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REGOLITH-LANDFORM RELATIONSHIPS IN THE BOTTLE CREEK ORIENTATION STUDY, WESTERN AUSTRALIA

H.M. Churchward, I.K. Butler and R.E. Smith

CRC LEME OPEN FILE REPORT 51

December 1998

(CSIRO Division of Exploration Geoscience Report 247R, 1992.
Second impression 1998)

CRC LEME is an unincorporated joint venture between The Australian National University, University of Canberra, Australian Geological Survey Organisation and CSIRO Exploration and Mining, established and supported under the Australian Government's Cooperative Research Centres Program.

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Headquarters: CRC LEME c/o CSIRO Exploration and Mining, Private Bag, PO Wembley, Western Australia, 6014

RESEARCH ARISING FROM CSIRO/AMIRA REGOLITH GEOCHEMISTRY PROJECTS 1987-1993

In 1987, CSIRO commenced a series of multi-client research projects in regolith geology and geochemistry which were sponsored by companies in the Australian mining industry, through the Australian Mineral Industries Research Association Limited (AMIRA). The initial research program, "Exploration for concealed gold deposits, Yilgarn Block, Western Australia" (1987-1993) had the aim of developing improved geological, geochemical and geophysical methods for mineral exploration that would facilitate the location of blind, buried or deeply weathered gold deposits. The program included the following projects:

P240: Laterite geochemistry for detecting concealed mineral deposits (1987-1991). Leader: Dr R.E. Smith.
Its scope was development of methods for sampling and interpretation of multi-element laterite geochemistry data and application of multi-element techniques to gold and polymetallic mineral exploration in weathered terrain. The project emphasised viewing laterite geochemical dispersion patterns in their regolith-landform context at local and district scales. It was supported by 30 companies.

P241: Gold and associated elements in the regolith - dispersion processes and implications for exploration (1987-1991). Leader: Dr C.R.M. Butt.
The project investigated the distribution of ore and indicator elements in the regolith. It included studies of the mineralogical and geochemical characteristics of weathered ore deposits and wall rocks, and the chemical controls on element dispersion and concentration during regolith evolution. This was to increase the effectiveness of geochemical exploration in weathered terrain through improved understanding of weathering processes. It was supported by 26 companies.

These projects represented "an opportunity for the mineral industry to participate in a multi-disciplinary program of geoscience research aimed at developing new geological, geochemical and geophysical methods for exploration in deeply weathered Archaean terrains". This initiative recognised the unique opportunities, created by exploration and open-cut mining, to conduct detailed studies of the weathered zone, with particular emphasis on the near-surface expression of gold mineralisation. The skills of existing and specially recruited research staff from the Floreat Park and North Ryde laboratories (of the then Divisions of Minerals and Geochemistry, and Mineral Physics and Mineralogy, subsequently Exploration Geoscience and later Exploration and Mining) were integrated to form a task force with expertise in geology, mineralogy, geochemistry and geophysics. Several staff participated in more than one project. Following completion of the original projects, two continuation projects were developed.

P240A: Geochemical exploration in complex lateritic environments of the Yilgarn Craton, Western Australia (1991-1993). Leaders: Drs R.E. Smith and R.R. Anand.
The approach of viewing geochemical dispersion within a well-controlled and well-understood regolith-landform and bedrock framework at detailed and district scales continued. In this extension, focus was particularly on areas of transported cover and on more complex lateritic environments typified by the Kalgoorlie regional study. This was supported by 17 companies.

P241A: Gold and associated elements in the regolith - dispersion processes and implications for exploration. Leader: Dr. C.R.M. Butt.
The significance of gold mobilisation under present-day conditions, particularly the important relationship with pedogenic carbonate, was investigated further. In addition, attention was focussed on the recognition of primary lithologies from their weathered equivalents. This project was supported by 14 companies.

Although the confidentiality periods of the research reports have expired, the last in December 1994, they have not been made public until now. Publishing the reports through the CRC LEME Report Series is seen as an appropriate means of doing this. By making available the results of the research and the authors' interpretations, it is hoped that the reports will provide source data for future research and be useful for teaching. CRC LEME acknowledges the Australian Mineral Industries Research Association and CSIRO Division of Exploration and Mining for authorisation to publish these reports. It is intended that publication of the reports will be a substantial additional factor in transferring technology to aid the Australian Mineral Industry.

This report (CRC LEME Open File Report 51) is a Second impression (second printing) of CSIRO, Division of Exploration Geoscience Restricted Report 247R, first issued in 1992, which formed part of the CSIRO/AMIRA Project P240.

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ABSTRACT

Regolith-landform Relationships

A framework of regolith stratigraphy and landforms was established for the area surrounding the Bottle Creek gold deposits, some 200 km north west of Kalgoorlie, as a basis for geochemical studies. An early phase of broad reconnaissance provided several sites at which the regolith was examined in detail and the landform-regolith relationships were defined. A regolith-landform map (1:10,000 scale) was produced for the upper Bottle Creek catchment. To test the findings of the detailed investigation a study of the regolith was carried out over an area of approximately 450 km^2 surrounding the detailed study at a reconnaissance scale. A 1:25,000 map of this was produced.

Several well-defined regolith types were identified by these studies which relate, directly or indirectly, to a deeply weathered mantle and to its modification by landform processes. These regolith materials were either horizons of a deep profile developed by *in situ* weathering of basement rock or of transported debris, derived from this profile by erosion. Generally they form extensive surface and subsurface bodies so that the regolith, at any particular location, commonly comprises several strata.

The nature of the regolith stratigraphy is strongly related to the landforms with which they are associated so that a framework of landform regimes provides a useful concept for considering the regolith in this area. Thus units of relatively stable, deeply weathered tracts were recognized as relics of a once more extensive landsurface that has been fragmented by fluvial action and replaced by erosional and depositional regimes.

At Bottle Creek, regolith types associated with the ancient, deeply weathered landsurface (the residual regimes) are mainly various expressions of the (upper) ferruginous horizon of the laterite profile, along with the mottled zone, the pallid saprolite and the saprock. Several transported regolith types, of colluvial and alluvial origin, were recognised in both erosional and depositional regimes.

Ferruginous Horizon(s)

The ferruginous horizon comprises various types of lateritic residuum but the more common are duricrusts having abundant lateritic pisoliths, generally with yellow-brown skins, set in a brown to red-brown clayey matrix. At depth this material merges with the more ductile clays of the mottled zone. In addition large irregular to lensoid bodies occur in the upper part of the regolith. The rock-like nature of these masses contrasts with the surrounding brittle, pisolitic, lateritic residuum referred to above. Some of these masses are Fe-rich, having a dusky red matrix and dark brown to black nodules that can be magnetic. Such materials have been placed in the broad class of Fe-rich duricrusts. Another rock-like mass is diffusely mottled brown to pale brown and some have vermiform voids. These can be variously classified as ferruginous saprolite, vermiform duricrust or fragmentary duricrust. Other Fe-rich bodies in the upper regolith are goethite-rich pods which generally have box-work textures. At Bottle Creek, these gossan-like bodies occur close to a carbonaceous, previously pyritic shale in the underlying parent greenstone sequence.

Residual Regimes

The residual regimes at Bottle Creek form gently undulating tracts that are extensive on the divide between the Raeside and Ballard drainages. The principal type site for the regolith stratigraphy of this regime is at the Emu test pit, within this undulating tract. Most crests in this terrain are slightly stripped with consequent exposure of an array of ferruginous materials from the upper

parts of the regolith. These are predominantly ferruginous saprolite but there are also some pisoliths and pieces of Fe-rich duricrust, as well as clay and sand released by weathering. Such materials contribute to the colluvial mantle that extend downslope from the crest, covering the pisolitic, lateritic residuum; the latter forming the more extensive substratum of the residual regime. Whilst on the mid- and upper slopes, colluvium is less than 1 m thick; beneath the lower slopes and local drainage floors, the colluvium is as much as 4 m thick. The lag composition also varies with topographic position; coarse fragments of ferruginous saprolite dominate the crests. Some yellow-brown cutan-coated pisoliths also occur here and are generally indicative of some subcropping pisolitic, lateritic residuum. On surfaces, down-slope from these crests, lags of dark brown to black granules are dominant; there is little quartz or lithic material. The soils are acid and have developed in a fine, sandy loam colluvium which has granules of similar composition to the lag. Hardpans appear at a depth of 1 m and continue for depths of from 3 to 8 m.

Erosional Regimes

The landforms and the regolith types in the erosional regimes present a more complex picture reflecting active geomorphic processes. Deeper units of the weathered mantle, as well as country rock, are exposed. This regolith is dominated by a shallow, generally calcareous soil, and a lag of lithic fragments; there are outcrops of vein quartz and goethitic Fe-segregations. Gentle slopes occur as pediments below low breakaways. These slopes are mantled by acid red earths, developed on colluvium, and have a lag dominated by coarse, ferruginous saprolite, lithic fragments and quartz. Erosion is active in such areas.

Depositional Regimes

The most extensive depositional tracts are mantled by a friable clay, being an alluvium of sheet flood origin; acid red earths have developed on this material. The lags are dark brown to black granules of mixed origin, with medium sized (2-4 cm) lithic and ferruginous saprolite fragments, and quartz clasts, as a minor, though characteristic component. This alluvium overlies pallid saprolite and saprock at a depth of from 1 to 1.5 m but it may also be found mantling pockets of pisolitic lateritic residuum or coarse deposits in paleochannels. Some of the depositional tracts are being further modified by erosion resulting in landsurfaces having regolith types comparable with those in other erosional regimes.

Regolith Evolution and a Framework for Geochemical Dispersion

The topographic relationships and regolith stratigraphies revealed by this study indicate a polyphase, multiprocess history. Many of the regolith types resulting from this complex array of processes, have a distinctive pattern. The residual regimes at Bottle Creek are dominated by a regolith that is the result of intense *in situ* weathering, some of which is transported and deposited by local colluviation. These areas have had a relatively stable geomorphic history. In contrast, depositional regimes here represent areas that have received fluvial detritus from much further afield and this material varies from highly weathered to relatively fresh and is generally of diverse lithological origin. Prior to deposition, these areas can have been subjected to widespread, though incomplete, stripping of the more weathered regolith types. The regolith in erosional regimes is, in detail, complex with exposure of a variety of variably weathered lithologies. Understanding this general geomorphic framework assists our appreciation of geochemical dispersion and thus it provides a basis for the developing sampling strategies for this weathered terrain.

CONTENTS

1.0 PROJECT LEADER'S PREFACE

1.1 General

Fundamental building blocks of the CSIRO/AMIRA Laterite Geochemistry Project are four substantial, district-scale, multidisciplinary, geochemical, orientation studies at Mt. Gibson, Bottle Creek, Lawlers, and Boddington (Figure 1). In each case geochemical dispersion arising from concealed gold deposits, is studied by first understanding the regolith, landform and bedrock relationships, not only within the immediate ore environments but also of the district within which these deposits lie.

The Bottle Creek gold deposits were discovered in 1983 by the Electrolytic Zinc Company of Australia Limited and are amongst the few 'greenfield' discoveries which resulted from the 1980's gold boom (1979 to 1988). Discovery of these deposits resulted from a sequence of exploration activities by the company including strategic planning, geological concepts of ore genesis, and the use of multi-element surface geochemistry of lateritic pisoliths and nodules, initially collected with an electromagnet, at 1 km-spacing (Legge *et al.,* 1987).

Bottle Creek was chosen for an orientation study within the Laterite Geochemistry Project, because of the importance of multi-element geochemistry in its discovery. Here a large tract of prospective greenstones are mantled by laterite, alluvium and colluvium. The Bottle Creek area is also the focus of some other research activity within the CSIRO/AMIRA Yilgarn Research Programme: gossan and saprolite profiles have been studied within the Weathering Process Project (P241) and the application of remote sensing to mineral exploration within the WA Remote Sensing Project (P243). Unweathered bedrock from the ore environments has been studied by Binns, (1988). This, coupled with support by the tenement holders, Electrolytic Zinc Co Ltd/Geopeko, the funding from sponsoring companies through AMIRA, and the exposures in the open pit as mining progressed have provided excellent research opportunities upon which this study is based.

1.2 Objectives of the Bottle Creek Orientation Study

The objectives were to establish a well-controlled regolith-landform framework for the geochemical orientation study of the gold deposits, and surrounding surficial regolith materials.

1.3 Attributes of the Bottle Creek District

The following attributes were important in choosing Bottle Creek for an orientation study:

- the area contained Au deposits, discovery of which used multi-element geochemistry of lateritic pisoliths/nodules;
- various ferruginous gravels occur extensively, including lateritic nodules and pisoliths;
- the laterite profiles show various degrees of truncation and burial;
- the area was little disturbed at the commencement of the study.

1.4 Components of Research at Bottle Creek

Multi-disciplinary research carried out at Bottle Creek, within the Laterite Geochemistry Project, has the following components:

- District-scale regolith-landform framework;
- Regolith-landform relationships of the mine environments;
- Regolith stratigraphy at local and district scales;
- Classification of regolith units;
- Nodule clasts and pisolith clast types, classification, origin;
- Orientation geochemistry focussed upon regolith units above saprolite;
- Siting and bonding of elements of interest within geochemical anomalies;
- Surficial dispersion processes;
- Reference data sets of specific regolith units;
- Multivariate geochemical data interpretation;
- Generalized models of regolith evolution and geochemical dispersion.

This report presents the research carried out by the Laterite Geochemistry Group, covering several of the components listed above. It is focussed upon regolith-landform relationships at district and local scales, and had established the framework within which findings on geochemical dispersion will be presented in a subsequent report.

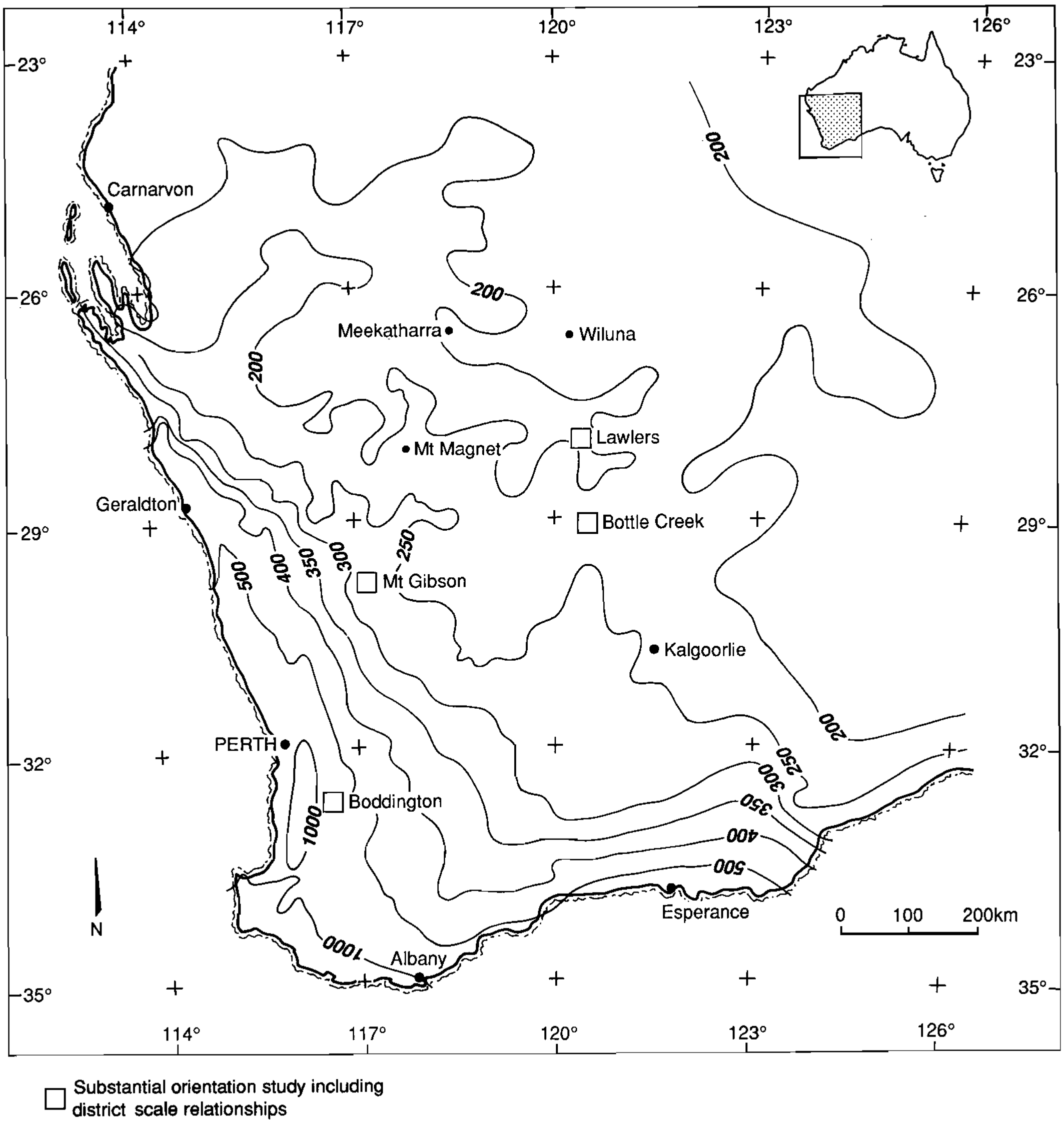


Figure 1. **Location of the principal geochemical orientation districts of the CSIRO/AMIRA** Laterite Geochemistry Project P240.

2.0 INTRODUCTION

2.1 Location and Access

The Bottle Creek gold deposits, held by Norgold Limited, are located 210 km NW of Kalgoorlie at 120°27'E, 29°10'S, on the MENZIES 1:250,000 sheet (SH 51-3). Access is by a gravel road (Figure 2) and, within the mining and exploration tenements, along grid lines and fences.

2.2 Climate

The Bottle Creek area has an arid climate with a recorded average annual rainfall of 180 to 190 mm, much of which falls between January and April and results from convectional summer storms. Rainfall variability is very high. Some heavy falls come from rain-bearing depressions that are related to decaying cyclonic activity. Spring (Sept-Nov) is the driest season; summers are hot to very hot; winters are cool and frosts are common.

2.3 Vegetation

The vegetation is dominated by mulga (*Acacia aneura*) and by various types of poverty bush and turpentine (*Eremophila spp*). On the major depositional surfaces, *mulga* communities have the structure of a scrub but there are tall shrub communities on the steeper slopes and breakaways. Thickets of eucalypts grow on erosional tracts but there are scattered trees on the sandy, gravelly soils of long gentle slopes. Isolated kurrajong trees (*Brachychiton sp*) occur on a variety of landsurfaces.

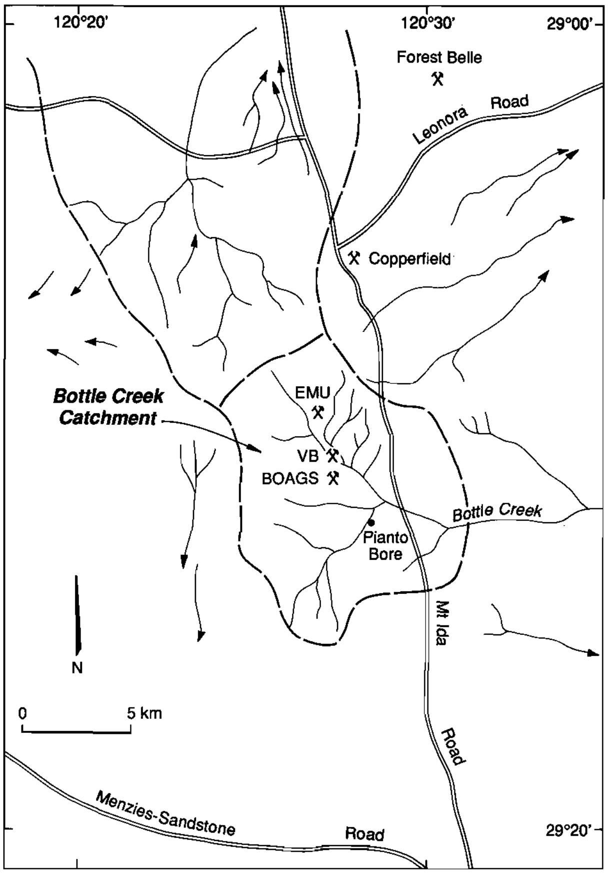


Figure 2. District location of the Bottle Creek mining project.

3.0 GEOLOGICAL SETTING

3.1 Regional Bedrock Geology

The Bottle Creek gold deposits are located at the northwestern tip of the Mt. Ida Greenstone Belt (Figure 3), which is the most westerly greenstone sequence of the Kalgoorlie subprovince of the Western Australian Shield (Griffin 1990). The Mt Ida Greenstone Belt comprises a NNW striking, eastward dipping succession, surrounded by variably deformed adamellitic rocks (Menzies 1:250,000 map sheet, Kriewaldt, 1970). Facings suggest that the succession is youngest to the east. The western part of the belt, is marked by a laterally extensive sequence of banded iron formations and interspersed coarse grained mafic rocks. The remainder of the belt is dominated by high-magnesian basalts that are intercalated with interflow meta sediments (black shales and cherts). To the N a prominent metatholeiitic unit in the centre of the belt changes along strike to intensely sheared and brecciated black shales and felsic porphyries to the S. This is informally referred to as the Emu Complex, or Emu Formation, and is host to the mineralized zone. Metakomatiites are intercalated with high magnesian metabasalts in the eastern portion of the belt.

The regional foliation is subparallel to the bedding. Immediately east of Bottle Creek, in the Mt. Ida-Copperfield area, the greenstones are folded into a tight, south-plunging anticline with the Copperfield granite in its core. The eastern margin of the belt, the Mt. Ida lineament, shown by strong contrast and regional extent on airborne magnetic surveys, is regarded as a major crustal suture.

3.2 Local Bedrock Geology and Mineralisation

The Bottle Creek gold deposits are hosted by silicified, sulphidic, black shales in biotite-altered mafic metavolcanics, which are part of a high-magnesian metabasalt sequence. In areas of greater mineralisation, the volcanics and the ore zone itself, have been intruded by quartz-feldspar porphyry, which is now a quartz-sericite schist. The mineralized zone has been affected by strong potash and carbonate metasomatism and silicification.

The mineralized zones dip steeply and in places have been warped and cross faulted. They have undergone intense, ductile deformation followed by later, brittle deformation (Binns, 1988). There are two types of ore; one within the main mineralized zone and the other, a stockwork ore within the adjacent porphyries and altered volcanics.

Micron size gold (electrum) and a species of silver-bearing tetrahedrite are intimately associated with pyrite in the fresh ore zones. Sphalerite, pyrrhotite, arsenical pyrite, arsenopyrite and chalcopyrite have been recognized. A total of 908,273 tonnes of ore had been mined till November 1989, with an average grade of 2.25 g/t Au and 7.82 g/t Ag.

Legge *et al.* (1987) considered the Emu formation to be a volcanic-related, auriferous, exhalative horizon of sulphidic, graphitic shales, chert and felsite which now contains massive pyrite and pyrrhotite. They concluded that gold concentration took place during a period of strong deformation and intrusion by quartz-feldspar porphyry. On the other hand Binns (1988) suggested that the shale horizon, within the Emu Formation, is not an interflow sediment, but part of a zone of strong deformation and alteration in a basaltic sequence. Accordingly, it may be a previously unrecognized style of mineralisation in the greenstone sequences of the Yilgarn Block.

