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REGOLITH DEVELOPMENT AND LANDSCAPE EVOLUTION IN THE MERREDIN REGION, WESTERN AUSTRALIA

Li Shu, B. Singh and M. Cornelius

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CRC LEME Report 93R, 1998)

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PREFACE

The Astro Yilgarn Regolith Project - Diamond exploration in regolith-dominated terrain, Yilgarn Craton, Western Australia - was sponsored solely by Astro Mining NL. The project commenced in January 1997 and was completed in early 2000.

The principal objective of the project was to develop concepts, methods and technologies for locating diamond-bearing pipes (and associated regolith deposits) in the Yilgarn Craton, within the framework of the regolith-landscape evolution. The specific objectives were (i) to establish a regional overview and framework of the geomorphic history and landform evolution of the Yilgarn Craton relevant to the project objectives, (ii) to establish district-scale frameworks of regolith relationship (mapping, stratigraphy and characteristics) for key tenements of Astro Mining, (iii) to establish through orientation, modelling and deduction, geochemical and mineralogical exploration methods optimised to the chosen regolith-landform regimes, and (iv) to translate research findings into practical exploration techniques to be applied by the Astro Mining Exploration team.

At the beginning of the project, Astro Mining nominated the Merredin tenements as a high priority area for exploration and hence CRC LEME conducted a major case study in the Merredin region. The study had two main objectives: firstly to map the main regolith-landform units and develop a model of landscape evolution for the region. This report summarizes the results of the regolith mapping, addresses various aspects of regolith-landscape evolution, presents advanced sampling strategies, and provides the necessary background information for the interpretation of geochemical data collected by Astro Mining NL. The second objective of the Merredin study was to investigate the regional regolith geochemistry and identify geochemical anomalies that could indicate the presence of kimberlite pipes. Outcomes of this work will be published by Cornelius et al. in the journal *Geochemistry: Exploration, Environment, Analysis* (GEEA) in 2005.

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disintegration of the drainage into a series of salt lakes. Sediments in the main drainage largely comprise colluvium from surrounding valley sides and minor alluvium supplied by tributaries.

Regolith formation

Intense chemical weathering began in the late Cretaceous-early Tertiary, and altered rocks to secondary clay minerals and Fe oxides. At the top of the profile, Fe oxides formed nodules as part of a duricrust.

Disintegration of the duricrust leads to the formation of the gravelly sandplain. Nodules in granitic terrain contain a considerable amount of remnant quartz grains. Further weathering of the nodules frees these quartz grains, which accumulate on the surface and form extensive sandplains. The sandy sandplain, therefore, characteristically overlies lateritic gravels. Both gravely and sandy sandplain are considered to be residual for the purpose of geochemical exploration, as lateral and vertical transport distances generally are limited. There is, however, some local redistribution.

Implications of regolith studies for kimberlite exploration

Sampling media - Relict regimes are the most important part of the landscape for the approach used in this project, because geochemical signatures of kimberlitic bedrock may have been preserved in lateritic residuum, such as the lateritic gravels and duricrust in the gravely sandplain. In the erosional regime, soil-covered saprolite and saprock are generally unsuitable for regional geochemical sampling, because of restricted dispersion. There areas may, however, provide local geochemical information on underlying bedrock, hence the residual soil on saprolite can be used to test discrete exploration targets such as aeromagnetic anomalies. In the depositional regime, colluvium and alluvium are generally unsuitable for the approaches used here. Some transported lateritic gravel may appear residual and identification of these components is most important to avoid misinterpretation of geochemical data. On the other hand, soils along slopes may contain fragmental remnants of the eroded lateritic residuum, which can provide a sampling medium in areas with little or no residual laterite.

Indicator minerals - Surficial sediments in the drainage are mainly derived from local valley sides. Alluvial sediments from upstream catchment areas have been buried at depth. The discontinuous nature of the drainage is fundamentally different from active streams in which indicator minerals come from distant upstream catchment areas, rather than local sources. Indicator minerals in loam samples from valleys of inactive drainage represent the geology of the surrounding valley sides and, as such, have local rather than regional application.

Kimberlite preservation - The river rejuvenation and seismic activities on the western margin of the Yilgarn Craton, development of a discontinuous drainage in the central region, and the preservation of Permian sediments on the eastern margin, suggest upward tilting in the west. Such tilting would have increased denudation along the western margin of the Yilgarn Craton, but led to increased stability along a hinge line in the central part and decreased denudation or even caused sedimentation on the

EXECUTIVE SUMMARY

Key objective

The objective of this study was to establish a regolith-landform framework for the Merredin region, guiding geochemical exploration for kimberlites and assisting with the interpretation of geochemical and mineralogical data. As part of this work, a regolith-landform map of the Merredin region, covering most of Astro Mining NL's Merredin tenements was completed at a scale of 1:100 000.

Morphological setting

The Merredin region is situated within the Great Plateau of Western Australia and is characterised by flat broad valleys, gentle valley sides, sandplains and isolated granite outcrops. The drainage system consists of large inactive streams (the Yilgarn and Salt rivers), which have not been tectonically rejuvenated since at least the beginning of the Tertiary. The interfluves are formed by broad sandplains.

Regolith classification

This study confirmed that the extensive sandplains in the Merredin region are relict features. Accordingly the RED (relict, erosional and depositional regimes) scheme was adopted to classify the regolith units for geochemical sampling. Mapping was based largely on radiometric data and supported by extensive fieldwork.

Relict regime - comprises the gravely sandplain. Its main component, lateritic residuum, has been shown to be largely residual and hence reflects the geochemistry of the local bedrock types.

Erosional regime - consists of soils on saprolite and saprock, commonly along valley sides.

Depositional regime - comprises alluvium and colluvium on valley floors and along slopes, which have little significance for geochemical sampling.

Landscape evolution

The overall flatness of the Yilgarn Craton may be ascribed to a Proterozoic erosion surface. The early Permian glaciation, that affected the whole of Western Australia, erased most of the pre-existing regolith and established the palaeo-drainage, which delivered large amounts of sediment into the surrounding basins. During the Late Cretaceous to Eocene, ample rainfall allowed rivers to develop broad and shallow valleys in which coarse sediments were deposited. Remnants of such sediments are found on present interfluves. During the Oligocene-Miocene period, the climate became drier, but there was still sufficient rainfall for deep weathering to occur. Uplift of the western margin of the Yilgarn Craton, coupled with a climatic change, may have led to a relatively sudden change in the water flow of the main drainage in the central Yilgarn, and consequently the rivers in the Central Yilgarn became sluggish. From the late Miocene to the present, this trend continued and led to the

eastern part of the Craton. This concept would explain high sedimentation rates in the westerns basins, compared to relatively low rates in the eastern and southern basins. While kimberlite pipes emplaced on the western part of the carton might be largely eroded, the conditions in the central and eastern part are favourable for preservation of any post-Archaean pipes.

Interpretation of radiometric data - Radiometric images are a very important tool for regolith mapping, although regolith studies have shown some limitations. Thick sands with underlying lateritic gravels are also easily confused with thick sands on saprolite, because both have little K and Th, and therefore show no difference on radiometric images. There are some cases in which radiometrics indicate lateritic materials but the materials are not residual. Moreover, lateritic gravels formed on Th-poor parent rocks have very weak Th responses, whereas colluvium can produce a high Th signal if soils on the colluvium are rich in Th. The origin of lateritic materials can, therefore, be established only by fieldwork accompanying the regolith mapping.

1. INTRODUCTION

1.1 The objective of this study

The Yilgarn Craton, like other Archean cratons without a cover of platform sediments, has long been considered favourable for hosting diamond-bearing pipes, and diamond exploration has been in progress for many years. Large tracts of the craton are, however, covered by considerable thickness of regolith, dominated by variably preserved deep weathering profiles and areas of transported overburden. The land surface thus has a range of highly weathered to fresh materials in a variety of geomorphic and lithological settings. The great extent and variation of the regolith are a major impediment to exploration, and drainage-mineralogical approaches to diamond exploration are ineffective and inappropriate in approximately 70% of the Craton.

The presence of the regolith can be important for diamond exploration because lateritic residuum represents lengthy exposure during their formation and the preservation of ancient land surfaces. Diamond-bearing pipes are most likely to be best preserved beneath the residuum, which represent the preservation of relict weathering surfaces. Residual accumulation of resistant minerals, including diamond, could occur during land surface reduction, one of the chief characteristics of lateritic weathering. There are, however, many possible factors that influence geochemical and mineralogical variation in the regolith on a deeply weathered plateau, in particular the geomorphology, lithology and the nature of weathered materials. Understanding regolith-landform development is, therefore, essential in evaluating the most suitable exploration technique to be applied to a particular terrain so that exploration strategies can be configured accordingly.

The key objective of the Merredin study is to provide a regional overview and framework of regolith development and landscape evolution of the region and the Yilgarn Craton in general for diamond exploration. This has been achieved through studies of the regolith-landforms over key districts of Astro Mining N.L.'s tenements selected to represent an important range of regolith-landscape settings. Accordingly, this study has established the regolith stratigraphy, mapped various regolith units at a scale of 1:100 000, and developed a model of landscape evolution of the region. During regolith mapping, detailed studies were carried out on the relict regimes, and attention paid to erosional and depositional regimes only where it is necessary to understand evolution of the landscape. The study aimed to improve sampling strategies and to provide background information for interpretation of geochemical analyses.

1.2 Previous work

Classification and description of soils at Merredin was attempted at the beginning of the century (*e.g.*, Jutson, 1914). Teakle (1938) briefly described soils in broad, flat valleys and on sandy and gravelly rises (*i.e.*, sandplains) around Merredin. Bettenay and Hingston (1961, 1964) gave a brief account of soil studies in Merredin prior to 1960s.

Major studies on soils and landscape evolution around Merredin were conducted by the CSIRO Division of Soils in the late 1960s and 1970s (Bettenay and Hingston, 1961, 1964; Hingston and Bettenay, 1961; Brewer and Bettenay, 1973; Bettenay *et al.*, 1962, 1964). Bettenay and Hingston (1961, 1964) classified the soils around the town of Merredin into three broad groups, based on parent material and topographic relationship. They are soils formed on (i) lake sands and clay, (ii) country rock and colluvium- alluvium, and (iii) lateritic parent material. Groups (ii) and (iii) were further subdivided into erosional and depositional units, which, however, were not shown on their soil map.

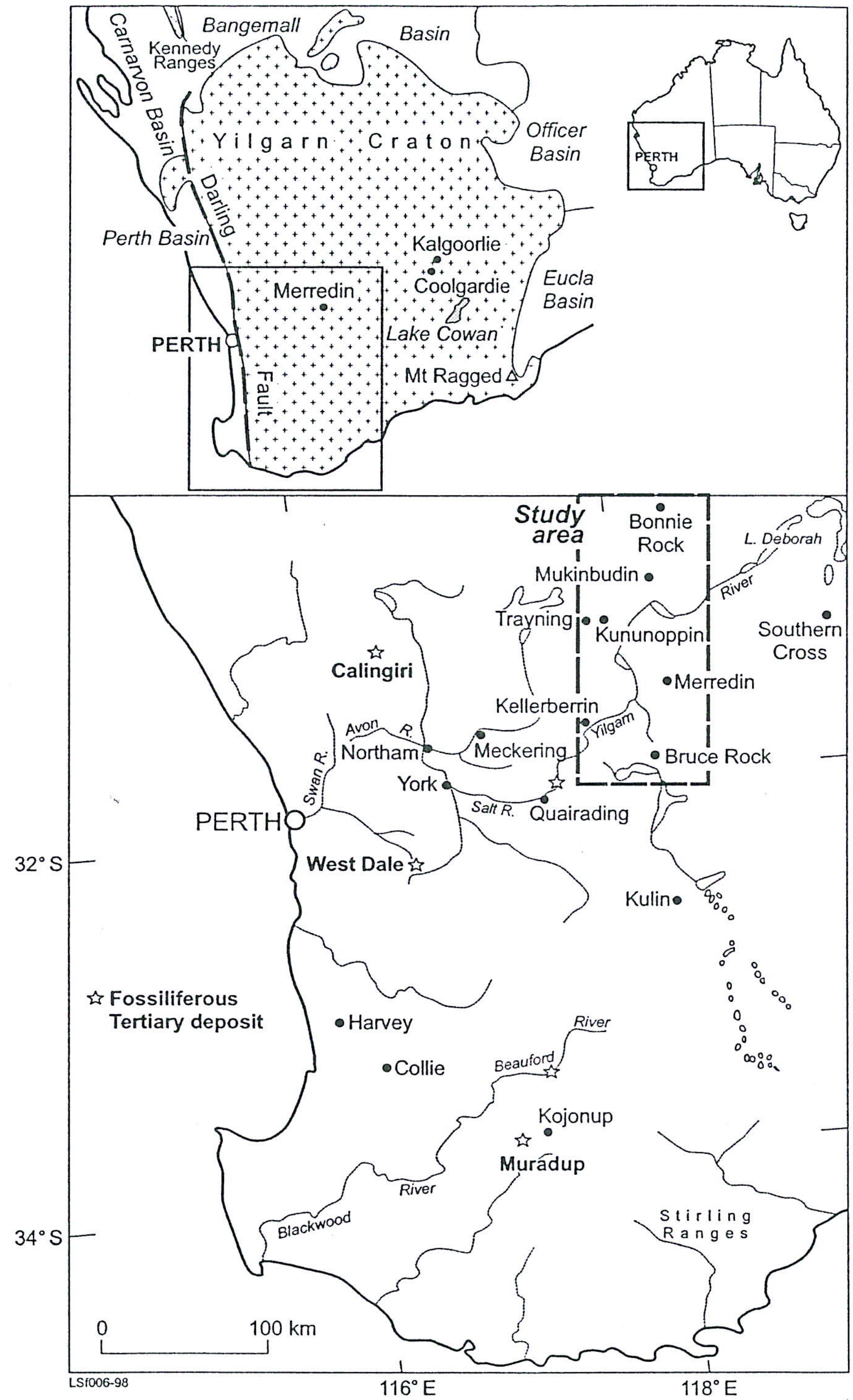


Figure 1. Location of the Merredin region.

