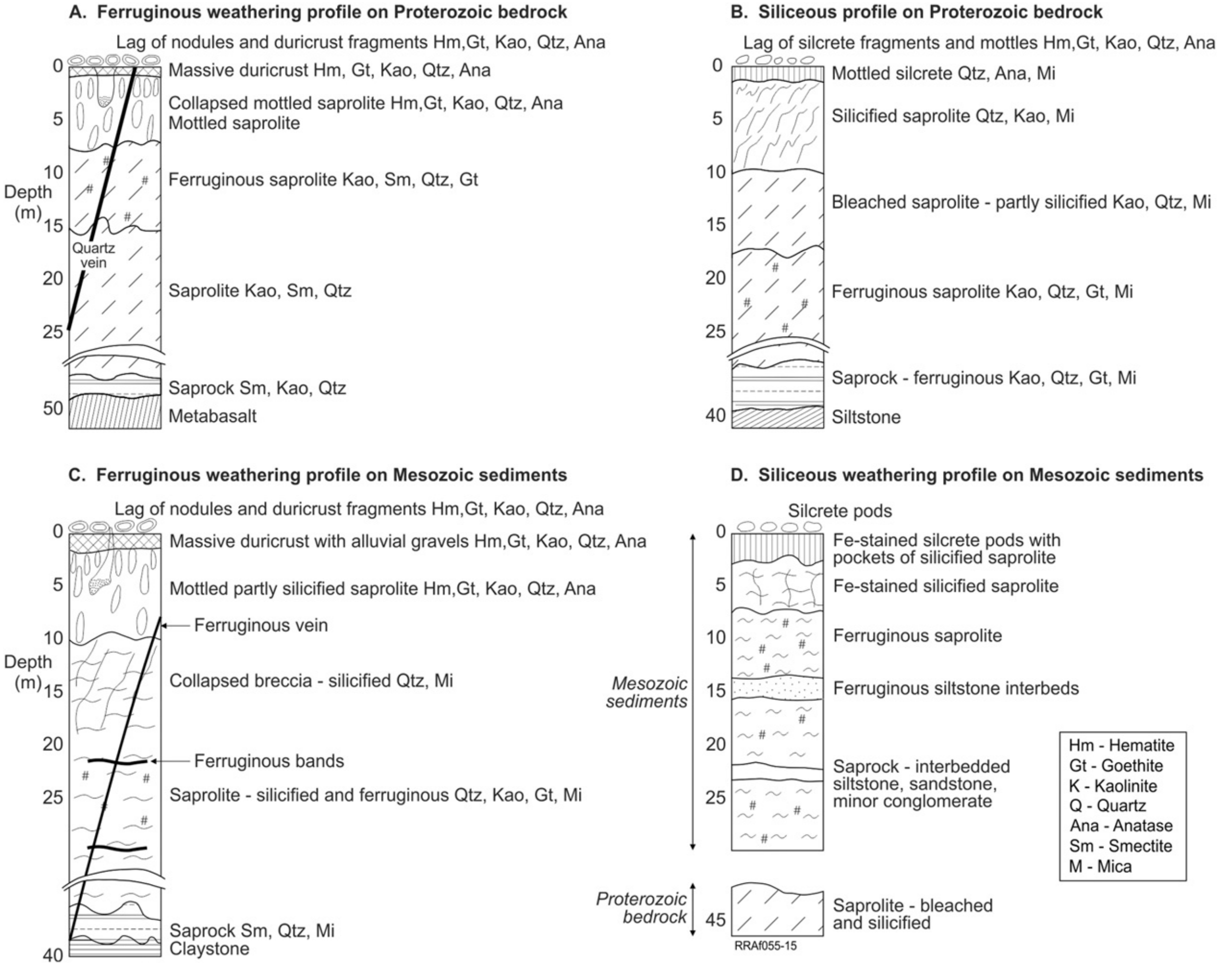

Fig. 6. Ferruginous and siliceous weathering profiles developed from weathering of Proterozoic bedrock (A, B) and Mesozoic sediments on mesas (C, D). Location: A (324605 mE, 7755409 mN), B (306213 mE, 7794340 mN), C (482988 mE, 7581477 mN) and D (450615 mE, 7618443 mN).
(After Anand et al., 1997; Wilford, 1997a).

5.4. Plains

This geomorphic province represents low-lying areas with minimum dissection and whose upper regolith may comprise Mesozoic, Tertiary and Quaternary deposits, commonly many tens of metres thick. They are underlain by regolith developed on basement rocks. The sediments are highly variable in genesis, provenance, composition and thickness. They have been derived either from erosion of either fresh or weathered bedrocks, or by reworking of younger sediments, either locally or from many kilometres away. The sediments themselves may have been subjected to extreme post-depositional weathering especially ferruginization and silicification (Anand and Paine, 2002).

Gently sloping plains are very extensive in the south, southwest and southeast of the mapped area (Fig. 3). Twidale (1966) refers to them as inland plains that drain southwards to Lake Eyre. Low hills and ridges are common on the plains. Undulating to rolling plains with discontinuous low hills become more numerous closer to the hill belts. They extend to the southeast, east and north of Cloncurry. Twidale (1966) referred to them as the Carpentaria plains because they drain to the Gulf of Carpentaria. Flat plains rise from about 90 m in the north to about 120 m in the south and their flatness is enhanced by predominant grassland. Local relief is due to incision by streams. Black soils are common on the plains.

6. Geochemical dispersion processes and sample media

Much of the Mt Isa region has Mesozoic sediments that have partially or wholly buried the basement rocks. Subsequently, some of the covering sediment has been eroded. The weathering history is complex, with some weathering prior to sedimentation, but the strongest weathering occurred after exposure, during the late-Cretaceous to early Tertiary and subsequent periods. These weathering episodes affected both the sediments and the underlying basement. Contemporaneous erosion has partially exhumed the basement rocks, exposing them directly to weathering at different stages. The result is a landscape having (Fig. 8):

(i) Continuously exposed, exhumed and buried basement rocks that have undergone varying intensities of weathering and, in eroded areas, partial stripping;
(ii) Weathered and locally eroded Mesozoic cover sequences;
(iii) Areas with younger transported cover of various types, including black soil plains, concealing basement and Mesozoic cover.

Similar landscapes have been also reported to occur in several other regions of Australia (Butt, 2005). The basement rocks that have been continuously exposed have complete or truncated weathered profiles. The regolith on exhumed basement has truncated profiles, similar to those on continuously exposed rocks. The cover rocks may also have complete or truncated weathered profiles, which may influence any geochemical expression of buried mineralization. Secondary geochemical dispersion patterns associated with bedrock mineralization are the cumulative products of the successive weathering episodes and landscape processes. The broad effects of this weathering history are recorded in the landforms and regolith, hence they form an appropriate basis for describing and interpreting the patterns (Anand and Butt, 2010). The dispersion characteristics for different terrains are summarized below.

6.1. Continuously exposed or exhumed weathered basement

6.1.1. 'Complete' profiles on Proterozoic bedrocks

This regime is generally typical of upland areas (mesas) in which the pre-existing weathered profile is mostly preserved. The surface consists of ferruginous duricrust and/or nodular and pisoliic gravels, or a semi-residual soil overlying these materials. Residual accumulation and lateral dispersion together can cause widespread geochemical and mineralogical patterns related to concealed mineralization derived from resistant primary minerals and fragments of gossan incorporated within it (Smith and Perdrix, 1983; Smith et al., 2000; Anand, 2001). However, ferruginous duricrusts in the Mt Isa region have formed in different ways and in different substrates. For example, massive and nodular duricrusts (lateritic residuum) are largely residual, formed from underlying or nearby bedrock but slabby duricrust (ferricrete) is developed in transported materials and is not genetically directly related to underlying lithologies.

The principal examples of dispersion from base metal deposits in lateritic residuum and ferricrete in the region are from the Lady Loretta deposit and the Buckley River prospect. The Lady Loretta deposit is a synclinal, stratiform, Mt Isa-style Ag-Pb-Zn ore body hosted in shales and dolomitic siltstones. It occurs beneath remnants of a deeply weathered landsurface, relics of which appear on a mesa about 60 m above the surrounding plains. The subcrop of the ore and adjacent pyritic shales consists of barite-bearing hematitic and limonitic gossans, which are ferruginized and silicified and grade into a mottled, ferruginous zone at 5 m depth (Alcock and Lee, 1974; Carr, 1984). This is underlain by bleached saprolite which passes into oxidized metasediments at 50 m; oxidation penetrates to 100 m and, near faults and shears, locally to >300 m. Lead oxidation products (anglesite and cerussite) occur within a few metres of the surface. Complete leaching of Zn extends to 100 m depth but Zn forms an extensive halo lower in the landscape (Alcock and Lee, 1974; Cox and Curtis, 1977). There is little Cu.

Eleven samples were collected over a 1.0 × 1.5 km area to investigate any significant geochemical halo in the very patchily-developed hematite–goethite-rich duricrust on the mesa (Anand et al., 1996). It was necessary to search extensively for very small, pockets of nodular duricrust, which were developed on favourable lithologies. Background was estimated from a geometric mean of samples collected over >400 m from the mineralization. In the southeast of the area, the majority of nodular duricrust sites overlie the subcrop of the ore horizon and its contiguous pyrite unit, indicating that the duricrust probably formed preferentially on ferruginous parts of the stratigraphy. Nodular duricrust samples are

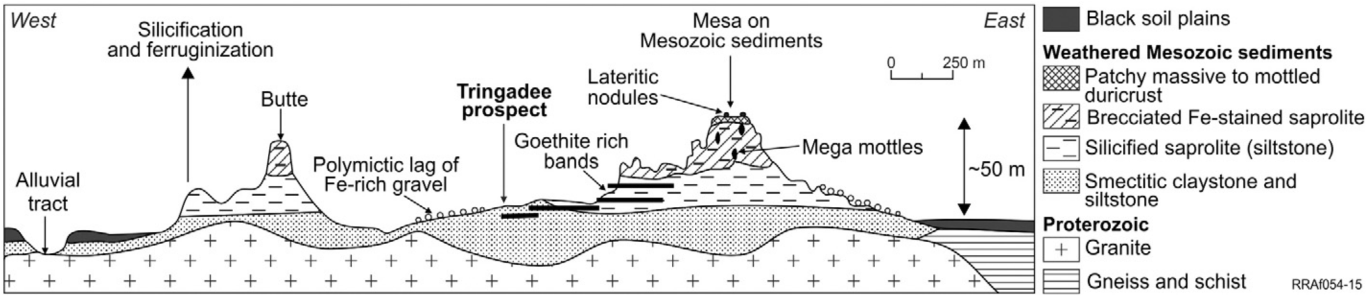

Fig. 7. Schematic regolith cross section showing dissected paleosurface on Mesozoic sediments, Tringadee Prospect. Location: 482988 mE, 7581477 mN. (After Anand et al., 1996; Phang et al., 1997a).

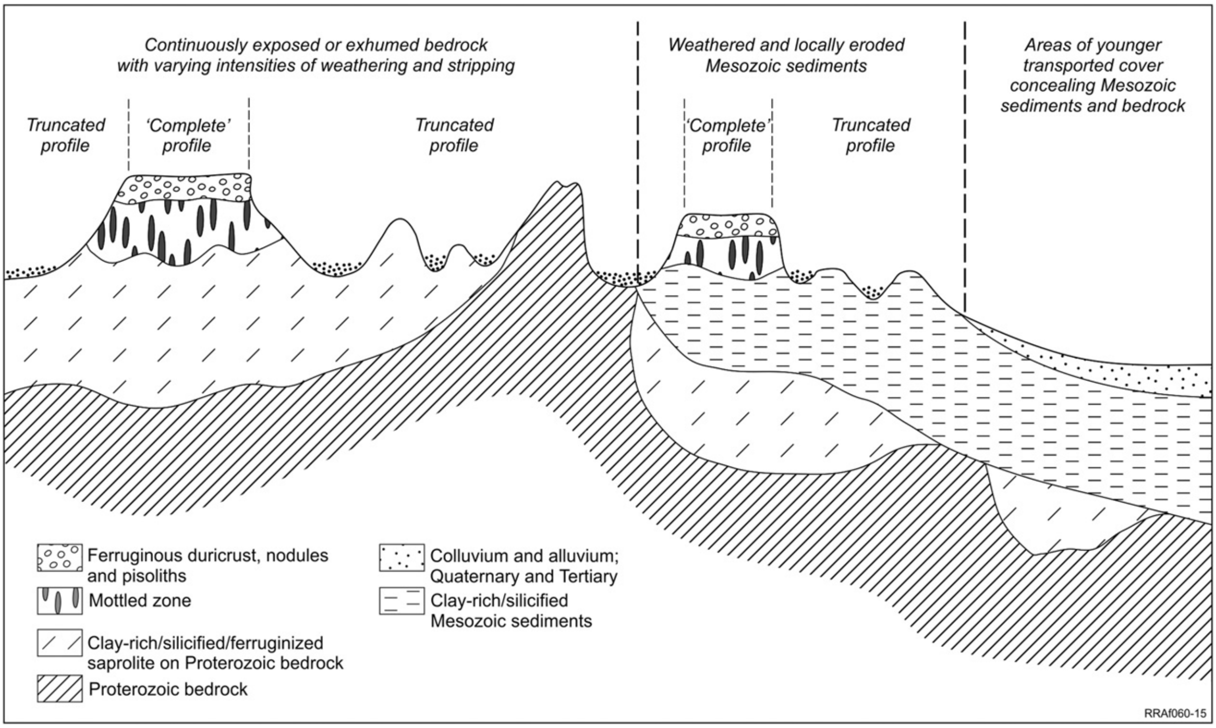

Fig. 8. Schematic diagram showing the landscape characterized by continuously exposed or exhumed bedrock with varying intensities of weathering and stripping, weathered and locally eroded Mesozoic sediments and areas of younger transported cover concealing Mesozoic sediments and bedrock.

rich in Fe (Fe_2O_3 max 48.6%) and very anomalous in As (max 937 ppm; background 170 pm), Sb (max 359 ppm, background 3.5 ppm), Pb (max 1526 ppm, background 37 pm), Ba (max 646 ppm, background 81 ppm) and S (max 1360 ppm, background 295 ppm) (Fig. 9). The concentrations of these elements are low relative to the underlying primary mineralization, due to leaching. These elements exhibit a wide dispersion halo (>600 m). Molybdenum and W may be weakly anomalous but it is difficult to assess such a small data set. Zinc is strongly leached. Other elements, such as Cr and V, are commonly immobilized in resistate minerals and accumulate residually in the ferruginous horizon, together with Fe. It is concluded that residual nodular duricrust would be a useful geochemical medium to detect Pb–Zn–Ag mineralization in areas where the duricrust is well developed and that As, Sb, Ba, Mo and W should be used as pathfinders additional to Pb and Zn.