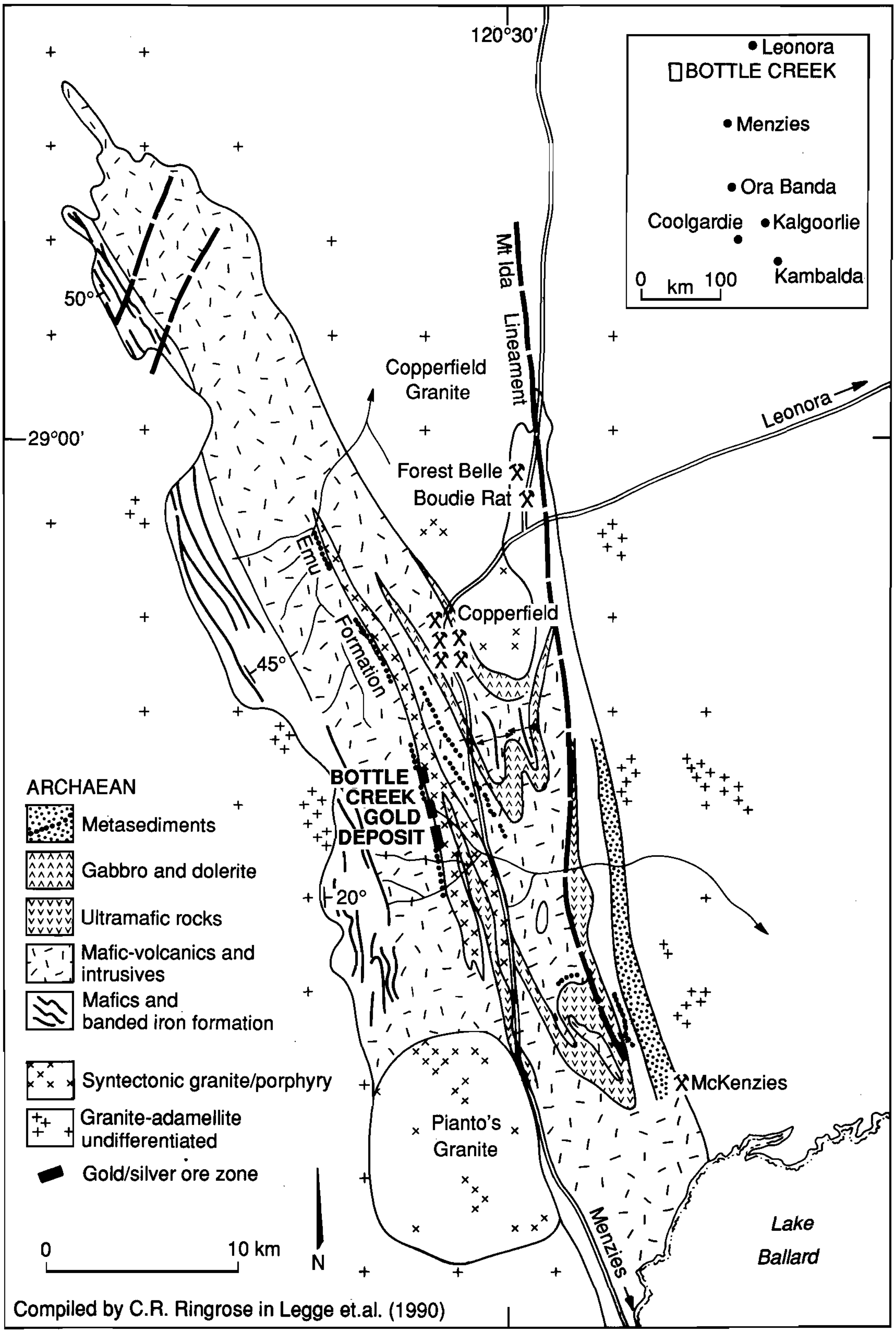


Figure 3. Bedrock geology of the Bottle Creek district.

4.0 LANDFORM AND REGOLITH SETTING

4.1 Introduction

The term regolith, first proposed by Merrill (1897), refers to the whole range of unconsolidated material that mantles the Earth's surface. Although "unconsolidated" is used in the original definition of regolith, indurated types, such as weathered crusts and others due to such processes as secondary enrichment and dehydration, are now included. Many regolith materials are the result of *in situ* weathering of the underlying rocks but others, such as alluvium and colluvium, have been transported. Thus the regolith is seen as a product of weathering and/or other geomorphic processes.

The terminology used in this report for regolith materials and the alphanumeric codes, such as LG206, LT103, etc., for regolith materials is in the Atlas of Fabrics of Microstructures (Anand *et al.*, 1989). Some of the terms used in this report are not yet included in this i.e. ferruginous saprolite, ferruginous lithic fragments and iron-stained lithic fragments. *Ferruginous saprolite* occurs *in situ*, as a modification of a kaolinite-dominated saprolite. This brown to very dark brown material is variably infused with Fe and can be mottled, commonly diffusely pale brown, light brown and light brownish yellow, some with sporadic pseudomorphs of individual mineral grains. Lithic fabrics textures are generally rare but are more common in *ferruginous lithic fragments*. Many ferruginous lithic fragments have a smooth, dark brown to black, matt to glossy surface, generally referred to as varnish. Some of these lithic types have only a brown Fe staining on the surface, generally over a saprock or unweathered rock interior. These are *iron-stained lithic fragments*.

Types of regolith at Bottle Creek include soil, lag, colluvium, alluvium, lateritic residuum, saprolite and saprock; siliceous hardpans (such as Wiluna hardpan) are widespread and there are also pockets of calcrete. In this report *lag* is used for the thin continuous to discontinuous mantle of stony material remaining on the land surface after removal of the fine fraction from the upper regolith type. Lag fragments range in size from fine granules to coarse cobbles. They can be derived from *in situ* outcrops of country rock or weathered crusts but more commonly they are the coarse fraction of colluvial and/or alluvial sheets after loss of the finer fraction by fluvial or aeolian action. Although lag can be regarded as reflecting a relatively stabilised surface, this is only temporary since any part of the lag can be submerged in fines from further up slope (or up wind). Where fluvial processes are active the lag may be entrained, along with other debris and moved further along the drainage.

Each regolith type can vary spatially and such changes can be gradual or sharp. This can be compared to facies change. An hypothetical weathering profile in Figure 4 shows the more common horizons and regolith types referred to in this report. The figure also uses terminology that has been standardized within the Laterite Geochemistry (P240) and Weathering Processes (P241) projects.

4.2 General Geomorphology

The Bottle Creek orientation area lies within the extensive plateau of southwestern Australia, referred to by Jutson (1934) as the Great Plateau of Western Australia, and as the Yilgarn Plateau by Jennings and Mabbutt (1977). It comprises very gently undulating uplands, interspersed with sheet flood plains, tributary to major regional valleys, that are in part occupied by extensive playa lakes. The low relief of this landscape is broken by sporadic strike ridges, many with northerly trends. Here local topographic complexities generally occur where the extensive, deep

weathered mantle has been modified by erosion. These erosional zones physiographically separate the gently undulating uplands from alluvial plains. Jutson (1934) referred to these uplands as portions of the "Old Plateau". He perceived a "New Plateau" developing as a consequence of the erosion of the "Old Plateau". However, in many parts of the Yilgarn, there are areas that could, within the content of the theory, be classified as the "Old Plateau", but are not clearly separated from the younger surface and merge with it, by way of long, gentle slopes, and, by burial under extensive sheets of transported detritus, mainly derived from discontinuous erosional tracts. An alternative to this theory is the etchplain concept (Wayland 1933) which emphasises deep, chemical weathering and differential stripping of the deep weathered mantle rather than regional drainage rejuvenation and continent-wide landsurfaces. This concept has been used to classify weathered terrain in west Africa (Thomas, 1965) and in south-western Australia (Finkl and Churchward, 1973) and has widespread application to the Yilgarn Block. It is essential to recognize those terrains resulting from the erosion of a stable, and older landsurface, and those that are extensively mantled by a residuum of lateritic weathering. The associated depositional terrains are sumps containing the detritus generated by partial dismantling of the lateritic weathered mantle. The etchplain concept is used in the study of the regolith at Bottle Creek.

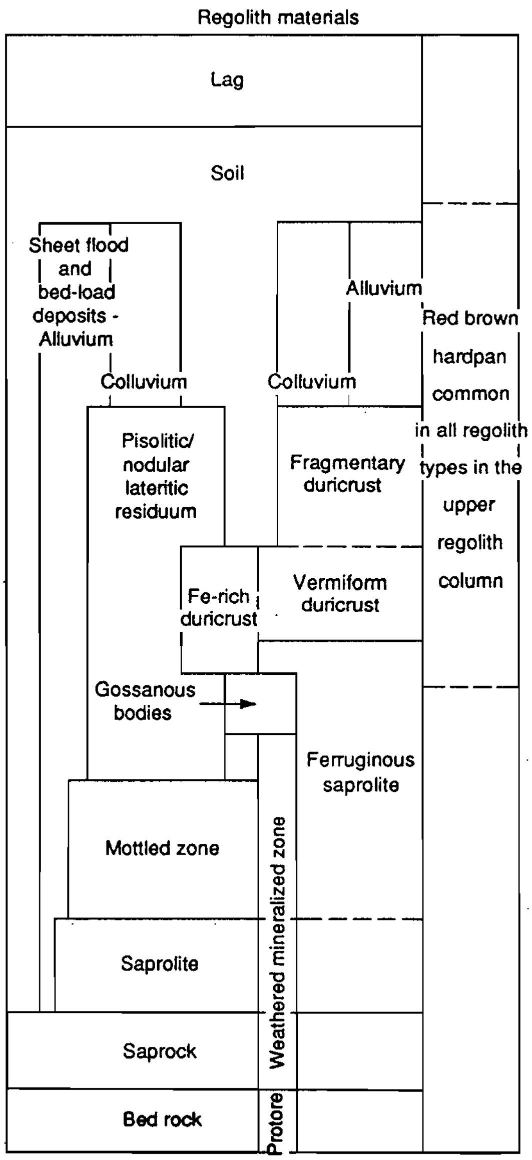
4.3 Regional Trends of Landforms and Regolith

4.3.1 Introduction

Variations in regolith at Bottle Creek can be explained in terms of *erosional and depositional regimes* that modified a relatively stable, weathered landsurface, scattered remnants of which form *residual regimes*. *Residual regimes* are defined as areas characterized by widespread preservation of lateritic residuum. These residual regimes have a relatively stable geomorphology which has favoured retention and accumulation of less mobile products of weathering in a deep mantle, parts of which are relatively rich in iron oxides, that is often further segregated locally.

Where erosion has occurred, one set of regolith types has been destroyed (by removal or burial) and replaced by another set. *Erosional regimes* are defined as areas where there has been widespread removal of the lateritic residuum. Thus the mottled zone, saprolite, saprock or fresh bedrock are either exposed or mantled by shallow soils, which in some parts, are developed on locally-derived transported detritus. The transported regolith of *depositional regimes* can have been derived locally or distally, and their thickness can reach tens of metres. Here also, pockets of the deeply weathered profile can form discontinuous substrates.

Although many of these processes respond to the shape of the landsurface, the resultant materials can themselves be the cause of striking changes in landscape. Specific arrays of regoliths generally can be related to particular landforms. Thus regolith mapping often requires recognition of these landforms. Landforms and regoliths contribute to air photo patterns and are commonly visible directly or indirectly e.g. through vegetation patterns for instance. The interpretation of these patterns is greatly enhanced by the use of the stereoscope. In places there is no clear boundary between residual and depositional regimes, particularly where gentle, laterite-mantled backslopes become progressively covered by a thin wedge of colluvium, derived largely from the slight upslope-bevelling of this mantle. In such situations, map unit boundaries are arbitrary.



Comments

Lag: *Coarse fraction remaining after loss of fines by wind or water action. Wide range of size, shape and composition.*

Soil: *Acid red earths common; very friable fine sandy loams to medium clays. Coarse fraction similar to lag.*

Colluvium: *Fine sandy loam to fine sandy light clay. Coarse fraction related to individual slopes.*

Alluvium: *Fine sandy clay loams to medium clays as sheet flood deposits. Coarse sandy to gravelly palaeo-channe (bed load) deposits are local substrates. Coarse fraction related to a wide range of lithologies.*

Pisolitic to nodular lateritic residuum: *Dark brown to black pisoliths and nodules with yellow-brown cutans, in red-brown kaolinitic matrix. Indurated and lateritic process (dehydration and oxidation) and by silica.*

Fe-rich duricrust: *Nodular to pisolitic ferruginous material. Dark brown to black in dusky red to red-brown matrix. Dense and rock-like.*

Gossanous bodies: *Black to steel grey bodies with clinker like appearance and some box-work textures.*

Fragmentary and vermiform duricrusts: *Much less pisolitic structures. Generally diffusely mottled to uniformly coloured.*

Ferruginous saprolite: *Comparable to the fragmentary vermiform types but generally with a massive appearance - all occur as indurated material.*

Mottled zone: *Clear but diffuse, coarse to medium sized mottles in pale brown to whitish-grey, clayey mass.*

Saprolite: *Soft, pale coloured clay with few if any mottles.*

Saprock: *Pale, more brittle and harder than saprolite. Major rock structures evident.*

Ore: *Enriched between 30m and 60m depths within oxide zone.*

Protore: *Sulphidic sediment, pyrite, pyrrhotite, arsenopyrite, Ag-tetrahedrite, electrum, etc.*

Figure 4. The main regolith types at Bottle Creek and their relationship to the weathering profile.

4.3.2 Regional Pattern of Landforms and Regolith

Broadly, the open-cut mines of the Bottle Creek gold project lie in an elongate plain (Figure 5), developed on a greenstone sequence. The plain, centrally placed in Figure 6, is represented by both residual (mR, *f*R) and depositional regimes (mD, *f*D). Lower case m refers to mafic bedrock sequences and f for felsic.

To the west of this plain, hill belts (unit mE in Figure 6) include prominent strike ridges which form summits such as Mt. Mason and Mt. Ida. The less elevated hills to the east are commonly mesas, remnants of a once more extensive, weathered landsurface. Drainage within this area is to the north, east and south, across extensive sheet flood plains. These are tributary to the major regional drainage axes which are, in part, occupied by the playa systems (Lakes Ballard and Raeside). North, south and east, beyond the greenstone hills, granitic rocks crop out as domes and pavements (much of unit *f*E). The western peripheries of the area have extensive, broadly undulating sandplains (*f*R) developed on granites. These smooth landsurfaces are, in places, broken by local erosional catchments.

The central plain is some 25 km long, striking N-NW; adjacent to the mine pits it is 2 km wide. To the north and south this tract merges with much more extensive plains where it loses its identity. Midway along the plain, near the northern limits of the mining operation, the topography has a gently undulating character (mR) and portions of the Raeside-Barlee drainage divide can be identified. This terrain comprises broadly convex summits, long gentle slopes and broad, shallow, concave drainage floors. The surface has an extensive lag of fine, black gravels. There are scattered blocks of various ferruginous materials outcropping on local summits; the soils are generally acid red earths in fine sandy loams, over red-brown (siliceous) hardpans. A tongue of this gently undulating upland tract rises gradually to the east where it passes into a belt of hills (mE).

The broad, shallow, concave, drainage floors of the divide progressively become more clearly defined downstream. Here shallow channels are flanked by narrow terraces, set below the flat, low-gradient portions of this central plain. Some of these drainages originate within the hill tracts to the east and west and enter the plain through gaps in a flanking array of low cuestas.

The clay-rich units of this flat plain, forming friable acid red earth soils, are extensively mantled by a medium (5 to 40 mm) to fine (<5 mm) lag of various ferruginous regolith types, as well as quartz and lithic types. The erosional regimes (mE) are a complex of mesas, breakaways and steep pediments, and have a lag of lithic and ferruginous fragments, with subcropping to outcropping weathered rock. Patches of friable calcrete are common in these erosional regimes. The interrelationship between some of these landforms is illustrated as a block diagram, Figure 7.

Erosional regimes on granite (*f*E) are dominated by outcropping domes and pavements and occur east of the greenstone belt. West of this belt, the granite is largely overlain by gently undulating sandplains (*f*R). In places the sandplains have been eroded, exposing pale granitic saprolite in the face of breakaways, from which extend gently inclined pediments, local alluvial fans and low granite domes.

Figure 5A. Looking westward to the VB and Boags pits, of the Bottle Creek gold project, arrayed on a flat, depositional plain. Beyond the right hand edge of the photo, this plain merges with a gently undulating tract on which the Emu pit is situated. Strike ridges form the western backdrop, and an erosional tract is in the foreground.

Figure 5B. Looking southward across the undulating terrain at Emu pit, to the plain on which VB and Boags pits are situated. S-SE trending strike ridges are on the skyline.

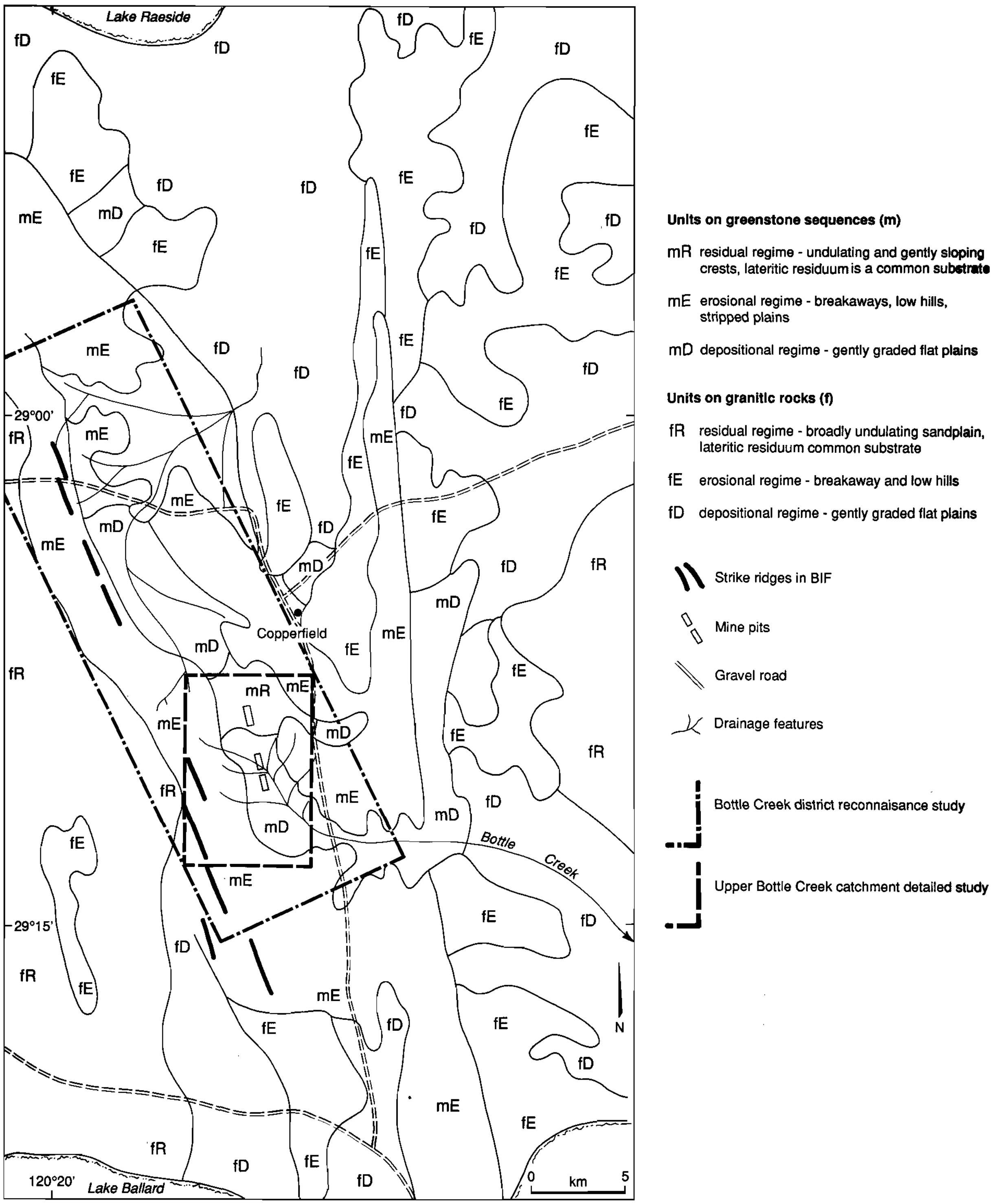


Figure 6. General regional pattern of landforms and regolith about the Bottle Creek area. This map has been reduced for publication from a scale of 1:250,000 .

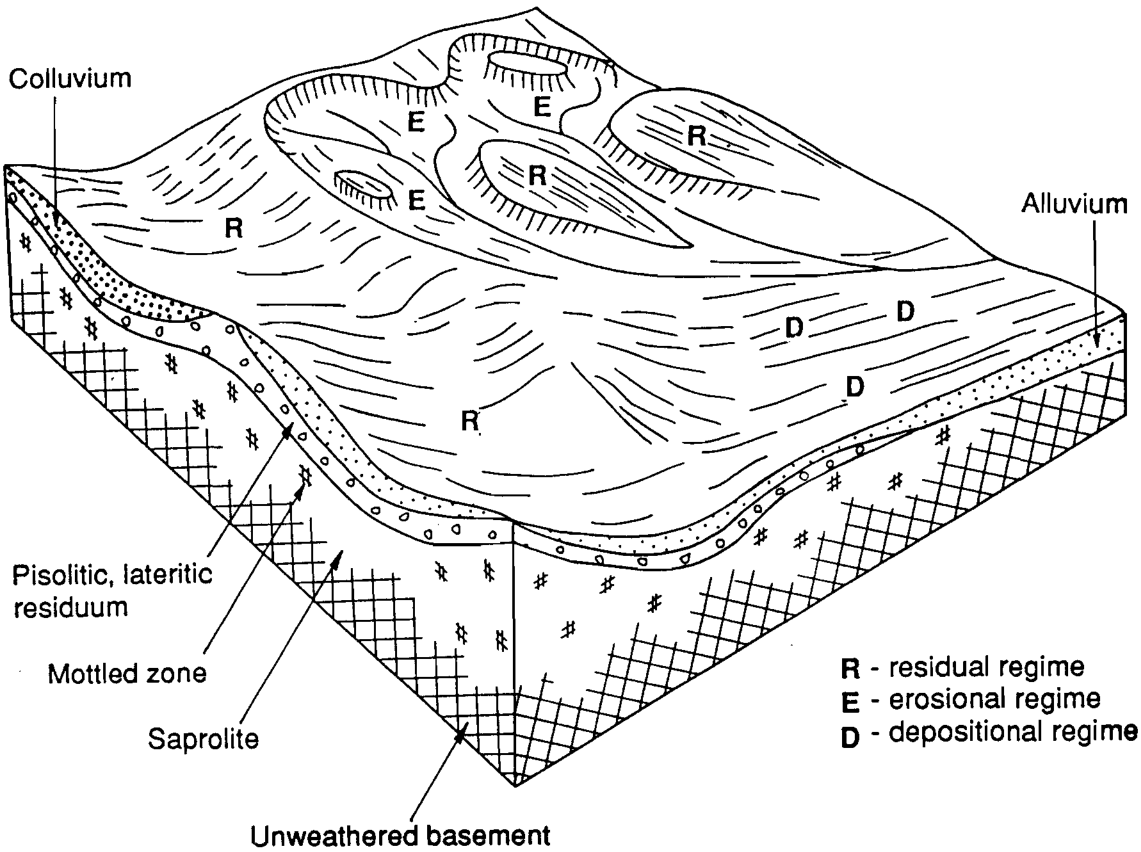


Figure 7. General relationship of the residual, erosional and depositional regimes at Bottle Creek, illustrated with a block diagram.
The generalized regolith stratigraphy is exposed on the edges of the block. This exposure represents a length of some 20 km and the vertical scale is exaggerated. The weathering profile is as much as 20 to 50 m thick.

5.0 REGOLITH STRATIGRAPHY

5.1 Introduction

Although reconnaissance indicated a general relationship between the surface regolith types and landforms drill spoil, examined during this phase, showed changes in the regolith which were not evident on the surface. A more complete picture of the regolith, including stratigraphic relationships, was needed to formulate a rational sampling strategy for mineral exploration in this type of weathered terrain.

5.2 Sites for Detailed Observations

Detailed observations were made at a number of type locations, identified during reconnaissance and shown in Figure 8. Although many type sites were in the faces of mine cuts, supplementary information was provided by drill spoil. In addition, surface trends in the nature of the lags and soils were observed in areas considered to be typical of a particular regime.