McArthur (1992) mapped soils in the Kellerberrin region at 1:100 000 scale, extending the map coverage of Bettenay and Hingston (1961). He adopted the terminology developed by Bettenay and Hingston (1961),but the accuracy of his boundaries appears to be less than that of Bettenay and Hingston's work around Merredin. The northern part of the study area was also mapped for agricultural purposes by Grealish and Wagnon (1995) at a scale of 1:250 000. Grealish and Wagnon combined Bettenay and Hingston's mapping units (*e.g.*, Ulva - 50% and Booraan - 50%) into a new mapping scheme thus severely complicating its use for regolith-landform mapping.

1.3 Regional settings

Location

The study area comprises Astro Mining N.L.'s exploration tenements around Merredin in the western Yilgarn Craton. Its boundaries range from 117°36' to 118°00'E and from 30°39' to 32°00'S, and include an area of 14 220 km² within Zone 50 of the Australian Map Grid (Figure 1). The region forms part of the Central and Eastern wheat-belt of Western Australia, and is easily accessible by a network of roads. The distance between Merredin, the major town in the centre of the study area, and Perth is about 350 km. Bruce Rock, Trayning, Kununoppin and Mukinbudin are other towns within the area, generally referred to in this report as the Merredin region.

Climate

The climate in the Merredin region is semi-arid with dry, hot summers and wet, cool winters. About 70% of the mean annual rainfall of 309 mm is received during the winter months of May to October (Bureau of Meteorology, 1988).

Due to the low rainfall, there is little run-off through the drainage, particularly in summer. In winter, run-off takes place only in bare, fallow or steep and rocky areas; elsewhere, most of the rainwater infiltrates the soil. Only in years of exceptionally high rainfall does the major drainage resume its function.

Vegetation

The Merredin region forms a part of the wheat-belt of Western Australia and hence, most of the land has been cleared for agriculture. Natural vegetation is estimated to cover less than 5% of the total area. Satellite images, therefore, display a mosaic of paddocks and crop types; plough seasons and soil moisture also affect the appearance of the areas on the satellite images.

The natural vegetation, where present, is closely related to soil types and lithological units in the area (Bettenay and Hingston, 1961). Due to extensive clearing, natural bush is only preserved in reserves and along roadsides. Halophytic plants such as samphires (*Salicornia* sp.), Chenopodiaceae (*Atriplex*, *Kochia* and *Bassia* sp.), *Hakea preisii* and *Casuariana lepidophloia* inhabit salt lakes and their margins. Salmon gum (*Eucalyptus salmonophloia*) and gimlet (*E. salubris*) grow in broad, flat valleys with deep, clayey soils. A number of mallee species of eucalyptus and wandoo (*E. redunca var. elata*) are found on the valley sides connecting the valley floors and the sandplains. A dwarf native pine (*Callitris* sp.) is associated with breakaways; on the sandplains is a low scrub formation consisting of wodgil (a general name for rigid, erectly branched *Acacia* shrubs) and a shrubby Casuarina (*C. campestris*).

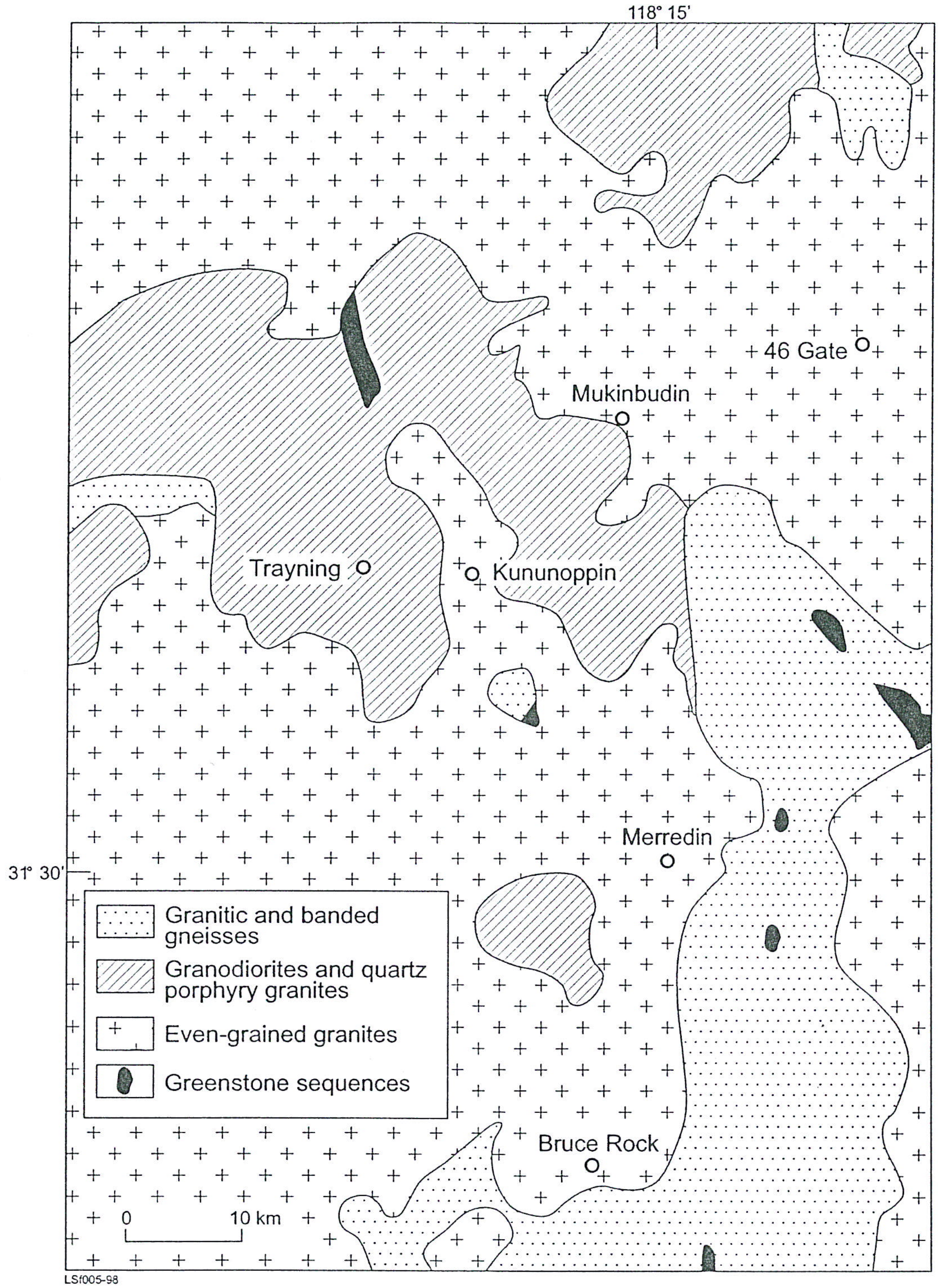


Figure 2. Geological setting of the Merredin region.

1.4 Geological and structural settings

The study area has been geologically mapped by the Geological Survey of Western Australia and is covered by the eastern part of the Kellerberrin and the southeastern part of the Bencubbin 1:250,000 geological sheets (Chin, 1986; Blight *et al.*, 1984). More recently, the granite distribution and petrography was re-assessed by J. Klominsky (personal communication) for Astro Mining N.L. On a broad scale, the Merredin region forms a part of the Southern Cross Province (Gee *et al.*, 1981), which covers the medium-grade metamorphic part of the central Yilgarn Craton.

There are four main lithologies within the study area (Figure 2): granitic and banded gneisses in the east, granodiorites and quartz-porphyry granites in the northwest, even-grained granites, including the Kellerberrin granite batholith in the west, and the Bencubbin greenstone belt in the central part. Scattered mafic and ultramafic rocks also occur as minor components.

Granitic and banded gneisses

The eastern part of the study area forms the northernmost part of a gneiss belt that extends to the southeastern portion of the Dumbleyung geological sheet (Chin and Brakel, 1985). The gneiss belt, which ranges in width from 50 km in the south to 20 km in the north, contains scattered enclaves of metamorphosed banded iron formation and mafic rocks. The rocks are overprinted by high-grade metamorphism that formed granoblastic textures. Younger granitic and granodioritic plutons also intrude the gneiss.

Granodiorites and quartz-porphyry granites

Medium- to coarse-grained biotite granites and granodiorites intrude the older gneisses. The rocks are homogeneous and most show no deformation fabrics. Locally, however, minerals have preferred orientations (Blight *et al.*, 1984).

Even-grained granites (Kellerberrin batholith)

Seriate, medium- and coarse-grained granites form a continuous 'sea' that pervades the southwest Yilgarn Block (Gee *et al.*, 1981). These granites enclose gneisses, greenstones and post-tectonic granites. In the Merredin region, the Kellerberrin batholith covers the western half of the study area. It is generally leucocratic and uniform across the whole batholith.

Bencubbin greenstone belt

Approximately 7 km west of Bencubbin, a greenstone sequence, about 1 to 2 km wide, extends for approximately 18 km to the southeast (Blight *et al.*, 1984). The greenstone sequence consists of amphibolites with minor ultramafic schists and metamorphosed banded iron formation. Five km north-northwest of Kununoppin and about 24 km southeast of the Bencubbin sequence, another greenstone sequence and several small outcrops of amphibolite occur. Drilling by Astro Mining N.L. has also intersected greenstone lithologies, including micaceous schists, mafic schists and possible metasediments, beneath alluvial sediments in the Lake McDermott drainage northwest of Kununoppin (Figure 2). The distribution of mafic rocks in the Kununoppin area suggests that the Bencubbin greenstone belt may extend a further 24 km southeast. The belt appears discontinuous, and thins out to the southeast.

Miscellaneous mafic/ultramafic rocks

A small enclave of amphibolite is located approximately 21 km east of Mukinbudin. About 16 km north of the amphibolite, near 46 Gate Road, drilling by Astro Mining N.L. has intersected several ultramafic units, up to 2 m thick, hosted by biotite-rich granite/gneiss. The origin of these 'dykes' is not yet known.

East of Bruce Rock, in the southern part of the study area, strongly silicified rubble, probably after an ultramafic rock, occurs. The source of the silicified material has, as yet, to be confirmed.

A small ultramafic outcrop is located approximately 20 km south of Cunderdin, immediately west of the study area. The ultramafic outcrop, which was intensively sampled because of its analogy with a kimberlite diatreme, is an isolated occurrence; it may form part of a small sill-like mafic-ultramafic body.

Fine- and medium-grained dolerite dykes, trending predominantly east-northeast, infill fractures, joints and some fault planes (Blight *et al.*, 1984).

1.5 Geomorphology

The main geomorphological elements in the Merredin region are broad valleys with salt lakes on their flat floors, long and gentle valley sides, uplands (largely sandplains) and isolated hills of granite. In general, the topography of the area is subdued; except for small erosion scarps or breakaways, there are no sharp inflections in the landscape (Bettenay *et al.*, 1964). The low intensity and low gradient of the drainage, and extensive sandplains with low relief (<80 m), are the main morphological features in this region.

There are no perennial streams in the central wheat-belt because the area is semi-arid. The Yilgarn River, once the main drainage in the Western Yilgarn Craton, is rather discontinuous. It originates from Lake Deborah East, about 125 km to the west of Kalgoorlie. Its tributaries, in a pattern roughly perpendicular to the main drainage lines, are through broad-floored valleys of low gradient (Bettenay, 1968). The main valley may be as much as 15 km wide, with larger tributaries up to 8 km in width. The valley floors are, however, generally only about 60 m below the smooth and gently rounded interfluves (Mulcahy, 1971). The river becomes the Salt River from Kellerberrin downstream to Quairading, and runs into the Avon River that enters the sea via the Swan River at Perth (Figure 1). In this report, the whole drainage system (Yilgarn River – Salt River – Avon River – Swan River) is referred to as the Yilgarn River System.

The Yilgarn and Salt rivers consist of series of salt lakes. The origin of salt lakes has been attributed to various processes, including wind deflation (Woodward, 1897), glacial action (Campbell, 1906) and riverine action (Gibson, 1909; Gregory, 1914). Gregory (1914) suggested that salt lakes are the remnants of ancient river systems that are now blocked and distorted in various ways, and function only in years of extremely high rainfall. This suggestion is now generally accepted. The width of the valleys, with series of salt lakes, indicates that the major drainage in the Merredin region is an underfit river. It appears too small to have eroded the valley in which it presently flows even during high rainfall seasons, and must, therefore, be a relict feature of a much larger palaeo-river system (Gregory, 1914, 1916). The drainage system is thought to have developed during the Late Cretaceous and ceased regular flow in inland areas by the mid-Miocene (Van de Graaff *et al.*, 1977).

Broad sandplains, capped with lateritic gravels and sandy earths, form the interfluves of the main drainage lines. Extensive sandplains are a characteristic feature of the landscape around Merredin and form a part of the Great Plateau of Western Australia (Jutson, 1914, 1934) or the Darling Peneplain (Woolnough, 1918a). Lateritic materials on the sandplains are well preserved because streams do not have the capacity to remove much of the lateritic duricrusts.