The Buckley River Cu–Au prospect lies on a slabby duricrust-capped mesa (Figs. 10, 11) and has a number of drill intersections showing significant oxidized Cu mineralization (MIM unpublished data). Extensively eroded units of the Paradise Creek and Esperanza Formations of the McNamara Group are the main Proterozoic bedrocks exposed in the area. In outcrop, the Paradise Creek Formation is white bleached siltstone and grey cherty lenses whereas the Esperanza Formation has extensive stromatolitic cherts and less siltstone. The Proterozoic bedrock has undergone extensive post-weathering faulting that has disrupted the continuity of ferruginous and siliceous regolith units in the landscape. The bedrock has been weathered to a depth of 90 m with loss of carbonates and oxidation of sulfides. The stromatolitic units of the Esperanza Formation form high siliceous ridges that control drainage. The pyritic units of the Esperanza Formation are softer and form low points between the ridges.

The mesa in the middle of the prospect has an extensive cap of 1–2 m of slabby duricrust and nodular and pisolitic lag developed in colluvium and alluvium (Anand et al., 1996; Figs. 10, 11). The slabby duricrust and nodules and pisoliths are composed of horizontally arranged massive goethite-rich sub-rounded to rounded quartz plates that grade abruptly into a mottled zone below. A geochemical anomaly was found by analyzing ferruginous nodular lag (N = 31) collected on a 500 × 250 m grid. Fifty two samples were taken from a drill hole (BR 36; Fig. 10) located within the main anomaly. The ferruginous nodular lag (0–0.2 m) from the top of drill hole 36 largely consists of hematite, goethite and quartz with minor amounts of kaolinite and mica (Fig. 12). They are the most ferruginous materials (59.4% Fe_2O_3) in the profile and are anomalous in Cu (1109 ppm), Pb (75 ppm), As (196 ppm), Sb (31 ppm) and Mo (4 ppm). The mottled zone samples contain ≤ 10% Fe_2O_3 and consist dominantly of quartz (>60% SiO_2). The trace elements (Cu, Pb, As, Sb) decrease proportionately with Fe from the surface to the mottled zone. The saprolite is dominated by quartz, mica and kaolinite and has low concentrations of metals but the goethite veining around which Cu (3%) and the other trace elements reach their highest concentrations in the profile (Pb 366 ppm, As 238 ppm, Sb 77 ppm, Mo 5 ppm and Au 17 ppb). The bedrock consists of quartz, dolomite and mica. It contains <3.5% Fe_2O_3 but the metal contents are low (e.g., Cu 250 ppm).

Surface samples show that anomalies in Cu (max 1560 ppm), Pb (max 137 ppm), Sb (max 22 ppm), Au (max 150 ppb) and As (max 452 ppm) at the Buckley River prospect are restricted to slabby duricrust and ferruginous nodules in the centre of the mapped area (Anand et al., 1996; Fig. 13). Zinc is very low (max 30 ppm). Thresholds were chosen from normal probability plots. The Pb and Cu concentrations show the most distinct break at 50 ppm and 1000 ppm respectively. Antimony (>20 ppm) defines the anomaly but As (not shown) is little help. There are no meaningful correlations between the indicator elements. Element mapping of the slabby duricrust has illustrated distribution of Cu and As within Fe and Mn minerals. The highest Cu concentrations occur within Mn in cracks around goethite grains. Arsenic is concentrated in the hematite-rich areas. A Cu-rich manganiferous material fills cracks as the latest phase of accumulation. The enrichment of trace elements in transported slabby duricrust and nodules and pisoliths cannot be explained by residual accumulation but metals were largely sourced from a fault that cuts through the duricrust-capped mesa and pyritic units in the Proterozoic bedrock (Anand et al., 1996). The fault is 2 to 5 m wide and has cherty margins and ferruginous veining (Fig. 10), which is visible at surface for approximately 200 m from the eastern end of the low escarpment on the south-east of

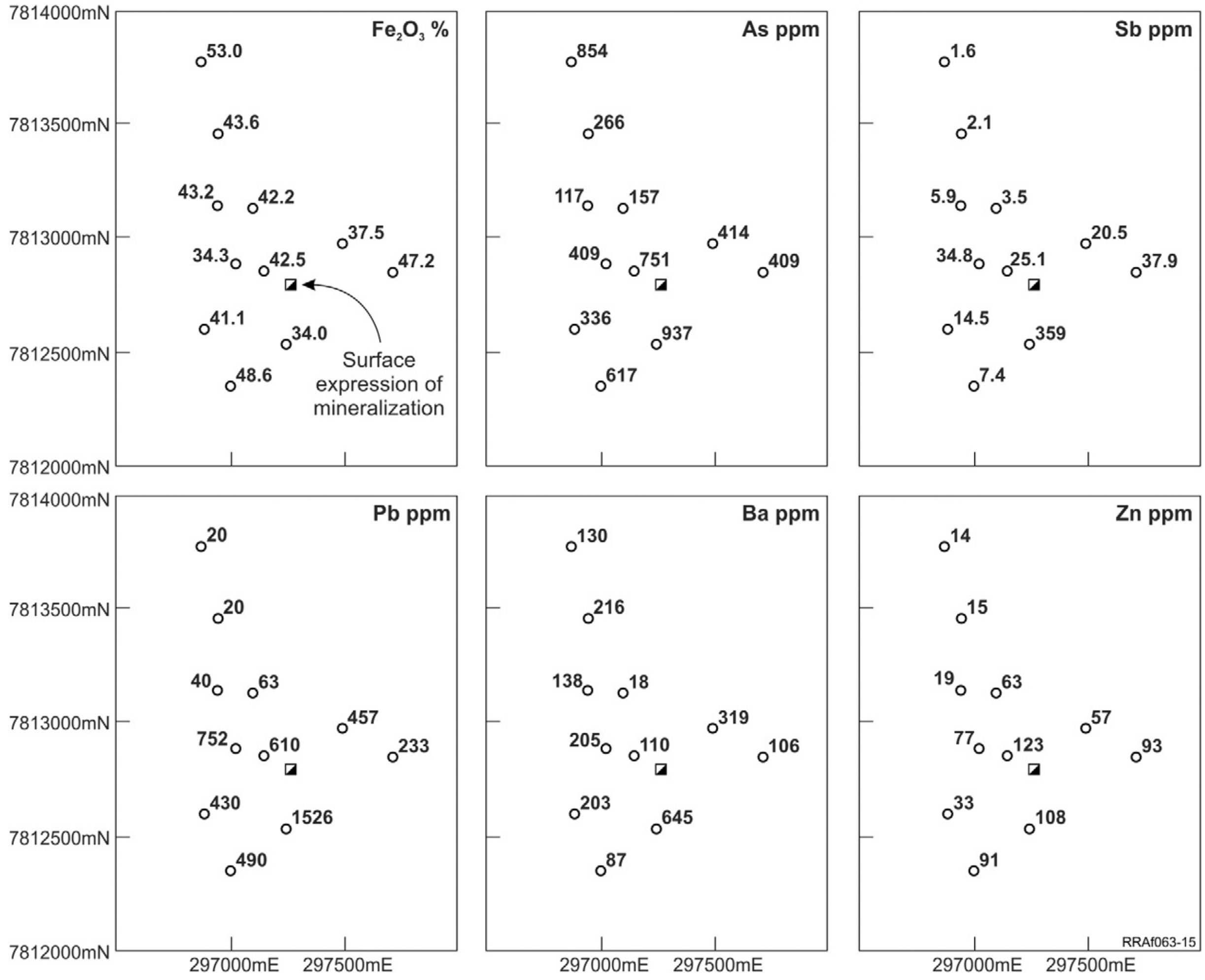

Fig. 9. Geochemical plots of nodular, ferruginous duricrust sampling around the Lady Loretta deposit (After Anand et al., 1996).

a mesa on a low siliceous hill east of the creek. Several samples from the ferruginous part of the fault contain anomalous Cu, Pb, As, Sb and Au (Fig. 10). Quartz grains have inclusions of fresh sulfides and contain up to 990 ppm S.

6.1.2. Truncated profiles on Proterozoic bedrock

This regime occurs in low to moderate relief where the uppermost horizon is saprolite or bedrock and is generally covered by semi-residual soils or colluvium. Ferruginous duricrust and gravels are absent in this environment. The Little Eva magmatic Fe oxide Cu–Cu prospect provides an example of this erosional environment (Robertson et al., 1995). The prospect lies in the Corella Formation of the Eastern succession in an area of greenschist facies pelitic metasediments with thin limestone layers, interlayered scapolitic limestones with calcareous, micaceous, quartzose metasediments and a podiform, cupriferous magnetite lens (Edwards, 1978). The prospect is located on a gently inclined, undulating pediment covered by 1–2 m colluvium, with the alluvium of Cabbage Tree Creek to the NW and an extensive area of colluvium to the SE (Fig. 14A).

CRA Exploration investigated the Cu distribution in weathered bedrock by drilling. There is a north-striking anomalous band, about 300 m wide and over 1 km long, centred on the shaft, in the erosional regime, and this extends both 400 m to the north, under the alluvium of Cabbage Tree Creek, and 700 m to the south, under the colluvium. There are two strong peaks of 10,000–20,000 ppm Cu in the south. Most of the Cu anomaly is >2000 ppm but reaches 5000 ppm near the old shaft (Fig. 14B). This substantial bedrock Cu anomaly formed the target for a subsequent orientation soil geochemical survey (Robertson et al., 1995).

Early work by Nicolls et al. (1965) showed broad (150–300 m) total and cold extractable Cu anomalies (maxima 1000 and 100 ppm respectively) over the Little Eva prospect and its strike extensions. Although the anomaly was 'cut off' by the alluvium of Cabbage Tree Creek, there had been some dispersion at depth from drainage waters contaminated by the mine workings.

A soil study was conducted by Robertson et al. (1995). Soil samples were collected on a triangular grid, using a sample spacing of 150-200 m. About 1kg of complete soil was collected from a depth of 5 to 20 cm. The study showed that the widest ranges in composition occurred in the 710–2000 μm and the <75 μm soil fractions and these were selected for analysis and compared. Indicator elements for Little Eva mineralization are Cu and Au. Copper yielded similar results for both fractions although maximum abundances were five times greater in the fine fraction (compare Fig. 14E and F). The erosional area near the Little Eva shaft is defined clearly by Cu in the fine fraction (Fig. 14F) but the anomaly decreases by about an order of magnitude in the colluvial environment, where a subtle anomaly indicates the underlying bedrock anomalous trend of Fig. 14B. There is no soil Cu anomaly in the area covered by alluvium, with Cu abundances close to detection (10 ppm). Gold in the fine fraction also accurately targets the shaft area in the erosional regime with a bullseye anomaly (100 ppb), with a weak trend into the colluvium to the south (Fig. 14D). The anomaly is similar but weaker (50 ppb) in the coarse fraction (Fig. 14C) but there is no clear trend into the colluvium. It is possible to marginally improve the trend under the colluvium by weighting soil sample data from the colluvium by a factor designed to make the means of the two populations (erosional and depositional) approximately equal. The mineralization in

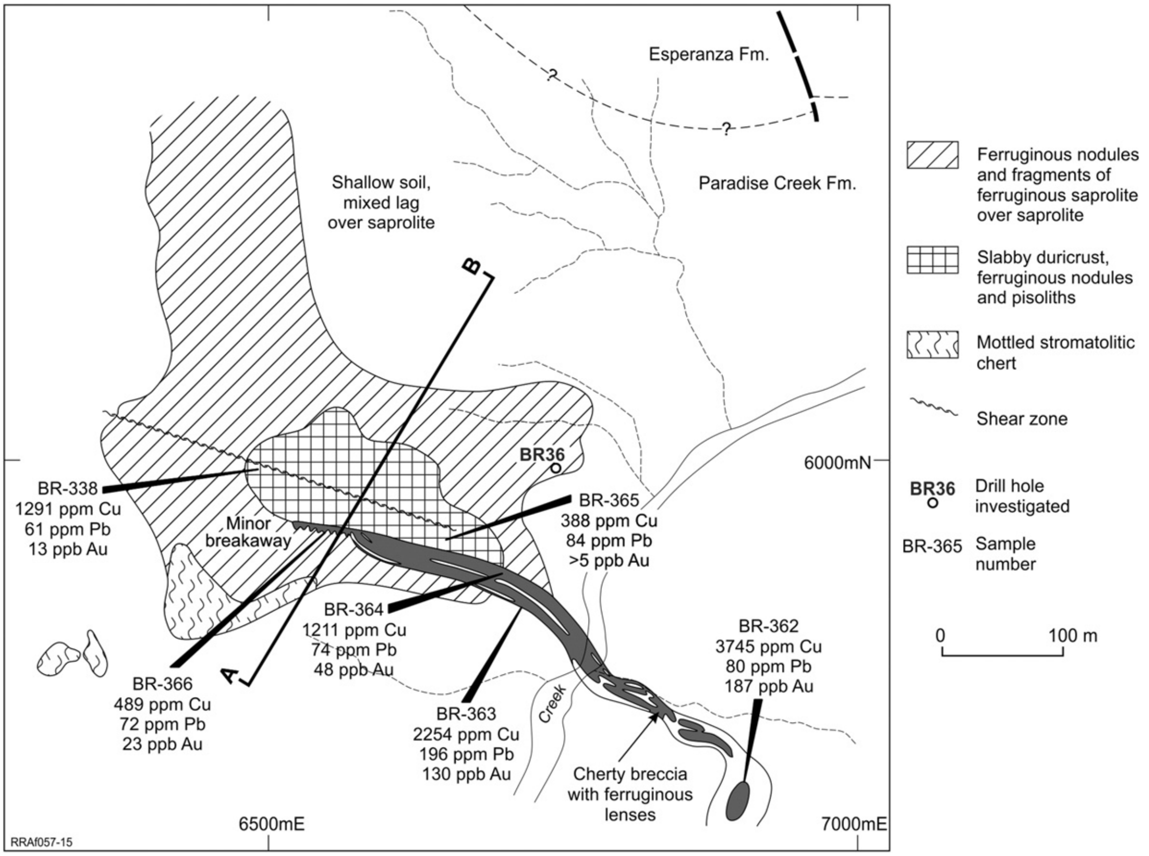

Fig. 10. A regolith map of the slabby duricrust capped mesa at Buckley River Prospect with location and analysis of some sampling points. (After Anand et al., 1996).

the erosional regime is also reflected by bullseye anomalies in Co (50 ppm) and V (300 ppm) against backgrounds of 20 and 150 ppm respectively probably indicating the magnetite-rich parts. There is no useful response from Pb or Zn.