Suitable stratigraphic sections of the residual regime were exposed in the Emu test pit, supplemented by bulldozer cuts along a strike length of 200 m to the north of it. Down-slope trends in the lags, soil and other surface expressions of the regolith were observed along lines 14800 N and 16000 N. The mine pits at VB and Boags, in the south-central part of the area, exposed the stratigraphy of the depositional regime. The erosional regime was observed during detailed mapping centred on 15100 N; 11700 E (the large rectangle in the NE sector of Figure 8).

5.2.1 Residual Regime

Emu Test Pit

Pisolitic, lateritic residuum occupies a large part of the exposures at the Emu pit and is the principal regolith type in the residual regime. An idealized section, presented in Figure 9, shows the regolith types exposed in the S face of this pit (see also Figure 10). The lateritic residuum merges into the mottled zone at a depth of about 5 m and thence, as seen in drill chips, to pale saprolite, and saprock, beneath the pit floor. Hardpan has developed in much of the lateritic residuum at this site. The soil over this profile, which was approximately 0.75 m thick before removal by mining, was observed in a shallow cutting to the SE of the pit (14900 N; 9500 E).

In the S face of the Emu test pit (15030 N; 9400 E) the *lateritic residuum* occurs at a depth of about 3 m where it forms a brown to reddish brown mass with moderate to abundant pisoliths (Figure 11a,b). It is hard and is classed as *duricrust* (LT202) or *pisolitic-nodular duricrust* (LT203). The pisoliths are clearly defined and are generally ovate to spherical with a diameter of from 3 to 15 mm with yellow-brown cutans. Some are diffusely mottled, with lighter and darker, roughly concentric zones (see Figure 11b). Some pisoliths are magnetic and generally have dark, metallic grey to black cores. Spheritic structures (Killigrew and Glassford 1976) are common in the matrix and, are in places, intensely developed. Examination of the polished surfaces of samples by low-powered binocular microscope suggests a trend in development of spherites in the matrix from depth to surface. In the deeper parts of the lateritic residuum there is extensive, very fine fragmentation of the kaolinitic matrix, possibly by iron-infusion along fine cracks. Towards the surface the very fine fragments assume a rather spherical shape and eventually dominate the matrix. At a depth of about 1.5 m, the matrix is composed almost entirely of spherites. Other changes in the residuum are evident from deeper parts to the surface. Nodules/pisoliths are more common and smaller at a depth of 1.5 m than at 3 m. Angular and platy types are more common, and generally have a dark, metallic grey, interior, although brown to reddish brown types are still present.

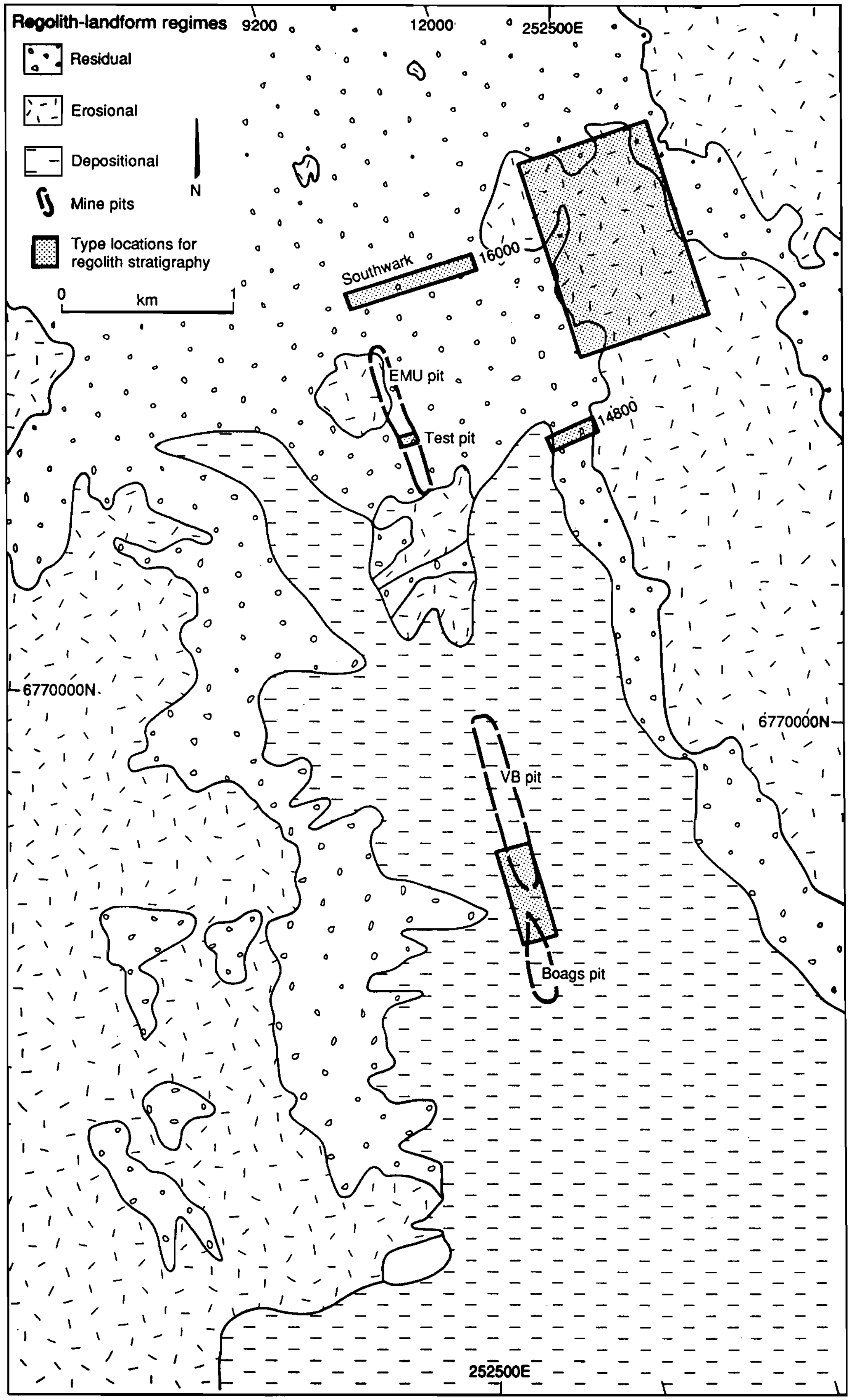


Figure 8. Location of sites for the detailed regolith study in the upper Bottle Creek catchment.

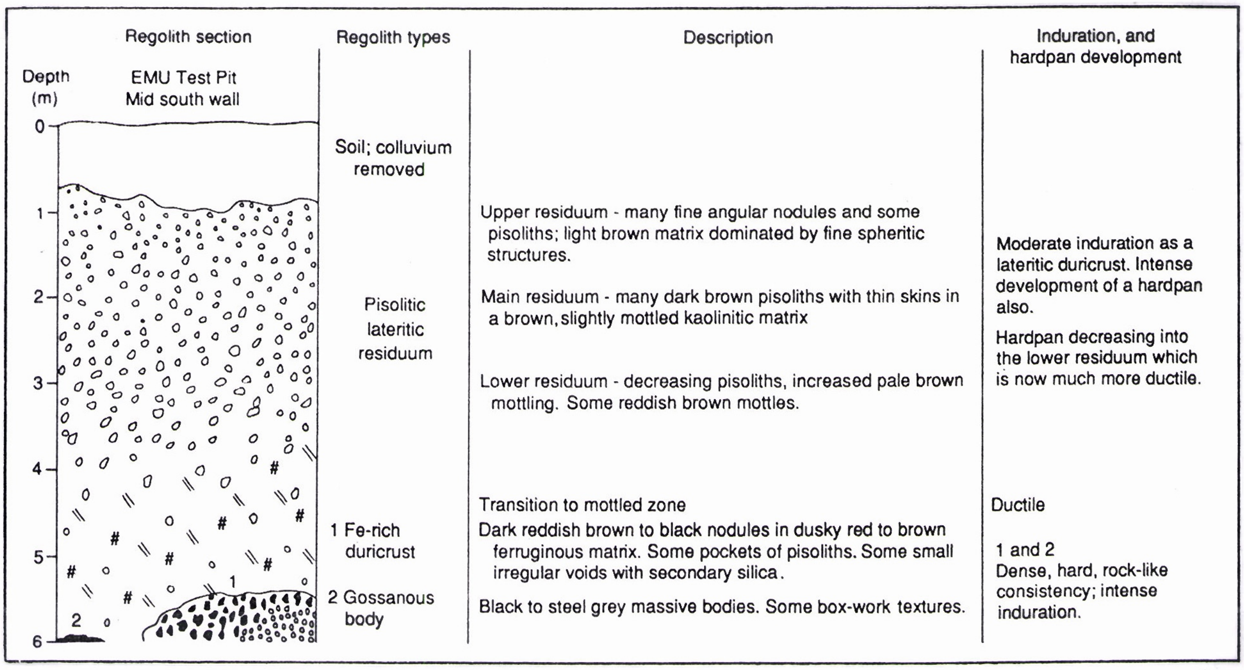
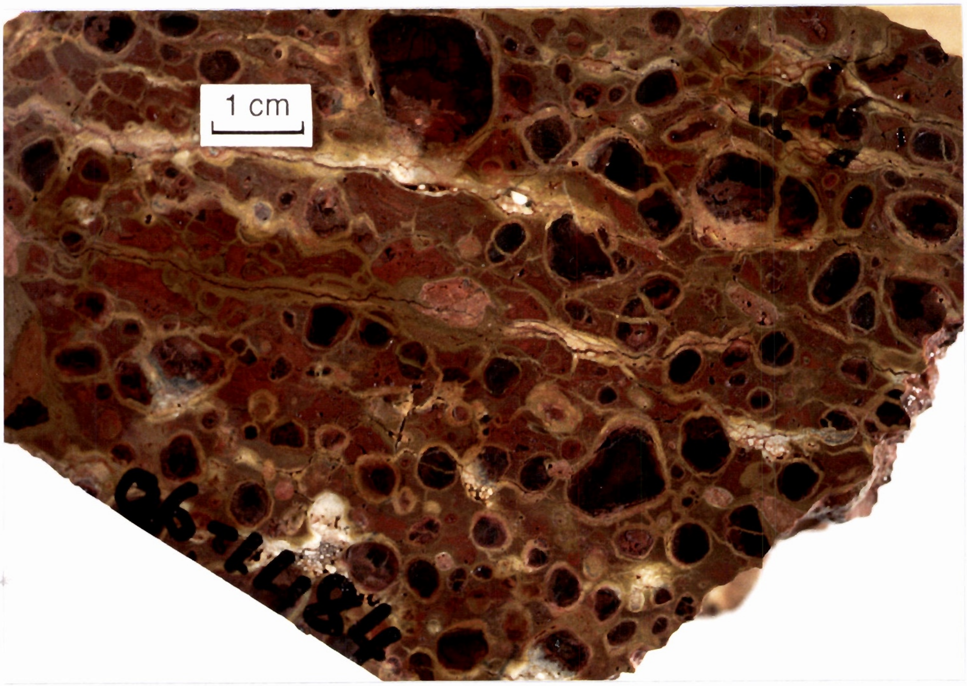


Figure 9. Regolith section, mid-S face of Emu test pit.

Figure 10. South face of Emu test pit showing extensive duricrust of pisolitic, lateritic residuum with (1), hardpan development (2), material transitional between pisolitic residuum above and the mottled zone beneath, (3) a slab of Fe-rich duricrust and (4), coarse reticulate mottling.

A. At 3 m depth, coarse, horizontal partings due to hardpanization.



B. Polished face of lateritic residuum, showing pisoliths with light brown cutans, set in an indurated clay matrix.

Figure 11. Pisolitic, argillic, lateritic residuum exposed in the mid-south face of the Emu test pit.

They have thin, clearly defined, yellow-brown cutans and there is much less matrix at this shallower depth. At present it is not clear whether the upper metre of the residuum here is transported, or is the result of more intense *in situ* weathering of the lateritic residuum.

At a depth of about 4 to 5 m the lateritic residuum becomes more ductile. Pisolitic structures are less common and are generally poorly differentiated from the matrix (Figure 12 a,b). With depth, as pale grey and light olive-grey mottles become common, the *mottled zone* is more evident. A coarse reticulate pattern of pale grey mottles in the SE corner of Emu pit (Figure 13) appears to be a localized phenomenon that is possibly of biogenic origin, related to a particular redox environment of tree roots. The *pallid saprolite* is mainly a pale yellowish or brownish grey clay that merges at depth into *saprock* that has a firmer and more brittle consistency.

Although the lateritic residuum observed at this site is classified as a duricrust, it has many features of hardpan (compare to the Wiluna Hardpan described by Bettenay and Churchward 1974). Exposures of the lateritic residuum in the south face of the Emu pit, have well-developed horizontal and, to a lesser degree, vertical partings resulting in a mass that is coarsely laminate, with plates from 10 to 50 mm thick and as much as 1 m long. Some of the horizontal and vertical partings are coated with very fine, white to pale brown silica. Similar silicious zones extend across blocks of hardpan as narrow wavy bands. Many of the partings have a uniform red patina, with irregular black patches and coarse flecks of manganese oxide. The fracture faces are irregular and have a dull, earthy appearance and the mass is finely porous. It is very brittle and makes a dull thud when struck with a hammer. The relative contributions to this hardening by lateritization, and silicification (hardpanization) is, at present, not clear.

Large ferruginous bodies are exposed in the Emu pit. Their stone-like condition (on hammering they ring sharply) contrasts with the firm but rather fragile state of the surrounding pisolitic, argillic, lateritic residuum (a hammer blow gives a dull thud). These bodies occur at varying depths in the pisolitic, lateritic residuum, usually 2 to 5 m from the present ground surface. They range from ovate, pod-like bodies (100 by 200 mm in diameter) and lenses (1.5 m long) through to large slabs 4 to 8 m across (Figure 14 a,b). Others have a very irregular outline.

Most of these very hard bodies can be classified into two regolith types. Firstly there are those that, as hand specimens, are comparable with *Fe-rich duricrust* (LT228). A large slab of this material is exposed in the floor of the Emu pit at the foot of the S face, and several large lenses (reaching 1.5 m dia) occur at a depth of about 2 m in a cut near the west of the pit. These materials commonly have black to dark brown equant to oblate nodules of (Figure 15), set in a brown to red-brown matrix (diameter from 4 to 25 mm). Some nodules have no clear cutans but cutans are well-developed on others. Where these are ovate to spherical they are pisoliths. Some small (<5 mm) voids occur (particularly where pisoliths are common), with a yellow-brown lining and are partly occupied by finely crystalline, secondary silica. Many of the pisoliths and nodules in this type of duricrust are magnetic. These Fe-rich duricrusts are dominated by much of iron oxides in both the nodules and pisoliths and in the matrix. By way of contrast, the adjacent, pisolitic lateritic residuum has a clay-dominated matrix.

A second type of very hard, non-magnetic, ferruginous material is irregularly and diffusely mottled various shades of light brown and red-brown. It is classified as *mottled duricrust* (LT241) (Figure 15b). Vermiform, nodular and incipiently, pisolitic structures are present. Where coarse, vermiform voids are common such materials are referred to as *vermiform duricrust* (LT231). A large body of this is in the N face of the Emu test pit (Figure 16). This irregular, crudely globular mass has wedge-like protuberances. Its position in the regolith column is illustrated in Figure 17.

Some duricrusts comprise ferruginous saprolite and these are generally brown and massive. In part, these can have irregular, diffuse, light brown mottles. Portions that show intense development of irregular, coarse voids have been called vermiform duricrusts (LT231) in the Atlas (Anand *et al.*, 1989). The development of voids can lead to physical collapse of the duricrust and the individual pieces can occur as nodules with yellow-brown cutans in a friable, sandy matrix. On the other hand the voids can refill, usually with a light brown, kaolinitic clay dominated by spherites. Duricrusts developed in this can be referred to as fragmental (LT205). Where the pieces (or zones) of ferruginous saprolite in this duricrust are angular, the mass has a brechiform appearance. On the other hand, irregular, rather curvate shapes can lend a colloform appearance.

Some pods and lenses of *gossan* (comparable to LT229 and IS101) are set in the lateritic residuum (Figure 16). Some are physically continuous with the competent ferruginous bodies, others are only a few meters from them. This gossan is dull, brownish black or metallic, blue-black and steel grey material and is brittle, often clinker-like, and non-magnetic. It has a complex system of fine voids, some with reddish yellow, goethitic linings. A crudely developed box-work is common, and the use of the term gossan is further supported by the presence of Fe-oxyhydroxide pseudomorphs after subhedral pyrite.

Calcrete, usually as small, roughly lenticular pockets, occurs only rarely in the upper lateritic residuum, such as near the surface at the mid-point of the N face of Emu pit (Figure 18). The calcrete is generally a mixture of powdery calcium carbonate with hard, calcareous nodules/pisoliths and moderately firm, irregular sheets and fragments of calcium carbonate. Ribbons of carbonate extend some metres from these pockets, along horizontal partings in the hardpan.

Soil profile (14900 N; 9500 E)

A shallow cutting, S-SE of the Emu test pit, has exposed gravelly colluvium which overlies the upper portions of the underlying pisolitic-nodular, lateritic residuum. An acid red, very friable, earth has developed in red-brown, fine sandy loams to fine sandy clay loams which have light to moderate amounts of black, irregularly shaped, ferruginous granules (generally <10 mm dia.) of irregular shape. This is a colluvial component and overlies material that is more closely related to the underlying lateritic residuum. At a depth of from to 30 to 50 mm the proportion and size of the gravels increases sharply. Large amounts of gravel range from 10 to 50 mm diameter. These clasts generally have a yellow-brown to dark brown, smoothly irregular exterior. The light to dark brown interiors of some are diffusely mottled and contain fragments of ferruginous saprolite. In others, pisolitic structures are evident. These compound nodules are probably derived from the breakdown of the lateritic duricrust. At about a depth of 1 m this coarse gravelly mass merges to an indurated, pisolitic, lateritic residuum within which hardpan is developed, as described in the Emu test pit.

Traverses along 14800 N and 16000 N

The surface expression of the regoliths developed in residual regimes grades from the crests, down the long, gentle slopes, to broad concavities. This gradation is well represented along grid lines 14800 N and 16000 N, E of 9200 E. Here slopes grade gently to the west, from the broad convexities that cap low, E-facing breakaways, which mark the western limits of the neighbouring erosional terrain. These features are referred to as the backslopes (Figure 19) of the breakaways. On the broad, smoothly convex crests are scattered blocks of ferruginous saprolite

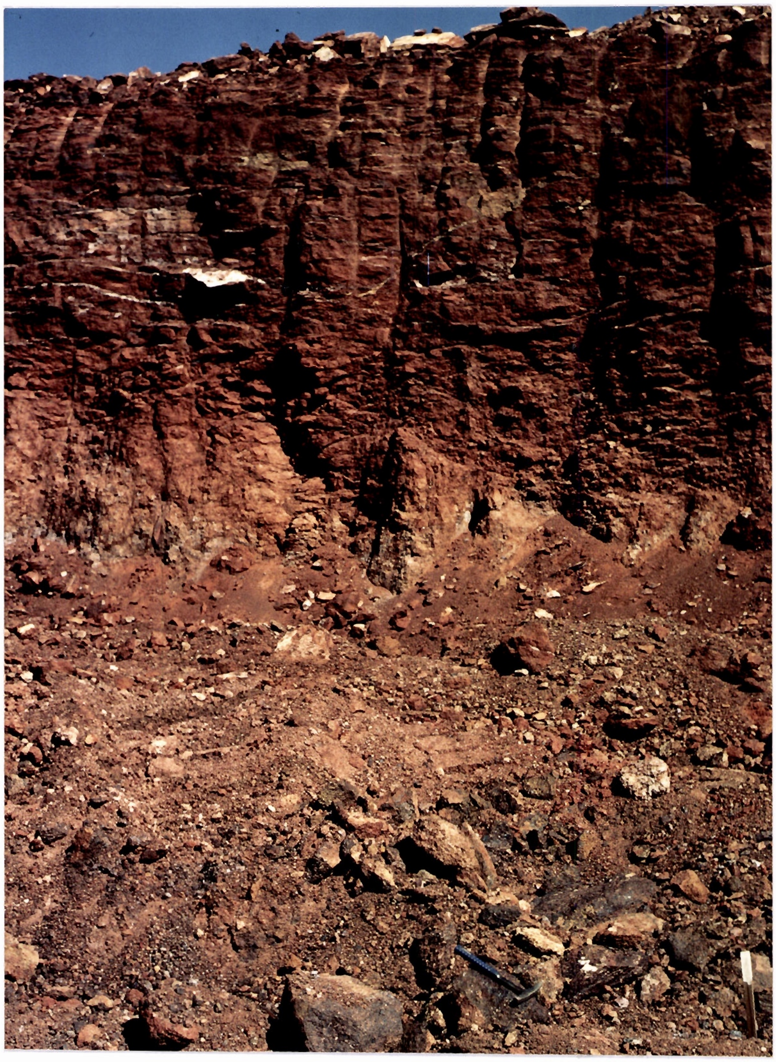
A. In the upper parts, pisolitic, lateritic residuum, that shows well developed hardpan decreasing with depth; mottling is clear at the base of the section.

B. Close-up of the transition from lateritic residuum to mottled zone showing mottling, low pisolith content, and no hardpan.

Figure 12. Transition from lateritic residuum to mottled zone, mid-south face of Emu test pit.

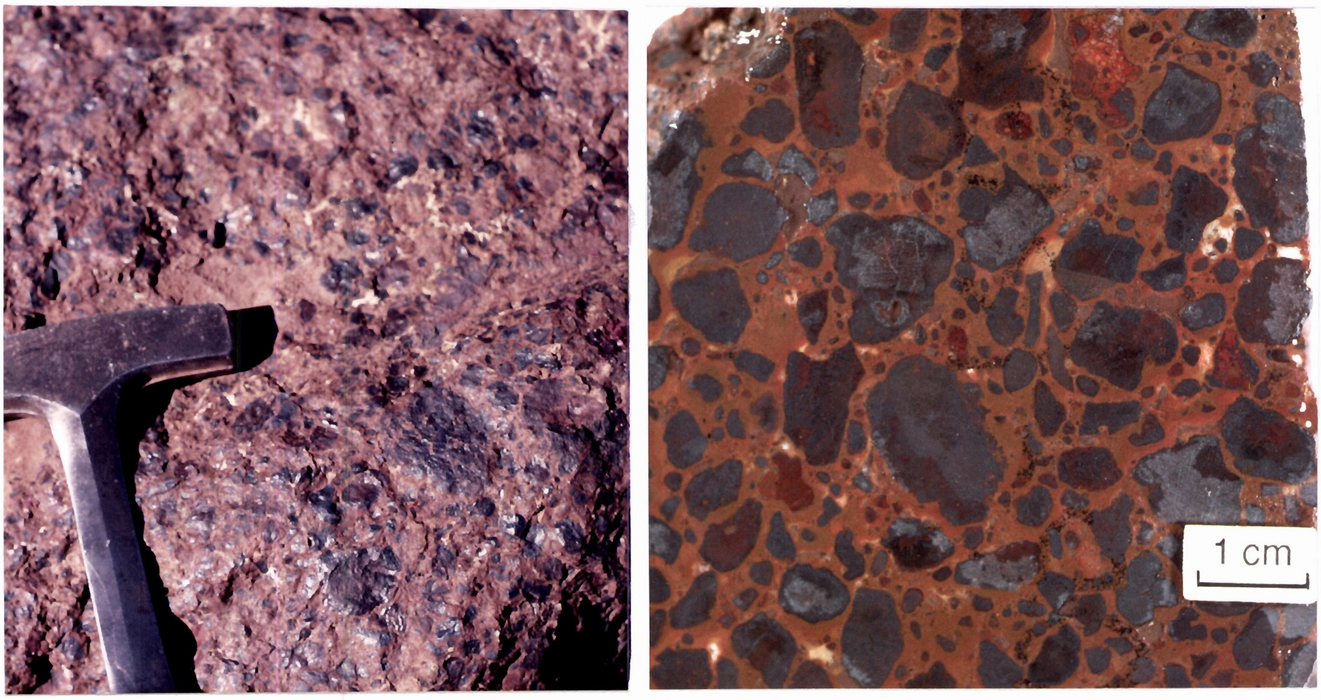
Figure 13. Coarse, reticulate mottling beneath the hardpanized, pisolitic, lateritic residuum, in the SE corner of the Emu test pit.