There are two main types of sandplains, *i.e.*, sandy sandplain and gravelly sandplain, which Bettenay and Hingston (1961, 1964) called 'depositional Ulva' and 'erosional Ulva', respectively. The former consists of deep, yellow sands overlying ferruginous gravels, while the latter is characterized by heavy ferruginous gravels on the surface. As the terms erosional and depositional Ulva are interpretative rather than factual, this report refers to sandplains with deep yellow sands on the surface as ***sandy sandplain*** and to the sandplains with ferruginous gravels on the surface as ***gravelly sandplain***. The

less defined term ***sandplains*** is used to refer to both of them. Field investigations show that sandy sandplains are the major component of the sandplains in general, and that gravelly sandplains occur, in most cases but not always, behind breakaways and, in a few places, at the lower end of the sloping sandy sandplains.

Long, gentle slopes commonly connect the surface of the sandplains and the broad, flat valley floors. Most of these slopes are about 1 to 3 km long; local relief, *e.g.*, the vertical difference between sandplains and valley floors, is approximately 50 to 80 m. In this report, the slopes will be referred to as valley sides.

Within the sandplains, and in the main valleys, there are some low, isolated, residual granite hills (bornhardts), locally known as 'rocks'. These rocks stand generally about 10 to 30 m above the surroundings and form prominent features in the landscape.

2. REGOLITH STRATIGRAPHY AND REGOLITH-LANDFORM UNITS

2.1 Regolith classification and mapping

Anand *et al.* (1989, 1993) classified regolith into three broad groups, *i.e.*, Relict, Erosional and Depositional regimes, known as the RED scheme. Relict regimes consist of areas characterized by preservation of lateritic residuum - survivors of an ancient weathered landsurface. Erosional regimes consist of areas characterized by mottled zone, clay zone, saprolite, or fresh bedrock, either exposed or concealed beneath shallow soil. Depositional regimes comprise alluvium and colluvium. This scheme is well suited for the design of geochemical sampling strategies and was adopted at one of the steering committee meetings of the project to establish the broad regolith framework in the Merredin region.

Lateritic materials in the relict regime are critical for geochemical exploration, because they offer the optimal geochemical sampling medium. Previous work by CSIRO (Smith *et al.*, 1992; Anand *et al.*, 1993) has shown that large geochemical haloes form in lateritic residuum, significantly enlarging a target. It is essential to determine the distribution of residual lateritic material to extend the geochemical sampling program to the maximum possible area. Detailed regolith mapping in this study has, therefore, focussed mainly on the relict and erosional regimes because these are most important for the current surface geochemical exploration program.

The mapping of regolith-landform units is primarily based on radiometric data supplied by Astro Mining N.L., and partly obtained from World Geoscience and CRA Exploration. As the area is extensively cultivated, radiometric images provide much better information than aerial photographs and satellite images. The Th signal of the radiometric data highlights ferruginous materials, whereas the K signal shows granitic outcrop and sub-crop as well as saprolitic material. Erosional regimes can be distinguished from depositional regimes using the K signal combined with digital terrain information. In some areas, a high Th signal may not correspond with lateritic gravels but reflect Th-rich soils on colluvium-alluvium.

The sandy sandplains, which are underlain by lateritic gravels, have very low signals of both Th and K, because the yellow sands consist mainly of quartz. However, thick sands on saprolite also produce similar radiometric responses. Distinction of these units is important, because the sandy sandplains are invariably underlain by lateritic nodules, which are a suitable geochemical sampling medium, whereas sands on saprolite offer no equivalent sampling medium.

Field traverses were carried out to verify the preliminary regolith maps, and to resolve any inconsistencies arising from the limitations of the radiometric data. A detailed regolith-landform map

of the Merredin region (1:100 000) is included in this report. A simplified map, with the main regolith units, is shown in Figure 3. It is estimated that the relict, erosional and depositional regimes each occupy about one third of the total area.

2.2 Relict regime - lateritic gravels and duricrust

2.2.1 Regolith stratigraphy

In the Merredin region, several lines of evidence show that the sandplains are residual (Profiles 1 to 5) and that they may represent an undulating palaeo-plain. Profiles through the sandplains show that yellowish, unsorted quartz sands or yellow sandy earths overlie lateritic gravels and duricrust. Where lateritic gravels are present at the surface, they are considered to be part of a relict regime if a lateritic profile is still preserved beneath the gravels and the mottled and/or clay zones have not been exposed (see Figures 4, 5, 8 and 9). If the overall lateritic material has been eroded away from a profile, the remaining regolith material is classified as erosional regime, even though remnants of loose gravels may still be present on the ground.

Profile 1 Sandy sandplain

This profile is exposed at a gravel pit, south of Merredin (621900 mE 6505600 mN) and shows a typical section through the sandy sandplain (Table 1 and Figure 4). Disintegration of indurated saprolite has given rise to the formation of incipient lateritic gravels underlain by lateritic nodules. The presence of the incipient gravels indicates the residual nature of the profile.

Table 1 Profile 1 through the sandy sandplains near Merredin.

Depth (m)	Description	Interpretations
0.00-0.25	Unsorted, angular and homogeneous quartz sand and sandy loam. The thickness of the sand varies from 0.1 to 0.25 m. The fabric of the sand indicates neither aeolian nor fluvial origin.	Locally derived colluvium.
0.25-0.35	Lateritic gravels, mainly nodules.	Lateritic residuum.
0.35-0.68	Incipient lateritic gravels, mainly nodules formed by disintegration of Fe-indurated material.	Disintegration of indurated saprolite in a residual profile.
0.68-1.60	Mottled saprolite, gradually changing upwards to incipient nodules. The base is not exposed.	The upper part of a deeply weathered profile.

Profile 2 Gravelly sandplain

This profile consists of a breakaway north of Mukinbudin at 621435 mE 6609730 mN (Figures 5 and 6A-C). An erosional plain has been developed in front of the breakaway, with remnants of ferruginous and silicified saprolite remaining as isolated blocks during erosional retreat of the breakaway.

A quartz vein, about 3 cm wide, can be traced from the saprolite of the lower part of the profile into the overlying lateritic material, where it is present as fragments in indurated nodules (Table 2). The breakaway has a backslope, the upper part of which is occupied by lateritic nodules and pisoliths with some vein quartz fragments. The quartz vein in saprolite and quartz fragments in nodules provide incontrovertible evidence that the profile is residual. The gravelly material gradually gives way to quartz sands at the middle and lower parts of the backslope.

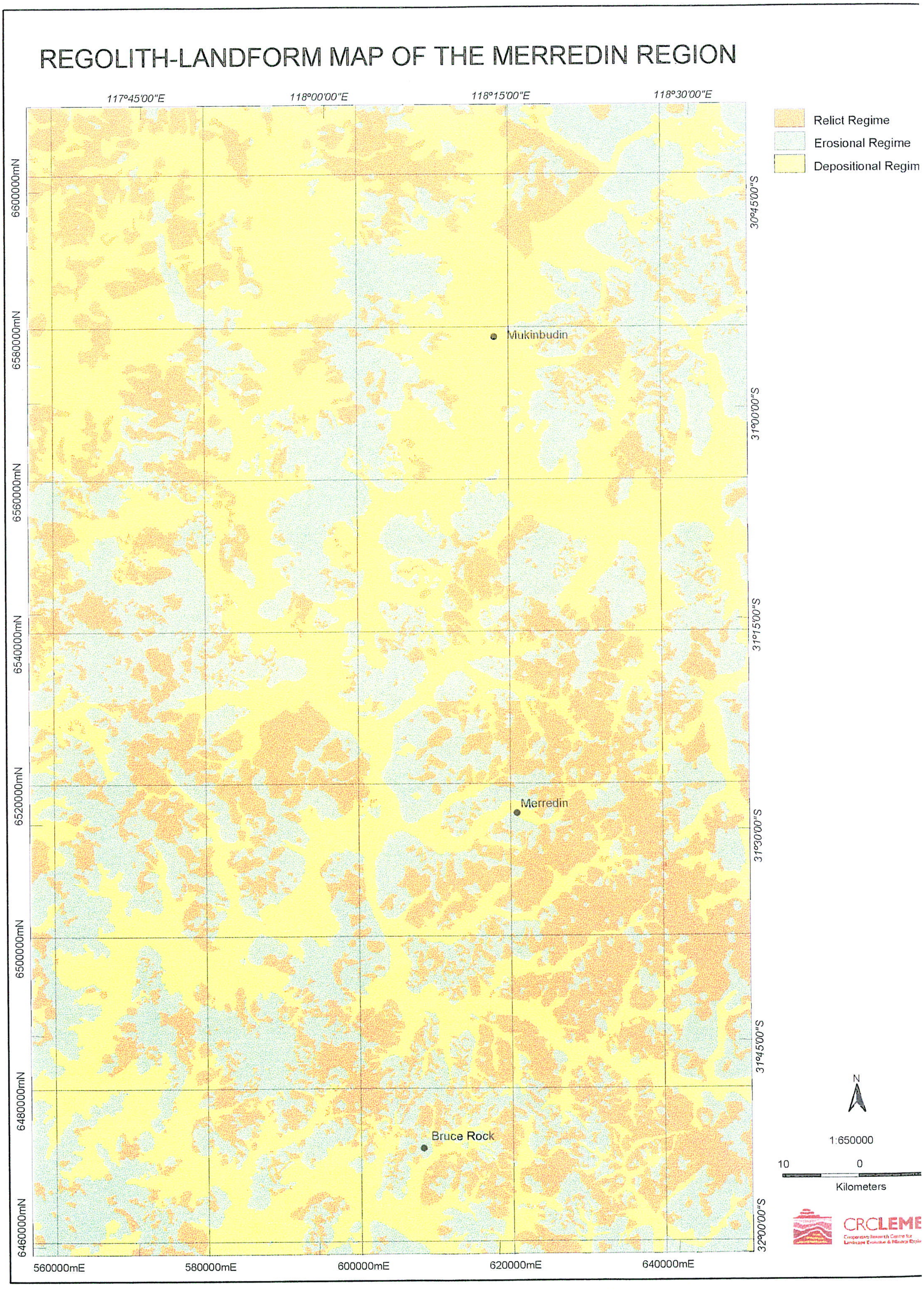


Figure 3. Simplified map of main regolith units.

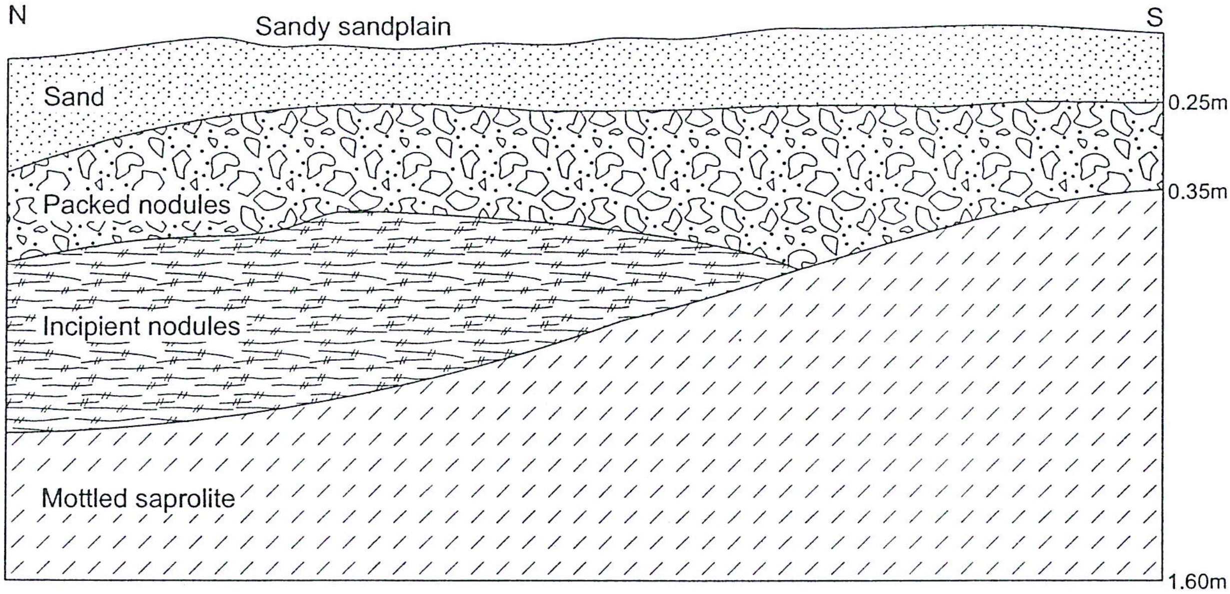


Figure 4. The lateritic profile of the sandplains near Merredin at 621900 mE 6505600 mN.