It is concluded that a thin (<2 m) colluvial mantle provides little barrier to the dispersion of Cu and Au from basement to soil, provided that the fine fraction (<75 μm) is used. However, anomalies tend to be muted by an order of magnitude. The alluvium was not penetrated successfully by soil geochemistry. Geobotanical anomalies coincide with all geochemical anomalies and may also occur in areas of transported cover where there is no geochemical response. These geobotanical anomalies are related to Cu toxicity and are characterised by *Tephrosia* sp. *nov*. and *Polycarpaea glabra* which are Cu tolerant (Nicolls et al., 1965). Bioturbation by soil mesofauna plays an important and active role in mixing soils in the near surface (Stewart and Anand, 2014). Termitaria are an important feature of the landscape in areas mantled by colluvium at Little Eva. They have the capacity to carry fine soil particles (including clays and Fe oxyhydroxides which carry the geochemical signal) from the weathered basement, through thin colluvium and deposit them in the soil.

6.2. Weathered and locally eroded Mesozoic cover sequences

6.2.1. 'Complete' profiles on Mesozoic sediments

The Osborne Cu–Au deposit provides an example of such settings where the upper horizon is ferruginous duricust similar to that developed on Proterozoic bedrock. The following description is largely taken from Lawrance (1993, 1996, 1999) and Rutherford et al. (2005). Osborne is situated on a mesa (eroding plateau) capped with ferruginous duricrust and silcrete, surrounded by alluvial flats. The Osborne deposit is hosted by the Proterozoic Soldiers Cap Group (Fig. 15) comprising metapelite, metapsammite, quartzite, ironstone, and amphibolite rocks, part of the Mount Norna Quartzite, near the contact with the Llewellyn Creek Formation (Blake, 1987; Williams, 1995). The host rocks are unconformably overlain by 30–60 m of Mesozoic marine

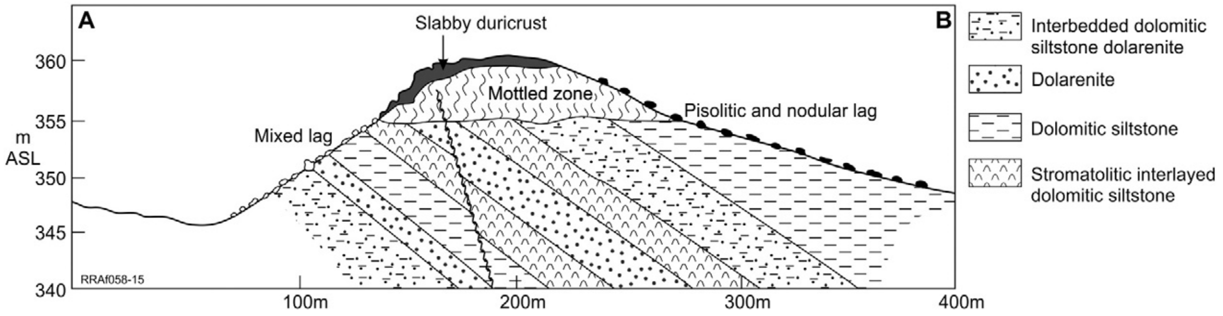

Fig. 11. Cross section of mesa shown as A–B in Fig. 10, Buckley River Prospect. (After Anand et al., 1996).

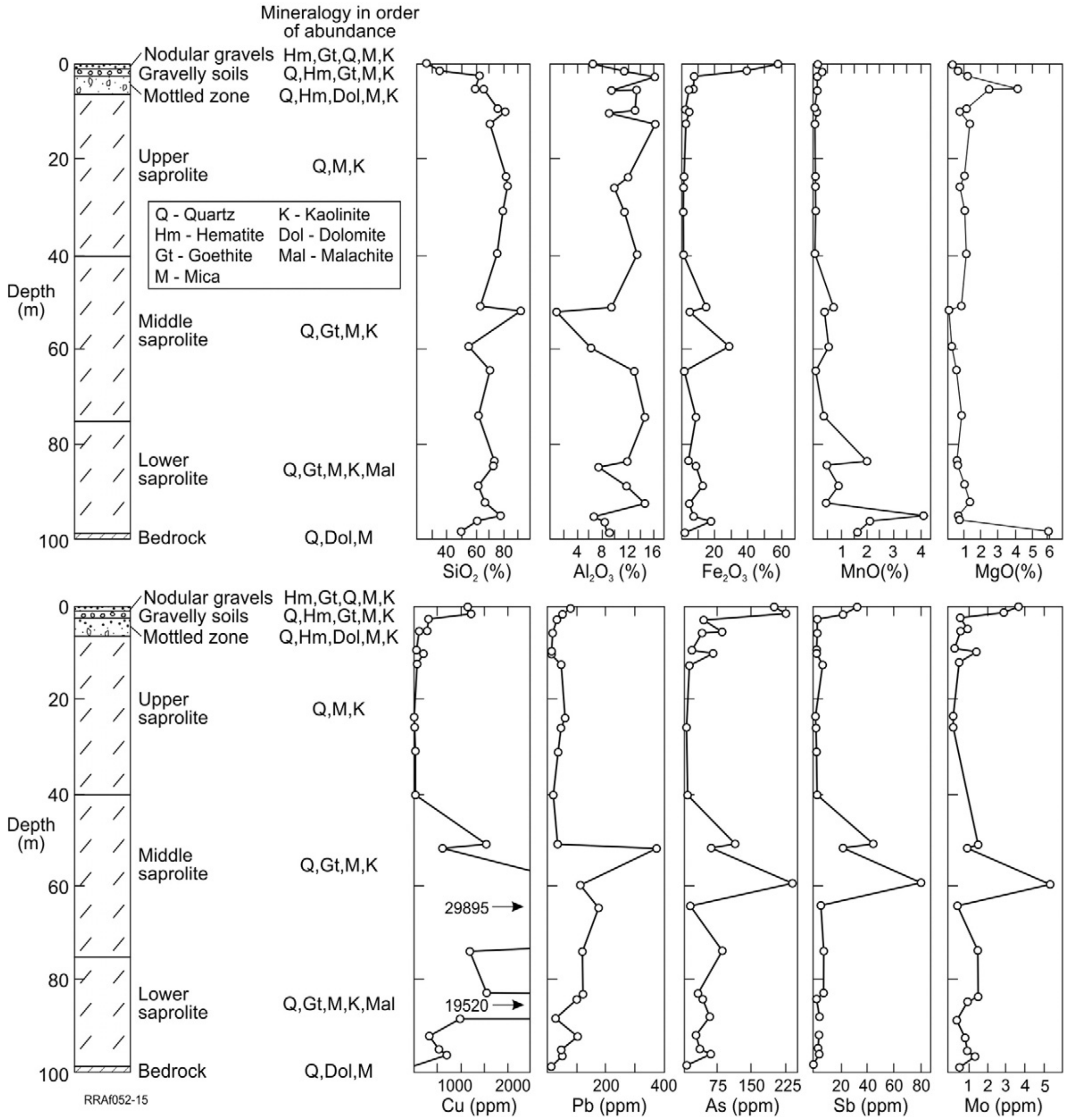

Fig. 12. Geochemistry and mineralogy of weathering profile, drill hole BR36, Buckley River Prospect.
(After Anand et al., 1996).

sediments of the Eromanga Basin. These comprise a basal grit, the Longsite Sandstone, and fine sandstone, mudstone and claystone of the Wilgunya Formation. The upper part of the deposit is near vertical and three mineralized zones subcrop at the Proterozoic-Mesozoic unconformity (Lawrance, 1996).

Osborne is a structure-hosted silica–magnetite–Cu–Au replacement deposit. Ore minerals are predominantly chalcopyrite and pyrite with pyrrhotite in some parts. The Au is largely free but is closely associated with Cu sulfides. Common gangue minerals include pyrrhotite, pyrite, magnetite, siderite, talc, chlorite and ferropyrosmalite and the minor elements include Ag, Bi, Co, Hg, Mo, Se, Sn, Te, W and F. The ore body sub-crops beneath the Precambrian-Mesozoic unconformity as a gossan. A zone of secondary carbonates, mainly malachite and cuprite, overprinted by chrysocolla and minor atacamite and tenorite, 5–10 m thick, separates the gossan from the underlying steeply E-plunging primary sulfides (Lawrance, 1993, 1996; Scott and Meyer, 1993; Adshead, 1995; Tullemans et al., 2001). Siliceous gossanous ironstone pebbles, cobbles and boulders are spread along the unconformity from the ore.

The Precambrian metasediments that host the mineralization and the overlying Mesozoic marine sediments are both deeply weathered. The mineralized bodies were weathered prior to burial to siliceous gossan, which sub-crop as a basement topographic high some 20 m above the general elevation of the Mesozoic unconformity (Rutherford et al., 2005). The surrounding basement has been truncated to the lower saprolite. Rounded fluvial pebbles, cobbles and, less commonly, boulders mark the paleosurface. Subsequent marine incursion and regression during the Mesozoic resulted in deep burial of the basement by reduced sediments. More recent extended sub-aerial exposure has resulted in weathering and oxidation of the upper Mesozoic. A trend towards aridity during the Tertiary and Quaternary, has produced several generations of siliceous and ferruginous duricrusts in the near-surface that mark paleo- and present drainage valleys (Lawrance, 1996). This older surface is undergoing degradation, collapse and dissolution to form a locally transported, ferruginous duricrust that caps the pit area and slopes away from it. A widespread hematitic scree, up to 1 m thick, is derived from erosion of the mottled zone exposed on the upper parts of the plateau (Rutherford et al., 2005).

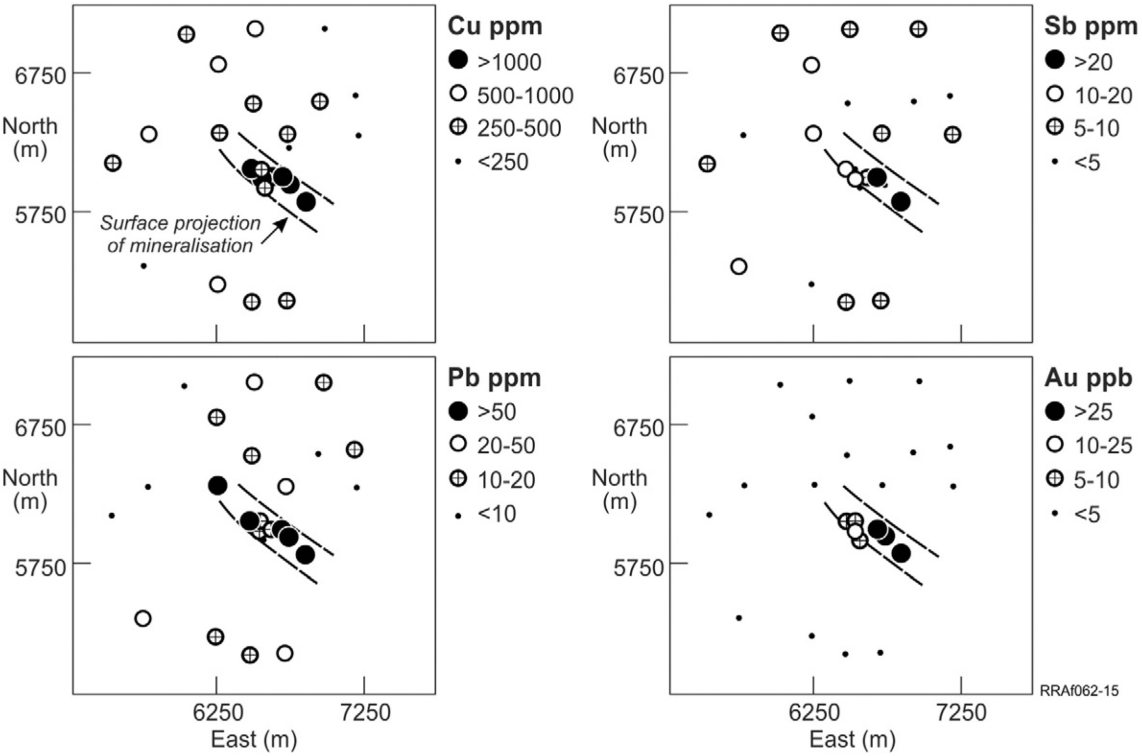

Fig. 13. Geochemical maps for ferruginous nodules and pisoliths and slabby duricrust, Buckley River Prospect. (After Anand et al., 1996).

The Mesozoic sediments are strongly faulted and fractured (Lawrance, 1996). The silcrete and ferruginous duricrust around the pit shows dissolution, collapse and erosion above the orebody. Despite the intense weathering of the Mesozoic sediments, erosion and burial of the mineralization, there was a distinct geochemical anomaly for a range of elements (Cu, Bi, Cd, Ge, Hg, Se, Eu, Sm) in ferruginous materials and soils. The most distinctive anomalies in soils were identified by a cold 0.1 M HCl leach and from pSirogas analysis (Lawrance, 1993; Scott and Meyer, 1993). Geochemical traverses across the deposit are very spiky, typical of partial leach extraction in areas of deep weathering and thick cover. The spikes in the surface geochemistry reflect the variable permeability of the sediments. This substrate is controlled by near-vertical fractures that extend through the Mesozoic cover and are known to be geochemically anomalous above the buried ore and the variable geochemical dispersion processes affecting ore elements through the weathered profile (Rutherford et al., 2005).

Element dispersion patterns interpreted from 18 percussion holes across the Osborne ore zone (Fig. 16) highlight the controls on element distribution through the weathered profile (Lawrance, 1996, 1999). These show a distinct anomaly 'plume' directly above the ore for a range of elements, the influence of paleoredox zones through the Mesozoic profile, and the present active redox zone at depth. There is a significant enrichment in major ore elements in the top 5 m of the profile, coincident with ferruginous upper mottled zone and duricrust. The leached saprolite beneath is poor in most elements, reflecting intense alteration during weathering.

Sampling of paleoredox zones, country rock and fractures transgressing upward through the pit walls, marginal to the mineralization, indicates that geochemical dispersion from the ore occurred preferentially through discrete sub-vertical fractures (Rutherford, 2002a, b). The best-expressed paleoredox zones within the Mesozoic are coincident with thin beds (about 100 mm) of pyrite-rich sediment within the sequence, now seen as massive concordant botryoidal hematite, with abundant alunite in the beds immediately above the sulfide-bearing horizon. The country rock and paleoredox zones only appear to host low-order anomalies close to the vertical fractures or where redox fronts intersect the ore. The compositions of the redox zones away from ore appears to reflect that of the Mesozoic sediments, with a local overprint imposed after the water-table had fallen to below the unconformity, and weathering and oxidation of the ore recommenced (Rutherford, 2002b). Redox zones only become anomalous if they intersect mineralization or anomalous structures, such as fractures, extending from mineralization (Lawrance, 1996). This has implications for the use of shallow redox zone geochemistry as a regional indicator of mineralization beneath very thick cover. A dispersion halo from this is unlikely to be significant at the surface or in shallow paleoredox horizons until the present weathering and redox front has re-intersected the ore and active dispersion of ore elements has recommenced (Rutherford et al., 2005).