A. A large slab at a depth of about 4 m beneath the pisolitic, lateritic residuum, and within the transition to the mottled zone.



B. A lens of Fe-rich duricrust within the lateritic residuum

Figure 14. Fe-rich duricrust at Emu test pit.



A. Fe-rich duricrust from the large slab, S face, Emu test pit (see Figure 14).

B. Mottled duricrust with a complex pattern of mottling and some vermiform voids, from the north face of Emu test pit (see Figure 16).

Figure 15. Close up views of duricrusts in the Bottle Creek study area.

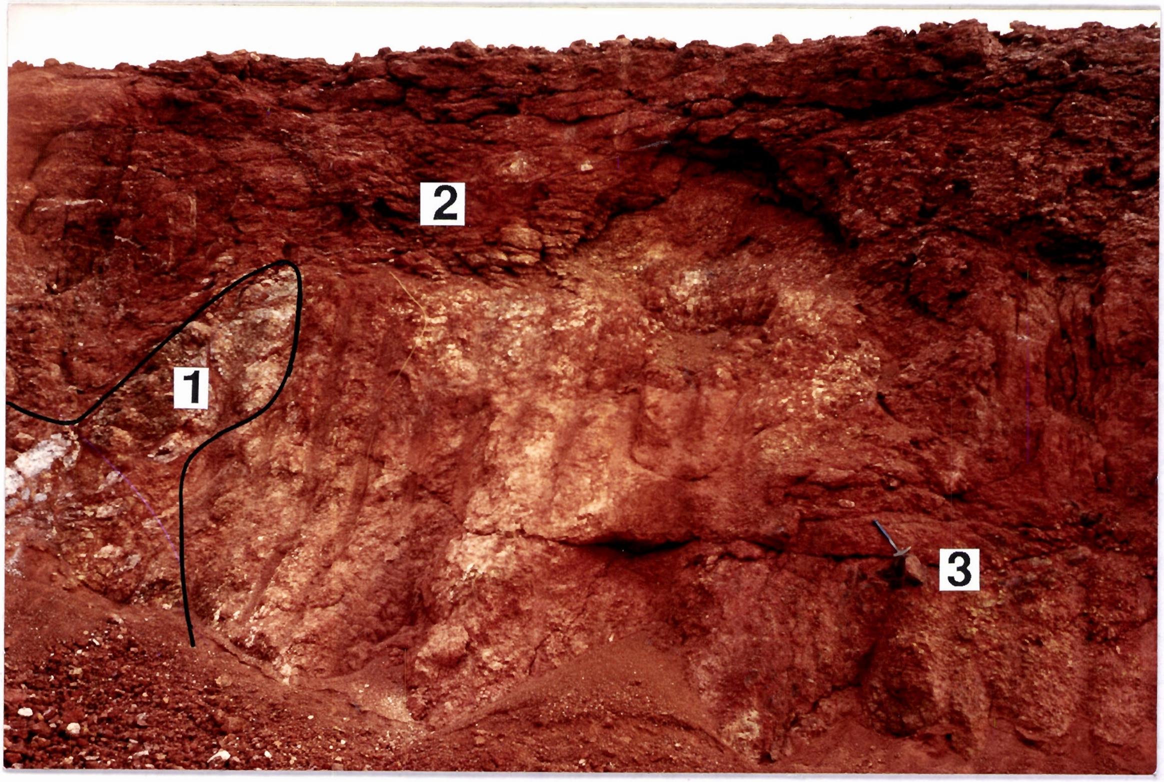


Figure 16. Mottled duricrust exposed in the N face of Emu test pit. (1) Irregularly shaped mass of mottled duricrust, at the base of the lateritic residuum (2), or partly surrounded by it. The hammer rests on a goethite pod (3) with a gossanous fabric.

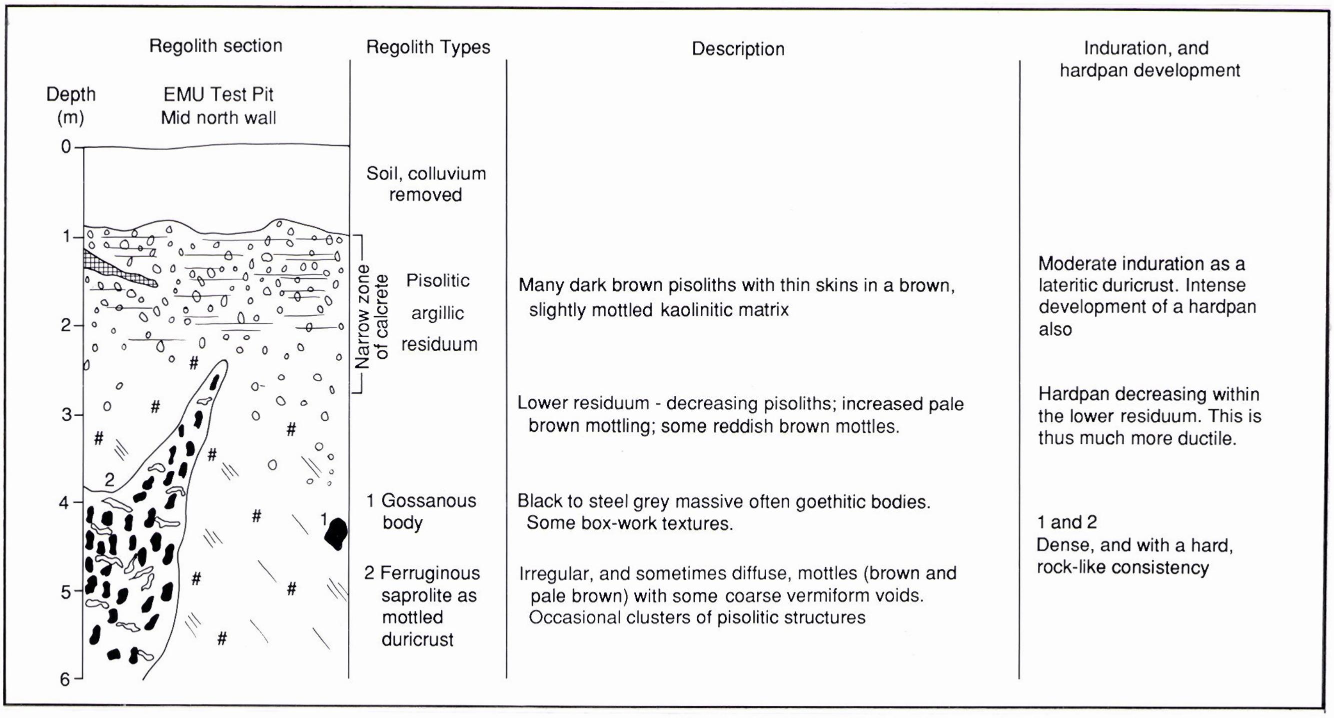


Figure 17. Regolith section from the N face of Emu test pit.

Figure 18. A pocket of calcium carbonate (the pale area above the vehicle) in the upper regolith of the N face, Emu test pit.

Figure 19. Smooth, gently inclined backslope along 14800E, Bottle Creek gold project grid. This includes Unit 1 (upslope) and a portion of Unit 2, of the detailed survey. The foreground comprises a minor alluvial tract, Unit 9a.

(Figure 20 a,b,c), along with some Fe-rich duricrust. On the surface of fragments of the Fe-rich duricrust, nodular and pisolith structures stand out in relief. This has informally been referred to as "pebbly" duricrust. A few irregular blocks of steel grey to black, gossanous material occur. Fragments of all these materials form a coarse (to <40 mm) lag, containing small amounts of lateritic pisoliths, with yellow-brown cutans. The lag is underlain by a shallow, light brown, friable, acid, fine, sandy soil, containing like fragments. Many of these regolith types are seen at depth in the Emu pit. These crests appear to have been slightly bevelled by erosion. Thus, conceptually, these are part of an erosional regime. However, when mapping, they are more effectively considered as part of a residual regime since erosion is minimal, and they occur as a complex pattern with other components of the residual regime where they are a major source of the colluvium that mantles the residual surfaces.

Outcrops of blocks and slabs of Fe-rich duricrust are not as common as outcropping ferruginous saprolite on the crests in the Bottle Creek area. An exception is at 17080 N; 9250 E. Strongly pisolitic materials, particularly with yellow-brown cutans are also not common outcrops on crests. There are exceptions, however, such as at 14500 N; 12500 E (Figure 20c).

A short distance downslope from the crest, the lag is much finer (<15 mm) and is largely ferruginous saprolite. A few pisoliths can be present but very few have yellow-brown cutans; more commonly they have a dark brown surface and no cutans. On mid-slope (Figure 21), most of the lag is fine (<10 mm) ferruginous fragments of gravel; sizes coarser than 10 mm are not common on the surface but medium sizes appear at depths of 300 to 500 mm. Pisoliths are not common and quartz and other lithic fragments are very rare. Some of the crests have a lag with a high proportion of yellowish brown pisoliths. This is usually associated with brown, coarse fragments (<80 mm) of ferruginous saprolite, some with incipient pisolitic structures. These crests are less stripped than many of the others (e.g. east of the VB pit, at 13200 N; 10500 E).

The lower slopes and broad concavities of this terrain are particularly obvious at Southwark (see Figure 8, approximately 16100 N; 9200 to 9500 E), north of Emu. The lag (Figure 22) is fine (<5 mm), with dark brown to black, generally ferruginous fragments; pisoliths with yellow-brown cutans are rare while quartz is not generally present. The lag mantles an acid, red earth in a fine, sandy, light clay colluvium, which has moderate amounts of black, ferruginous granules. These fine granules contrast with the gravels at depth in the soil profiles upslope. In the wall of a costean (16000 N; 932O E), hardpan first appears at about 800 mm as horizontal white flecks and is well developed at a depth of 1 m. Drill spoil, at about 4 m depth, contains pisoliths with yellow-brown skins, and this grades into lateritic residuum as a substrate. Absence of the residuum from some drill spoil indicates sporadic truncation of the old landsurface, before burial by colluvium.

Cutting along a slope north of Emu test pit (9450 E; between 15100 and 15700 N)
This is the E face of an investigation excavation that extends northward from Emu to a low broad crest (Figure 23 a,b). The southern two thirds of the cutting is dominated by extensively hardpanized pisolitic residuum. It has many features comparable with the S face of the Emu pit described above. There is a small pocket of calcrete near the surface at about 15500 N. To the north, halfway along the cutting pale grey saprolite and/or saprock appear beneath some ferruginous saprolite which in turn, blends upward into the pisolitic, lateritic residuum. The saprock occurs at a depth of about 3 to 4 m but progressively comes closer to the surface as the crest is reached where it is at about 2 m, beneath red-brown, ferruginous saprolite. Although the ferruginous saprolite continues to the surface there are a few small pockets of pisolitic, lateritic residuum. The regolith pattern indicates bevelling of the crest with down-slope transport of most of the residuum.

5.2.2 Erosional Regime

Type location centred on 11700 E; 15100 N (rectangle in Figure 8)
In areas of the *erosional regime*, components of the regolith are generally exposed at the surface where outcrop and subcrop of various regolith types supply detritus to local colluvial and alluvial systems. The surface is mantled by a coarse lag, the nature of which relates to local variations in outcrop and subcrop. Most of the lag is ferruginous. Black cobbles and pebbles flank vein-like outcrops of Fe-segregations and coarse quartz cobbles are shed from outcrops and subcrops of quartz veins. The fragments of Fe-segregations are dark brown, brownish black and dark bluish black, and generally have a dull, lustrous surface (desert varnish). Internally, these are massive. They are non-magnetic and dense. Saprock lag, occurring as platy fragments variously stained with iron, is common and is generally interspersed with minor saprock outcrop. Calcrete occurs as scattered pockets and is common on the steep pediments, low hills and the intervening, broadly concave areas. Light brown, ferruginous saprolite and saprock are extensively exposed on the face of breakaways and associated crests.

Narrow alluvial tracts, with active streams, have been modified by erosion and deposition. They are occupied by a clay loam alluvium on which have developed earths, that are sometimes calcareous. The lag is mainly of small, platy, saprock fragments.

Smooth, gently concave pediments extend from the base of low breakaways and are included in the erosional regimes. There are generally no outcrops on these gently inclined surfaces, rather they are mantled by soils, acid red earths in fine, sandy, light clay colluvium, that overlies saprock at a depth of from 400 to 800 mm; they are hardpanized at depths of from 300 to 500 mm. The lag is coarse (30 to 50 mm), irregular, brown to dark brown, ferruginous saprolite fragments, a few pieces of Fe-rich duricrust, Fe-coated lithic fragments, Fe-stained saprock and minor quartz.

5.2.3 Depositional Regimes

VB and Boags pits
Regoliths of the *depositional regime* are extensively exposed in the face of the VB and Boags pits (Figure 24). Here one or more of the transported units (colluvium and alluvium) overlies saprock, saprolite, or relics of lateritic residuum. Thick deposits of a palaeochannel are also present.

Lag mantles most of the depositional regimes. Much of it is dark brown to black and it has a smooth, varnished surface. This lag often comprises fragments of ferruginous saprolite and Fe-segregations, some saprock (ferruginized or merely iron-stained), and quartz (Figure 25). These fragments generally are <10 mm in diameter with a minor portion of medium size (<25 mm) and range in shape, the more platy fragments are generally lithic.

A. Blocks of ferruginous saprolite are common.

B. Coarse gravels of ferruginous saprolite are common.

C. A rare occurrence of pisoliths, as a dominant feature.

Figure 20. Surface expression of regolith on crests in residual regimes.

Figure 21. Lags within residual regimes; on mid-position of the backslope along 14800N.

Figure 22. Fine lags of ferruginous material, characteristics of lower slopes and swales in residual regimes (Unit 2 of the detailed mapping, see Figure 32) at Southwark location.

A. Thickness of lateritic residuum and ferruginous saprolite (1) increasing downslope from crest (left hand side of photo); pallid saprolite and/or saprock (2) substrate.

B. Section on crest, with saprock (2), at a relatively shallow depth, beneath ferruginous saprolite (1).

Figure 23. Regolith exposures immediately north of Emu test pit.

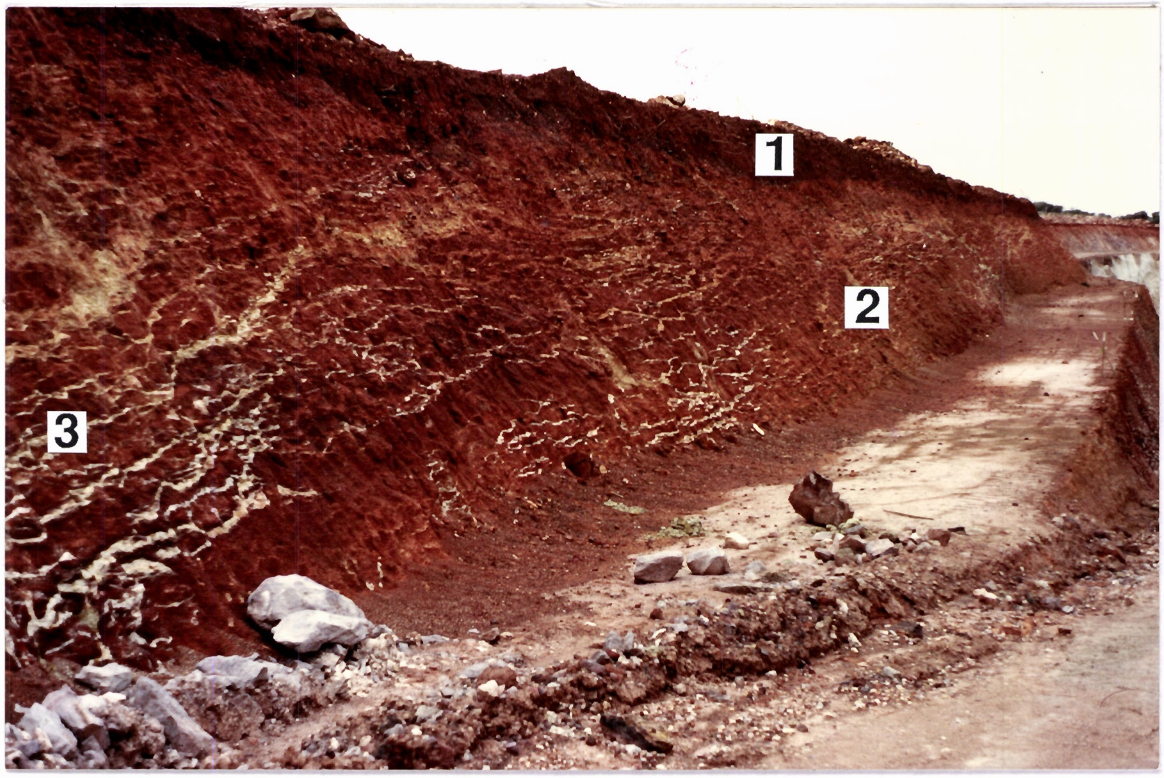


Figure 24. East face of the entrance to Boags pit. Regolith stratigraphy comprises (1), an upper alluvial member of sheet flood deposits, with a stone line at the interface to (2), partially hardpanized, lateritic residuum and (3), coarse alluvium occupying a palaeochannel.

Figure 25. Lag on the depositional plain at Boags and VB pits. The medium size fragments, though in the minority, are a characteristic fraction. They include ferruginous saprolite and Fe-segregations, some lithic pieces, and quartz.

The lag occurs on a flavial deposit, comprising a light clay with some ferruginous and quartz gravels. This fluvial sediment is not confined by clearly developed stream channels but is the result of sheet floods. Some would regard it as colluvium but it occupies low gradient plains; colluvium is a deposit on, or at the base of, hillslopes so that the term, alluvium, is favoured here for this material. An acid red earth, comprising a very friable, fine, sandy, light clay, has developed. Exposures in the face of the VB and Boags pits show a discontinuous stone line, about 100 to 200 mm thick, at the base of the alluvium. Gravels forming this stone line are similar to those within the alluvium.

A thick body of coarse *alluvium* forms a substrate to the upper alluvium, near the S end of the VB pit (9300 E; 12250 N) and continues to the N end of the ramp into Boags pit (9240 E; 11775 N) (Figure 26). It occupies a broad trench some 12 m deep and about 400 m wide. The alluvium is a mixture of sand, subrounded and subangular granules and gravels of quartz and various ferruginous and lithic types (Figure 27). These materials are crudely laminated and were probably the bed-load deposits of a braided stream. There is a sharp stratigraphic break, generally marked by the stone line, between these coarse, confined alluvial deposits and the more clayey, upper alluvium derived by unconfined sheet flooding (Figure 28).

A large pocket (75 m long) of pisolitic-nodular, argillic, lateritic residuum substrate is exposed at the entrance of the Boags pit, some metres N and S of 9230 E; 11700 N (Figure 29). This lateritic residuum is comparable to that at the Emu pit (Figure 30). Pisoliths with yellow-brown clay cutans, many with diameters of from 10 to 15 mm, are set in a firm but fragile (to a hammer blow) clayey matrix. This is diffusely mottled, light brown, pale brown and reddish brown. Beneath the lateritic residuum (at the level of the first pit terrace) is a large, irregular, dense, ferruginous body that extends a further 3 m deeper into the saprolitic regolith (Figure 31 a,b). This is dominated by dark brown, black and metallic grey, nodules in a red-brown matrix. Some of these nodules have red-brown to red cutans but some incipient oolitic structures occur in both matrix and nodules. There are some irregular voids coated with goethite and secondary silica. A zone about 1 m thick, within the lateritic residuum, above this large ferruginous body, contains many coarse (to 40 mm dia) nodules (Figure 31b) that have yellow-brown cutans and dark, Fe-rich cores, and which are generally magnetic.

At Boags there are well defined changes in the upper part of the residuum to a more fine, gravelly (or granular) condition (see Figure 30). Here also nodules have a wider range of composition, and shape, and have thin, pale, brown cutans. The matrix is more uniform, light brown, and is almost completely made up of fine (<1 mm) clay spherites. This is comparable with the matrix of the upper part of the lateritic residuum, described previously for the Emu pit.

Much of this pisolitic, lateritic residuum is overlain by sheet flood alluvium, the more common surficial regolith type for the depositional regime at Bottle Creek. However, the northern flanks of the residuum are buried by the coarse alluvium of the palaeochannel.

Although the lateritic residuum is an important indicator of the complex history of the regolith of the depositional regime, the more common substrates to the upper alluvial member of this stratigraphy is the mottled zone with coarse, yellow-brown and red-brown mottles in a olive-grey plastic clay. In places, the substrate is a pale brown and brownish grey saprock, particularly at the south end of Boags pit.

The picture of the regolith, provided by this detailed examination at specific sites can be placed in a broader context by mapping landforms and regolith types in the immediate environs of the Bottle Creek mining project and, subsequently, at a sub-district scale.

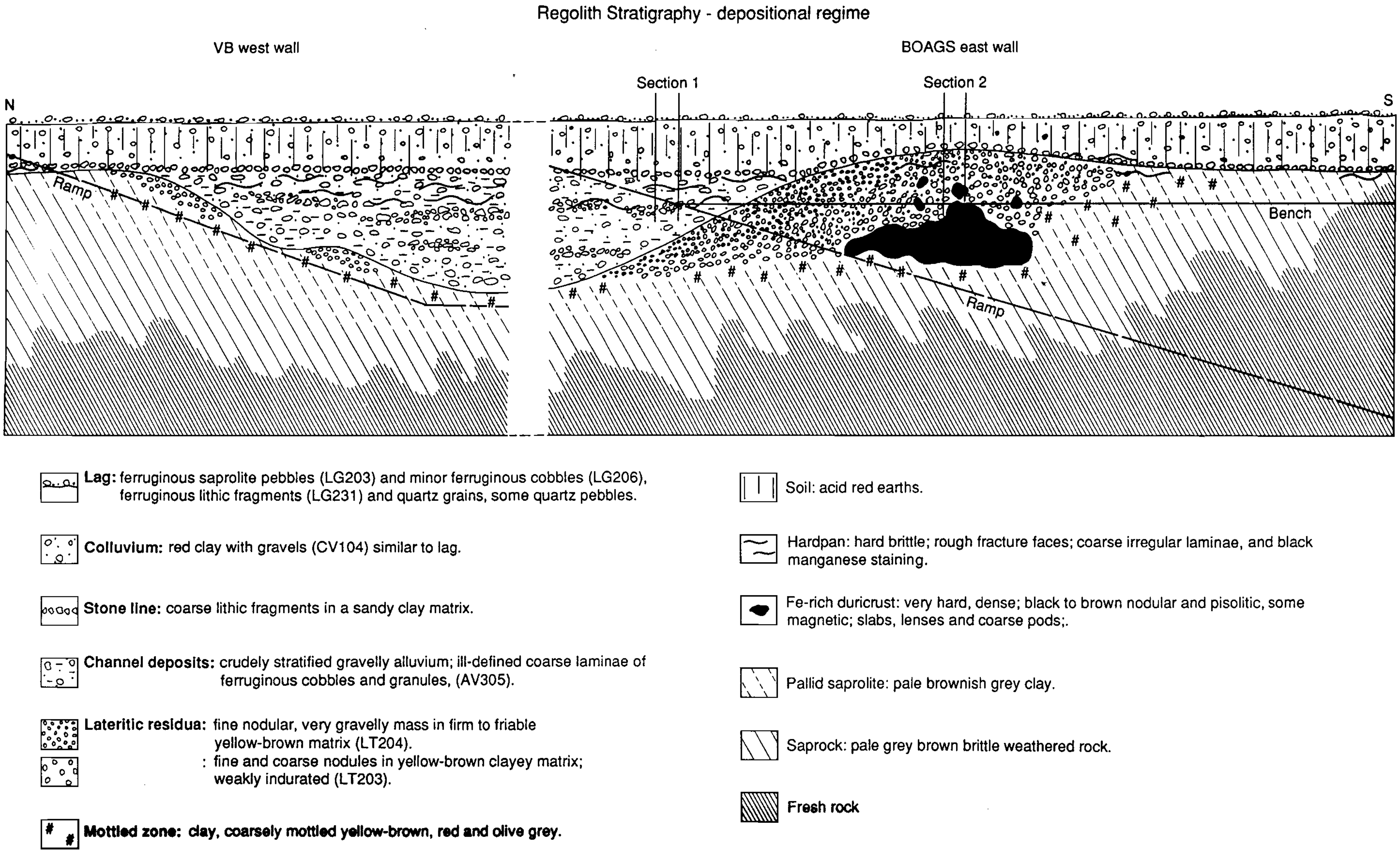


Figure 26. A diagrammatic N-S section linking Boags and VB pits, illustrating the regolith stratigraphy.