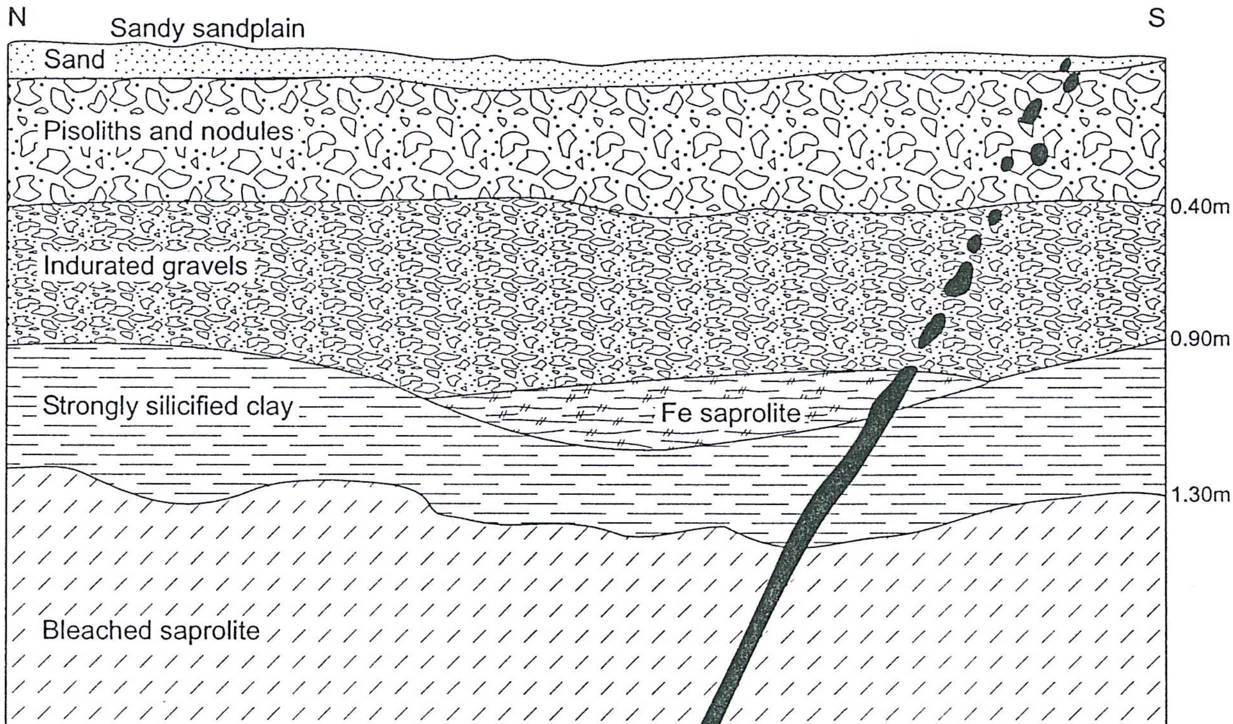
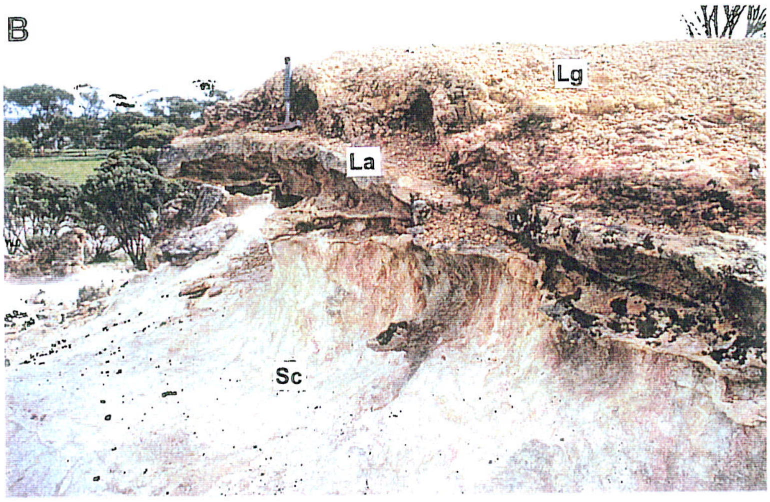
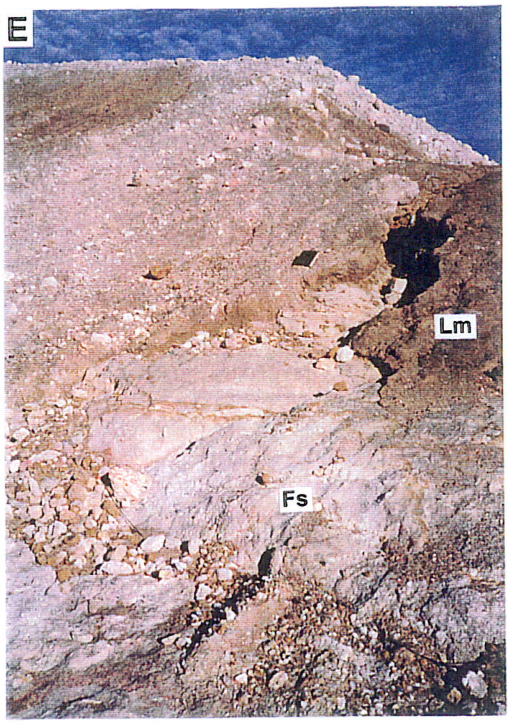


Figure 5. The lateritic profile of the sandplains north of Mukinbudin at 621435 mE 6609730 mN.





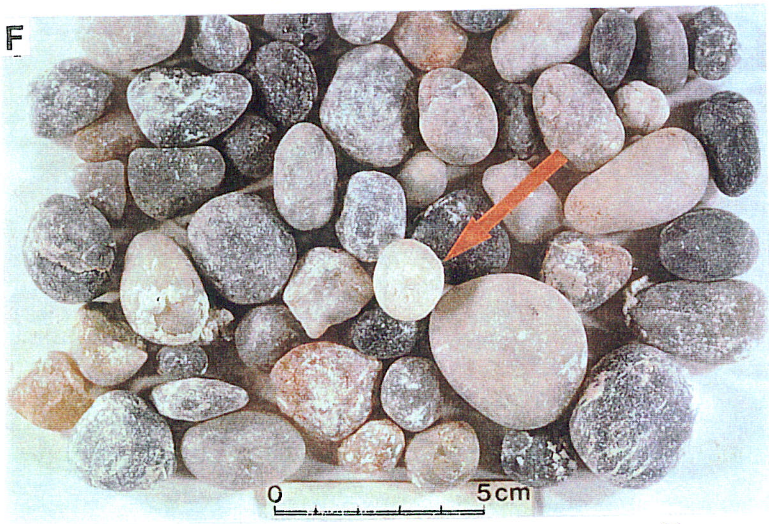
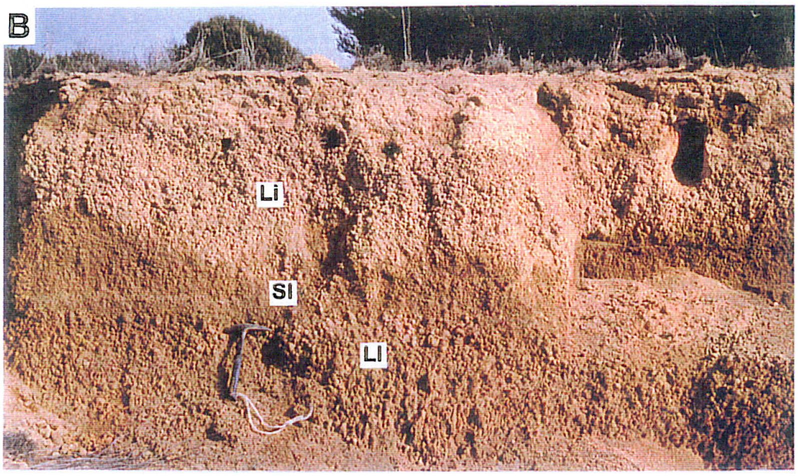
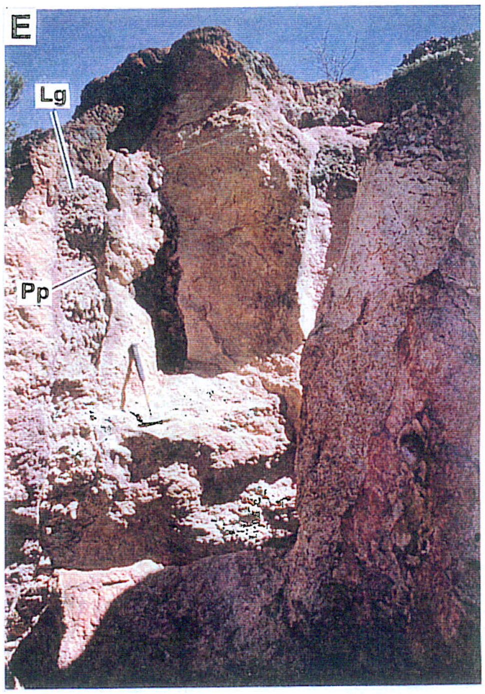


Figure 6.
A. Erosional retreat of a duricrust-capped breakaway (Br) as indicated by a remnant of the breakaway (Rm) on erosional plains (Ep).
B. The breakaway in A with lateritic gravels (Lg), indurated laterite (La) and silicified clay (Sc).
C. A close-up of the breakaway in A showing a quartz vein (Qz) whose fragments are found in lateritic gravels (Lg).
D. The sandy sandplain where a palaeo-river is unearthed at a dam (Dm), northwest of Trayning.
E, Colluvium consisting of lateritic material (Lm) on fluvial sediments (Fs) at the dam in D.
F. Rounded quartz gravel from the palaeo-river.





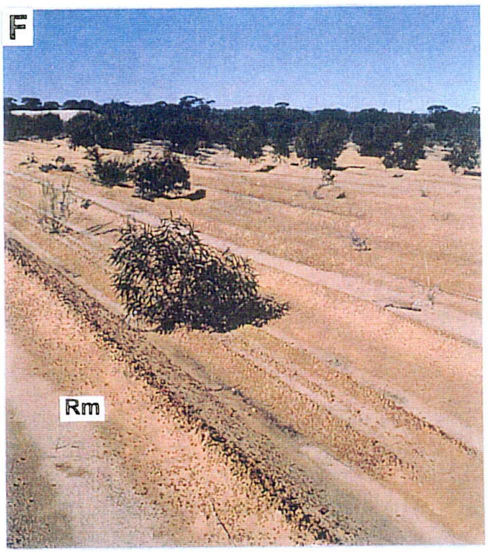


Figure 7.
A. Lateritic gravels and Fe indurated duricrust (Dc) on gravelly sandplains (Rl), northwest of Trayning (563201 mE 6559422 mN).
B. Small lateritic gravels (Sl) sandwiched in large gravels (Ll), indicating local redistribution of lateritic material on sandplains, north of Mukinbudin (609158 mE 6598158 mN).
C. A lens of coarse gravels (Cg) in yellow sands as locally-derived colluvium.
D. A close-up of the coarse gravels.
E. The face of a breakaway with solution pipes (Pp)) filled with lateritic gravels (Lg), northeast of Mukinbudin (632277 mE 6582853 mN).
F - Loose lateritic gravels hosted by a sandy matrix on remnants of gravelly sandplains (Rm), northwest of Trayning (567658 mE 6555354 mN).

Table 2 The lateritic profile of the gravelly sandplains north of Mukinbudin.

Depth (m)	Description	Interpretations
0.0-0.1	Topsoil on sandy loam and unsorted, angular quartz sands, with floats of vein quartz fragments.	Locally derived colluvium.
0.1-0.4	Lateritic gravels, mainly nodules, and some large elongated, hollow nodules formed in association with insects. Fragments of broken down quartz veins among the lateritic nodules.	Lateritic residuum. The fragments of vein quartz in the lateritic gravel show the residual nature of the profile. Insect-associated nodules indicate near-surface process with little subsequent erosion.
0.4-0.9	Silica indurated duricrust with incipient nodules on mottled and silicified saprolite.	Mottled zone.
0.9-1.3	Strongly silicified clay; saprolitic fabric is unidentifiable.	Bleached zone.
1.3-2.7	Bleached clay with angular quartz grains.	Saprolite.

Another feature of the profile is the presence of lateritic nodules formed in association with insects. The nodules are commonly elongated, about 4 cm long, and have smooth hollows inside. Incorporated in duricrust with lateritic nodules and pisoliths, the 'hollow' nodules are indurated. As associated with insects and probably developed near the surface, the 'hollow' nodules indicate that erosion since their formation must have been very minor at this location.

Profile 3 Sandy sandplain

This profile is exposed at a gravel pit located at 609158 mE 6598158 mN, north of Mukinbudin (Figure 7B). The main feature of the profile is fine lateritic gravels in a matrix of clay and sand interbedded in two horizons of large nodules (Table 3 and Figure 8). Packed Fe-indurated nodules in the lower part of the profile overlie highly silicifed clay on saprolite. Compared to other residual profiles in the region, these nodules are probably residual in nature. The interbedding of the gravels, however, suggests that the coarse gravels in the upper part are colluvium. Most of the nodules still have intact cutans, which are thought to indicate a short distance of transportation. This profile is regarded as residual but shows that local distribution of lateritic material is also involved in the formation of the sandplains in the relict regime.

Table 3 Profile 3 through the sandy sandplains north of Mukinbudin.

Depth (m)	Description	Interpretations
0.00-0.25	Topsoil on sandy loam and unsorted, angular quartz sands.	Locally derived colluvium.
0.25-0.65	Lateritic gravels, mainly nodules some pisoliths, ranging from 1.0 to 2.0 cm across.	Locally derived lateritic material.
0.65-1.10	Small lateritic gravels, ranging from 0.5 to 1.0 cm across, embedded in clay and sand matrix. Pisoliths and cutans are preserved.	Locally derived lateritic material.
1.10-2.10	Packed nodules ranging from 1.5 to 2.0 cm across, the lower part is Fe indurated.	Lateritic residuum.
2.10-2.30+	Angular quartz sands on silicified saprolite.	Saprolite.