Reworking of anomalous redox horizons and fractures during duricrust formation, and subsequent surface and sub-surface hydromorphic dispersion, are thought to account for a broad secondary sub-surface halo in Cu and other ore elements away from the pit area (Rutherford, 2002a). In some locations, ferruginous horizons associated with zones of active silcrete development along drainages contain low but distinctive partial leach (Regoleach) ore signatures (Cu, Hg, Mo, Tl, Ag). At one locality, 1 km from the pit site, duricrust breccia beneath silcrete contains up to 140 ppm Cu. Low pH groundwaters (pH 4.2) in the vicinity of the mineralization may be contributing to these processes (Johnston et al., 1993; Lawrance, 1993, 1996, 1999).

6.2.2. *Truncated profile on Mesozoic sediments*

Variably eroded Mesozoic sediments to saprolite characterise the Brumby (Cu–Au) and Tringadee (Zn) areas (Phang et al., 1997a). Brumby Cu–Au prospect is situated in low hills of Mesozoic sediments (up to 70 m thick) over steeply dipping Proterozoic bedrocks (Phang et al., 1997a). Hydrothermal mineralization in the Proterozoic contains magnetite, chalcopyrite and gold. Both the Mesozoic sediments and Proterozoic bedrock are weathered to saprolite. Horizontal ferruginous bands and sub-vertical ferruginous veins occur within the Mesozoic sediments

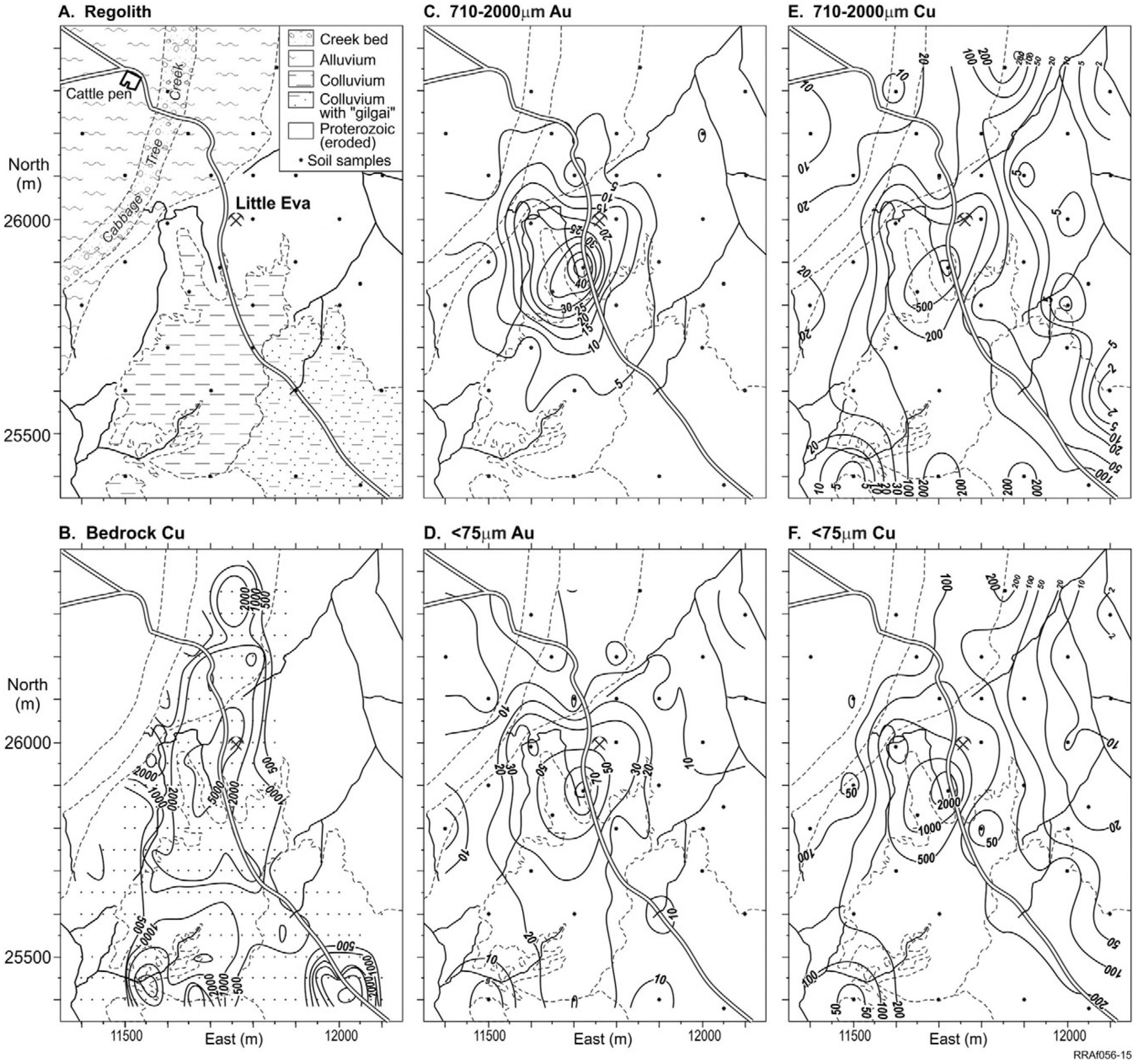

Fig. 14. (A). Regolith map of the Little Eva prospect. (B) Bedrock Cu. (C) Soil Au in the coarse and fine (D) fractions. Soil Cu in the coarse (E) and fine (F) fractions. Sample points as dots. (After Robertson et al., 1995).

(Fig. 17). The sub-surface ferruginous bands are sub-horizontal and represent either redox zones or preferred pathways for induration by Fe-rich fluids in the more permeable layer of the sediments. The structurally controlled surface ferruginous veins follow tectonically induced partings (Phang et al., 1997a).

Surface samples were collected along two transects over minor mineralization drilled by Aberfoyle Resources (Anand et al., 1996; Phang et al., 1997a). These include ferruginous veining and induration on bedding planes and faults in the Mesozoic sediments and consist largely of hematite, goethite, kaolinite and quartz. Goethite abundance tends to increase with depth. Bulk analyses of eleven samples showed Au <5 ppb and low abundances of Cu (50 ppm). Partial extractions using buffered ammonium acetate followed by hydroxylamine hydrochloride did not add any new information to the bulk analysis information (Phang et al., 1997a). Thus, it is concluded that there is no expression of mineralization in the surficial ferruginous veins.

Sub-surface samples of horizontal ferruginous bands were chosen from RAB drilling clustered holes around percussion drill hole PETD6 which all showed Cu less than 50 ppm in the 15 m of Mesozoic drilled (Aberfoyle Limited Unpublished data). The Mesozoic sediments are approximately 45 m deep. Zinc increases in the top 10 m, showing an accumulation that is unrelated to mineralization (Fig. 18). However, Au, Cu, Zn and other trace elements increase around the Fe-rich Mesozoic/Proterozoic boundary (unconformity). At 25 m, there is a ferruginous band that represents an old water table at which Cu and Zn have accumulated (Fig. 18). Below 25 m, Fe, Cu and Au correlate well but, above 25 m, the correlations between Au and Cu, and Cu and Fe break down. Copper is increasingly depleted towards the surface, decreasing from a maximum of 8000 ppm in the Proterozoic to 400 ppm at 25 m and 40 ppm at surface. It appears that Au and Cu are sourced from mineralization and their dispersion is controlled by redox processes similar to that observed at the Osborne deposit (Phang et al., 1997a).

Aberfoyle Resources Ltd found the Tringadee Zn anomaly in 1992 by drilling aeromagnetic anomalies through the Mesozoic sedimentary cover. A widespread Zn anomaly (Fig. 19), up to 1000 ppm, occurs in white to brown claystone in the Mesozoic sediments that is confined

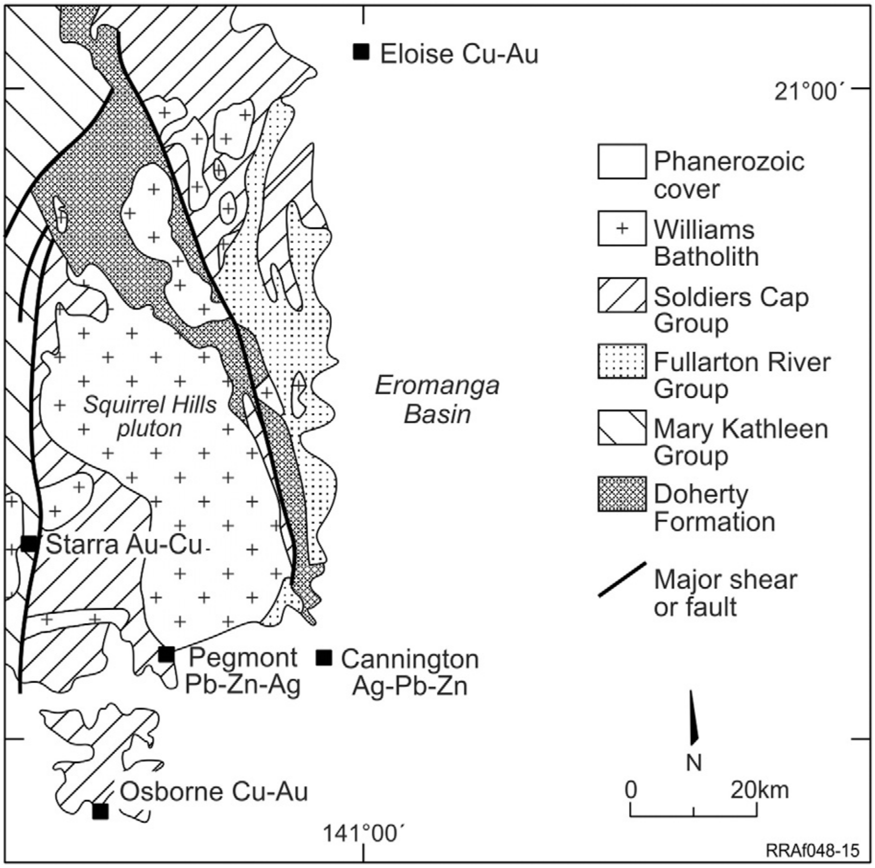

Fig. 15. Location of the Osborne deposit in relation to geology and other deposits. (After Adshead et al., 1998).

to a north striking paleovalley. Drilling data indicate that the Tringadee anomaly is separated from the Cannington Pb-Zn-Ag deposit by a paleohigh. The Tringadee Zn anomaly lies beneath a pediment developed from hills of Mesozoic sediments and is covered with a polymictic lag of goethite- and Mn-rich lithic fragments and Fe-stained brecciated, silicified saprolite (Phang et al., 1997a).

The Tringadee Zn anomaly is underlain by rocks of the Eastern Succession of the Proterozoic Mt Isa region. These basement rocks are covered by 20–30 m of variably eroded and weathered Mesozoic sediments, largely siltstones, with poorly sorted and commonly cross-bedded, basal sandstones and conglomerates (Phang et al., 1997a). In some places, exposure of sub-horizontal goethite–Mn oxide-rich bands in the saprolite has formed low knolls or a step-like micro-relief (See Fig. 7). Manganese oxides from the surface were dated by ^{40}Ar/^{39}Ar (Vasconcelos, 1998) as late Miocene (12 Ma).

The surrounding depositional plains have extensive smectitic black soils with gilgai microrelief, caused by shrinking and swelling of clay. These soils are commonly 1–2 m thick and are developed on recent colluvium-alluvium on weathered Mesozoic and Proterozoic rocks.

No primary basement-related mineralization has been identified in the Proterozoic granites beneath the extensive Zn anomaly in the Mesozoic sediments. The Tringadee Zn anomaly appears to be associated with accumulated Fe and Mn oxides in ferruginous bands within the weathered Mesozoic sediments and the source of the Zn is thought to be external, lateral and distal. A RAB drill intersection at Tringadee (ROTR156 at 479500 mE, 7,580,000 mN) containing >1000 ppm Zn was investigated as part of a more detailed study (Phang et al., 1997a) to determine the source of the Zn anomaly. Colluvial–alluvial plains, near low mounds of Fe- and Mn-stained Mesozoic sediments, surround this site.

A schematic regolith profile of ROTR156 shows the dispersion of Zn and related elements (Phang et al., 1997a; Fig. 20). Analyses of different size fractions of the intersection in ROTR156 showed that the median concentration of Zn, Cu, Pb, As and Sb were similar in the >2000 μm and the 710–2000 μm fractions, but with very variable abundances of Fe_2O_3 (2–60%), Al_2O_3 (6–20%) and SiO_2 (22–70%). For most of the remainder of the samples, the >710 μm fraction was analysed; however, in about 20% of the samples this was insufficient, so that the <710 μm fraction, which is dominated by quartz and kaolinite, was used instead. Samples at various depths within a profile were selected for analysis based on colour (reds and browns). For ferruginous bands in the saprolite, the >710 μm fraction was hand separated into Mn-rich and Fe-rich materials.

Zinc is relatively enriched in sub-surface ferruginous bands at depths of 5–10 and 20–25 m, where the concentration of Fe_2O_3 reaches 60% (Fig. 20). The 20–25 m interval contains goethite with dendritic overgrowths of hollandite. The Zn content of the ferruginous bands is 1300–2000 ppm compared to <200 ppm in the pale, clay-rich, Fe-poor materials. Copper is also enriched, to a maximum of 170 ppm. Lead concentrations are low in both fine and coarse fractions but reach 200 ppm in two Mn-rich samples. The As contents vary from 1–50 ppm, with the high concentrations associated with Fe-rich samples. Goethite and hollandite are the most probable hosts for Zn, Cu and possibly Pb thought to have been mobilized by weathering.