Figure 27. Close up of the coarse, palaeochannel deposits at Boags pit entrance, showing its mixed composition.

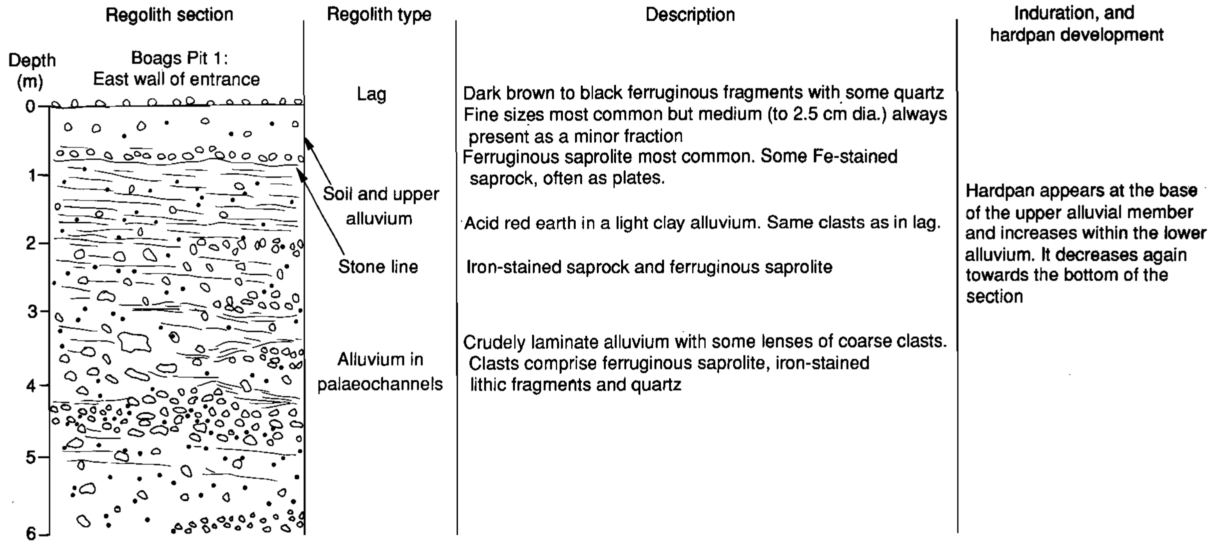


Figure 28. Regolith section through the palaeochannel at Boags pit (section 1 in Figure 26).

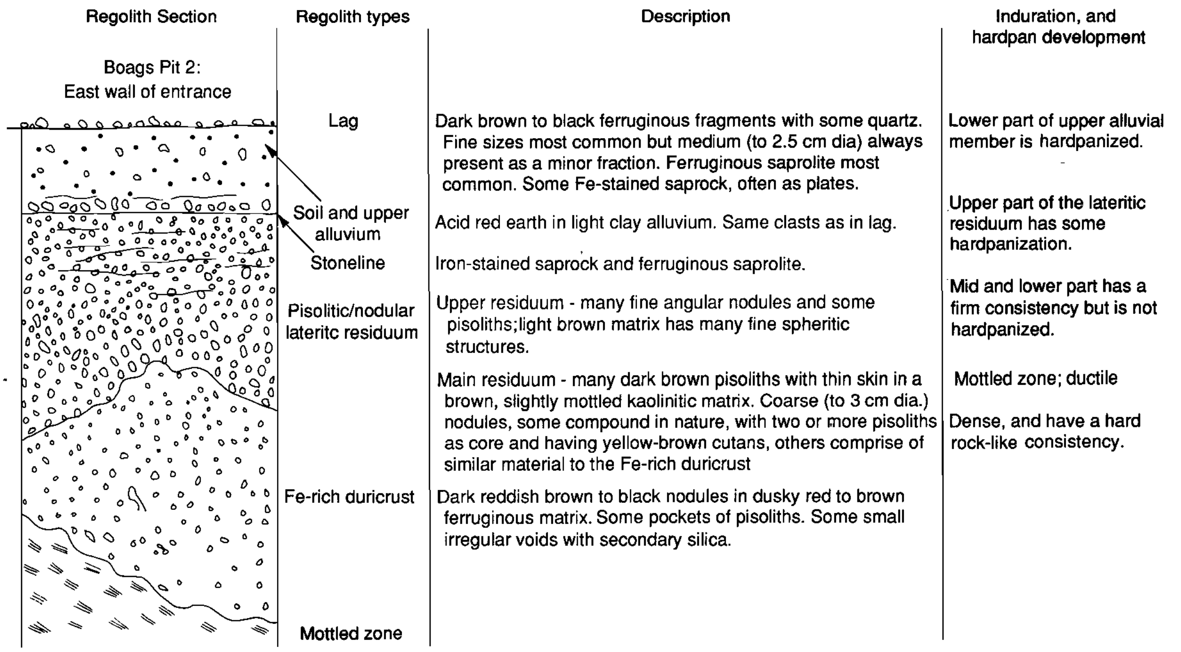
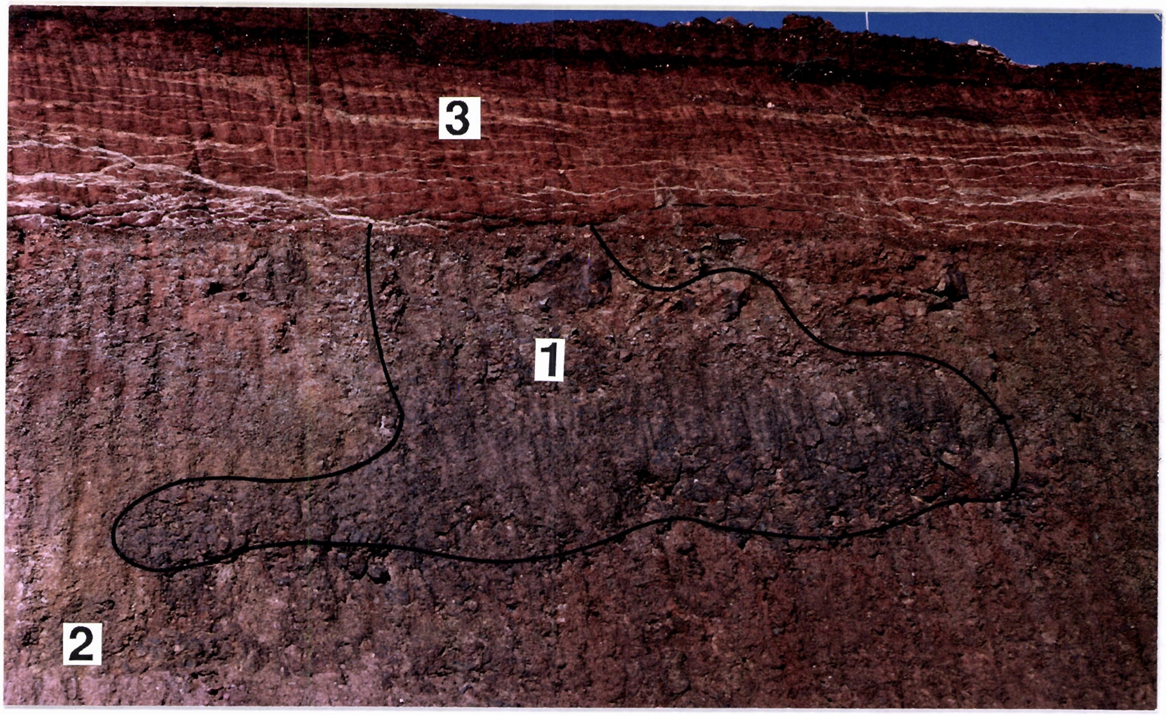


Figure 29. Regolith section through the pocket of lateritic residuum at Boags pit (section 2 in Figure 26).

Figure 30. Pisolitic, lateritic residuum in the E face of the entrance to Boags pit: finer sizes of pisoliths in the upper parts, with coarser sizes prominent in the lower parts.



A. Fe-rich duricrust (1) set in mottled zone (2), beneath the lateritic residuum (3).

B. A close-up showing Fe-rich duricrust (indicated by the hammer) beneath lateritic residuum, with very coarse pisoliths. Some of the pisoliths have cores that are morphologically similar with those in the underlying pisolitic Fe-rich duricrust.

Figure 31. Fe-rich duricrust at Boags pit.

6.0 THE REGOLITH-LANDFORM MAPPING UNITS IN THE UPPER BOTTLE CREEK CATCHMENT

6.1 Introduction

Colour air photos (Kevron Aerial Surveys KN/C935, flown for Norgold, 15 March 1980, Run 6/120 and Run 7/137), enlarged to 1:10,000, provided a base for the detailed mapping of an area of 5 by 8 km in the upper catchment of Bottle Creek. Ground investigation was supplemented by stereoscopic interpretation of black and white air photos (1:50,000; (5083-5085; WA2255 Menzies: Run 3; 26/10/84; photos 5083-5085). The units delineated are referred to as *regolith-landform mapping units*. The regolith-landform map is presented as Figure 32.

6.2 Details of the Regolith-Landform Mapping Units in the Upper Bottle Creek Catchment

The stratigraphic study (section **5**) provided a basis for a detailed legend of the regolith-landform units of the upper Bottle Creek catchment. The general characteristics of the regolith-landform mapping units are given in Table 1 with further details in Appendix I.

A sketch cross section (Figure 33) shows the general relationships of these units to their topographic settings.

Residual Regime

Unit 1: **Broadly convex crests and flanking upper to mid gentle slopes** (Figure 19).

(a) **Crests**

These have scattered blocks of ferruginous saprolite (see Figure 20 a,b,c) with a few blocks of Fe-rich duricrust (in part, the "pebbly" type), Fe-segregations and coarse gossanous bodies. Pockets of calcrete are small and rare.

Lag is dominated by coarse (20 to 40 mm dia.) fragments of ferruginous saprolite with some of Fe-rich duricrust. Lateritic pisoliths and nodules (<10 mm), with yellow-brown cutans, are also present. The shallow soil is a gravelly, light brown, very friable, fine sandy loam on a substrate of ferruginous saprolite and some pisolitic-nodular, lateritic duricrust. Pale saprolite and/or saprock occur at from 1.5 to 3 m depth.

Some crests have only a few blocks of ferruginous regolith and the surface is covered by a lag of coarse, ferruginous saprolite fragments. Some of these fragments have incipient pisolitic structures. On such crests there can also be many pisoliths in the lag (see Figure 20 c).

(b) **Upper to mid slopes.**

Here there are no outcrops of indurated material, saprolite, or fresh bedrock. The lag is dominated by fine (generally <10 mm), dark brown, ferruginous gravels with a few reaching 20 mm (Figure 21). A small proportion of the gravels, being round to ovate pisoliths with yellow-brown cutans. The soil is an acid, gravelly, friable, light brown to reddish brown, fine sandy loam, with moderate, fine black gravel. At a depth of about 150 to 200 mm the gravel fraction sharply increases in size (<50 mm dia.) and comprises ferruginous nodules. It seems that the upper part of this soil has developed in a colluvium, in which the gravel fraction is predominantly fine, ferruginous fragments. Below 150 to 200 mm the size and amount of gravel increases. The clasts are generally coated, light brown to yellowish brown, some are ovate, most are coarse, irregularly shaped, generally composed of ferruginous saprolite and pisolitic, lateritic residuum. This gravelly material, occurring at depth, relates closely to the underlying pisolitic

lateritic residuum and is not likely to have been transported very far. Pisolitic-nodular, lateritic residuum in which hardpan has developed occurs at a depth of about 1 m . It overlies mottled zone, pallid saprolite and saprock. Some very hard, Fe-rich duricrusts appear at depths of 2 to 5 m depth as discrete slabs and lenses; gossanous ironstone occurs as pods.

Unit 2 Lower slopes and broadly concave drainage floors (Figure 34). Fine lag of dark brown to black ferruginous gravel is dominant, there is little or no quartz and lithic fragments are very rare; outcrops of indurated material are rare (Figure 22 a,b). Acid, red-brown, fine, sandy loam to fine sandy clay loam soils occur and are very friable to a depth of 1 m, where hardpan appears. These soils have developed on fine, sandy, clay colluvium which contains much fine (<10 mm) dark brown to black, ferruginous gravel. Pisolitic-nodular, lateritic residuum, sometimes as a brittle duricrust, can occur in places, at depths of 2 to 4 m. Lateritic residuum is not present everywhere, so that the colluvium can rest directly on mottled and/or pallid saprolite.

***Erosional** Regime*

Unit 3: Intensively stripped areas: These are commonly associated with prominent, in places, cliff-like, breakaways (Figure 35 a); the stripped crests above these are included in this unit. Ferruginous saprolite and saprock are extensively exposed and shed a coarse lag. There is very little soil.

Unit 4: Steeply concave to linear slopes below breakaway scarps (Figure 35 a). Saprock outcrops and a lag derived from saprolite is extensive; there are scattered pockets of calcrete. Veins of Fe-segregations occur as low, narrow ridges and are flanked by a lag of coarse, black cobbles. Quartz veins also outcrop and all of these contribute substantially to local regolith variation. The dominant soils are shallow, stony, calcareous earths but some non-calcareous earths occur.

Unit 5: Stripped surfaces on complex lithologies. There are two subunits:

Unit 5a: **Low rounded hills**. Here there is extensive outcrop and subcrop of saprock with associated lag and much calcrete. Quartz veins shed coarse quartz lag and a few wide veins and pockets of Fe-segregations which yield coarse, dense, black cobbles with a vitreous sheen. The dominant soils are shallow, stony, calcareous earths.

Unit 5b: Low rises and gently concave slopes.
Saprock outcrops and subcrop, with its derived lag, and pockets of calcrete are common. Shallow, stony, calcareous earths are dominant, with small pockets of acid, red earths. In places, Unit 5b, occupies the smooth, broadly concave, gently sloping floors of erosional amphitheatres.

Unit 6: Gentle smooth slopes. This generally forms pediments to minor breakaways and is illustrated in Figure 35 b. Acid red earths occur in a colluvium of fine, sandy clay loam. Hardpan is present at 300 to 600 mm and overlies pallid saprock. The medium sized lag fragments are mainly brown, ferruginous saprolite, with some brownish black and steel grey Fe-segregations with appreciable quantities of ferruginized or iron-stained, often platy, saprock fragments. Some of these pediments, particularly just below the breakaway, can have a lag mixed with minor amounts of brown to dark brown pisoliths. Locally, the lag also contains some Fe-rich duricrust with some medium sized quartz fragments.

Unit 7: Minor alluvial tracts;
Some parts are locally incised by minor channels. The lag is sparsely distributed and generally comprises fine fragments of saprock. The alluvium generally consists of sandy loams with some gravel beds. The soils are mainly calcareous earths with some areas of neutral, light brown, sandy loams.

Depositional Regimes

Unit 8: Flat, low-gradient plains.
The lag comprises ferruginous saprolite with appreciable ferruginous, lithic fragments and iron-stained saprock and quartz (see Fig.25 a,b). Fine clast sizes are dominant but a medium size fraction is always present. The soils are very friable, acid, red earths in a fine, sandy, light, clay alluvium that contains some clasts similar to the overlying lags. The substrate is commonly pale saprolite or saprock but there are scattered pockets of nodular-pisolitic, lateritic residuum. Fluvial, bed-load materials, with a high proportion of rock fragments are found occupying the broad trench of a palaeo-drainage system. Hardpan is extensive, generally occurring at a depth of about 1 to 4 m, within the various substrates to the alluvium. A few pockets of friable calcrete occur in the hardpanized sheet flood deposit. This hardpanization is equated with that of the Wiluna Hardpan (Bettenay and Churchward 1974).

Unit 9: Alluvial tracts as low terraces;
These are slightly incised by channels of the present drainage. The alluvium is a loose, light brown, fine sandy loam, with coarse gravel at 0.5 to 1 m depth; there is little or no lag. Unit 9a comprises the minor tributaries of this unit and merges downstream with the wider tracts of Unit 9b.

TABLE 1

GENERAL SURFACE FEATURES OF REGOLITH-LANDFORM MAPPING UNITS FOR THE UPPER BOTTLE CREEK CATCHMENT

Geomorphic Regime	Mapping Unit	Landforms	Regolith
Residual	1	Smoothly rounded crests and flanking upper and mid slopes.	Crests: *Lag:* mainly fragments of ferruginous saprolite; few Fe-rich duricrust (<50 mm); trace gossan. *Outcrop:* some blocks of above types; a few gossanous ironstones; some yellow-brown lateritic pisoliths and nodules. *Soil:* acid, shallow, stony, very friable, light brown, fine sandy loam. Gradual change to flanking slopes. Slopes: *Lag:* fine (<15 mm) dark brown and black ferruginous fragments; trace lateritic pisoliths and nodules. *Outcrop*: none. *Soil:* acid, gravelly, very friable, light brown to reddish brown, fine, sandy loam. Substrate of pisolitic-nodular, argillic, lateritic residuum.
	2	Long, very gentle, lower slopes and broadly concave floors.	*Lag:* fine (less than 10 mm dia) dark brown to black ferruginous fragments; trace pisoliths. *Soil:* acid, red, very friable, fine sandy clay loam to light clay.
Erosional	3	Steeply sloping, breakaway faces; some gently bevelled, crests.	*Lag:* coarse, iron-stained saprock with coarse quartz fragments. *Soil:* very thin, stony calcareous earths. *Saprolite:* extensive exposure.
	4	Steeply concave, pediments.	*Lag:* coarse fragments of saprock, Fe-segregation and vein quartz. *Outcrop:* widely scattered, of weathered rock; some quartz veins and calcrete pockets. *Soil:* grey-brown, calcareous earths common.
	5a	Low hills and shallow vales.	*Lag:* usually coarse and of variable composition. *Outcrop*: scattered saprock; some iron-stained saprock; quartz and calcrete. *Soil:* red earths and calcareous, grey-brown earths.
	5b	Low rises and gently concave slopes.	*Lag:* generally coarse; variable composition. *Outcrop:* few, saprock and ferruginous saprolite, quartz and calcrete. *Soil:* calcareous, grey-brown earths, and some red earths.
	6	Gently concave, pediments.	*Lag*: ferruginous saprolite. *Outcrop:* none. *Soil:* uniform cover of acid, red earths in clay loam colluvium.
	7	Narrow, alluvial tracts.	*Lag:* sparse. *Soil:* calcareous, grey-brown earths.
Depositional	8	Upper, tributary plains	*Lag:* ferruginous types, mainly saprolitic; some iron-stained saprock; mantled by co-alluvium. Quartz always present. Finer fractions dominant but some medium sizes always present. *Soil:* acid, red earths in friable, light clay.
	9a	Alluvial tract, 50 to 120 m wide.	*Lag*: none. *Soil:* brown, silty to sandy loam.
	9b	Alluvial tract, 120 to 350 m wide.	*Lag*: none. *Soil:* brown, silty to sandy loam.

Landform regime	Mapping Unit	*Abbreviated characteristics*
Residual		
	1	Crests and upper to mid slopes with lateritic substrate
	2	Lower slopes and local broad valley floors with lateritic substrate
Erosional		
	3	Saprolite outcrops: breakaway scarps and crests
	4	Steep pediments with pedogenic carbonate
	5a	Low hills, red earths, calcareous earths
	5b	Low rises, calcareous earths, acid red earths
	6	Smooth pediments with pedisediment, acid red earths
	7	Minor alluvial tracts; calcareous sediment
Depositional		
	8	Flat gently graded plains: alluvium
	9a	Alluvium, minor tributaries
	9b	Alluvium, medium-sized tributaries

Abbreviated legend for the detailed map of regolith-landforms units in the upper Bottle Creek catchment (Figure 32)

Figure 32. Detailed map of regolith-landform units in the upper Bottle Creek catchment.
Aerial photographs 6/120 and 7/137, 15.3.80, Kevron Aerial Surveys, published with permission of North Ltd.

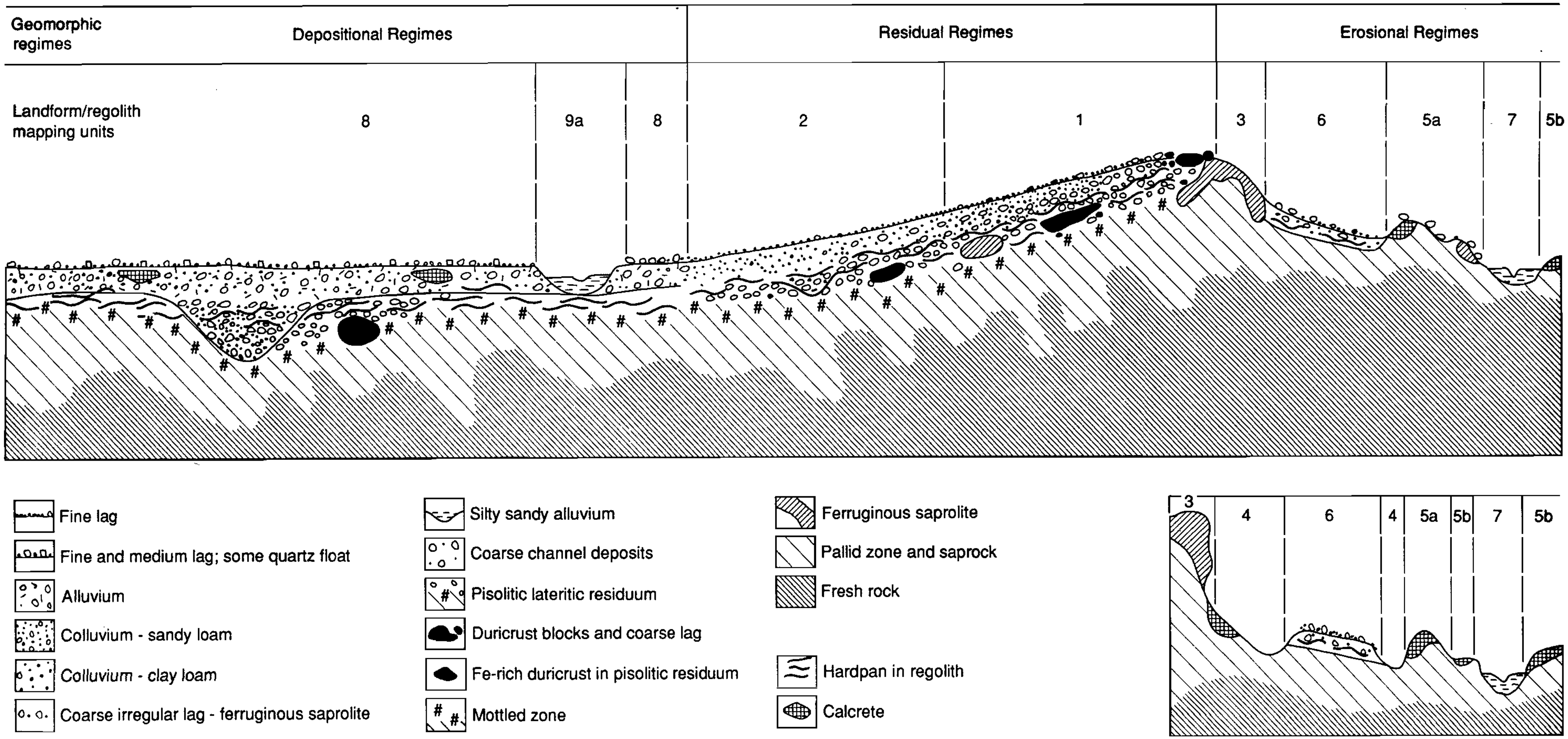


Figure 33. Idealized cross-section, illustrating the relationship between landforms and regolith types, in the upper Bottle Creek catchment.