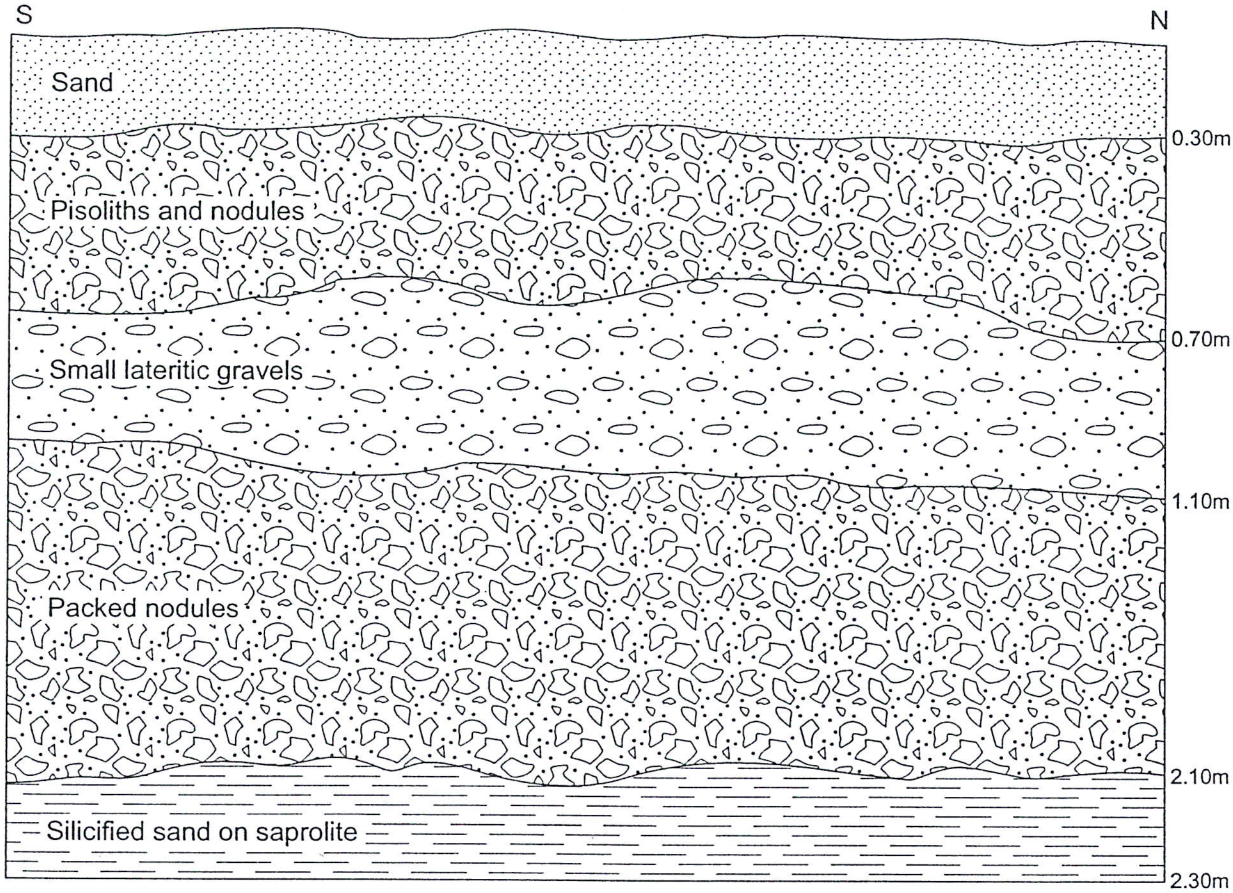


Figure 8. The lateritic profile of the sandplains north of Mukinbudin at 609158 mE 6598158 mN.

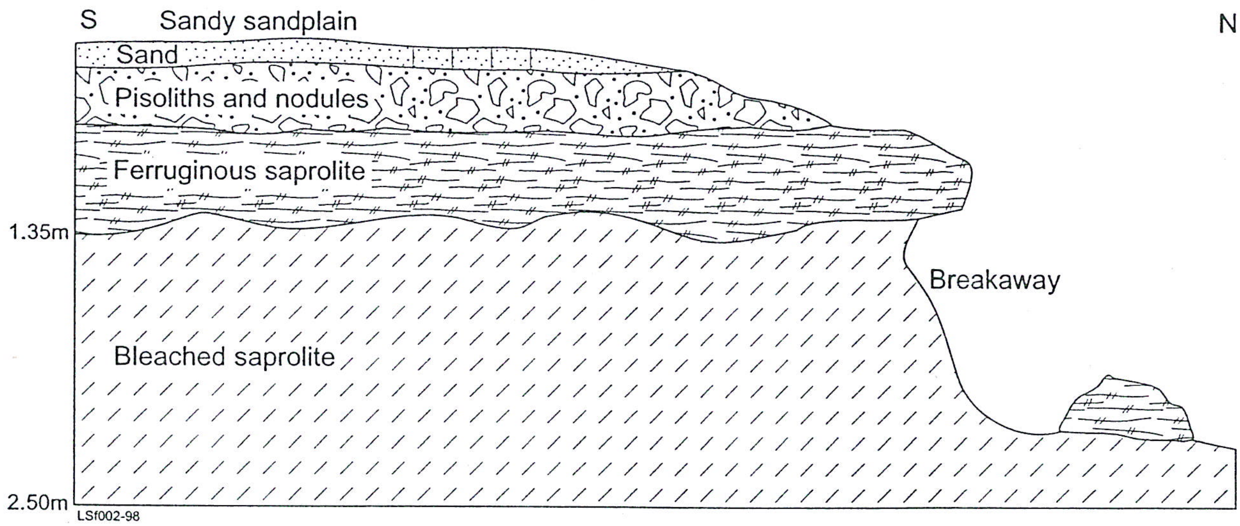


Figure 9. The lateritic profile of the sandplains north of Mukinbudin at 626021 mE 6613385 mN.

Profile 4 Lateritic duricrust of sandy sandplain

This profile is exposed at a breakaway north of Mukinbudin at 626021 mE 6613385 mN where the overlying sands have been stripped (Table 4, Figure 9). It consists mainly of ferruginous saprolite at the breakaway, behind which is a narrow belt of lateritic duricrust. Unlike most sandplains in the Merredin region, there is no backslope at this site. This profile shows that lateritic gravels are exposed upon removal of sands from the edge of the breakaway.

Table 4 Profile 4 through the sandy sandplains north of Mukinbudin.

Depth (m)	Description	Interpretations
0.00-0.30	Topsoil on sandy loam and unsorted, angular quartz sands.	Locally derived colluvium
0.30-0.85	Lateritic gravels, mainly nodules and some pisoliths 1.0 - 2.0 cm across.	Lateritic residuum.
0.85-1.35	Angular quartz sands in clay matrix, strongly ferruginised.	Mottled saprolite.
1.35-2.50	White clay.	Saprolite.

Profile 5 Lateritic duricrust of sandy sandplain

This profile (627054 mE 6494408 mN, south of Merredin) shows that not all lateritic duricrusts occur in association with breakaways. At this site, the sandy sandplain descends gently to a patch of gravelly sandplain where sandy material has been removed (Table 5, Figure 10). It has both magnetic and non-magnetic nodules.

Table 5 Profile 5 through lateritic duricrusts of the sandy sandplains south of Merredin.

Depth (m)	Description	Interpretations
0.0-0.2	Topsoil on sandy loam and unsorted, angular quartz sands.	Locally derived colluvium.
0.2-0.7	Magnetic and non-magnetic lateritic gravels, mainly nodules 0.5 - 2.0 cm across.	Lateritic residuum.
0.7-1.3	Fe-indurated gravels.	Lateritic residuum.
1.3-2.6	Angular quartz sands in clay matrix with mottles.	Mottled saprolite.

2.2.2 *The nature of gravelly and sandy sandplains*

The profiles presented above have characteristics of residual development and hence the gravelly sandplains in the Merredin are developed largely *in situ*. This interpretation is consistent with observations by many previous workers who investigated sandplain formation in Western Australia (Woolnough, 1927, 1928; Terrill, 1956; Prider, 1966; Sadleir and Gilkes, 1976; Anand, 1995, 1998; Anand *et al.*, 1991; Davy, 1979). Prescott and Pendleton (1952, p.26) considered that the laterite had not been transported laterally at all, but had undergone only vertical accumulation due to chemical weathering of the bedrock. Similarly, various early workers demonstrated the *in situ* nature of several lateritic profiles in Western Australia by tracing bedrock characteristics, such as quartz veins, foliation, etc, through the laterite and to the surface (Walther, 1915; Woolnough, 1927, 1928; Terrill, 1956; Prider, 1966).

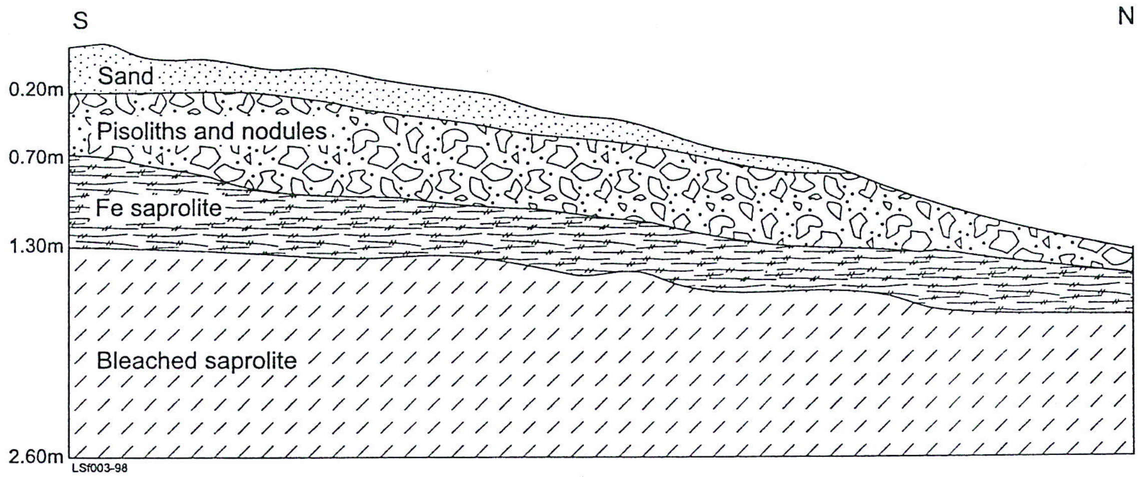


Figure 10 The lateritic profile of the sandplains south of Merredin at 627054 mE 6494408 mN.

The origin of the sandy sandplains, however, has been a subject of controversy. Carroll (1939) studied heavy minerals and grain shapes on the sandplains of the Yilgarn Goldfield and concluded that those sandplain soils that contain a laterite horizon are residual. Prider (1966) considered abundant brittle kaolinite spherulites in the yellow sandy material of the sandplains at Boorabbin as indicative of little or no movement. Ollier *et al.* (1988) and Anand *et al.* (1989) also suggested that yellow sands are residual.

In contrast, Mulcahy (1960, 1961, 1964, 1973, 1981), Hingston and Bettenay (1961), Bettenay and Hingston (1964), and Brewer and Bettenay (1973) considered yellow sands as colluvium that had moved downslope for a short distance only and were derived largely from the ferruginous duricrust of pre-existing laterites, filling valley depressions and leveling out irregularities in the upland laterite remnants.

In this report, the yellow sands on sandy sandplains are interpreted to be largely residual or colluvium of very local origin. This conclusion is based on the following:

(i) All sandplain samples contain pale grey to yellowish kaolinitic glaebules (Figure 11), formed by concentric deposition of clay particles around a central core of isotropic kaolin (Brewer and Bettenay, 1972). The kaolin constituting the core is fine-grained and poorly ordered as indicated by its broad X-ray diffraction reflections. The glaebules occur in both unconsolidated sand and nodules as well as pisoliths contained within the sands (Figure 12). They are most common in the 180-250 and 250-350 μm fractions of the unconsolidated sands.

Energy dispersive X-ray analyses of glaebule cores show a chemical composition consistent with pure kaolinite and provide no evidence of induration by amorphous silica, suggesting that glaebules are fragile and prone to disintegration during wind erosion. In comparison to the kaolinitic core, the argillans or clay layers (Figure 11A and 11B) exhibit a yellowish colour in cross-polarized light, probably due to the presence of goethite within kaolinite plates. The thickness of argillans varies from tens to hundreds of microns.