These data and RAB geochemical data supplied by Aberfoyle Resources Ltd indicate the Zn anomaly in the Mesozoic sediments is associated with accumulated Fe and Mn oxides (Phang et al., 1997a). Zinc appears to be more closely associated with Fe than with Mn, but where both Fe and Mn contents are high, Zn concentrations exceed 1000 ppm. However, low contents of Pb, which is less mobile, suggest a distal source

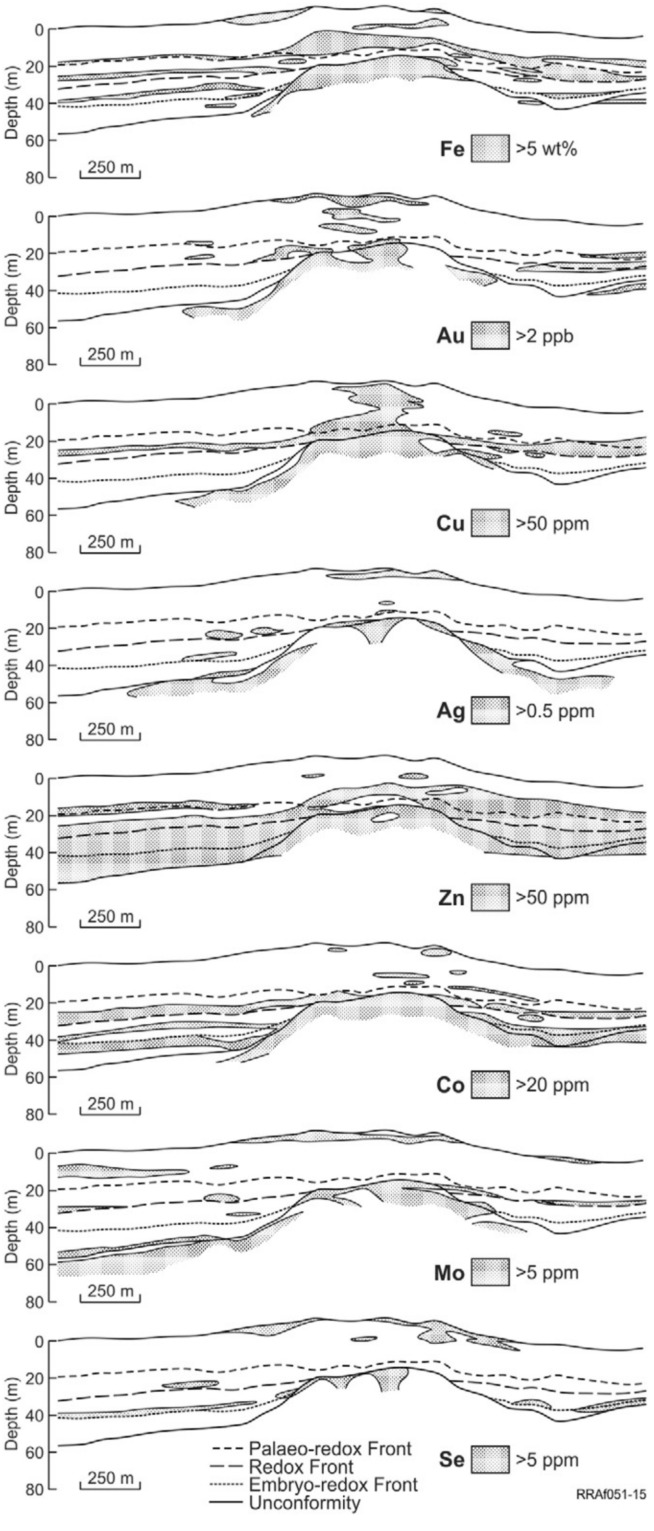

Fig. 16. Distribution of Fe and selected elements through weathered profile. (After Rutherford et al., 2005).

(the only high Pb is associated with about 40% Mn). The Tringadee area is thought to have been low in the landscape before, during and after deposition of the Mesozoic sediments. Although contemporaneous accumulation of metals with the sediments is possible, it is more probable that it occurred during diagenesis or weathering. Iron, Mn and Zn were derived from external sources, migrating laterally along permeable layers, precipitating at redox fronts within the sedimentary pile. The Fe and Mn oxides precipitated to form the ferruginous bands and scavenged Zn. It is concluded that there is no proximal relationship between Zn anomalies in the sedimentary cover and any base metal mineralization in the basement. The sources of Cu, Pb and As are, as yet, undetermined.

6.3. Areas with younger transported cover of various types, including black soil plains, concealing basement and Mesozoic cover

The Eloise Cu–Au deposit represents this regime. It is situated on rolling plains and is masked by largely unweathered transported cover on basement in the Mt Isa region. The mineralization is hosted by greenschist-metamorphosed metasediments and mafic rocks with major retrograde shears in which early hornblende–biotite–quartz assemblages occur. They were overprinted by chlorite–muscovite–pyrrhotite–chalcopyrite ± calcite ± magnetite and, later, by calcite–chlorite–quartz ± pyrite assemblages during subsequent brittle deformation (Baker, 1994). The two main orebodies (western 'Elrose Lode' and eastern 'Levuka Lode') lie within meta-arkoses and biotite schists parallel to and between the major shears.

Around Eloise, little pre-Cretaceous weathering is preserved, so that Proterozoic rocks, intersected by diamond drilling, are unweathered, except at and near the unconformity, where there is very weak weathering to saprock (Li Shu and Robertson, 1997; Anand and Robertson, 2012)). Any pre-Cretaceous weathering rind was probably eroded almost as quickly as it formed and the unconformity quickly sealed by thick (50–150 m), impermeable Mesozoic sediments (Fig. 21) which were deposited during a marine transgression. This environment was characterized by oxygen-depleted waters and abundant macerated organic material. Around Eloise, the Mesozoic sediments are in turn buried beneath Tertiary and Quaternary fluvial sediments (Fig. 21). The surface is covered by brown and black soil, strewn with a lag of pebbles and ferruginous pisoliths.

To date, exploration in these environments has been by investigation of geophysical targets by drilling. At Eloise, the degree of weathering, below the unconformity and transported cover, is minimal so weathering-related dispersion in basement and cover is also expected to be minimal. In these environments, the most promising geochemical target is the Proterozoic-Cretaceous unconformity, marked by a thin, discontinuous layer of gravelly sand and conglomerate, sealed in by a thick mass of semi-pelitic to pelitic sediments. The basal, high-energy sediments developed on and from the basement might be expected to retain down-slope dispersions from any parts of the Eloise deposit that were exposed in Cretaceous times.

The paleotopography of this unconformity was obtained from mine and broad-scale (>1 km) water bore drilling (Fig. 22). The Eromanga Basin deepens to the NE. The gradient of the unconformity, close to the mine, is slight (1:1250) but there appears to be a much steeper slope (1:100) about 3 km NE, suggesting a scarp. The local paleotopography is well controlled by mine drilling. Together with the regional paleotopography it is clear that there is an arcuate gully to the E and NE, draining towards the upper edge of the scarp. Dispersion from the mineralization that outcrops at the unconformity north of the Median Fault would have been largely carried east, down the scarp. However, some leakage from the Median Fault could have dispersed W into the arcuate paleodrainage. Geotechnical drillhole ENG2 is the nearest to the fault; drillhole ENG1 is more distant. The point where the mine decline intersected the unconformity is more distant still and is probably up-slope of any point where mechanical dispersion from the Eloise mineralization or from the Median Fault subcrop could have entered the paleodrainage.

Mesozoic sediments below the concrete casing of the mine decline and core from the two geotechnical diamond drillholes (ENG1 and ENG2) were sampled. Near the mine, coarse, high-energy basal Mesozoic sediments are anomalous in Cu (75 ppm), Au (90 ppb) As (125 ppm) and, weakly, in Sb (0.7 ppm) at or very close to the unconformity in diamond drillholes ENG1 and ENG2 (Fig. 23). There are no anomalies in the decline or in the upper parts of the Mesozoic stratigraphy.

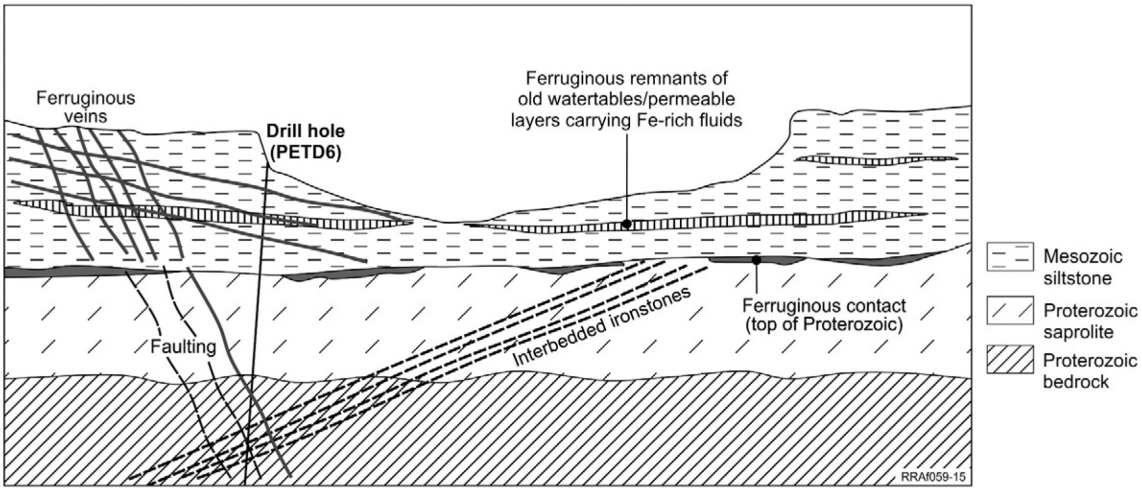

Fig. 17. Simplified regolith geology showing distribution of ferruginous veins and bands, Brumby prospect. (After Phang et al., 1997a).

Backgrounds are typically <5 ppb for Au, 20 ppm for Cu, 10 ppm for As and 0.2 ppm for Sb.

Three km from the mine, there is a small Cu anomaly (80 ppm) at the upper surface of the basal sandstone in diamond drillhole 1TT about 2.5 m above the unconformity. There are very weak Au anomalies in 2TT (57 ppb at the sandstone base and 26 ppb in a thin conglomerate 0.3 m above the unconformity). Arsenic and Sb anomalies (102 and 1.5 ppm respectively) also occur in drillhole 4BTT in sandstones and conglomerates 1.3 m above the unconformity. The remainder of the Mesozoic stratigraphy (largely pelitic) is at background concentrations for these indicator elements. Typically, interface or basal sediment anomalies are weak and subtle and require well-controlled analysis for reliable detection. However, they provide a much larger target than the far stronger anomalies found in the top of the basement.

The basement rocks are unweathered, consisting of an assemblage of quartz, sericitic plagioclase, green chloritized biotite and granules of ilmenite that have been shattered and veined with calcite, closely associated with crystalline pyrite and minor chalcopyrite. Some of the quartz contains accessory rutile and monazite. In basal conglomerates and grits proximal to mineralization, clasts of the basement assemblages are common and are remarkably unweathered. Contained sulfides are unweathered. Other clasts are largely round to subangular grains of sandy to silty vein quartz in a brown, sericitic, silty clay-quartz matrix. Bits of this material are found clinging to clasts of metamorphic basement. There are a few grains (3–5 μm) of pyrite in the clay matrix.

In similar rocks distal to the mineralization but down-slope, sulfides occur both in clasts of unweathered basement rocks and as replacements of cell interiors in fossil organic matter (Li Shu and Robertson, 1997; Anand and Robertson, 2012). The cell walls appear to be carbonaceous (grey, weakly reflective, brown to black in transmitted light). Slides from the proximal locations showed that the pyrite clusters, noted above, were also associated with carbonaceous material and were probably from highly macerated fragments of organic matter, so much so that the cell structures are unclear, but their sizes are consistent with this interpretation. Pyrite patches within individual clusters are relatively uniform in size. These size ranges are similar to those reported by Wilkin and Barnes (1997) and Paktunc and Dave (2002) for framboids occurring in both modern sediments and sedimentary rocks.

7. Summary and conclusions

There has been erosion, deposition and weathering during the Mesozoic and Cenozoic, to form complex landscapes and regolith in the Mt Isa region. Secondary geochemical dispersion patterns associated

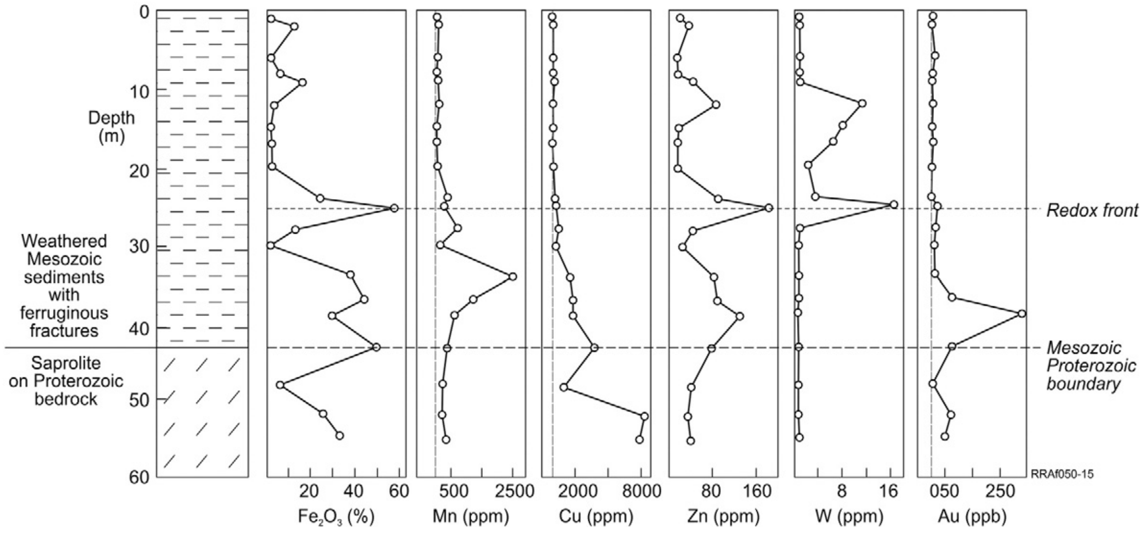

Fig. 18. Geochemistry of weathered profile on Mesozoic sediments and saprolite on Proterozoic bedrock, Brumby prospect. (After Phang et al., 1997a).