Figure 34. Long, very gentle, lower back slopes of a residual regime at Southwark.

A. A major breakaway comprising an erosional escarpment (Unit 3) that gives way to a steep debris slope below (Unit 4). Halfway down the sloping, right hand skyline is the smooth outline of a remnant of an earlier phase of pediment development (Unit 6). This is being destroyed by a more recent phase of active erosion with consequent development of the steeper slopes of Unit 4).

B. A minor breakaway with a convexo-concave profile, merging to the smooth, gentle pediment below (Unit 6).

Figure 35. Breakaway types at Bottle Creek

7.0 THE REGOLITH AND LANDFORMS OF THE BOTTLE CREEK DISTRICT

7.1 Introduction

A reconnaissance study was carried out on a rectangular area of 445 km^2 (32.5 km NW by 14.0 km) to test the general application of the detailed studies in defining the regolith, on a greenstone sequence, surrounding the upper Bottle Creek catchment. This area is underlain by both granite and greenstones and so furnishes an opportunity to compare the respective effects of contrasting lithologies on the regolith stratigraphy. In addition to the upper Bottle Creek catchment, the detailed reconnaissance included the divide between the Raeside and Ballard drainages. The Copperfield mining centre and the Bottle Creek mining operations, lie within this area studied. This involved stereo interpretation of the black and white (1:50,000) air photographs and ground traversing.

The resultant regolith-landform map (1:25,000) and has been reduced for inclusion in the text, Figure 36 (in pocket). The map shows seventeen landform-regolith units developed mainly on mafic lithologies. Details of these units are presented in Table 2 and their general topographic relationships are illustrated as a schematic cross section, Figure 37. Three of the units comprise a residual regime, two of which are on mafic rocks. Five units, representing erosional regimes, occur on the greenstones and two on granitic rocks. The depositional regime comprises three units developed on greenstones and two on granites. The two units of residual regimes on greenstones may be equated with those in the detailed study of the upper Bottle Creek catchment. The residual units on granitic rocks comprise gently undulating sandplains. Erosional units, mE(i), mE(ii) and mE(iii), on greenstones, represent a transition from dissected tracts, dominated by breakaways, through low hills, and finally to a gently sloping to slightly undulating, stripped plain. The unit mE(iv) comprises erosional amphitheatres and other areas of localized stripping; mE(v) are hill belts with strike ridges developed on banded-iron formations. Erosional units on granitic rocks are generally amphitheatres partially ringed by breakaways *f*E(i), with domes, tors and platforms of relatively fresh granitoids of unit *f*E(ii). The depositional regimes are generally represented by extensive, gently graded, flat plains and, locally, some of these have been affected by further stream incision and resultant erosion.

Table 3 compares the units of the three map scales used in this study. This change of scale has allowed progressive subdivision from broad reconnaissance units to units of the detailed map. For example mE, at 1:250,000, has been subdivided to five units, mE(i) to mE(v), at 1:25,000. At a scale of 1:10,000, a unit such as mE(i) may be further subdivided into four units as more detail was gathered.

7.2 Comparison of the Regolith and Landforms of Greenstone Terrain with Granitic Terrain

The characteristics of the regolith units and landforms on greenstone sequences and adjacent granitic rocks in the Bottle Creek district, are summarized in Table 4.

7.2.1 Residual Regimes

Table 4 shows that residual regimes on both greenstone or granite are, in general, gently undulating tracts comprising broad drainage floors with an intervening complex of broadly convex crests. The topography of residual regimes on granitic rocks appears to be more broadly undulating and less complex than that of the greenstones. Small areas of shallow stripping in granitic terrains are associated with the crests and these also occur as narrow zones immediately

behind breakaways. A few longitudinal dunes reflect the sandy nature of the upper regolith over granitic rocks which is characterized by brown and red-brown sands and clayey sands, generally with hardpan developed at about 2 m. There are a few scattered outcrops of brown, coarse, nodular, lateritic materials, some with brown pisoliths (<15 mm), on broad crests. Coarse cobbles and blocks of silcrete are common on the surface of a narrow zone of slightly greater stripping, above the breakaway scarps. Apart from these materials, pebbly lag on residual granitic terrain is rare. In contrast, pebbly lags of various ferruginous materials, saprolitic or lithic are widespread feature of areas over greenstones. Fine lag dominates the long, gentle slopes and floors of the residual terrain. Brown to reddish brown soils, with a readily perceptible fine sand fraction and a high proportion of ferruginous fragments occur on greenstone terrain and these contrast with the medium and coarse sands and clayey sands of the soils of residual areas on weathered granites.

7.2.2 Erosional Regimes

Breakaways on both granites and greenstones are generally capped by saprolite or saprock. Well-developed nodular or pisolitic structures are not common in the face of breakaway scarps on either lithology. The capping on granitic rocks is generally greyish white, gritty, kaolinitic clay, case-hardened by mild ferruginization and/or silicification; this feature provides much of the bold appearance of breakaway scarps on the granitoid rocks. Silcrete also occurs as blocks and cobbles. In places this silcrete has a granitoid texture but generally it is arkosic, due to partial loss of kaolinite (Butt, 1983). In contrast many breakaway scarps on weathered greenstones are developed in more uniformly ferruginized and indurated saprolite. Fe-rich duricrusts as extensive caps, as blocks, slabs and large lenses, are not common in the Bottle Creek study area.

On the gentle pediment slopes, just below the breakaways in weathered granitic rocks, the upper regolith comprises pale, gritty, clayey saprolite overlain by a veneer (<0.5 m thick) of pale, gritty, quartzo-feldspathic sands. Locally, the pediments can have a dense mantle of coarse silcrete cobbles. However, sporadic outcrops of fresh granite, often as domes and tors, yield a light brown, gritty detritus. There are a few pockets of calcrete on low outcrops of weathered granite and small areas affected by salinity. There is no ferruginous lag on pediments on felsic rocks, which contrasts with the coarse ferruginous saprolite lag that characterizes the smooth pediments below low erosional scarps on mafic rocks. This ferruginous lag overlies reddish brown, friable, fine, sandy, acid clay soils with hardpan at depth.

In the more active erosional tracts, variously weathered greenstones are exposed extensively on the upper pediments (the debris slopes); calcrete is also extensive, though not continuous. More active erosion appears to have little effect on the array of regolith materials in areas of granitic rocks.

Where banded-iron formations occur strike ridges are present in erosional tracts. These areas contrast with the more subdued relief of granitic erosional terrain which, in the Bottle Creek area, comprises low domes and gently inclined pediments. Extensive, very slightly undulating, erosional plains occur on the greenstones, notably in the vicinity of the Copperfield Mining Centre where friable, calcareous clays extensively overlie bevelled, greenstone saprolite, at a depth of about a metre. The lag varies in composition and size and consists of ferruginous saprolite with a relatively high proportion of lithic and quartz fragments. These are related to small outcrops and subcrops of various elements of the greenstones.

7.2.3 Depositional Regimes

On the main depositional terrain of the greenstone sequence, the regolith is characterized by a uniform mantle of friable, acid, red clays, with a hardpan at one metre depth. The lag is characteristically coarser than that on residual surfaces although there can be a high proportion of fine lag. A significant proportion of lithic fragments is present, including saprock and quartz. The detailed stratigraphy recorded above has indicated the variable nature of the substrate. Bevelled surfaces on weathered rock and saprolite are most common but there are a few pockets of pisolitic lateritic residuum preserved as well as some palaeochannels and associated coarse channel deposits reaching 10 m in thickness. There is no lag on deposits from granites other than fine granules of quartz and feldspar as the main deposits on these areas comprise gritty, sandy loams close to the erosional tracts, grading laterally into sandy, clay loams 1 to 2 km from the source. Hardpan is continuous within 1 m of the surface. These deposits form extensive plains. Sets of wanderrie banks (Mabbutt, 1963) can be present on these deposits. These are the result of differential deposition by unchannelled sheet flood action which has moulded the coarse fractions into low sandy rises, and which are preferred by mulga plant communities.

7.3 Summary of the Regolith-Landform Patterns of the Bottle Creek District

The pattern of regolith types at Bottle Creek relates closely to bedrock geology, landforms and to the varying degrees of erosional and depositional modification of the deeply weathered mantle. Generally, areas developed on greenstones at Bottle Creek are mantled by various ferruginous lags, and on some crests, blocks of various ferruginous duricrusts (of various kinds) are common. Pockets of calcrete are rare. In contrast, areas that overlie granitoids have little lag, much less carbonate and have more sandy soils.

In more detail, a large area of fine, ferruginous lag occupies a low, broad saddle that straddles a portion of the Raeside-Ballard drainage divide, just N of the Bottle Creek mine pits. It has an extensive substrate of pisolitic, lateritic residuum. This smoothly undulating surface is interpreted as a relic of an ancient, weathered landsurface. Mild bevelling of broad crests, part of the undulations within this unit, has exposed blocks of ferruginous saprolite, Fe-rich duricrust, gossanous ironstone and some pisolitic, lateritic residuum. As a consequence the relief of the ancient landsurface has been slightly reduced and relief reduction has been accentuated by local accumulation of derived detritus. The results of this mild bevelling and localized downslope accumulation are reflected in units mR(i) and mR(ii).

To the N and S of this undulating surface, the landsurface gives way to flat, gently graded plains (mD(i)) mantled by lag. This lag has a large amount of medium size fraction of ferruginous saprolite as well as lithic fragments and quartz. The detailed studies above show that pockets of lateritic residuum form a discontinuous element of the regolith stratigraphy on this depositional plain and that these are buried by sheet flood alluvium. This further suggests that the landsurface, occupied by the lateritic residuum, had slightly more relief than the present land surface. Fragmentation of the weathered mantle indicates at least one earlier erosional phase in the genesis of stratigraphy of this plain, possibly in response to active trenching by parts of the ancestral Bottle Creek drainage. Parts of this earlier drainage is seen, exposed in the face of the VB and Boags pits, covered by extensive sheet flood deposits.

The undulating tract, mantled by fine, ferruginous gravel, shows scattered remnants which rise slightly to the east and, more so, to the west. Here, prominent summits relate in part to zones of banded-iron formation. The tract is also extensively fragmented by minor upper tributaries. At the other topographic extreme, there are also scattered pockets of pisolitic, lateritic residuum

beneath the alluvial mantle of depositional areas as at Boags pit. It seems that the weathered surface was once an undulating landscape which had a range in elevation only slightly greater than the present one.

The more striking consequence of erosion is the N-NW oriented zone of breakaway scarps west and southwest of the Copperfield mining centre (mE(i)). Eastwards from the line of scarps, towards Copperfield, this erosion has been so effective that the breakaways and mesas give way to erosional plains, through an intermediate stage dominated by low hills (mE(ii)). The very slightly undulating surface of this plain has very low, broad rises, generally less than 2 m high, interspersed with alluvial floors. Friable calcareous clays are probably the most extensive regolith type and these overlie a bevelled saprock surface at a depth of approximately 1 m. Although the plain is essentially erosional, there is evidence that an earlier depositional phase occurred during planation. West of Copperfield, extending E from the main line of breakaways, are a series of very low, broad, flat-crested, elongate spurs, capped with alluvium. This alluvium is comparable to that of the main depositional plain in which the Boags and VB pits are situated. Thus it is a friable red clay alluvium having acid red earths and hardpan, and the lag is typical of the depositional regime, i.e. dark ferruginous fragments, including a medium to coarse component, along with lithic fragments and quartz. Given sufficient scale, it could have been mapped as mD(i). These low crests are flanked by gentle breaks in slope which have pockets of calcrete and some exposure of saprock and quartz veins. The crests are relics of a more extensive body of alluvium, the result of an earlier aggradational phase.

Erosional amphitheatres, (mE(iv)), representing various degrees of mild stripping, are scattered throughout the main tract of residual regimes. These contribute alluvium as local fans, comparable to elements of the depositional regime (mD(i)). Thus, the lag on such areas of alluvium contrasts with the fine gravel on the surrounding residual regimes (mR(i)). They are locally distinct and can be particularly useful for geochemical sampling because of their significant, locally-derived, lithic fraction.

Within the area chosen for this study, areas of granitic terrain are not as extensive as those on greenstone. Residual regimes in granitoids to the NW are represented by very broadly undulating, sandplains (fR(i)). There are local erosional catchments with characteristic breakaways and pallid saprolite exposed. The minor depositional fans resulting from these catchments have wanderrie banks _D(i)). Several extensive clusters of low domes and tors on the eastern and northeastern limits of the mapped area represent more extreme etching of the weathered granitic rock (_E(ii)). Extensive bodies of alluvium (_D(ii)) extend N from these although, at their margins, it merges with detritus from the greenstone sequences. Alluvial trains from granitic rocks lack any pebble lag and contrast with the adjacent alluvial trains derived from the greenstones that are extensively strewn with medium to fine, ferruginous lags.

TABLE 2

REGOLITH-LANDFORM UNITS FOR THE BOTTLE CREEK DISTRICT (Refers to Figure 36, the map at the back of this report)

Greenstone sequence (mainly mafic/ultramafic rocks) - m. **Granitic rocks** - *f*.

Residual Geomorphic Regime - gently undulating upland, extensively mantled by lateritic materials.

Regolith-landform units	mR(i)	mR(ii)	*f*R(i)
Landform	Broadly rounded crests and long, gentle, smooth, upper to mid slopes.	Long, gentle, smooth, lower slopes and broadly concave floors.	Very gently, undulating uplands; a few longitudinal dunes.
Lag	*Crests*: medium to coarse, brown, ferruginous saprolite; some Fe-segregations and Fe-rich duricrusts; and gossanous types; some pisoliths with yellow-brown cutans. *Slopes*: Lag becomes finer down from crest; lag coating darkens down slope; also there are less cutans.	Fine, brown to black, ferruginous types of mixed origin; little or no quartz.	Pavements of coarse silcrete boulders on local stripped crests.
Soils	*Crests*: shallow stony, acid, brown, friable, sandy loams. *Slopes*: gravelly, brown, friable, acid, sandy loams; coarse, gravelly at depth. Widespread gravelly, sandy loam colluvium to 2 m thick, by mid slope.	Acid, red earths on very friable, fine, sandy clay loam.	Acid, red clayey sand.
Transported regolith types	Widespread gravelly, sandy loam colluvium to 2 m thick, on mid slope.	Colluvium continuous, 2 to 4 m thick. Friable, fine, sandy, clay loam to light clay with fine, black ferruginous gravels of mixed origin.	Sandy colluvium; locally sorted by wind action.
Lateritic residuum and associated materials	Discontinuous on crests; continuous substrate to upper and mid slopes as a slightly mottled, red and brown clay containing many pisoliths with yellow-brown cutans. *Crests*: blocks of Fe-rich duricrusts, ferruginous saprolite and Fe-segregation. Much lateritic residuum removed by gentle stripping. *Slopes*: indurated lateritic residuum a common substrate with lenticular, tablular and irregular bodies of Fe-rich duricrust.	An almost continuous substrate; sometimes absent due to removal by an early erosional phase. Morphologically similar to the substrate of mR(i). Leticular, tabular and irregular bodies of Fe-rich duricrust within the lateritic residuum. Lateritic residuum, frequently partially indurated.	Coarsely mottled clay at 3 to 4 m; poorly indurated, coarsely pisolitic and nodular, lateritic residuum, locally on crests.
Hardpan	In the soils and lateritic residuum at about 1 m; 1 to 3 m thick.	At about 1 m and thence to about 3 to 4 m.	Extensive at a depth of about 2 m.
Mottled zone	Generally continuous substrate to lateritic residuum.	Generally continuous substrate to lateritic residuum.	Extensive.
Calcrete	Rare, small pockets on crests.	Not present.	Not present.
Outcrops	None.	None.	None.

Erosional Regime - includes hills, scarps, ravines and stripped plains.

Regolith landform units	mE(i)	mE(ii)	mE(iii)	mE(iv)	mE(v)
Landforms	Prominent scarps and some ravines above steep, debris slopes. Mesa-form hills capped by duricrust of ferruginous saprolite and saprock. Some local, gentle pediments and gently concavo-convex; low breakaways. Local, steeply graded, alluvial tracts with active runnels.	Complex of low stony hills and intervening narrow alluvial tracts.	Very slightly undulating plain comprising low, broadly convex, rises, flanked by long, gentle slopes. Narrow, intervening, alluvial tracts.	Shallow, local erosional catchments, generally amphi-theatre-like, flanked by concavo-convex slopes of low breakaways; includes some gently bevelled, broadly convex crests.	Hill tracts with strike ridges; narrow rounded crests flanked by steeply concave slopes. Strike valleys with narrow alluvial tracts.
Lag	Ferruginous saprolite, iron-stained saprock and lithic fragments; patches of coarse, black cobbles of Fe-segregations and of quartz; very rare Fe-rich duricrust.	Iron-stained, fresh and weathered rocks; patches of coarse cobble comprising Fe-segregations and quartz.	Iron-stained, lithic types; occasional ferruginous saprolite and Fe-segregations; black-coated ferruginous, lithic fragments.	Medium and fine fragments of ferruginous saprolite with occasional Fe-segregations and Fe-rich duricrust; some quartz. Some pisoliths on local crests and upper slopes.	Very coarse, angular fragments of saprock and fresh rock; generally with a brown or dark brown varnish.
Soils	Shallow, stony, friable, neutral to acid sandy loams; pockets of shallow, stony, alkaline earths on calcrete patches.	Shallow, stony, friable, calcareous earths.	Calcareous earths and sodic duplex soils; acid, red earths on local crests.	Acid, red earths; small pockets of calcareous earths.	Shallow, stony, red-brown lithosols.
Transported regolith types	Shallow, stony, colluvium on slopes. Local, alluvial trains; 1 to 2 m thick.	Shallow, stony, colluvium on slopes. Local alluvial trains; 1 to 2 m thick.	Thin, stony colluvium, on gentle, upper slopes, merging to alluvium, as a fine sandy, clay loam along the alluvial tracts; pockets of stony alluvium on low, local crests.	Stony colluvium.	Shallow, stony, colluvium; locally, stony alluvium.
Lateritic residuum	Usually absent; rare Fe-rich duricrust.	Not present.	Not present.	At depth, but not continuous.	Local patches of Fe-rich duricrusts and ferruginous saprolite.
Hardpan	Occasionally on local, gently sloping pediments.	Rare.	Limited occurrence, beneath acid red earths on local crests.	Extensive.	Rare.
Mottled zone	Not present.	Not present.	Not common.	Extensive deep substrate.	Rare.
Calcrete	Scattered small patches.	Scattered small patches.	Extensive.	Not common, a few local patches.	Scattered pockets of calcrete.
Outcrops	Patchy - extensive subcrop.	Patchy - extensive subcrop.	Sporadic.	Rare.	Frequent outcrops of greenstone sequence, including banded-iron formation.

TABLE 2 (cont)

Regolith landform units	*f*E(i)	*f*E(ii)
Landforms	Breakaway scarps, local pediments and alluvial floors.	A complex of low, rounded crests and narrow alluvial floors.
Lag	Very fine granules and coarse, quartzo-feldspathic, sand. Some cobbles of silcrete and granite.	Some fresh and weathered rock fragments on slopes; coarse quartz and quartzo-feldspathic grains.
Soils	Gritty, acid, red sands and clayey sands.	Gritty, acid, red earths.
Transported regolith types	Gritty colluvium; local gritty alluvium.	Gritty colluvium; some local stony phases.
Lateritic residuum	Not present.	Not present.
Hardpan	Rare.	Not present.
Mottled zone	Not present.	Not present.
Calcrete	Not present.	Not present.
Outcrops	Pale saprolite exposed in the breakaway face; forms a substrate to some soils on the pediment. Sporadic granite domes and tors.	Extensive, as granite domes, tors and platforms.

Depositional Regimes - low gradient flat plains mantled by alluvium.

Regolith-landform units	mD(i)	mD(ii)	mD(iii)	*f*D(i)	*f*D(ii)
Landforms	Low gradient upper tributary plains.	Drainage floors in upper tributary plains.	Lower tributary plains; multiple, discontinuous, shallow channels.	Upper tributary plains, few drainage floors.	Complex drainage zone; dominated by discontinuous, channelled tracts.
Lag	Much fine, dark brown, ferruginous fragments - mainly saprolite. Some medium fragments. Some lithic fragments, generally ferruginized. Some medium-sized quartz.	Patches of fine to medium gravels as in mD(i).	Medium to fine, brown to black, ferruginous saprolitic and lithic types; some medium-sized quartz fragments.	Quartz grains.	Scattered patches of fine, dark brown, ferruginous and lithic fragments; quartz uncommon.
Soils	Acid red earths with gravels, comprising friable, fine, sandy light clay.	Acid red earths, comprising very friable red clay.	Acid red earths, comprising very friable light clay.	Acid, red earths comprising very friable, gritty, sandy loam to coarse, sandy, clay loam.	Acid, red, earths, comprising very friable gritty clay loam.
Transported regolith types	Sheet flood deposits with some gravel, generally less than 2 m thick. Some coarse channel deposits < 10 m thick.	Alluvial silts and sands < 1.5 m thick, over gravels.	Continuous alluvial mantle; friable light clay with fine ferruginous gravel.	Extensive alluvium.	Extensive alluvium - some contribution from mafic/ultra-mafic terrain.
Lateritic residuum	Scattered pockets of pisolitic types as substrate.	Not present.	Scattered pockets of pisolitic type.	No information.	No information.
Hardpan	Extensive at about 1 m, and extending into the substrate to a depth of about 5 m; probably not as well developed as in areas of the stable regime.	None present.	Extensive, at a depth of about 1 to about 4 m.	Extensive at a depth of about 1 m.	Extensive at a depth of about 1 m.
Mottled zone	Extensive but not continuous deep substrate.	Not present.	Unknown.	No information.	No information.
Calcrete	Uncommon, as scattered pockets.	Very rare.	Uncommon, as a few small pockets.	Very rare.	Rare, as isolated pockets.
Outcrops	None.	None.	None.	None.	None.