Some glaebules contain clearly recognizable pseudomorphs after mica (Figure 11C and 11D). Such kaolinite pseudomorphs are unlikely to survive extensive movement by wind or water, neither can they form *in situ* (Carroll, 1939; Prider, 1966; Brewer and Bettenay, 1973). Their presence, therefore,

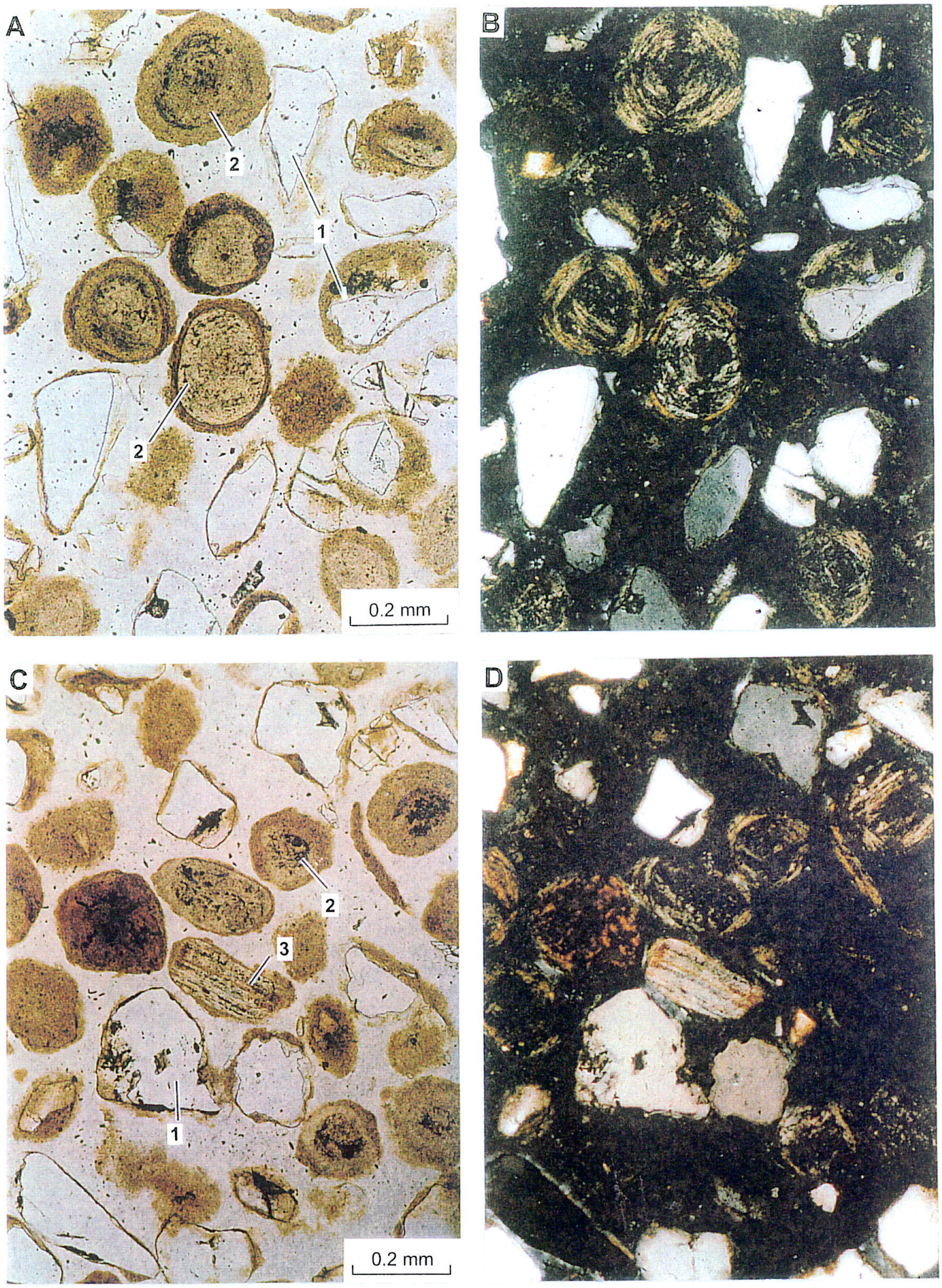


Figure 11.
Transmitted light photomicrographs of Merredin sandplain material (Sample No. 12-0074 from 632428 mE 6533021 mN).
A - Plane polarized, 1 - angular quartz grains and 2 - kaolinite glaebules.
B - Cross polarized, the same sample as A.
C - Plane polarized, 1 - angular quartz grains, 2 - Kaolinite glaebules and 3 - fragments of pseudomorphs of mica (Sample No. 12-0063 from 631043 mE 6523692 mN).
D: cross polarized, the same sample as C, location.

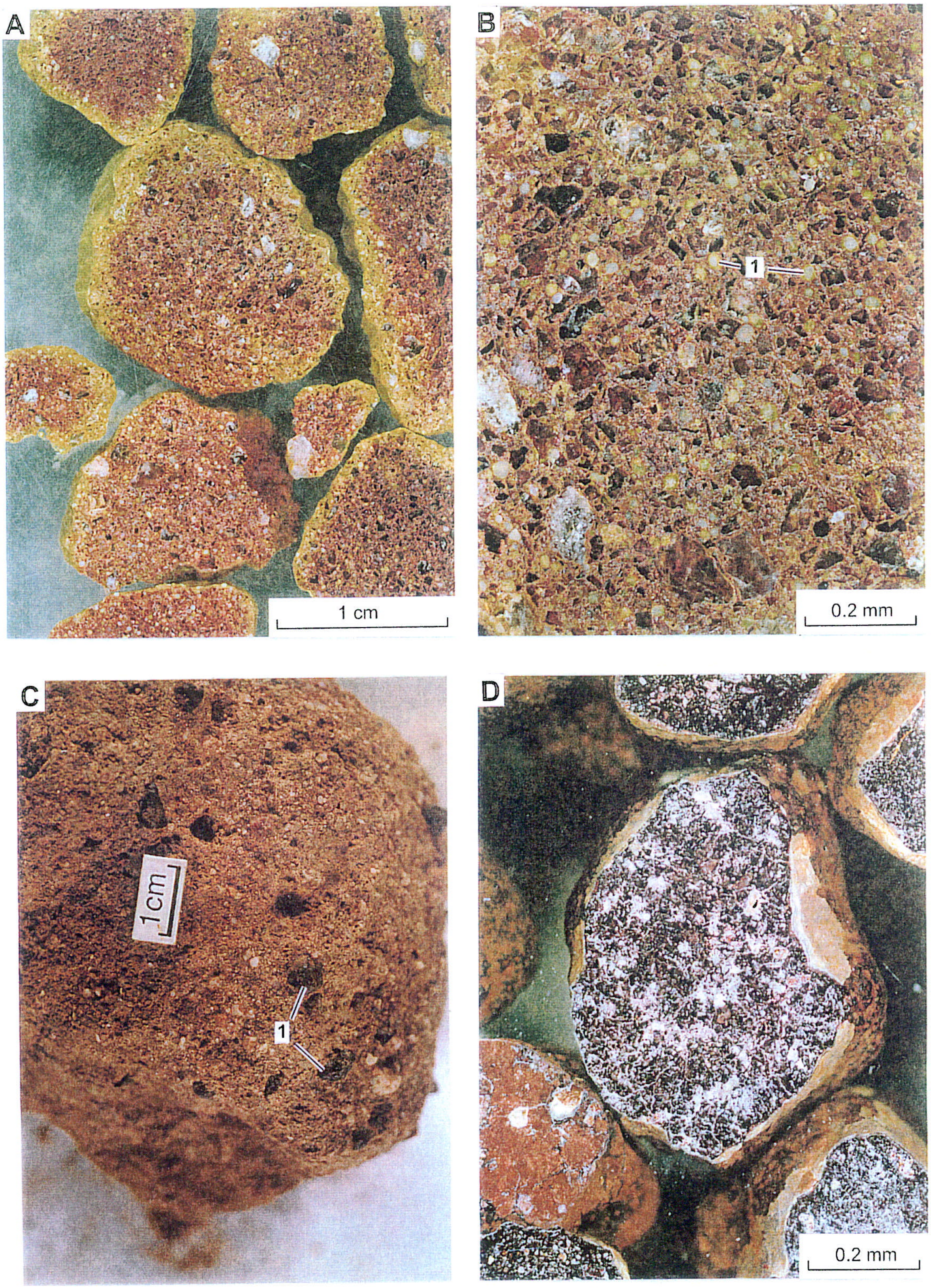


Figure 12.

A. Low magnification photomicrograph of a polished section of lateritic nodules (Sample No. 12-0074) from the Merredin region (632428 mE 6533021 mN). The nodules consist of a sandy soil matrix indurated by hematite and goethite.

B. High magnification photomicrograph of the same sample used in A. Kaolinite glaebules (1) are also present in nodules.

C. Black pisoliths embedded in Th-rich soil (Sample No. 12-0089 at 590615 mE 6550586 mN). These pisoliths are typical of maghemite-rich magnetic pisoliths commonly found in upper horizons of residual laterites.

D. A photomicrograph of polished section of the pisoliths shown in C.

suggests that sandplains have developed locally, with some possible redistribution over short distances of, for instance, a few hundred metres.

(ii) Most quartz grains in sandy sandplains are angular to sub-angular (Figures 11 and 12). Smaller quartz grains are partially enclosed by argillans of varying thickness. The homogeneous, angular and unsorted fabric of the sands also rules out involvement of alluvial or aeolian processes in the development of the sandplains.

(iii) Micro fractures within some large quartz grains are filled with hematite, indicating that these grains may have previously formed a part of hematitic mottles, nodules and other Fe-rich material. These features are consistent with sandplain material being derived from local mottled zone of the residual profile.

Killigrew and Glassford (1976), Glassford and Killigrew (1976) and Glassford and Semeniuk (1995) advocated aeolian and fluvial origins of the kaolinitic glaebules, which are inconsistent with the observations noted above. However, the sandplains cannot be considered as formed strictly *in situ* either, because they contain high proportions of skeletal quartz grains and a uniformly lower content of kaolinitic clay in the sandy, upper part. An *in situ* formation would have required significant clay eluviation and/or chemical destruction of kaolinitic clay to produce the sandy facies from the clay-rich mottled zone (Brewer and Bettenay, 1973). In some places, a lens of coarse gravels is evidently colluvium (Figures 7C and 7D).

The petrographic features of the kaolinite glaebules and the nature of quartz grains suggest that the sandy material of the sandplains in the Merredin region is probably derived from very local sources, and should be considered as residual on a broad scale. This interpretation also applies to the lateritic gravels beneath the yellow sands. The incipient nodules (Table 1) and the quartz fragments in duricrust with an underlying quartz vein (Table 2) show that the duricrusts are formed largely *in situ*. Nodular gravels in the upper part of Profile 3 (Table 3) appear to be of local origin because they are intact and their cutans are well preserved.

2.2.3 Regolith-landform units in relict regimes

Rl - Gravelly sandplains bounded in places by breakaways; lateritic gravels on duricrust

This unit consists of gravelly sandplains. The lateritic gravels, comprising nodules and pisoliths, are common on the elevated parts of the sandplains and are in general associated with breakaways (Figures 6B and 7A). This unit generally has a high Th signal and stands out well on pseudo-colour images. Bettenay and Hingston (1964) mapped the unit as Ulva (erosional). The radiometric data used in this study, however, allow a more accurate delineation.

The lateritic gravels in this unit may be non-magnetic or a mixture of magnetic and non-magnetic. The magnetic nodules, pisoliths and fragments occur in many parts of the study area, but are particularly common on gravelly sandplains in the gneiss belt (Figure 2). This magnetic character is mainly due to maghemite, although a similar amount of hematite is also present. The non-magnetic gravels consist mainly of hematite and quartz with minor kaolinite and goethite.

Geochemical analysis shows that the magnetic gravels contain more Fe and less Si and Al than the non-magnetic pisoliths (Table 6). Consequently, concentration of trace elements, such as Cr and Nb, associated generally with iron oxides, is greater in magnetic pisoliths.

Table 6 Major and trace element composition of magnetic and non-magnetic pisoliths of the Rl unit.

Elements	Units	Magnetic (N=29)	Non-magnetic (N=29)	Correlation coefficient
SiO_2	%	24.28	40.21	0.68
Al_2O_3		14.18	20.67	0.66
Fe_2O_3		56.82	32.09	0.65
MnO		0.05	0.03	0.92
MgO		0.1	0.07	0.53
CaO		0.08	0.05	0.8
Na_2O		0.04	0.03	0.04
K_2O		0.12	0.06	0.6
TiO_2		1.23	0.81	0.64
P_2O_5		0.08	0.05	0.51
Ba	ppm	224	82	0.91
Cl		77	69	0.72
Cr		428	238	0.51
Cu		2	2	0.55
Ga		74	62	0.77
Ni		7	17	0.52
Nb		28	18	0.65
Pb		130	84	0.74
Rb		10	3	0.6
S		276	249	0.46
Sr		36	24	0.7
V		779	502	0.82
Y		12	12	0.6
Zn		26	9	0.11
Zr		756	611	0.87

The micro-fabric of both pisolith types is massive and complex, showing several generations of Fe oxide precipitation. Although large quartz grains indicate granitic parent material, no saprolitic textures are preserved in the pisoliths.

Rm - Remnants of gravelly sandplains; mixture of loose lateritic gravels with yellow sands on iron-indurated nodules

The lateritic gravels in this unit are generally hosted by a sandy matrix; they have only low concentration of Fe_2O_3 (5 to 30%), due to their high quartz contents (Figures 7F and 12A). The matrix of the gravels is very similar to the surrounding sandy soil matrix. Iron induration of sandy soil is likely to have formed mottles, which then further matured into gravels. The accumulation of quartz grains and the development of thick sands may have been the result of weathering and subsequent breakdown of the quartz-rich lateritic material (Mulcahy, 1959, 1960). Thorium, commonly associated with lateritic gravels, is relatively abundant at the surface and gives a moderately strong radiometric response, despite dilution by the sandy matrix.

Geomorphologically, this unit (Rm) and the gravelly sandplains (Rl) are similar; both form uplands and generally merge into each other. The main difference is the higher sand component in Unit Rm and although the gravels are less ferruginous, they are as suitable as those in Unit Rl for geochemical sampling.