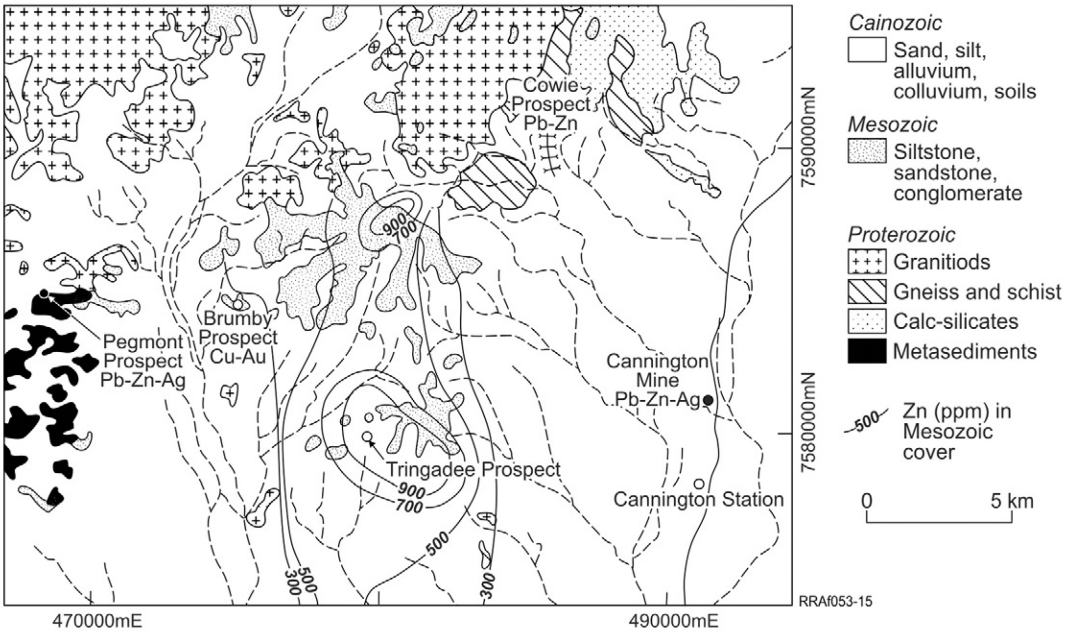

Fig. 19. Simplified geological map of the Tringadee prospect (Zn contours from Aberfoyle Resources Ltd).

with bedrock mineralization are the cumulative product of these successive weathering episodes and landscape processes under differing climatic regimes. The broad effects of this weathering history are recorded in the landforms and regolith, hence they form an appropriate framework for describing and interpreting the geochemical patterns (Figs. 24, 25). Weathered basement with a 'complete' lateritic profile on an eroded plateau (mesa) in the Mt Isa region exhibits large dispersion haloes of Pb, Sb and As as shown by wide (>600 m) dispersion in remnant hematite-rich nodular duricrust (lateritic residuum) at Lady Loretta. Lead, Sb and As are not strongly leached. In contrast, Zn is strongly leached and the highest concentrations occur about 500 m downslope, presumably due to hydromorphic dispersion (Cox and Curtis, 1977). Dispersion in lateritic residuum over VMS deposits has been described from Golden Grove in the Yilgarn Craton of Western Australia (Smith and Perdrix, 1983). Nevertheless, the relationship between gossan formation and disintegration, and pisolith formation and lateral dispersion remains uncertain (Butt, 2005). The principal gossans at Golden Grove outcrop on a prominent hill (Gossan Hill), whereas the anomaly in the pisoliths is on the flanks of the hill and in the surrounding plain. Pisoliths and nodules contain gossan fragments, but it is not certain that the hill was completely covered by pisolitic duricrust or, if so, whether this predated the first exposure of the gossans. Consequently, it cannot be assumed that gossans form at the same sites as pisoliths or, therefore, that pisoliths will contain gossan

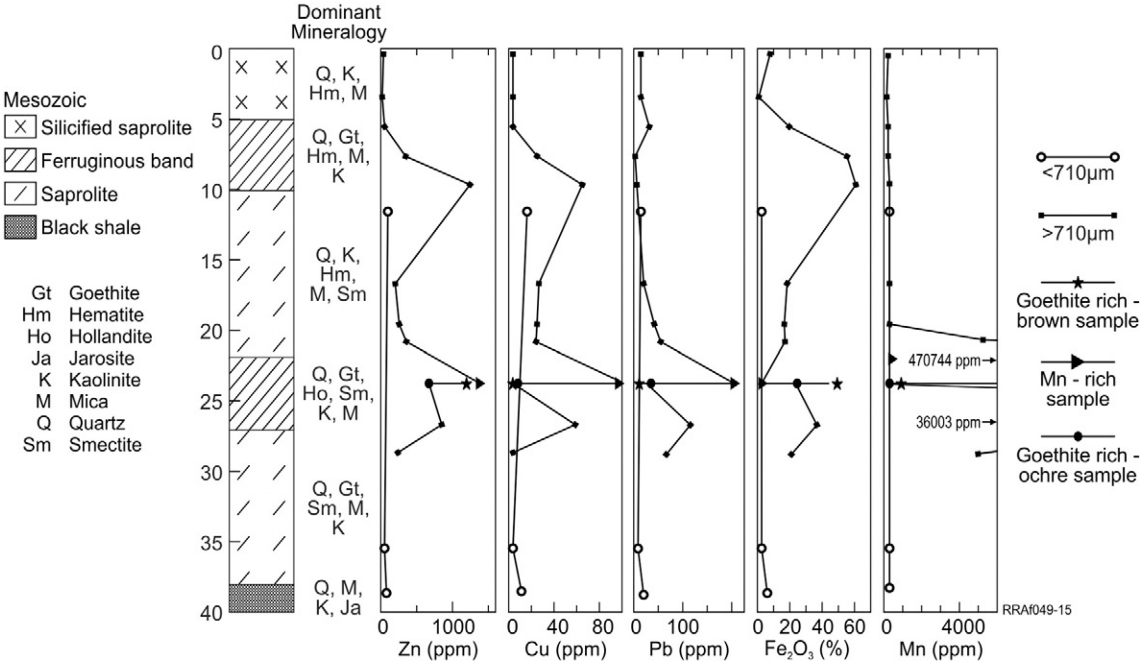

Fig. 20. Regolith profile for RAB ROTR 156 showing dominant mineralogy and distribution of Zn, Cu, Pb, Fe and Mn in various units of regolith profile, Tringadee prospect. (After Phang et al., 1997a).

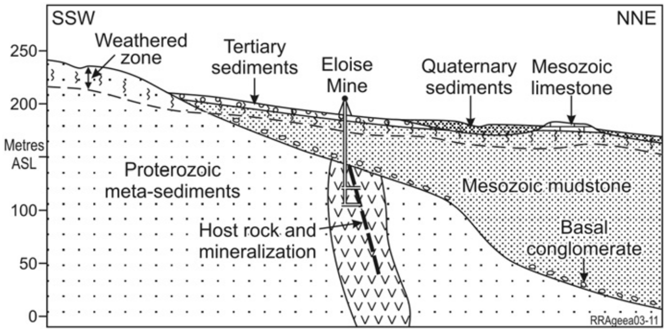

Fig. 21. Schematic section through the Eloise environment showing the weathered and unweathered Proterozoic basement partly covered by a thick wedge of Mesozoic sediments, in turn partly covered by Tertiary and Quaternary fluvial deposits.
(After Li Shu and Robertson, 1997; Anand and Robertson, 2012)).

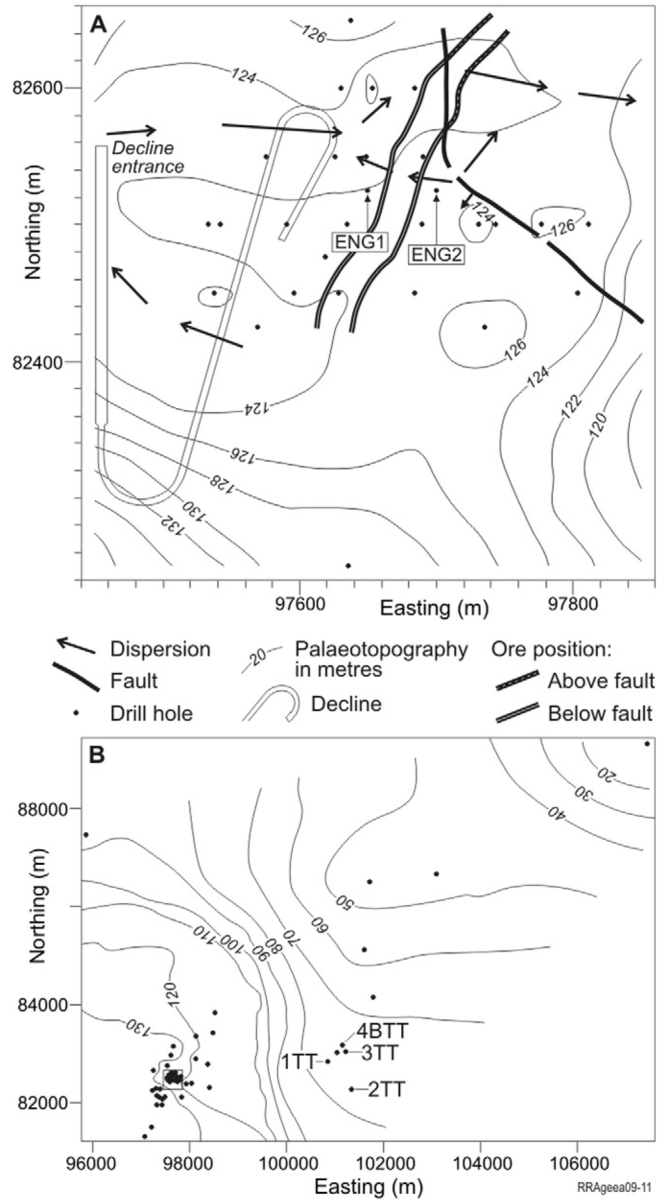

Fig. 22. Paleotopography of the Proterozoic-Mesozoic unconformity (m RL) as determined from drilling. (A) Detailed paleotopography around the Eloise Mine showing drill sites, sampled drillholes and the decline. (B) Regional paleotopography around Eloise and to the NE as determined from sparse water-bore drilling.
(After Li Shu and Robertson, 1997; Anand and Robertson, 2012).

fragments (Butt, 2005). At the Scuddles deposit, 4 km N of Gossan Hill, the terrain is subdued and no gossans are exposed (Smith and Perdrix, 1983). Pisolith sampling showed that both Cu and Zn are at background abundances similar to those observed at Lady Loretta. Several pathfinder elements (As, Sb, Bi, Se, Sn and Mo) are anomalous for up to 1.5 km from the projected sub-crop of the mineralized zone. Dispersion has been both chemical and mechanical; the latter possibly as individual minerals, such as cassiterite, rather than as gossan fragments.

Ferruginous duricrusts in the Mt Isa region have formed in different ways and on different substrates and are now on mesas. Massive, fragmental and nodular duricrusts (lateritic residuum) have formed residually on Fe-rich weathered bedrocks by accumulation of ferruginous materials from mottled saprolite after landscape-down wasting. Slabby duricrust (ferricrete) has formed on lower slopes by induration of saprolite and colluvium by laterally accumulated Fe and now forms mesas, by relief inversion. These ferricretes may not show a geochemical signature that relates to the underlying bedrock or adjacent bedrock, hence their use as a sampling media is restricted (Anand et al., 1997; Anand and Paine, 2002). However, at Buckley River slabby duricrust and nodules are also enriched in ore-related elements (Cu, As, Pb and Sb). Here, much of the geochemical dispersion in nodules and pisoliths has occurred in recently formed goethite and Mn oxides in cracks and coatings though leakage along a fault that cuts through the duricrust-capped mesa (Fig. 24). In contrast, enrichment in lateritic residuum at Lady Loretta is largely due to residual and chemical dispersion due largely to weathering of mineralized bedrock. Ferruginous duricrust, nodules and pisoliths are the most appropriate sampling media in these environments but the distinction between residual and transported categories is essential.

Truncated or severely truncated profiles on weathered basement have saprolite or bedrock as the uppermost horizon. They are generally covered with semi-residual soil or colluvium as at Little Eva (Fig. 24). Dispersion haloes are restricted, are limited to tens of metres from subcrop of the source, in contrast to the extensive anomalies in ferruginous duricrust and nodules at Lady Loretta and Buckley River. These observations are consistent with a number of base metals case histories summarized by Butt (2005). Examples include the Freddie Well Cu–Zn deposit (200 m; Smith et al., 1976) and the Teutonic Bore Cu–Zn deposit (minimal halo; Greig, 1983). Base metal mineralizations of various styles in the Cobar region, NSW (e.g., Elura, CSA; Munro et al., 2005) have similar haloes that generally extend less than 100 m in residual soils (Butt, 2005). Greater dispersion, extending to 200–300 m, may occur where there is high relief, such as the Hilton George Fisher deposits in the Mt Isa region (Conaghan et al., 2005). In each case, the anomalies have ferruginous outcrops as secondary sources and the geochemical pattern in soil and colluvium result from mainly mechanical dispersion of ironstone and gossan fragments (Butt, 2005). It is the landform regime in which gossan search is most appropriate and led to the initial discoveries in most base metal districts. Lag and soil sampling are the most common successful procedures for search for mineralization here, provided that the colluvium is less than 2 m thick and the fine soil fraction (<75 μm) is used, as shown by Little Eva. However, should there be significant dilution of the soil by aeolian sand, either a coarse soil fraction or a super-fine fraction (<2 μm) is highly recommended. Alluvium is not penetrated successfully by soil geochemistry.