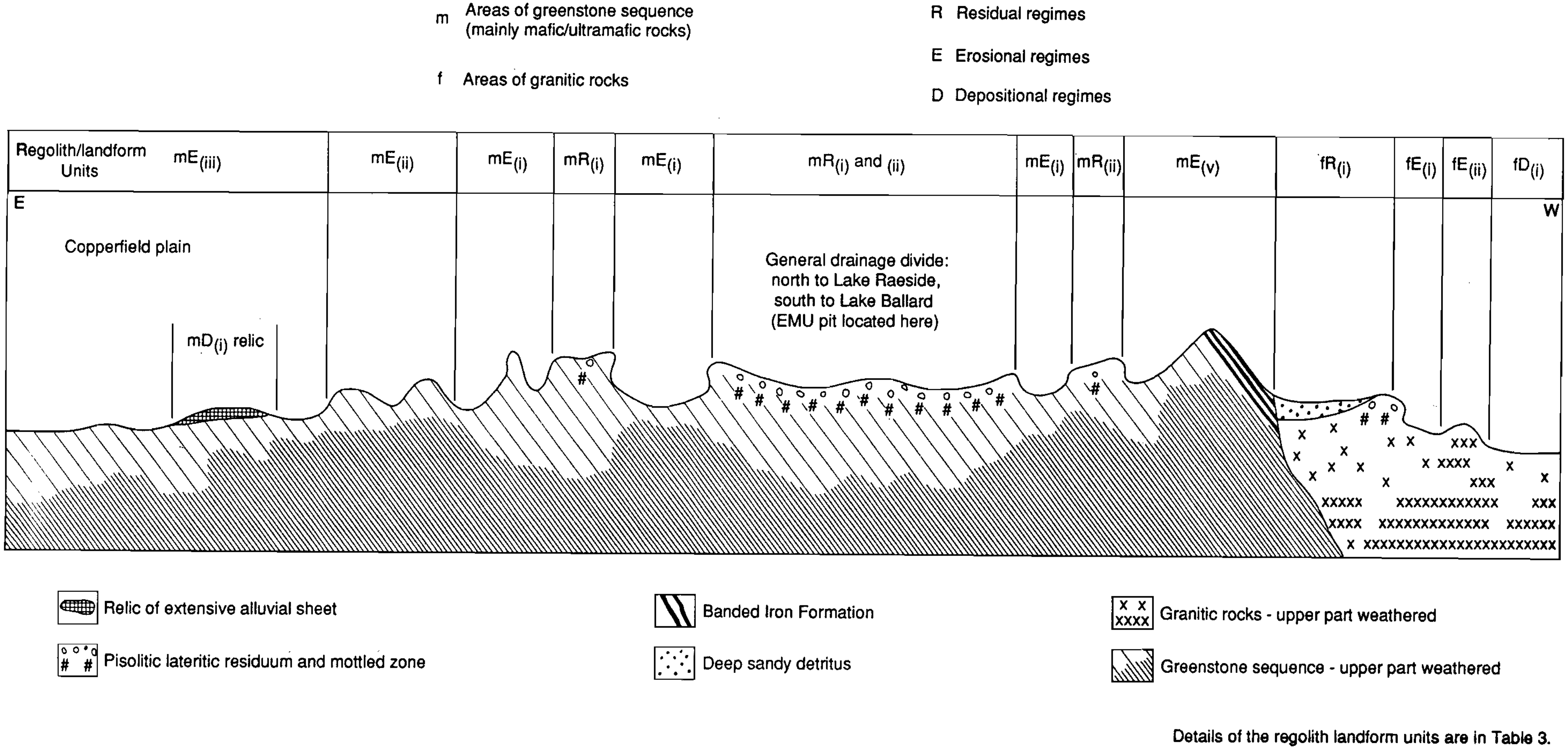


Figure 37. Cross-section, looking south, illustrating the broad relationships between regolith-landform units, recognized during the reconnaissance of the Bottle Creek district. Details of the regolith-landform units are given in Table 2.

TABLE 3

UNITS RECOGNIZED FOR THE THREE MAPPING SCALES USED IN THE BOTTLE CREEK STUDY

Lithology	Regolith-landform Regime	Map Scale		
		Subregional broad rec. map. Approx. 1:250,000	Bottle Creek District detailed rec. map. 1:25,000	Upper Bottle Creek Catchment detailed map. 1:10,000
Greenstone sequence	Residual	mR	mR(i) mR(ii)	1 2
	Erosional	mE	mE(i) mE(ii) mE(iii) mE(iv) mE(v)	3, 4, 6, 7 5a, 5b
	Depositional	mD	mD(i) mD(ii) mD(iii)	8 9a,9b
Granitic rocks	Residual	*f*R	*f*R(i)	No granitic rocks in the detailed study area
	Erosional	*f*E	*f*E(i) *f*E(ii)	
	Depositional	*f*D	*f*D(i) *f*D(ii)	

TABLE 4

COMPARISON OF LANDFORMS AND REGOLITH TYPES BETWEEN GREENSTONE AND GRANITIC TERRAIN, BOTTLE CREEK DISTRICT

	Greenstone sequence	Granitic rocks
Residual Regimes		
Landform	Undulating; vales more common.	Much more broadly undulating; vales broader and less common.
Regolith	*Soils:* gravelly, fine sandy loam. *Colluvium:* extensive gravels and fine sandy loam. *Lateritic residuum:* pisolitic, argillic types extensive. *Duricrust:* pisolitic, argillic residuum; Fe-rich duricrust; massive, massive-vermiform and fragmentary types. *Lags:* extensive. fine, ferruginous types most common; lithic fragments very rare. *Outcrop:* coarse fragments of duricrusts on crests, also as blocks and slabs. Some outcrops of Fe-segregations; ferruginous saprolite, where duricrust is locally absent. *Calcrete:* rare; small patches on crests. *Hardpan:* extensive at 1 m, then to a depth 4 to 5 m.	*Soils:* coarse sand and clayey sand. *Colluvium:* extensive sand and clayey sand. *Lateritic residuum:* nodular/mottled, argillic types occasionally present. *Duricrust:* mottled and nodular, argillic. *Lag:* Very rare patches of mottled, ferruginous nodules. *Outcrop:* blocks and slabs of duricrust as rare patches. *Calcrete:* Rare; in swales. *Hardpan:* extensive; at depths of >2 m.
Rock outcrops	Very rare; small pockets.	Rare; as small domes or pavements.
Erosional Regimes		
Landforms	Breakaways; pediments; stripped plains; low hills (sometimes as strike ridges).	Breakaways; gentle pediments; low hills as domes, tors and pavements.
Regolith	*Pedisediment:* as fine 'sandy' clay loams <1 m thick on low angle pediment. *Colluvium:* shallow, stony on steep slopes. *Saprock:* common subcrop. *Breakaway face:* indurated, ferruginous saprolite and iron-stained saprock; Fe-rich duricrust rare. *Lag:* medium to coarse, iron-stained, lithic fragments, ferruginous saprolite, Fe-segregations and quartz. *Calcrete:* widespread but as scattered patches. *Hardpan:* in colluvium on gentle pediments; none on steeper, erosionally active, slopes.	*Pedisediment:* pale 'grey-brown' gritty, on pallid saprolite; some light brown adjacent to fresh granite outcrop. *Breakaway face:* generally case hardened, pallid saprolite. Some large zones of induration, generally as sheets of silcrete; silcrete also as blocks and cobbles. *Lag:* quartz and feldspathic grains. *Calcrete:* Some present, coating granite outcrops. *Hardpan:* Uncommon.
Rock outcrop	Sporadic; some thick veins of quartz and Fe-segregations.	Sporadic; as domes, pavements and tors.
Depositional Regimes		
Landforms	Major and tributary plains; some local fans. Wanderrie banks not as well developed as on granitic rocks.	Major and tributary plains; some local fans. Wanderrie banks can be well developed.
Regolith	*Alluvium*: extensive. *Lateritic residuum:* patches as a substrate. *Mottled zone* and/or *saprock*: extensive substrate. *Lag:* medium and fine, ferruginous saprolite, ferruginous lithic and iron-stained lithic fragments; quartz. *Calcrete:* scattered patches. *Hardpan:* extensive at about 1 m, extends to about 4 m depth.	*Alluvium.* *Lateritic residuum:* substrate unknown. *Lag:* none. *Calcrete:* generally present. *Hardpan:* extensive at about 0.5 m, extends to depth; uncertain thickness.
Rock outcrop	None.	None.

8.0 SYNTHESIS OF REGOLITH DEVELOPMENT

8.1 Introduction

Development of the regolith at Bottle Creek is a multiprocess, polyphase phenomenon. On the one hand it involves several types of weathering of the country rock, including the physico-chemical segregation of the oxides of iron; on the other hand there is differential removal of the weathered regolith mantle by fluvial erosion and subsequent burial. The contribution of these processes to the regolith types in the study area is presented schematically in Figure 38.

8.2 Weathering

Weathering on the Yilgarn Block is generally of a lateritic nature, involving loss of alkaline earth elements, and silica (from the feldspars in particular), leading to deep kaolinization of the country rock. Much of the ferrous iron, released during weathering of the primary minerals can, if near ground surface be oxidized and precipitated. As a result a ferruginous horizon develops in the upper part of the deeply weathered mantle. The role of fluctuating water tables in this process is not clear, particularly in the early stages of weathering. Later, as the regolith deepens, a fluctuating water table could be less likely to have an effect on weathered mantle. Local segregation of the iron in the ferruginous horizon leads to the development of pisolitic/nodular structures.

The pisoliths may be the result of intense concentration of iron oxides around a range of loci. Their dark brown to black colour distinguishes them from the diffusely mottled, clayey matrix of the lateritic residuum; their distinction from the residuum is further enhanced by finely layered, light brown cutans. The concentration of iron around loci is likely to be associated with decreased permeability. A consequence of this suggested lowered permeability might be that iron- and clay-bearing groundwaters could move round such mottles, depositing goethitic and kaolinitic skins (perhaps through the development of menisci during recurring drying phases). Pisoliths are well developed in the lateritic residuum at Emu pit and here there is a decrease in the pisolith abundance with depth, possibly in response to less oxidized conditions deeper in the regolith.

Very fine, spheritic clay bodies (usually <1.0 mm dia.) are common in the matrix of the lateritic residuum. They become less abundant at depth, apparently being progressively replaced by more angular fragments of the kaolinite-rich matrix. These fragments could be due to infusion of iron oxides along fine cracks in the kaolinitic saprolite by a process similar to that suggested by Killigrew and Glassford (1976). This could have led to a rounding of the clay fragments and extensive development of spherites in the upper parts of the lateritic residuum.

Ferruginous saprolite could be the result of deposition of iron in the initial stages of weathering. Even this can show some Fe-segregation such as diffuse, irregular mottles and incipient pisoliths. Further weathering results in a marked degree of porosity at the mesoscopic scale, causing coarse (<10 mm), generally vermiform, voids. Some of these are lined with goethite and secondary silica and/or are occupied by a mass of clay spherites. Where such voids are intensively developed the mass is generally referred to as vermiform duricrust. Intensive amalgamation of these coarse voids leads to collapse of the ferruginous saprolite. However much of the void space still remaining may be reoccupied by elluvium from upper parts of the regolith, and this is generally dominated by spherites. Cutans are laid down on the surface of the fragments and the whole mass may be recemented, forming fragmentary duricrust that has a brecciform appearance, as a consequence of this complex history of development.

The origin of the discrete bodies of Fe-rich duricrust such as those on the floor of the S side of Emu pit and at the decline into Boags, is less clear than that of the pisolitic, lateritic residuum. Some of these masses appear to be closely associated with the weathering of iron-rich lithologies, such as the pyritic shales and associated gossanous bodies which release iron (Fe^{2+}), and locally cause very acid conditions. At Emu test pit they are in close proximity (<2 m) to gossanous ironstone and are, in places, continuous with them. Although the Fe-rich duricrusts could have been derived from these previously sulphidic materials, the origin of their magnetic characteristics while the process by which iron is differentiated into black nodules that are set in a dark red matrix, is not yet clear. However, some cutans have developed, as well as voids, which suggest that, locally at least, the process of Fe dissolution and precipitation could have occurred. These Fe-rich duricrusts contribute to the suite of nodules and pisoliths set in the overlying lateritic residuum, by a process similar to that suggested above for the fragmentary duricrusts.

It could be argued that these materials might not fall within the ambit of lateritic duricrust as envisaged by earlier workers such as Stephens (1946), and Prescott and Pendleton (1952). According to these earlier concepts, lateritic duricrusts were somewhat continuous features at or close to the top of the regolith. However, at Emu and Boags pits, in this study, the Fe-rich bodies, that are referred to as duricrusts, are discrete and discontinuous, and are at various depths, even extending down into the upper mottled zone. However, where mild stripping has removed some of the upper regolith, they are at the surface. One such site is at 17100N; 9300E where blocks of nodular Fe-rich duricrusts are on the smooth crest of a low hill. A more striking outcrop. is on the gently inclined crest of a low, mesa-form hill, some 4 km south of Copperfield, just east of the Copperfield-Menzies road. Mapped as Unit mE(i), in the reconnaissance map, it is flanked by a low erosional scarp comprising nodular, Fe-rich duricrust, and is set in an extensive erosional plain (Unit mE(iii)). The morphology of the Fe-rich duricrusts from both of these exposures is comparable with the Fe-rich nodular materials seen at depth beneath the pisolitic lateritic residuum at this south wall of Emu pit and at the entrance to Boags pit. As hand specimens it is reasonable and practical to place them in the some class of regolith material, i.e. Fe-rich duricrusts. Furthermore, until the understanding of the regolith advances, there is no reason to accept the earlier concepts of these materials, as being definitive.

8.3 Erosion

The weathering, discussed in the previous section, prepares the country rock for removal by erosion. This removal of the by-products of chemical weathering by water (the etch process) has long been recognized as a process of landsurface reduction, although only implicitly, since many of the more basic issues of this process have been clouded by the long-standing controversy between the major classical theories of geomorphology, peneplanation versus pediplanation. On the other hand some products of weathering, notably laterite, form indurated crusts that affect significantly, the course of erosion.

A more striking consequence of erosion in lateritic terrain are breakaways. For long they have been seen as classic examples of the parallel retreat of slopes and the extension of a lower (younger) erosional surface at the expense of an upper, older, relatively more stable landsurface. Ideally, breakaways comprise three principal slope facets - an upper, generally vertical, free face, protected by the hard capping to the breakaway; below this is a linear steep debris slope (15 to 25°) maintained by the hard capping above. The debris slope merges, through an open concavity, to the very gently-inclined, and generally more extensive, pediment. Where erosion has been more effective there is a cliff-like free-face with steep (20 to 30°) debris slopes, represented by Units 3 and 4 of the detailed study. Ferruginous saprolite is extensively exposed in the breakaway face and forms the principal regolith material maintaining the steep declivities of

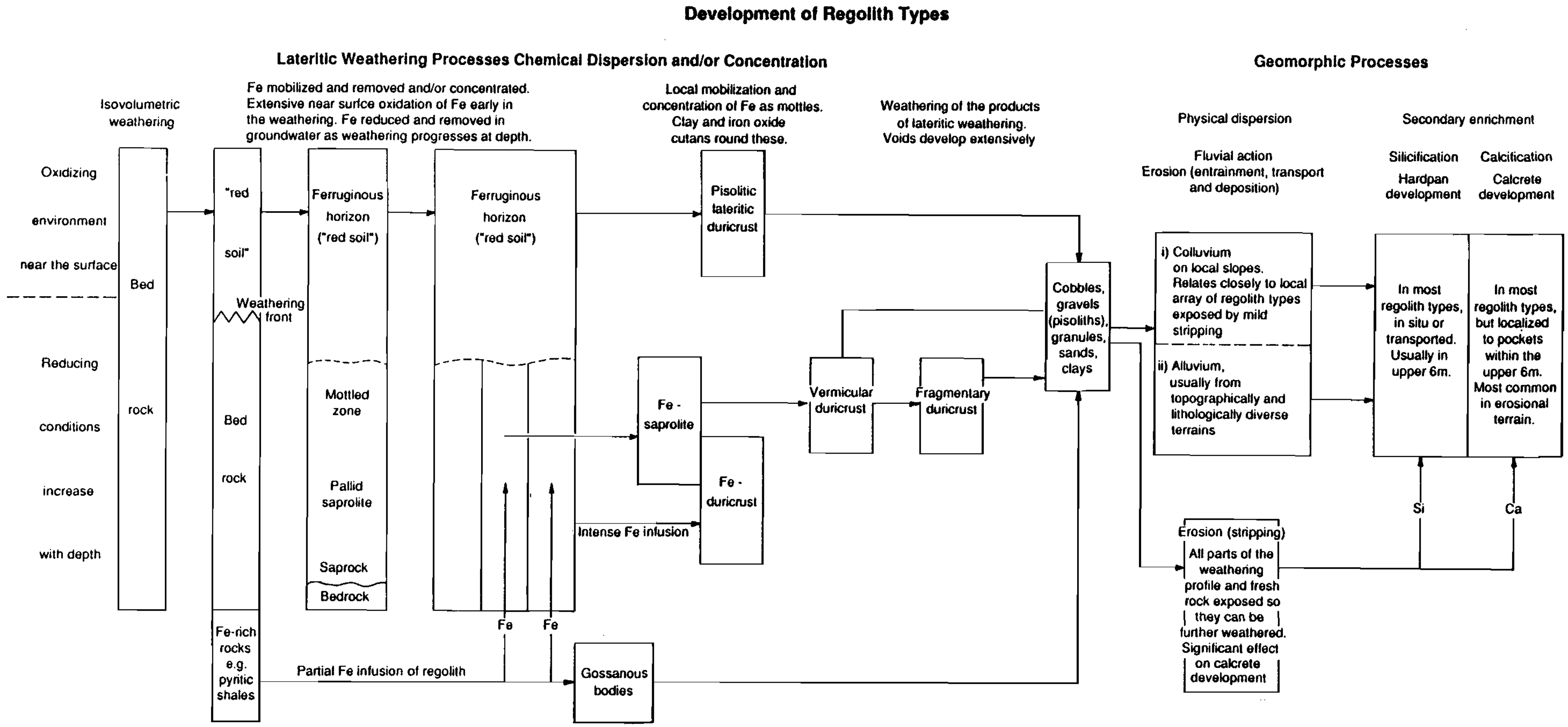


Figure 38. Schematic diagram showing an inferred genetic relationship between the principal regolith types at Bottle Creek.

the areas of more active erosion. There are very few breakaways, capped by a major outcrop of Fe-rich duricrust, in the Bottle Creek study area. The steep debris slopes have extensive subcrop and some outcrop of saprock and quartz veins. However, even these slopes are considered relatively stable, and are generally associated with a thin, colluvial mantle. Some of these slopes are breached, and erosion cut through the colluvial mantle into the underlying saprolite or saprock. Where this renewed erosion spreads across the debris slope, it can undermine the otherwise erosion-resistant duricrust cap. Eventually, as debris accumulates on the pediment below, the steeper debris slope above stabilizes, and is once more covered by a shallow (<30 mm), often stony, colluvium.

Breakaways, associated with erosionally less-active sites, also feature extensive exposure of ferruginous saprolite but there are important differences in landform and regolith here. These breakaways have a broadly convexo-concave profile that merges to smooth, gently inclined pediments. These pediments, mapped as Unit 6 in the detailed study, have a lag dominated by ferruginous saprolite (with some pisoliths, and minor lithic and quartz components) derived from exposures on the breakaway face. The size of the lag gradually becomes finer down the smooth, gentle slopes. It overlies acid, red earths which have hardpan developed at depths of about 0.5 to 0.7 m. Saprock appears at a depth of about 1 to 2 m. These soil- and hardpan-mantled pediments contrast with the slopes of the more active erosional tracts. They reflect a milder erosional environment but, because they are generally truncated by the erosionally more active areas, represent an earlier phase of erosion and stripping of the weathered mantle. The multiphase nature of erosion is also illustrated by scattered remnants of a once more extensive sheet of co-alluvium that cap very low spurs, extending eastwards from erosion tracts (in E(i)) across the stripped plain at Copperfield (in E(iii)).

Whilst the underlying lithologies are best exposed in the erosional regime even the broad smooth crests, that are an integral part of Unit 1 of the residual regime, frequently show the result of mild stripping. These regolith types may contain useful traces of underlying lithologies.

Stripping of the weathered mantle in the Bottle Creek area has been much more extensive than is indicated by the morphology of the present landsurface. Bevelled surfaces in saprolite and saprock are extensively buried by alluvial trains at Boags and VB. In contrast, some more stable landsurfaces, such as at Southwark, show an early phase of partial removal of the lateritic residuum by erosion. This indicates the complex nature of the landscape and associated regolith stratigraphy. The only extensive areas of carbonate-rich soil are on the plains near Copperfield where there is much mafic saprock (unit mE(iii) - Bottle Creek district map) at a shallow (<1 m) depth. These are erosional tracts and the role erosion plays in the distribution of calcrete at Bottle Creek is discussed later in this report.

8.4 Deposition

The regolith stratigraphy in the major areas of the *depositional regime* on the central plain at Bottle Creek (i.e. south of the Emu test pit) presents a picture of multi-phase landform development involving both erosion and deposition. Erosion has removed much of the lateritic residuum, prior to burial by fluvial deposits, and this regolith type is now only represented by scattered pockets. This stripping was probably in response to drainage incision and could be related to broad fluvial trenches such as that between the Boags and VB pits. In its later stage, the fluvial trench was aggraded by deposition of the bed-load material of a braided stream system, possibly as a consequence of more arid conditions.

The upper 1 to 1.5 m of the transported material that mantles this flat, low gradient plain, appears to be of sheet flood alluvium and it is not an overbank deposit, related to the underlying paleochannel. These two materials are separated by a sharp stratigraphic break marked by a stone line between these fine, sandy clays and the grits, gravels and sands beneath. These are the independent fluvial deposits related to separate phases of landform development.

The colluvium that mantles the long, gentle slopes of the residual terrain (generally the backslopes of breakaways) is derived from upslope, by gentle bevelling of the deeply weathered mantle. In contrast, the upper alluvial member on the depositional plain, with its consistent lithic and quartz component, is derived, at least in part, from areas of exposed country rock. Stripped surfaces are a common substrate to this alluvium and were an important contributor to these materials in the early stages of deposition so that some of the alluvium, at least, has local origin. A number of the elements of the Bottle Creek drainage system rise in the extensive erosional terrain and converge on the plain from the east and west through gaps in the line of low hills where erosional tracts are extensive. These tributaries, or their precursors, could have contributed to this alluvial sheet. The silty terraces, set slightly below the level of the alluvial plain and flanking the tributaries, indicate that fluvial activity has declined and the surface of this depositional plain is probably in relative equilibrium with the present fluvial regime.

Sediment contributed to the sheet flood alluvium from erosionally active areas, is also seen in local fans. These originate from amphitheatres, developed in otherwise extensive areas of residual terrain. These fans are mantled by lag and soil that are similar to those of the main depositional plain, adjacent to the VB and Boags pits. They contrast with the fine, dark, ferruginous gravels that cover the very gentle slopes of the flanking residual regime.

8.5 Relief Modification

The distribution of lateritic residuum, as a product of long continued weathering at or near the landsurface, can be seen as an indicator of the nature of the relief of the area prior to its modification by erosion and burial. The widespread lateritic residuum, either as extensive sheets or as scattered pockets in a variety of topographic situations, suggests that it once formed a somewhat continuous surface in the Bottle Creek area. There has been significant topographic modification since, not only reflected in the extent of erosional terrain, but also in the reduction of relief. Many of the summits have been bevelled since the early phase(s) of weathering, burial of lateritic residuum by fluvial sediment has also reduced the relief of the landsurface.

Ollier *et al.* (1988) consider that laterites have developed in valley floors and thus, occurrences of this material as ridge caps, are seen as indicators of relief inversion. Of particular interest is the case of Fe-rich duricrust. Anand *et al.* (1991) cite the presence of wood fragments in some samples of Fe-rich duricrust from the Lawlers district of W.A., as possible support for this theory. Such specific textural features were, however, not observed in the Fe-rich duricrusts at Bottle Creek. Furthermore, Fe-rich duricrust as ridge caps occur only rarely at Bottle Creek so this theory could not be adequately addressed. However, this shows that materials, placed in the general category of Fe-rich duricrusts, are not uncommon as discrete bodies at various depths in the *(in situ)* lateritic residuum, suggesting caution when using it as a general indicator of relief inversion. There could be several genetic pathways for this material and our present understanding of them is not sufficient to confidently make broad generalization.

However, relief inversion is clearly seen in more recent topographic features. On the erosional plain, adjacent to Copperfield Mining Centre, there are relics of a previously extensive alluvial plain, fragmented by a more recent phase of erosion. Such relics are now very low spurs, capped by acid red earths and hardpan with a lag similar to that on the depositional plain at Boags and VB pits.

8.6 Siliceous and Calcareous Pans

Extensive *hardpanization* of the regolith indicates widespread mobilization of silica and its deposition in the upper regolith. It is not known if this is the result of lateral movement and infusion of silica by groundwater or eluviation, as part of pedogenesis. It is likely that the acid nature of the regolith in general could favour movement of silica, particularly on stable tracts, where lateritic residuum occurs extensively. The transported detritus, forming colluvial and alluvial sheets, is derived, to a large degree, from the stripping of the highly weathered lateritic profile.