Rn - Undulating sandplains; thin yellow sands and grey soil over lateritic gravels

This unit marks the transition from the gravelly sandplains to the sandy sandplains, but bears more similarities with the latter. Lateritic gravels normally occur beneath a thin surficial cover of sand. The thickness of surficial sand varies and in some areas is so thin that loose gravels are exposed at the surface. The proportion of gravels in this unit is much smaller than that in the gravelly sandplains (Unit Rm). It has been separated from the sandy sandplains (Unit Rs) below, because lateritic material is present at or near the surface and can be sampled either by handpicking or by augering.

The Th signal of this unit (Rn) is relatively low, because of the predominance of quartz sands at the surface. Depending on the amount of lateritic material on the ground, the Th signal may vary from low to medium.

Rs - Sandy sandplains; thick yellow sands on ferruginous nodules

Yellow sands and sandy loams form sandy sandplains (Figure 13A and 13D), which gradually merge into clay-rich soils on mottled saprolite along the valley sides. The slopes are generally very gentle, falling about 1 m in 100 m. At the lower end of the slopes, lateritic gravels, formerly concealed by yellow sands, may be exposed. Yellow sands are much more common than lateritic gravels and make up about 70% of the total area of the sandplains. The profile generally changes from sand at the top to mottled material containing moderate to large amounts of ferruginous and generally indurated gravel (Figure 13B). The thickness of the sand varies from 0.5 m to 3 m.

Mineralogically, approximately 90% of the soil material is quartz; the remaining 10% is mainly clay and minor Fe oxides (see Table 11). Kaolinitic glaebules are most common in the unconsolidated sands (see Section 2.2.1). Both Th and K concentrations are extremely low in this unit, which therefore shows a very low signal. The sandy material is not suitable for geochemical sampling, but the underlying lateritic gravels can be sampled by augering.

2.3 Erosional regime - saprolite and saprock

2.3.1 Regolith stratigraphy

The past existence of lateritic residuum in some areas of erosional regimes is shown by scattered remnants of lateritic gravels or other lateritic material on iron- or silica-indurated clay over saprolite. Although lateritic gravels can be found, the regolith is classified as erosional rather than relict, because lateritic duricrusts and, in some cases, the upper portion of ferruginous saprolite have been eroded. Sites where granitic rocks outcrop and where removal of the lateritic residuum to fresh bedrock cannot be readily demonstrated, are also classified as erosional regimes in this study.

Profile 6 Remnants of lateritic nodules on a breakaway

This site is located to the northeast of Mukinbudin (632277 mE 6582853 mN). It consists of deeply weathered granitic rocks and pegmatite with overlying indurated clay (Table 7). Loose nodules in solution hollows on the top surface of the breakaway indicate that this site was once covered by lateritic residuum. Several pipe-like features, about 2.5 m deep and 0.5 to 1.0 m wide, are exposed along a breakaway; they are filled with debris including lateritic nodules (Figure 7E). Such pipe-like features are common in granite terrains and are interpreted to be solution holes. They may have developed along joints, intersecting fractures or tree roots in saprolites on granite.

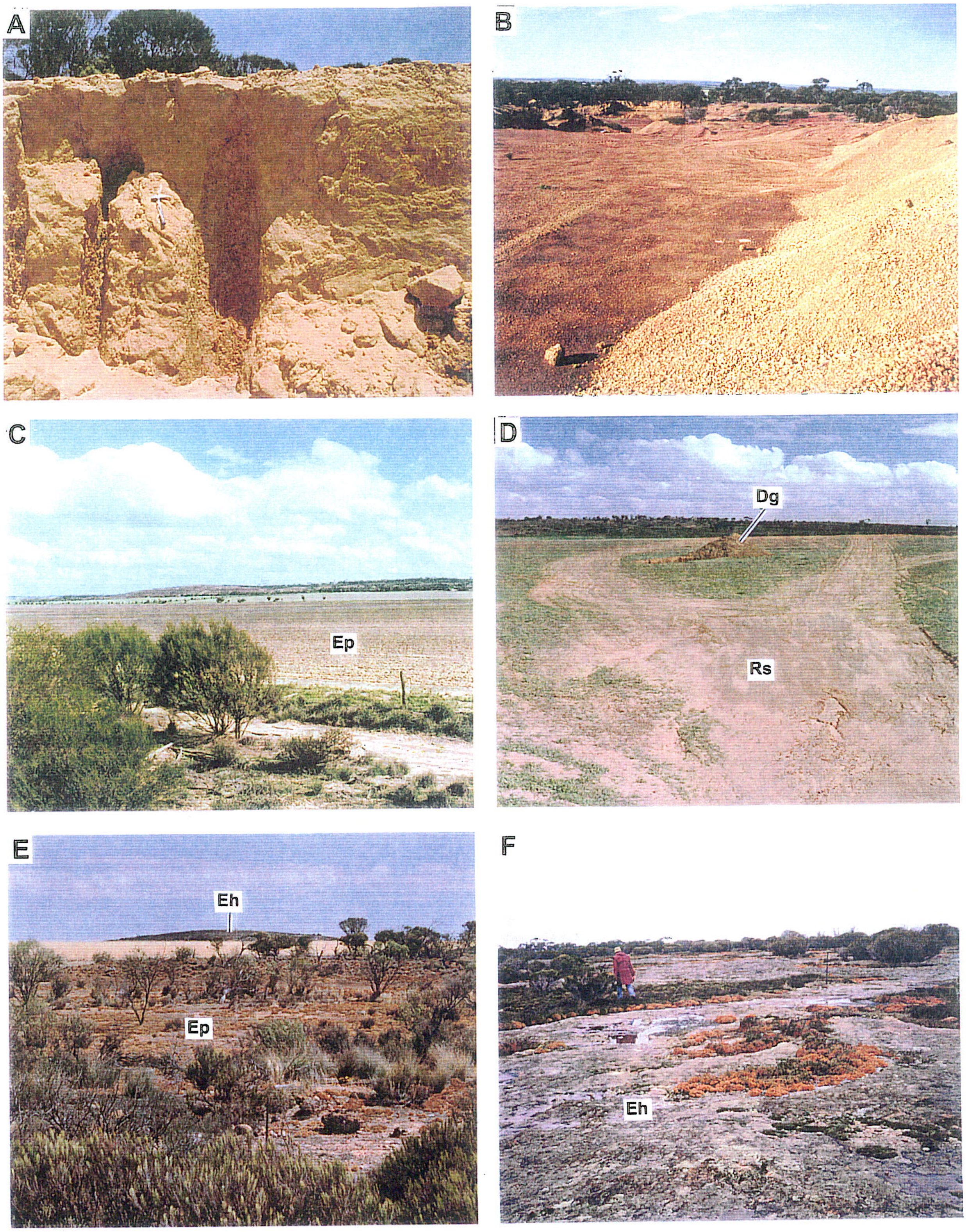


Figure 13.
A. Thick, unsorted, yellow quartz sands common to sandy sandplains, north of Mukinbudin (623269 mE 6618290 mN).
B. Undulating subsurface of indurated gravels exposed at a gravel pit where yellow sands and loose gravels have been removed, northeast of Merredin (640688 mE 6529662 mN).
C. Grey soil on saprock forming an extensive erosional plain, north of Burracoppin (642300 mE 6528850 mN).
D. Extensive sandy sandplain (Rs) overlying lateritic nodules as shown at a digging (Dg), north of Trayning (567393 mE 6556812 mN).
E. A veneer of grey lithic soil on granite subcrop forming an erosional plains (Ep), and Mt. Stevens, a low granite hill (Eh), north of Kununoppin.
F. Bare granite outcrop forming a low rise (Eh), southeast of Merredin.

Table 7 Profile 6 through an erosional surface northeast of Mukinbudin.

Depth (m)	Description	Interpretations
0.00-1.10	A few of loose lateritic gravels on ferruginised clay.	Ferruginous saprolite.
1.10-1.80	Quartz grains embedded in white to grey clay.	Bleached saprolite.
1.80-2.60	Angular quartz grains in clay matrix with mottles developed.	Saprolite.

2.3.2 *Regolith-landform units in erosional regimes*

Es - Gentle sloping valley sides; clay-rich soil on mottled saprolite

Clay-rich soils on mottled saprolite are the main regolith unit in the erosional regime. Bettenay and Hingston (1961, 1964) classified these soils as duplex soils, because they consist of two very distinct horizons, *i.e.*, a clayey and a sandy horizon. Mottled sands and saprolitic materials are exposed at many dam sites. Because the saprolite is generally covered by soil and/or sand, the unit looks almost identical to yellow sands and sandy loam on the sandy sandplains (Rs).

This unit has a low K signal in radiometric data. Depending on the thickness of the soil and sand cover, the unit can also have extremely low K counts. If the cover is more than 1 m thick, the sand-covered saprolites of this unit and the sandy sandplains (Rs) appear identical in both the Th and K signal and can only be distinguished accurately in the field. In general, this unit is situated at a lower level in the landscape than the sandy sandplains, it commonly occurs along the valley sides.

Ep - Erosional plains; yellow sands and grey lithic soil on saprock or granite subcrop

At the base of breakaways and on deeply eroded saprolite, where both the sandy and lateritic materials have been removed, 1-2 m thick saprock (slightly weathered bed rock) is exposed. Residual soil has developed in small pockets and is mixed with lithic fragments. It forms gently sloping pediments (Figures 6A and 13C) and has a medium radiometric K response, which distinguishes it from other units.

Eh - Hills and low rises; granite outcrop or subcrop with a thin cover of lithic soil

In the Merredin region, granite outcrops generally form prominent features, commonly as isolated hills (see Figure 13E). In most cases, chemical weathering of these rocks is limited and physical disintegration is the main process in shaping the landforms. The products of weathering are washed down hill, resulting in bare slopes and rock faces (Figure 13F). High K concentrations in unweathered granite give a well defined radiometric signature.

2.4 Alluvium and colluvium (depositional regimes)

2.4.1 *Regolith stratigraphy*

Depositional regimes in the study area comprise alluvium on broad valley floors and colluvium, or a combination of colluvium and alluvium on the lower part of shallow valley sides. Astro Mining N.L. drilled a number of holes through alluvium and colluvium and into bedrock near Kununoppin. Several boreholes in the main drainage west of Kununoppin provide information about the regolith stratigraphy.

Profile 7 Lateritic gravels in alluvial sediments

A line of RAB holes drilled on the valley floor south of Kununoppin (586450 mE 6558465 mN) show a lens of lateritic gravels, about 0.5 - 2.0 cm in diameter, between the saprolite and the alluvium/colluvium (Tables 8 to 10, Figure 14). The lateritic material is described as lateritic nodules in a matrix of sub-angular quartz sands (50% by volume, *e.g.*, Table 10) and pale green clay. Sand and clay are both uncommon in the lateritic duricrust on the sandplains, suggesting that the lateritic gravels are not residual. The nodular horizon is up to 40 m thick (Tables 8-10), which is too great to be produced by residual weathering. On the other hand, yellow cutans on the lateritic gravels suggest that they were only transported over a short distance. Therefore, these gravels appear to be colluvium derived locally from erosion of nearby gravelly sandplains.

This profile provides a case of inverted stratigraphy. The lateritic material, which occurred originally on the surface and was subsequently eroded and deposited in the ancestral drainage, is now overlain by sandy clay that may have come from the erosion of saprolite. Such inverted stratigraphy of an original laterite profile has also been observed in a number of districts on the Yilgarn (R.R. Anand, personal communication, 1998).

Bettenay and Hingston (1964) also reported the presence of colluvium-alluvium directly overlying the remnants of Tertiary lateritic material, which was interpreted by Mulcahy and Bettenay (1971, p.434; 1972, p.351) as 'the in situ weathered profiles preserved beneath the inland valleys'. Mulcahy and Bettenay did not present a detailed stratigraphy of the regolith in the depositional terrain or the characteristics of the buried lateritic horizons to support their statements. Comparison with the present data, which are in favour of a colluvial origin, is therefore, difficult.

Table 8 Regolith stratigraphy in depositional regime south of Kununoppin - Drill hole MERA015 (see Figure 14).

Depth (m)	Description	Interpretation
0-2	Sub-angular quartz sands and calcrete segregations.	Calcareous soil.
2-14	Pale green clay and white creamy clay with sub-angular quartz sands.	Alluvium.
14-20	Poorly sorted quartz sands in moderately indurated matrix.	Alluvium.
20-22	Pink brown clay, partly ferruginised, with sub-angular quartz sands.	Alluvium.
22-38	Sub-angular quartz sands in pale green, yellow, and creamy clay.	Alluvium.
38-42	Yellow limonitic clay with quartz sands and Fe-segregations.	Alluvium.
42-45	Sub-angular quartz sands in yellow and creamy clay.	Alluvium.
45-56	Sub-angular, smoky-grey quartz sands in pale green clay, partly indurated.	Alluvium.
56-70	Lateritic nodules and granules with yellow goethitic cutans intact, in sub-angular quartz sands and pale green clay.	Colluvium derived from erosion of laterite east of the drainage.
70-95	Yellow limonitic and pale green clays with Fe-segregations.	Ferruginous saprolite.
95-100	Weathered chlorite-biotite schist.	Saprock.
100-115	Chlorite-biotite schist and amphibolite.	Bedrock.