Mesozoic sediments that overlie mineralized basement present a considerable barrier to exploration in the Mt Isa region as well as in many other regions of Australia. These terrains may be partly eroded or covered by younger cover, concealing basement rocks (Fig. 25). Geochemical exploration in covered areas depends on the possible presence of dispersion through the sediments or leakage along faults or fractures, but may be complicated by the presence of high metal backgrounds in the sediments themselves. Anomalous concentration of base metals and Au in the sediments may be exposed by erosion or encountered during drilling as a follow-up of geophysical targets. Some of the most prominent anomalies occur in ferruginous materials at Osborne representing emergent residual terrain developed on Mesozoic

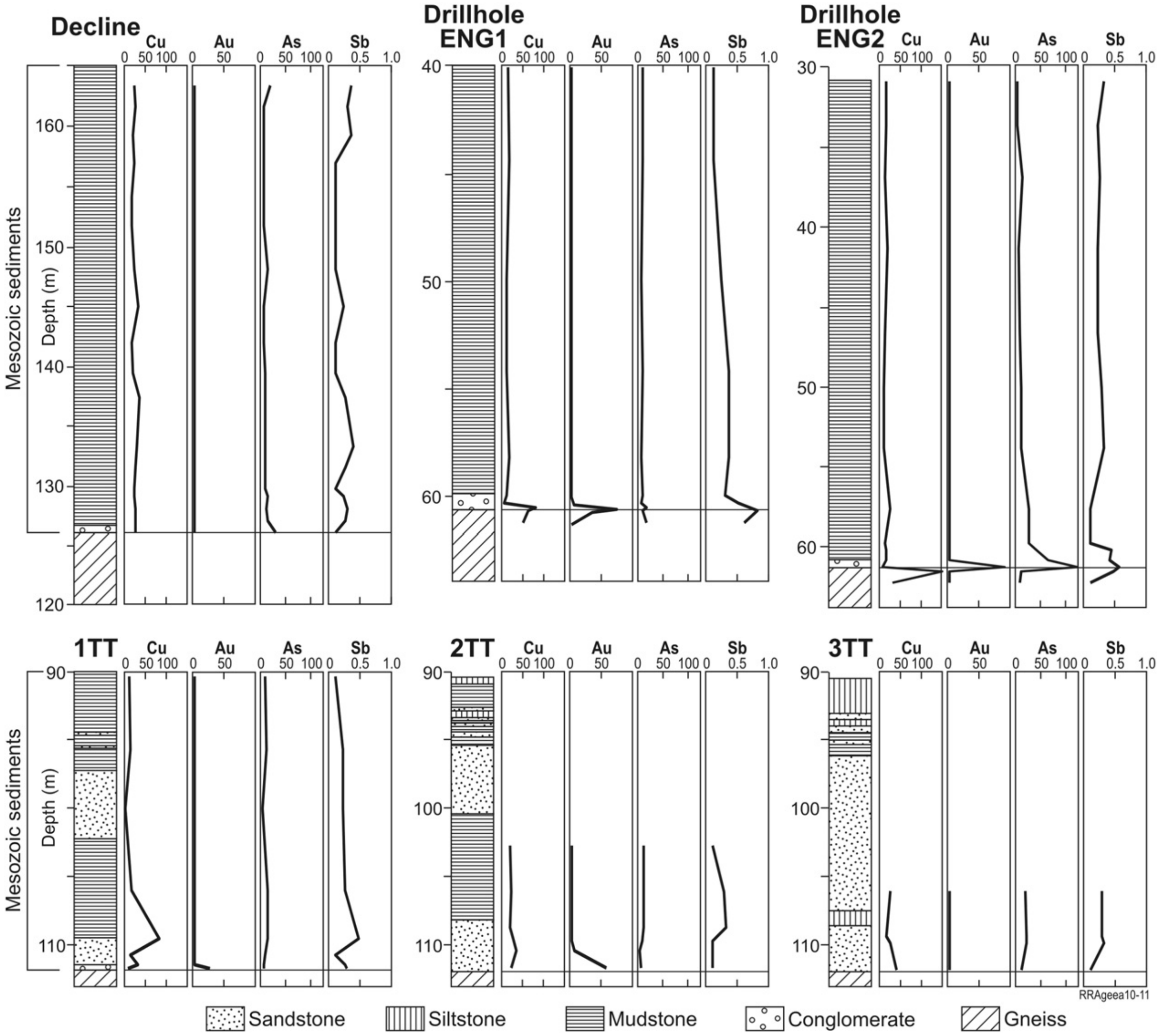

Fig. 23. Copper, Au, As and Sb geochemistry and geology of the decline below the concrete casing, the geotechnical drilling (boreholes ENG1 and ENG2) and water bore drilling (boreholes 1TT, 2TT and 3TT). Depths in metres below surface except for decline (m RL). Indicator elements in ppm except Au (ppb).
(After Li Shu and Robertson, 1997; Anand and Robertson, 2012)

sediments (Fig. 25). The anomalies interpreted to be due largely to weathering of sulfide mineralization that continued during submergence in a marine environment, with hydromorphic dispersion into the sediments as they accumulated (Lawrance, 1996; Rutherford et al., 2005). Further mobilization occurred during diagenesis and, following emergence, sub-aerial weathering. This has resulted in sub-horizontal zones of enrichment (Cu, Au, Ag, Zn, Mo, Co) at and below the present landsurface, in ferruginous horizons representing redox fronts in the sediments, and at the unconformity. Re-working under recent conditions has given rise to responses to partial extraction techniques (Rutherford et al., 2005). It is uncertain how widely this process has occurred in the region.

Similar accumulation of Cu and Zn with Fe oxides within the sediments, though not at surface, occurs at Brumby. Multi-element (Cu, As, Zn, Sb, Au) anomalies occur in basal sediments and at the unconformity at Eloise and Brumby (Fig. 25). The multi-element responses in the basal sediments, due to a combination of clastic and hydromorphic dispersion, represent a useful target for exploration sampling, especially where the sediments (and the underlying Proterozoic rocks) are fresh or little weathered. Metal-rich horizons in weathered sediments, higher in the sequence, can also be examined, particularly by specifically sampling ferruginous units and fragments (Anand and Robertson, 2012). However, these are less certainly related to mineralization. Zinc and Cu, concentrated in Fe (and Mn) oxides at redox fronts, may be derived by leaching from the sediments, and be unrelated to any basement mineralization. This is seen at Tringadee and possibly at Brumby. Such anomalies may be distinguished as false by regression analysis or by the absence of a multi-element signature – but with no certainty if the primary mineralization itself lacks other elements, or only Cu and Zn have been mobilized (Butt, 2005). Conversely, the sediments themselves may have a high, multi-element background, or contain low grade mineralization: This is the case for Cambrian sediments northwest of Mt. Isa, which yield strong surface anomalies from economically insignificant sources (*e.g.*, at Century, Agnew, 2005 and the Drifter prospect, Anand et al., 1997).

In all these regolith-dominated terrains, a clear understanding of local geomorphology, of the regolith framework, of the topography of unconformities and of the origins of ferruginous materials is essential to sample medium selection and data interpretation. This can be achieved by regolith-landform mapping and establishing regolith stratigraphy. Some geophysical techniques show promise for mapping regolith thickness and internal structure, with minimal drill-hole calibration (Papp, 2002; Munday, 2008).

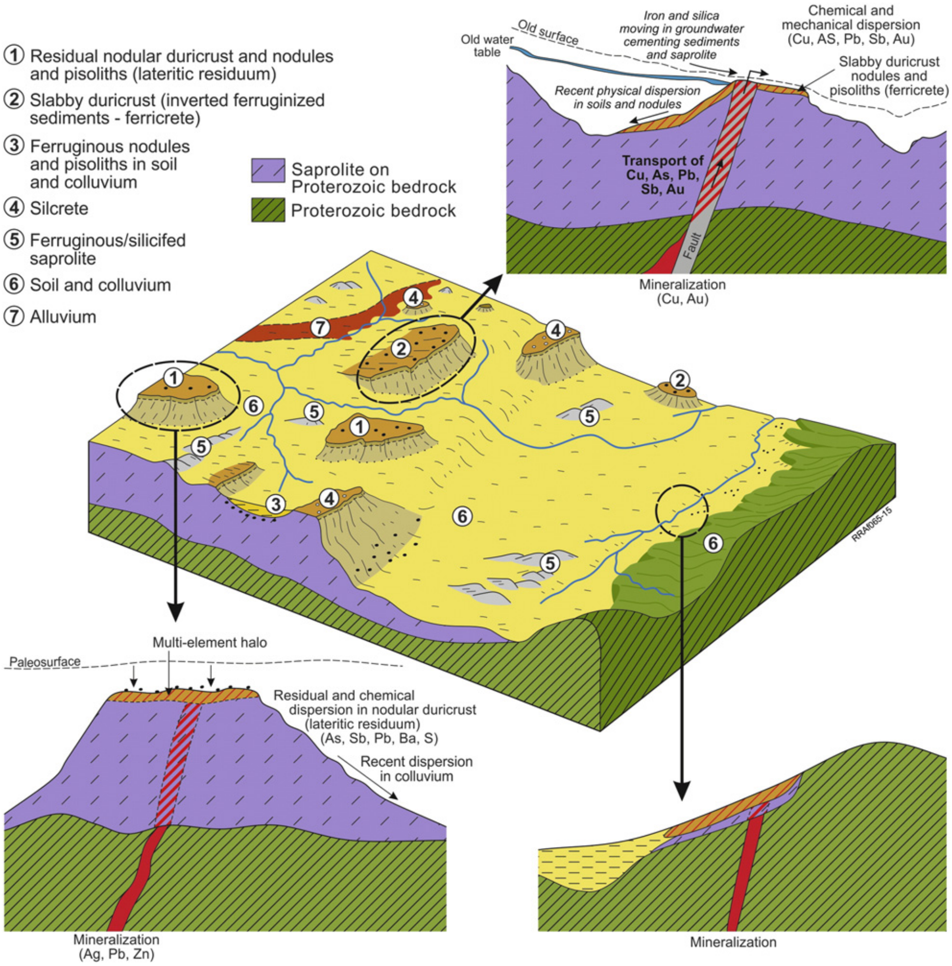

Fig. 24. Dispersion model for base metal deposits in dissected paleolandsurface developed on Proterozoic bedrock. Three situations are depicted.

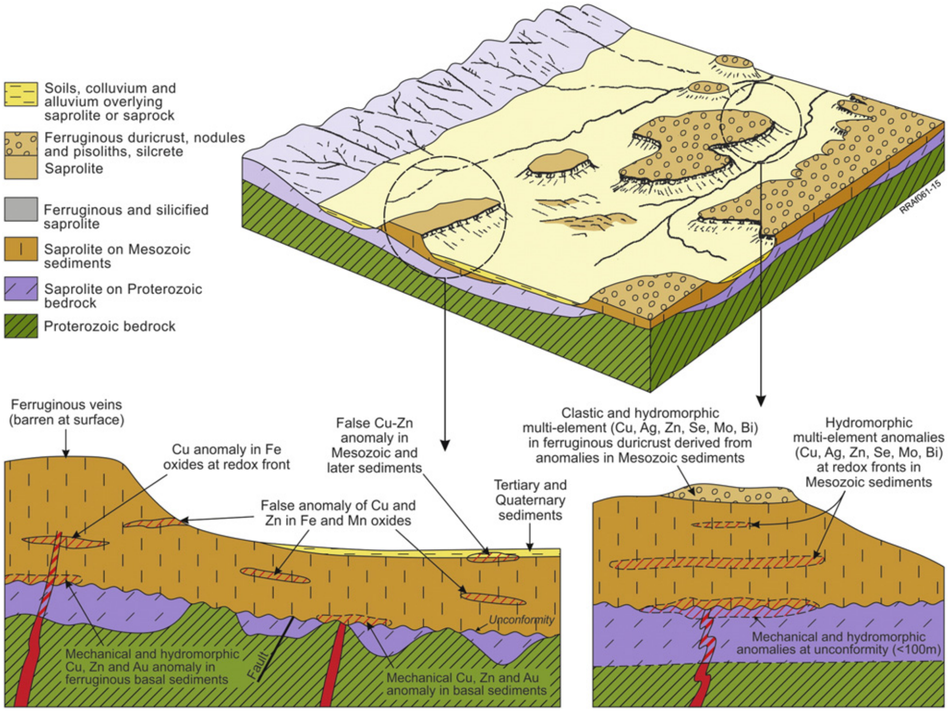

Fig. 25. Dispersion models for base metals in cover sediments, indicating a range of significant and false anomalies (Modified after Anand et al., 1997).

Acknowledgements

Industry members of Australian Mineral Industries Research Association Project P417 are thanked for their financial and logistical support over its three-year period, without which this research project would not have been possible. They also provided access to exploration sites and data; project geologists and staff provided hospitality and critical discussions. Support from Cooperative Research Centre for Landscape Environments and Mineral Exploration (CRC LEME) is gratefully acknowledged. Sample preparation was by Wayne Maxwell. Thin and polished sections were prepared by Ray Blitz. XRD analysis, SEM and electron microprobe studies were done by Michael Hart and Bruce Robinson. Diagrams were drafted by Angelo Vartesi. All this assistance is acknowledged with appreciation. The manuscript benefited greatly from detailed reviews and comments by Drs Ian Robertson and Robert Thorne.

References

Adshead, N.D., 1995. Geology, Alteration and Geochemistry of the Osborne Cu–Au Deposit, Cloncurry District, N.W. Queensland, Australia. Ph.D. Thesis, Department of Earth Sciences at James Cook University of North Queensland. (unpublished).

Adshead, N.D., Voulgaris, P., Muscio, V.N., 1998. Osborne copper-gold deposit. In: Berkman, D.A., Mackenzie (Eds.), Geology of Australia and Papua New Guinean Mineral Deposits. The Australasian Institute of Mining and Metallurgy, Melbourne, pp. 793–800.

Agnew, P.D., 2005. Century Zn–Pb–Ag deposit, Northwest Queensland. In: Butt, C.R.M., Robertson, I.D.M., Scott, K.M., Cornelius, M. (Eds.), Regolith Expression of Australian Ore Systems. CRC LEME, Perth, pp. 132–134.

Ahmad, M., Wygralak, A.S., 1990. Murphy inlier and environs — regional geology and mineralisation. In: Hughes, F.E. (Ed.), Geology of the Mineral Deposits of Australia and Papua New Guinea. The Australian Institute of Mining and Metallurgy 14, pp. 819–826.

Alcock, P.J., Lee, M.F., 1974. Aspects of geology and exploration of the Lady Loretta Pb–Zn–Ag deposit, northwest Queensland. The Australian Institute of Mining and Metallurgy Northwest Queensland Branch, Regional Meeting August 1974, pp. 207–215.

Anand, R.R., 2001. Evolution, classification and use of ferruginous regolith materials in exploration, Yilgarn Craton. Geochem. Explor. Environ. Anal. 1, 221–236.

Anand, R.R., Paine, M., 2002. Regolith geology of the Yilgarn Craton, Western Australia: implications for exploration. Aust. J. Earth Sci. 49, 1–163.

Anand, R.R., Butt, C.R.M., 2010. A guide for mineral exploration through the regolith in the Yilgarn Craton. Aust. J. Earth. Sci. 57, 1015–1114.

Anand, R.R., Robertson, I.D.M., 2012. Role of mineralogy and geochemistry in forming anomalies on interfaces and in areas of deep basin cover-implications for exploration. Geochem.: Explor. Environ. Anal. 12, 45–66.

Anand, R.R., Phang, C., Wilford, J.R., Wildman, J.E., Shu, Li, Robertson, I.D.M., Munday, T.J., 1996. Regolith-landscape characteristics, evolution and regional synthesis of the Mt Isa region—progress report. CSIRO Division of Exploration and Mining Restricted Report 158R (130 pp. (Reissued as Open File Report 125, CRC LEME, Perth, 2002)).

Anand, R.R., Fraser, S.J., Jones, M.R., Shu, Li, Munday, T.J., Phang, C., Robertson, I.D.M., Scott, K.M., Vasconcelos, P., Wildman, J.E., Wilford, J., 1997. Geochemical exploration in regolith dominated terrains, North Queensland. CRC LEME Restricted Report 63R (142 pp. (Reissued as Open File Report 120, CRC LEME, Perth, 2002)).

Baker, T., 1994. The geology of the Eloise Copper-Gold deposit, NW Queensland, Australia. Proceedings of the Australasian Institute of Mining and Metallurgy Annual Conference. Darwin, pp. 109–204.

Betts, P.G., Giles, D., Mark, G., Lister, G.S., Goleby, B.R., Ailleres, L., 2006. Synthesis of the Proterozoic evolution of the Mount Isa Inlier. Aust. J. Earth Sci. 53, 187–211.

Birot, P., 1956. Morphologie Structurale. Press University of France, Paris.