The absence of hardpan from the steeper, more active pediments (e.g. Unit 4) and its presence on more gently inclined slopes, (probably older landsurfaces e.g. Unit 6), indicate that landsurface stability is a prerequisite for optimal hardpan development. The gently inclined plain at Copperfield is a product of advanced stripping of the weathered profile. Hardpan occurs only as scattered pockets on this plain in remnants of a once more extensive alluvial sheet deposited during an earlier phase of aggradation, that has been fragmented by a more recent phase of erosion.

Many landsurfaces on which hardpan occurs are subject to periodic flooding. Whilst this could be an important contribution to its development, as originally suggested by Teakle (1936), there appears to be no clear relationship between the size of the catchment and incidence of hardpan. At Bottle Creek, the hardpan is best developed on the mid-slopes of the low hills of the residual regime, less than 500 m from the crest of the upper point of this particular catchment.

Calcium carbonate deposits can develop in the regolith as zones of crumbly calcrete whether it be *in situ* or transported. Some of the carbonate has developed subsequent to the hardpan, forming stringers of soft carbonate along subhorizontal partings. Calcrete is most extensive on the more stripped land surfaces at Bottle Creek. Erosion and stripping of the upper, more weathered, parts of the regolith, appear to be important factors influencing the gross distribution of calcium carbonate in the greenstone terrain. Scattered pockets of carbonate in the regolith in parts of the depositional regime and even in relatively stable residual areas, appear to be largely dependent on the occurrence of basement highs on mafic lithologies. These latter are associated with an irregular weathering front, protruding through the more weathered parts of the regolith. Upon weathering, these could be a source of calcium-rich solutions that would infuse the upper parts of the regolith.

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APPENDIX I

Details of the regolith-landform mapping units in the upper Bottle Creek catchment

Mapping Unit	1	2
Landforms	Broadly convex crests and flanking, gentle, upper and mid backslopes.	Long, very gentle, lower slopes and broadly concave drainage floors.
Boundaries	Gradual, down slope to Unit 2. Some breakaways as sharper boundaries to the erosional regime.	Gradual, upslope to Unit 1. Clear to gradual, to Unit 9a.
Vegetation	Mulga scrub; occasional eucalypt and kurrajong.	Mulga scrub.
Regolith Types:		
- Lag	Crests: Much ferruginous saprolite; fine to coarse (LG201 to LG207). Slight lateritic pisoliths and nodules having yellow-brown cutans (LG100). Occasional Fe-rich duricrust (LG106), Fe-segregations and gossanous (LG261) fragments. Quartz rare. Slopes: Much ferruginous clasts (LG201 to LG207); fine. Some lateritic pisoliths and nodules; some without yellow-brown cutans (LG100). Quartz usually absent.	Mainly ferruginous saprolite (LG261, 203); fine. Rare laterite pisoliths, usually with no yellow-brown cutans; mostly with dark brown to black surface.
- Soils	Light brown, very friable, sandy loams, as gravelly, acid red earths.	Fine sandy clay loams and light clays, as friable, acid red earths.
Alluvium	None	None
- Colluvium	Gravelly, fine sandy loam less than 0.5 m deep near crest, increasingly thicker (to 2 m) down backslope.	Brown to red, fine sandy clay loams and light clays with fine dark brown and black ferruginous gravels; to 4 m thick.
- Lateritic residuum	Nodular-pisolitic argillic type as substrate to slopes, rare on crests.	Nodular-pisolitic argillic type, often as duricrust; usually present at a depth of 2 to 4 m; 1 to 3 m thick.
- Fe-rich duricrust	Blocks sometimes outcrop on crests; also present in substrate.	Lenses and tabular masses at depth in or below lateritic residuum.
- Ferruginous saprolite	Blocks outcrop on crests; also in substrate.	Sometimes present at depth; irregular to tabular masses.
- Fe-segregations	Blocks outcrop on crests; also in substrate.	Irregular, to tabular masses at depth.
- Hardpan	In the upper and mid part of the lateritic residuum; weakly developed in soil.	Well developed at 1 m depth; continues to 4 m in colluvium and lateritic residuum.
- Calcrete	Rare, as small patches in the upper part of the lateritic residuum.	Rare, as small patches in the upper parts of lateritic residuum.
- Mottled zone	Sometimes present as substrate to lateritic residuum.	Beneath the lateritic residuum, at 5 to 7 m depth; 1 to 2 m thick.
- Saprolite, saprock	As substrate at 1 to 3 m depth.	Common at 6 to 8m depth; many metres thick
Bedrock outcrop	None	None

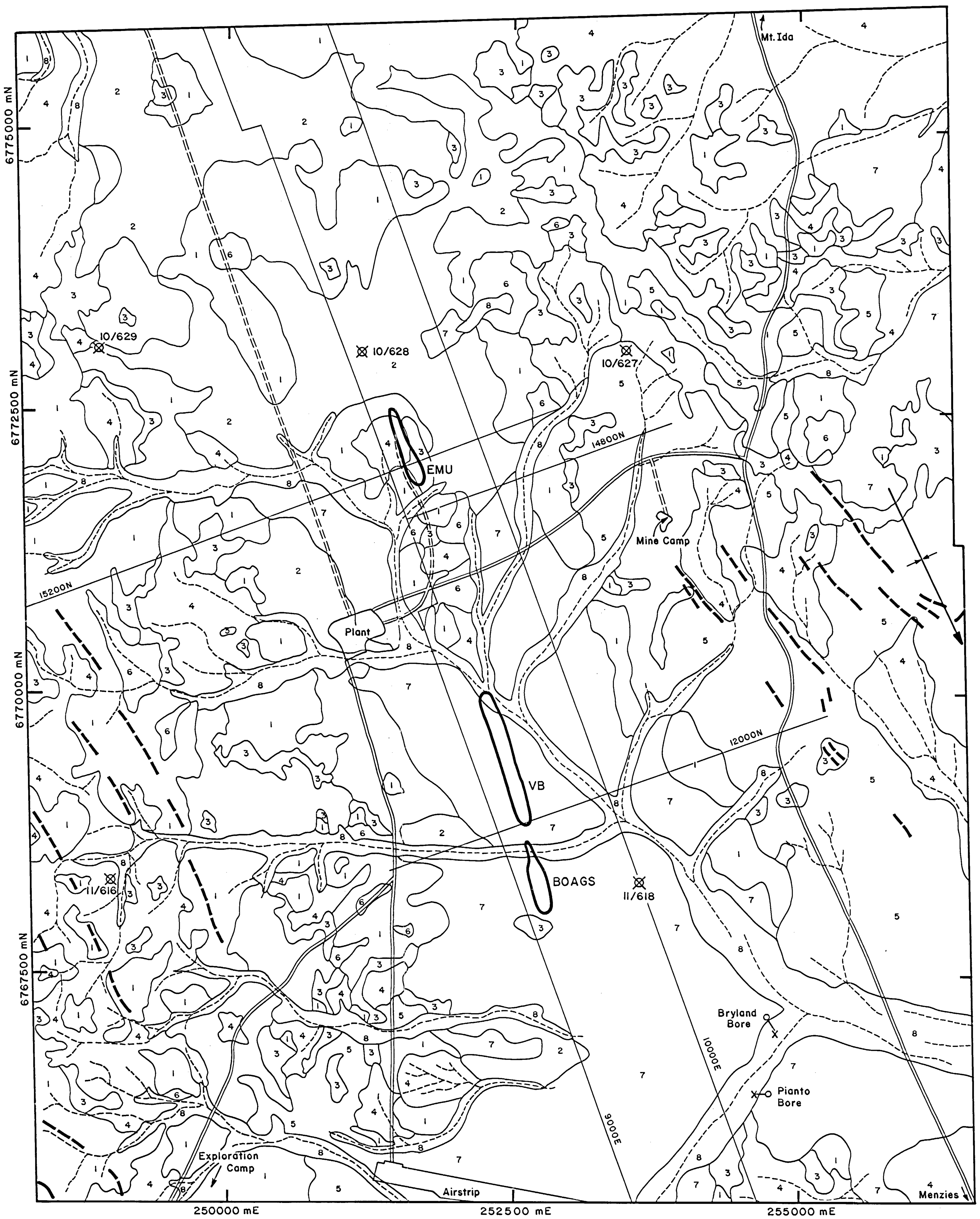
Mapping Unit	3	4	5a	5b
Landforms	Breakaway scarps and some associated crests above	Moderately steep pediment and debris slope below prominent breakaway scarps.	Low rounded hills.	Low rounded rises and long, very gentle slopes.
Boundaries	Clearly defined by topography and materials.	Clearly defined but merges into alluvial system of Unit 7.	Merge into Units 5b and 4.	Merge into Unit 5a and 4.
Vegetation	Sparse *(Eremophila sp.)* shrub communities.	Scattered eucalypts; understory of salt bush.	Low poverty bush *(Eremophila sp.)* and mulga scrub with some eucalypts.	Low mulga scrub with some eucalypts.
Regolith Types :				
- Lag	Ferruginous saprolite (LG203; 206). Slight coarse quartz.	Lithic, iron-stained, coarse. Black Fe-segregation; coarse. Ferruginous saprolite (LG203 to LG207). Saprolite. Quartz.	Lithic fragments, coarse, iron-stained (LG231). Ferruginous saprolite (LG201 to LG207) coarse size. Some Fe-segregations; coarse sizes. Some quartz; coarse sizes.	Lithic fragments, coarse (>30mm) Fe-stained. Some Fe-segregations; coarse (.30mm). Some quartz - coarse (>30mm).
- Soils	Scattered pockets of shallow sandy loams.	Shallow stony calcareous and non-calcareous earths.	Shallow, stony earths; sometimes calcareous.	Shallow stony, earths; sometimes calcareous.
- Alluvium	Not present.	Not present.	Not present.	Not present.
- Colluvium	Trace stony, sandy loam, in scattered pockets	Thin, stony, fine sandy clay loam.	Thin, stony, fine sand, sandy clay loam.	Thin, stony, fine sandy clay.
- Lateritic residuum	Not present.	Not present.	Not present.	Not present.
- Ferruginous saprolite	Extensive.	Scattered outcrops.	Some local outcrop.	Outcrops not common.
- Fe-rich duricrust	Rare.	Rare.	Some local outcrops.	Rare.
- Fe-segregations	Rare.	Scattered outcrops.	Rare.	Not present.
- Hardpan	Not present.	Not present.	Frequent patches.	Frequent patches.
- Calcrete	Not present.	Frequent patches.	Not present.	Not present.
- Mottled zone	Not present.	Not present.	Not present.	Not present.
- Saprolite, saprock	Scattered outcrop.	Outcrop and subcrop.	Outcrop and subcrop.	Outcrop and subcrop.
Bedrock outcrop	Greenstone sequence subcrop; outcrop rare.	Greenstone sequence subcrop common; some outcrop.	Greenstone sequence subcrop.	Greenstone sequence subcrop.

APPENDIX I (cont'd)

Mapping Unit	6	7	8	9
Landforms	Smooth, gently inclined, often concave slope elements sometimes as pediments to low breakaways.	Local alluvial tracts with minor incision.	Low gradient upper tributary plains.	
Boundaries	Clearly defined by breakaways, upslope to Units 3 and 1 and, down to Unit 4 but zones of more active erosion.	Gradual to Unit 4.	Sharp to Unit 1.	
Vegetation	Mulga scrub.	Low eucalypt woodlands.	Mulga scrub.	
Regolith Types :				
- Lag	Much ferruginous saprolite; medium (10-30mm) to fine (<1 cm). Some ferruginous lithic; platy. Some quartz. Some Fe-segregations - coarse.	Lithic - fine. Some ferruginous gravels. Some quartz.	Much ferruginous saprolite (LG200) - mainly fine but some medium; dark brown to black surface. Lithic fragments (LG221); Some iron-stained; often medium size. Some quartz.	None.
- Soils	Friable acid red earths from fine sandy clay loam	Friable calcareous earths.	Acid red earths in friable fine sandy light clay.	Brown silty loam.
- Alluvium	Not present.	Calcareous clay loam.	Surface mantle of sheet flood deposit to 1.5m thick. Coarse bed load as substrates to 10m thick in paleochannel, 0.5km wide.	Silty loam to 1m thick, often on cobbles of earlier deposit.
- Colluvium	Thin (<1 m) sheet of fine sandy clay loam as a pedisediment.	Local.	None.	None.
- Lateritic residuum	None.	Not present.	A few scattered patches of nodular/pisolitic argillic type, as duricrust, at a depth of from 2 to 4m; to 3m thick.	None.
- Ferruginous saprolite	None.	Not present.	Few irregular masses at depth of 3 to 4m.	None.
- Fe-segregations	None.		Scattered patches at 3 to 6m.	None.

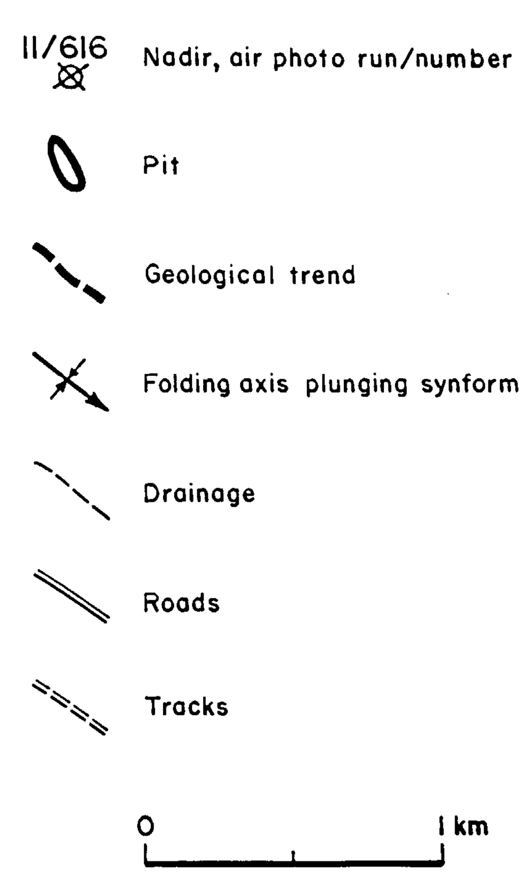
Mapping Unit	6	7	8	9
- Fe-rich duricrusts	None.		Scattered patches at 3 to 6m.	None.
- Calcrete	Rare patches at the margins of the unit.		Extensive, but sparse as elongate "stringers", in the coarse, bed-load alluvium and upper lateritic residuum.	None.
- Hardpan	At depth of about 0.5m in the colluvium; extending into saprock substrate; about 1 m thick.	Very rare,.	Extensive in the lateritic residuum and coarse bed-load alluvium to 1.5m thick. Slight, near the base of the sheet flood deposit.	None.
- Mottled zone	None.	None.	Common at depth; variable thickness to 3m.	None.
- Saprolite, saprock	None.	None.	Common at 2 to 8m depth; sometimes as substrate to the upper alluvium.	None
Bedrock outcrop	Greenstone sequence; no outcrop.	Greenstone sequence; no outcrop.	None.	None.

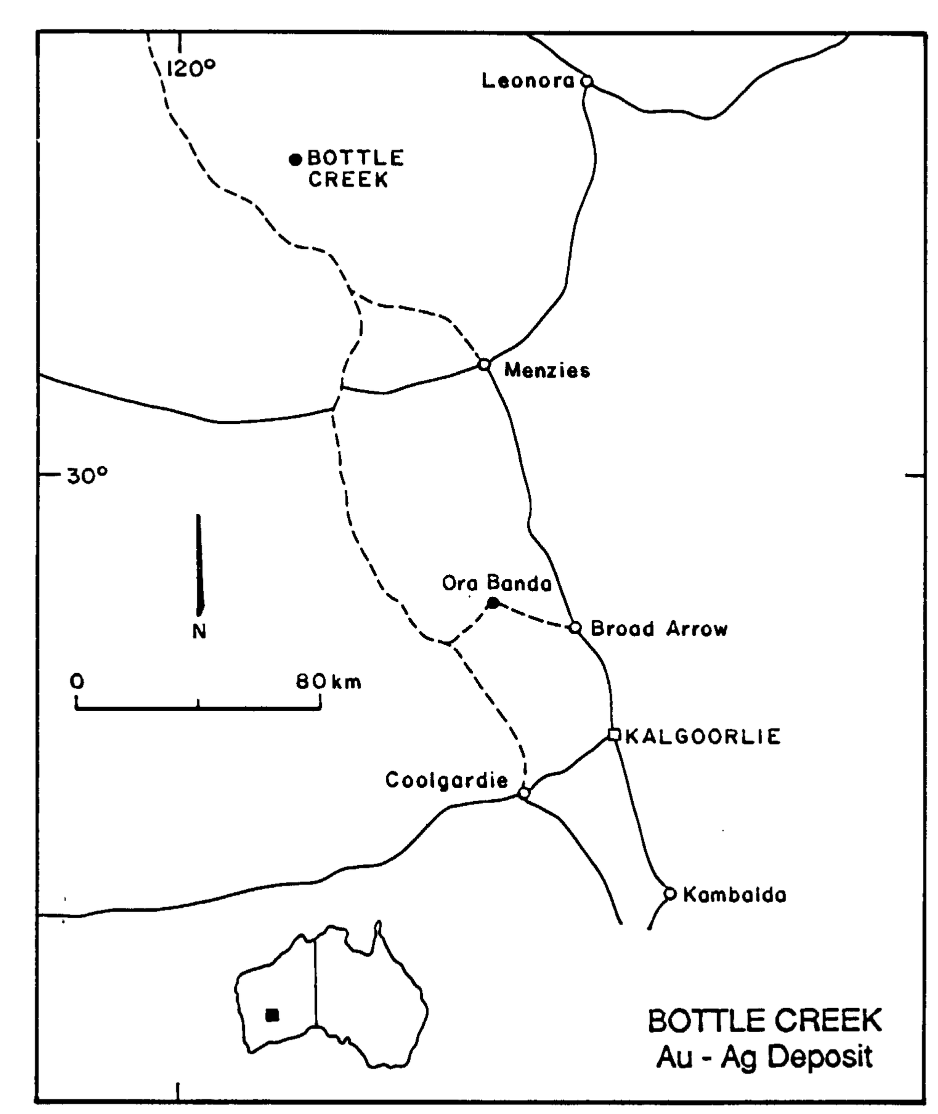
For legend see Table 2 Pp. 52-53



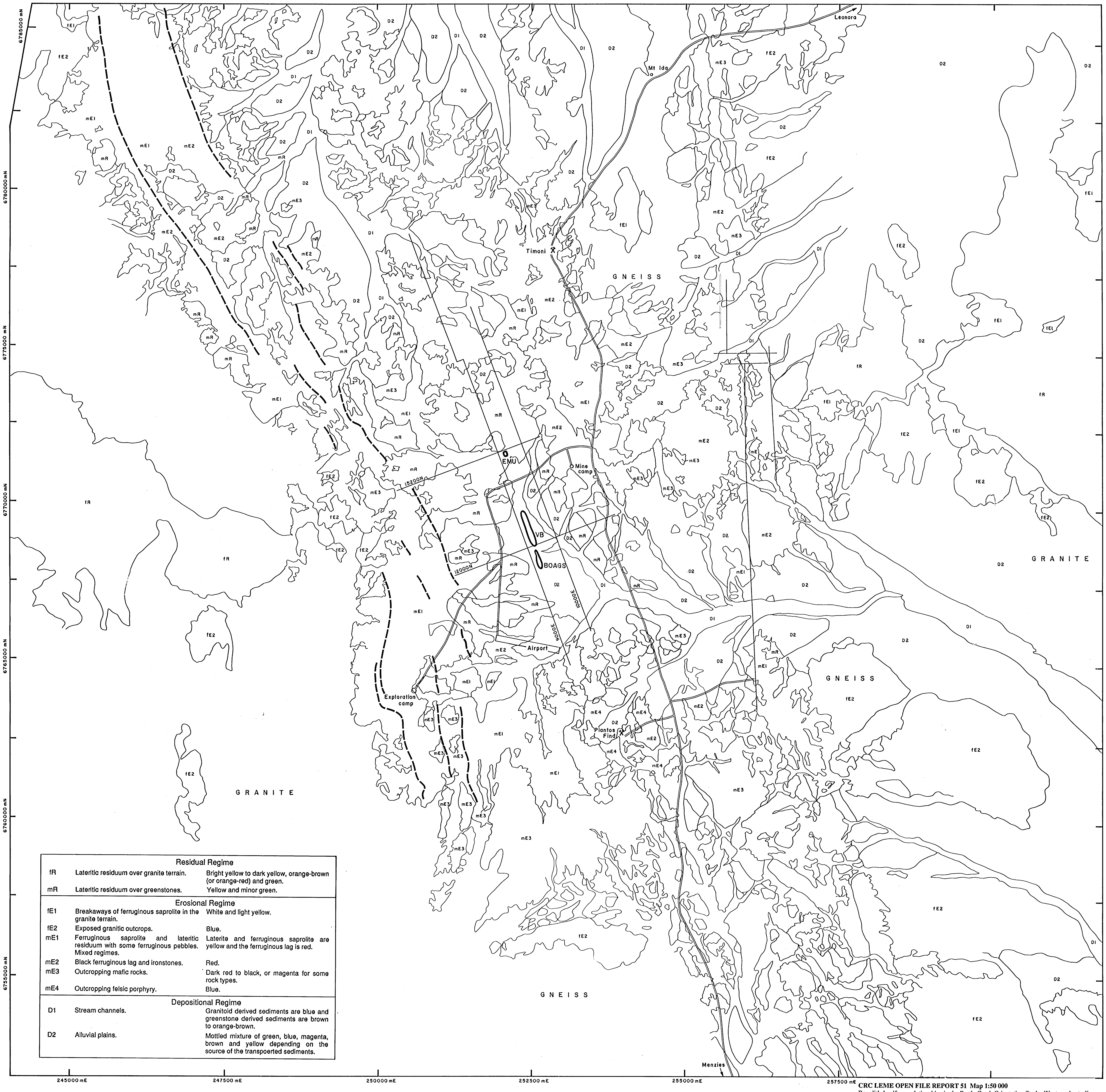
BOTTLE CREEK
Regolith-landform map

Unit	Landform	Surface Material
	Stable	
1.	Rounded crests and flanking slopes.	Lateritic residuum including fragments and loose nodules and pisoliths with cutans in yellow-brown soil.
2.	Lower slopes and broad valley floors.	Loose, purple to black nodules and pisoliths and red-brown soil derived by minimal transport from proximal slopes overlying lateritic residuum. Cutans are partially or wholly absent.
	Erosional	
3.	Bevelled edges of steep breakaways, pediment or scree slope directly below breakaways, isolated hills largely stripped, and stripped areas below the crest on broadly convex crests.	Ferruginous saprolite, pale brown to orange-brown. Occurs in-situ and as shed, loose angular clasts with a thin soil cover or no soil at all.
4.	Areas of current active erosion, usually at the head of drainage.	Varied material such as outcrop, saprock, saprolite and ironstone (lag or outcrop).
5.	Low relief (often gently undulating) where active erosion has ceased.	Varied material including red-brown (usually calcareous) soils, dark outcropping mafic rocks, black ferruginous lag and black outcropping ironstones, white vein quartz and white pockets of carbonate. More soil and vegetation than unit 4.
6.	Small, stable pediments where erosion has ceased (no active drainage) and substantial locally derived material has accumulated.	Ferruginous lag and red-brown soil.
	Depositional	
7.	Alluvial plains.	Polymictic lag, including quartz, ferruginous saprolite and lithic fragments (such as tabular BIF), and red clay soil.
8.	Stream channels and adjacent co-alluvial terraces.	Polymictic lag and clay soil (alluvium).





CRC LEME OPEN FILE REPORT 51 Map 1:25 000
Regolith-landform relationships in the Bottle Creek Orientation Study, Western Australia
H.M. Churchward, I.K. Butler and R.E Smith



CRC LEME OPEN FILE REPORT 51 Map 1:50 000
Regolith-landform relationships in the Bottle Creek Orientation Study, Western Australia
H.M. Churchward, I.K. Butler and R.E Smith