Blake, D.H., 1987. Geology of the Mount Isa Inlier and environs, Queensland and Northern Territory. BMR J. Geol. Geophys. 225 (83 pp.).

Blake, D.H., Stewart, A.J., 1992. Stratigraphic and tectonic framework, Mount Isa Inlier. Detailed Studies of the Mount Isa Inlier 243. AGSO Bulletin, pp. 1–11.

Blake, D.H., Jaques, A.L., Donchak, P.J.T., 1984. Selwyn Region Queensland-1:100 000 geological map commentary. BMR Australia, (29 pp.)

Blake, D.H., Etheridge, M.A., Page, R.W., Stewart, A.J., Williams, P.R., Wyborn, L.A.I., 1990. Mount Isa Inlier — regional geology and mineralisation. In: Hughes, F.E. (Ed.), Geology of the Mineral Deposits of Australia and Papua New Guinea. The Australian Institute of Mining and Metallurgy, pp. 915–925.

Bourman, R.P., 1993. Perennial problems in the study of laterite: A review. Aust. J. Earth Sci. 40, 387–401.

Butt, C.R.M., 1985. Granite weathering and silcrete formation on the Yilgran Block, Western Australia. Aust. J. Earth Sci. 32, 415–432.

Butt, C.R.M., 1995. Geochemical exploration for base metals in deeply weathered terrain, in: Ho, S.E and Amann, W.J. (Eds.), Recent developments in base metal geology and exploration Bulletin 16, Australian Institute of Geoscientists, Sydney, pp. 17–31. (Also published in T.F. McConaghy, T.F. and McInnes, B.A. (Eds.), Copper-zinc massive sulphide deposits in Western Australia. CSIRO Explores 2, CSIRO Exploration and Mining, Melbourne pp. 81–101.

Butt, C.R.M., 2005. Geochemical dispersion, process and exploration models. In: Butt, C.R.M., Robertson, I.D.M., Scott, K.M., Cornelius, M. (Eds.), Regolith Expression of Australian Ore Systems. CRC LEME, Perth, pp. 81–104.

Butt, C.R.M., Zeegers, H. (Eds.), 1992. Regolith exploration geochemistry in tropical and subtropical terrainsHandbook of Exploration Geochemistry 4. Elsevier, Amsterdam (607 pp.).

Carr, G.R., 1984. Primary geochemical and mineralogical dispersion in the vicinity of the Lady Loretta Zn–Pb–Ag deposit, Northwest Queensland. J. Geochem. Explor. 22, 217–238.

Conaghan, E.L., Hannan, K.W., Tolman, J., 2005. Mt Isa Cu and Pb–Zn–Ag deposits, Northwest Queensland. In: Butt, C.R.M., Robertson, I.D.M., Scott, K.M., Cornelius, M. (Eds.), Regolith Expression of Australian Ore Systems. CRC LEME, Perth, pp. 180–183.

Connah, T.H., Hubble, G.D., 1960. Laterites. In: Hill, D., Denmead, A.K. (Eds.), The Geology of Queensland. J. Geol. Soc. Aust. 7, pp. 373–386.

Cox, R., Curtis, R., 1977. The discovery of the Lady Loretta zinc-lead-silver deposit, northwest Queensland, Australia — a geochemical exploration case history. In: Butt, C.R.M., Wilding, I.G.P. (Eds.), Geochemical Exploration, 1976. J. Geochem. Explor. 8, pp. 189–202.

Day, R.W., Whitaker, W.G., Murray, C.G., Wilson, I.H., Grimes, K.G., 1983. Queensland Geology. A compilation volume to the 1:2,500 000 scale map (1975). Geological Survey of Queensland Publication, pp. 183–194.

Dell, M., 1997. Regolith-landform-Mt Isa geodynamic transect. CRC LEME Restricted Report 451R (67 pp. (Reissued as Open File Report 138, CRC LEME, Perth, 2002)).

Derrick, G.M., 1982. A Proterozoic rift zone at Mount Isa, Queensland, and implications for mineralisation. BMR J. Aust. Geol. Geophys. 7, 81–92.

Drummond, B., 1996. AGCRC Mt Isa Geodynamic Transect. (unpublished).

Edward, R.G., 1978. Little Eva Cu prospect, Northwest Queensland M.F. 3072, M. 25 5670, 5694, 5695, 5699, Exploration 78, CRA Exploration Internal Report no 9599 (unpublished).

Etheridge, M.A., Rutland, R.W.R., Wyborn, L.A.I., 1987. Orogenesis and tectonic processes in the Early to Middle Proterozoic of northern Australia. Am. Geophys. Union Geodyn. Ser. 17, 131–147.

Geological Survey of Queensland, 2011. North-west Queensland Mineral and Energy Province report. Queensland Department of Employment, Economic Development and Innovation, Brisbane.

Greig, D.D., 1983. Primary and secondary dispersion at the Teutonic Bore deposit. In: Smith, B.H. (Ed.), Geochemical Exploration In The Eastern Goldfields Region Of Western Australia: Tour Guide. Association of Exploration Geochemists, Perth, pp. 73–87.

Grimes, K. G., 1972. The Mesozoic and Cainozoic geology of the Cloncurry 1:250000 Sheet area, Queensland. BMR Australia, Record 11972/57.

Grimes, K.G., 1979. The stratigraphic sequence of old land surfaces in Northern Queensland. BMR J. Geol. Geophys. 4, 33–46.

Jackson, M.J., Scott, D.L., Rawlings, D.J., 2000. Stratigraphic framework for the Leichhardt and Calvert super basins: review and correlations of the pre-1700 Ma successions between Mt Isa and McArthur River. Aust. J. Earth Sci. 47, 381–403.

Johnston, C., Griffin, W.L., Giblin, A.M., Rutherford, N.F., Ryan, C.G., Suter, G.F., 1993. Sirogas. AMIRA Project 381. Final Report. CSIRO Division of Exploration Geoscience, Restricted Report 368R (60 pp.).

Jones, M., 1997. Alluvial landscapes of the North Kennedy Gap area, Mt Isa district, Queensland. CRC LEME Restricted Report 48R (37 pp. (Reissued as Open File Report 130, CRC LEME, Perth, 2002)).

Lawrance, L.M., 1993. Review of geochemical exploration strategies investigated at the Osborne Deposit, Trough Tank, North-West Queensland. Confidential Report to Placer Exploration Limited. (unpublished).

Lawrance, L.M., 1996. Review and interpretation of multi-element geochemistry, Osborne Deposit, Queensland, Australia: Assessment for regional geochemical exploration in buried terrain. February 1996 (Confidential Report to Placer Exploration Limited). 58 pp. (unpublished).

Lawrance, L.M., 1999. Multi-element dispersion in Mesozoic basin sediment over the Osborne Deposit, northern Queensland, Australia: implications for regional geochemical exploration in buried terrain. AIG Bull. 28, 73–81.

Munday, T., 2008. Regolith geophysics. In: Scott, K.M., Pain, C.F. (Eds.), Regolith Science. Springer, pp. 219–250.

Munro, D.C., McQueen, K.G., Stockton, I.R., 2005. CSA Cu–Zn–Pb deposit, Cobar district, New South Wales. In: Butt, C.R.M., Robertson, I.D.M., Scott, K.M., Cornelius, M. (Eds.), Regolith Expression of Australian Ore Systems. CRC LEME, Perth, pp. 135–137.

Nicolls, O.W., Provan, D.M.J., Cole, M.M., Tooms, J.S., 1965. Geobotany and geochemistry in mineral exploration in the Dugald River Area, Cloncurry District, Australia. Trans. Inst. Min. Metall. 74, 695–799.

Paktunc, A.D., Dave, N.K., 2002. Formation of secondary pyrite and carbonate minerals in the Lower Williams Lake tailings basin, Elliot Lake, Ontario, Canada. Amer. Miner. 87, 593–602.

Papp, 2002. Geophysical and Remote Sensing Methods for Regolith Exploration. CRC LEME Open File Report 144 (115 pp.).

Perry, R.A., Christian, C.S., 1954. Vegetation of the Barkly region. CSIRO Australia. Land Res. Ser. 3, 78–112.

Phang, C., Munday, T.J., Wildman, J.E., 1997a. Regolith-landform relationships and geochemical dispersion around Tringadee and Brumby prospects. CRC LEME Restricted Report 59R (67 pp. (Reissued as Open File Report 140, CRC LEME, Perth, 2002)).

Phang, C., Anand, R.R., Wildman, J.E., Robertson, I.D.M., Shu, Li, 1997b. Atlas of regolith materials, North Queensland. CRC LEME Restricted Report 66R (87 pp. (Reissued as Open File Report 136, CRC LEME, Perth, 2002)).

Robertson, I.D.M., Phang, C., Munday, T.J., 1995. Regolith geology and soil geochemistry of the Little Eva copper prospect, Quamby district, Northwest Queensland. CSIRO Restricted Report 128R (46 pp. (Reissued as Open File Report 123, CRC LEME, Perth, 2002)).

Robertson, I.D.M., Shu, Li, Wildman, J.E., 1997. Geochemical dispersion around the Maronan Cu–Au prospect, Northeast Queensland. CRC LEME Restricted Report 57R (19 pp. (Reissued as Open File Report 134, CRC LEME, Perth, 2002)).

Rutherford, N.F., 2002a pSirogas and selected leach geochemistry over deep mineralisation, Osborne Mine, NW Queensland. Confidential Report to Osborne Mines Limited. 40 pp. (unpublished).

Rutherford, N.F., 2002b. Confidential Report to Osborne Mines Limited covering regolith development, pSirogas, Regoleach and various other geochemical methods at Osborne. 36 pp. (unpublished).

Rutherford, N.F., Lawrance, L.M., Sparks, G., 2005. Osborne Cu–Au deposit, Cloncurry district, Northwest Queensland. In: Butt, C.R.M., Robertson, I.D.M., Scott, K.M., Cornelius, M. (Eds.), Regolith Expression of Australian Ore Systems. CRC LEME, Perth, pp. 380–382.

Scott, K.M., 1987. The mineralogical distribution of pathfinder elements in gossans derived from dolomitic shale-hosted Pb–Zn deposits, northwest Queensland, Australia. Chem. Geol. 57, 395–414.

Scott, P.A., Meyer, A., 1993. Review of Geochemical Exploration Strategies. Investigations at the Osborne Deposit, Trough Tank, NW Qld. Placer Exploration Ltd. Internal report on orientation geochemistry, Osborne pit area. Report Q14/93. (unpublished).

Senior, B.R., Mond, A., Harrison, P.L., 1978. Geology of the Eromanga Basin. BMR Geol. Geophys. Bull. 167 (102 pp.).

Shu, Li, Robertson, I.D.M., 1997. Surficial geology around the Eloise area and dispersion into Mesozoic cover from the Eloise mineralisation. CRC LEME Restricted Report 56R (71 pp. (Reissued as Open File Report 135, CRC LEME, Perth, 2002)).

Smith, R.E., Perdrix, J.L., 1983. Pisolitic laterite geochemistry in the Golden Grove massive sulphide district, Western Australia. J. Geochem. Explor. 18, 131–164.

Smith, R.E., O'Connell, A.M., Edwards, R.G., 1976. Freddie Well Zn–Cu deposit. In: Smith, R.E., Bettenay, E. (Eds.), Superficial mineral deposits and exploration geochemistry. Yilgarn Block, Western Australia: XXV International Geological Congress, Excursion Guide 41C, pp. 44–50.

Smith, R.E., Anand, R.R., Alley, N.F., 2000. Use and implications of palaeoweathering surfaces in mineral exploration. Ore Geol. Rev. 16, 185–204.

Stewart, G.A., 1954. Geomorphology of the Barkly region. In: Christian, C.S. (Ed.), Survey of the Barkly region, Northern Territory and Queensland, 1947–48. CSIRO Australia, Land Research Series 3, p. 113-149.

Stewart, A.D., Anand, R.R., 2014. Anomalies in insect nest structures at the Garden Well gold deposit: investigation of mound-forming termites, subterranean termites and ants. J. Geochem. Explor. 140, 77–86.

Taylor, G.F., Scott, K.M., 1982. Evaluation of gossans in relation to lead–zinc mineralisation in the Mt Isa Inlier, Queensland. BMR Geol. Geophys. Bull. 7, 158–159.

Tullemans, F.J., Agnew, P., Voulgaris, P., 2001. The role of geology and exploration within the mining cycle at the Osborne mine, NW Queensland. In: Edwards, A.C. (Ed.), Mineral resources and ore estimation - the AusIMM guide to good practice. The Australasian Institute of Mining and Metallurgy, Melbourne, pp. 157–168.

Twidale, C.R., 1966. Geomorphology of the Leichhardt–Gilbert area of Northwest Queensland. Land Research Series 16. CSIRO, Melbourne ((56 pp.)).

Vasconcelos, P., 1998. Geochronology of weathering in the Mt Isa and Charters Towers regions, Northern Queensland. CRC LEME Restricted Report 452R (184 pp. (Reissued as Open File Report 139, CRC LEME, Perth, 2002)).

Vasconcelos, P.M., Knesel, K.M., Cohen, B.E., Heim, J.A., 2008. Geochronology of the Australian Cenozoic: a history of tectonic and igneous activity, weathering, erosion, and sedimentation. Aust. J. Earth Sci. 55, 865–914.

Wildman, J.E., 1997. The geochemical discrimination of mineralised and barren ironstones from the Selwyn Au–Cu deposit, NW Queensland. CRC LEME Restricted Report 35R (21 pp. (Reissued as Open File Report 128, CRC LEME, Perth, 2002)).

Wilford, J., 1997a. Regolith-landform characteristics, evolution and implications for mineral exploration over the Buckely River–Lady Loretta region, Mt Isa. CRC LEME Restricted Report 47R (89 pp. (Reissued as Open File Report 132, CRC LEME, Perth, 2002)).

Wilford, J., 1997b. Regolith-landform characteristics, evolution and implications for mineral exploration over the Selwyn region, Mt Isa. CRC LEME Restricted Report 44R (83 pp. (Reissued as Open File Report 131, CRC LEME, Perth, 2002)).

Wilkin, R.T., Barnes, H.L., 1997. Formation of framboidal pyrite. Geochim. Cosmochim. Acta 61, 323–339.

Williams, J.K., 1995. The petrography, stratigraphy and structure of the Osborne mine sequence: Evidence for the origin of the banded iron-formation-hosted Cu–Au deposits in the Soldiers Cap Group, northwest Queensland. M.Sc. Thesis, Macquarie University. (unpublished).

Withnall, I.W., Hutton, L.J., 2013. Chapter 2 North Australian Craton. In: Jell, P.A. (Ed.), Geology of Queensland. Geological Survey of Queensland, Brisbane, pp. 23–111.