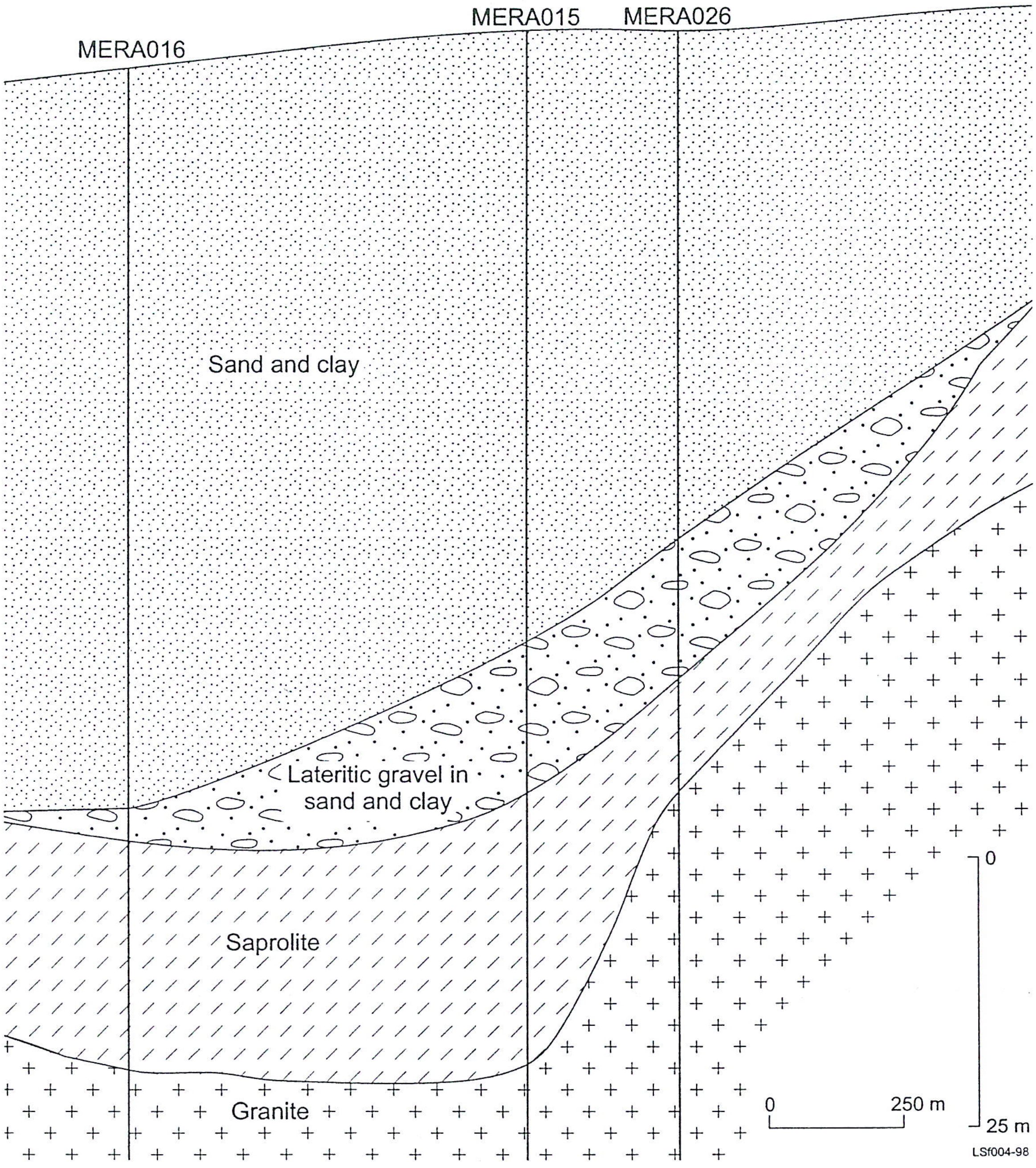


Figure 14. A cross-section through alluvium in the main drainage south of Kununoppin at 586450 mE 6558465 mN. The lens of colluvium consists of lateritic gravels, pale grey clay and quartz sands

Table 9 Regolith stratigraphy in depositional regime south of Kununoppin - Drill hole MERA016 (see Figure 14).

Depth (m)	Description	Interpretations
0-20	Sub-rounded, poorly sorted, clear quartz sands set in brown clay, Fe-segregations.	Alluvium.
20-50	Yellow clay with sub-rounded, poorly sorted, clear quartz sands, Fe-segregations.	Alluvium.
50-68	Puggy grey clay with minor sub-rounded quartz, Fe-segregations and white felspar. Grain size is decreasing upwards.	Alluvium.
68-71	Yellow limonitic clay with 1-2 cm Fe-segregations and lateritic nodules.	Colluvium.
71-92	Clay with angular quartz, feldspar and micaceous and chloritic clasts, partly ferruginised.	Saprolite.
92-111	Dark green amphibolitic rock with chlorite.	Bedrock.

Table 10 Regolith stratigraphy in depositional regime south of Kununoppin - Drill hole MERA026 (see Figure 14).

Depth (m)	Description	Interpretations
0-2	Pale brown clay with quartz sands and carbonate.	Calcareous soil.
2-9	Predominately quartz grains with ferruginised clasts in clay.	Alluvium.
9-12	Kaolinitic clays with abundant coarse sands.	Alluvium.
12-17	Coarse angular sands in limonitic clay, partly silicified and partly ferruginised.	Alluvium.
17-20	Yellow pisoliths with cutans in abundant sub-angular quartz. sands.	Alluvium/colluvium.
20-47	Strongly bleached grey-green clay with quartz sands and few pisoliths (<2 mm).	Alluvium/colluvium.
47-59	Ferruginous nodules and pisoliths (up to 50% by volume) both with and without cutans, in lime green and white clay, and/or quartz sands.	Colluvium.
59-66	Brown clay.	Saprolite.
66-70	Relict feldspar, ferruginous granules and white clay.	Saprock.
70-114	Fresh feldspar, quartz, mica, and fresh granite.	Bedrock.

2.4.2 Regolith-landform units in depositional regimes

Da - Salt lakes and broad valleys; grey soil on alluvium

This unit comprises the surface of alluvial tracts associated with the main valley of the now inactive Yilgarn River. Soils in the broad valleys are characterized by secondary salinity, due to saline ground water infiltrating the upper horizons of the soil. The alluvium consists mostly of fine clays and silt; lithic gravels or other coarse sediments are absent. A lens of lateritic gravels was intersected by drilling at 60m depth (see Table 8). These gravels are considered to be colluvial, derived from the valley sides.

Dc - Broad valley; grey to brown soil on alluvium-colluvium

This unit consists of colluvium and alluvium in broad and shallow valleys of the tributary streams draining sandplains. It is difficult to identify the source of the material, as it may have originated from nearby upper slopes and/or from upstream along the drainage. The sandy clay loam soils have a thin, medium-textured A horizon, a sporadically bleached A2 horizon and a structured clay B horizon. The clay content of the soils varies from 20-40%, and is dominated by kaolinite. The Fe_2O_3 content of the unit varies from 2-5%, which is mostly in dispersed form, imparting a reddish brown colour to the kaolinitic soil.

Dl - Backslopes or valley sides; lateritic gravels in colluvium

As erosion occurred on the sandplains, particularly at their edges, lateritic materials are transported downslope and deposited at valley sides or the lower portion of backslopes. The materials consist of lateritic nodules and pisoliths in a matrix of quartz sand and clay, but there are no duricrusts under the surface soils or quartz sands. In most cases, the lateritic gravels are unconsolidated, with loose nodules on surface soils. This gives rise to a high radiometric Th signal similar to that of residual gravels. The colluvial nature of Unit D1 can, however, be demonstrated by its geomorphological setting, the large amount of sand and clay and the lack of duricrusts.

Dt - Undulating plains; proximal colluvium from ferruginous nodules

Radiometric data from the Trayning area generally show a positive correlation between Th and the amount of ferruginous nodules on the surface. East of the salt lake drainage system at Trayning, the radiometric survey shows a high Th response in an area not covered by lateritic duricrust or Fe-rich nodules. Instead, the area is dominated by alluvial and colluvial soils, derived from the granitic terrain further to the east. This apparent contradiction was investigated. The study tested two hypotheses:

A) The colluvial soil is derived from residual laterite and Th is simply inherited from laterite and retained in the soil. If true, these soils may be used for geochemical exploration, as they are likely to retain immobile trace elements.

B) The Th-rich soils contain Th-bearing minerals, such as monazite, that originate from a Th-rich source, *e.g.*, a specific granite.

Ten samples were taken from different locations around Trayning. Two samples (120120A and 120161) represent Th-poor soils whereas the other samples were taken from Th-rich soils. The heavy mineral fraction of the soils was separated and investigated for Th-bearing minerals. The mineralogy, geochemical composition and pH of the samples were determined. For a representative set of samples, the clay fraction was also separated and analyzed by XRF.

A maghemite-rich, ferruginous material dominates heavy mineral concentrates of all Th-rich soils; no discrete Th-bearing minerals, such as monazite, were identified under the optical or the scanning electron microscope. Some Th-rich soils contain fragments of black maghemite-rich pisoliths typical of those found in surface horizons of residual laterite (Figure 12C). In contrast, the Th-poor sample contains negligible ferruginous material. The presence of maghemite in Th-rich soils indicates that a significant proportion of these soils was derived from lateritic residuum.

Total Th concentrations and other parameters for the soils are presented in Table 11. Except for one sample (120129A), the pH of Th-rich soils is significantly greater than that of the Th-poor sample

(120120A) and that expected in highly leached lateritic soil (pH 5-6). The change in pH would have assisted the dissolution of ferruginous material and the release of Th for sorption by clays.

Table 11 Thorium and major element analyses of a suite of Th-rich and Th-poor soils, Trayning.

Samples	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	K_2O	Th	pH
	%	%	%	%	%	%	ppm	
120088	71.41	11.58	3.81	0.41	0.29	1.38	39	7
120089	76.38	10.91	2.39	0.37	0.19	3.13	54	6.8
120090	78.39	9.77	1.8	0.28	0.29	3.25	75	7.9
120091	70.09	12.8	2.8	0.69	1.1	2.34	90	8.8
12120A	92.58	3.6	0.81	0.01	0.02	0.16	7	4.5
12122A	63.9	9.29	17.7	0.15	0.19	0.4	101	8.5
12124A	70.77	12.88	2.72	0.61	0.4	2.99	100	6.8
120128	79.9	9.74	3.97	0.03	0.03	0.53	56	6.5
120129A	69.58	13.24	2.51	0.67	0.42	2.39	142	5.4
120161	88.7	6	1.2	0.01	0.02	0.08	12	4.8

The Th-rich soils are relatively fine, containing 23-31% clay. In contrast, Th-poor soils are sandy, containing only up to 14% clay. The difference in the clay content is important, as even pure kaolinite clay, derived from granite, can contain up to 40 ppm Th. Chemical analysis of the clay fraction of Th-rich soils demonstrates that the clay fraction contains a significant proportion (about 40-70%) of the total Th in the sample (Table 12). The Th-poor soils have low concentrations of both clay (indicated by low Al_2O_3 abundance) and Fe_2O_3, the two main Th-bearing components of soils. The high concentration of Th in soils is attributed to (i) a high clay content, (ii) the development of these soils from lateritic residuum and (iii) the presence of ferruginous material and free Fe oxides in these soils.

Table 12 Clay content and proportion of Th in clay fraction of Th-rich and Th-poor soils, Trayning.

Sample No.	Clay Content (%)	Th (ppm)		Proportion of the total Th in the clay fraction (%)
		Bulk sample	Clay fraction	
120161	14	12	53	62
120120A	8	7	40	46
120088	27	39	57	39
120089	25	54	120	56
120090	23	75	217	67
120129A	31	142	270	59

Ds - Valley sides; well-sorted white sands as aeolian deposits

Along the major drainage, there are a few patches of white, well-sorted, and subangular to subrounded aeolian sands. They have very low radiometric response in both Th and K and can easily be misidentified as thick sands developed on saprolite. Field checks are required to identify this unit.

Df - Palaeo-channel on sandplains; fluvial sediments and gravel

Fluvial deposits occur in a palaeo-drainage on the sandplains northwest of Trayning. The deposits are quite high in the landscape, approximately 40 m above the nearby main drainage. Residual sandy

sandplains and breakaways, about 5 m above the deposits, are only a few hundred metres away from these sites. The sediments consist of well-rounded pebbles and gravels mainly of quartzite and vein quartz (Figures 6D-F). The gravel clasts range from 2 to 15 cm in diameter, and their well-rounded shape indicates that they were deposited by high-energy, fast-flowing streams. The sediments have been cemented in a matrix of silicified quartz sand and clay, fining upwards to coarse quartz sand about 1.3 m thick. These are overlain by fragments of lateritic nodules and small pisoliths, probably derived from the nearby sandplains. Heavy minerals separated from samples collected from each of the three dam sites include zircon, tourmaline and rutile. Most are well rounded and moderately worn.

3. LANDSCAPE EVOLUTION AND REGOLITH DEVELOPMENT

3.1 Introduction

The Yilgarn Craton has probably been exposed to sub-aerial conditions since the late Proterozoic, and it is possible that the overall flatness of the region is a Proterozoic erosion surface (Daniels, 1975; Playford *et al.*, 1975). The drainage network is arguably one of the oldest features on this craton, with various authors suggesting Mesozoic and Palaeozoic ages (Beard, 1973; Johnstone *et al.*, 1973; Van de Graaf *et al.*, 1977). The occurrences of Permian sediments in drainage in the Laverton and Kambalda regions (Robertson *et al.*, 1996; Clarke, 1994b) suggest some, at least, may be very ancient features. In general, the craton has been stable throughout the Phanerozoic, hence the regolith and landscape have evolved largely in response to climatic changes (Butt, 1981, 1982). Permian glaciation may be considered to have given a 'fresh start' to this evolution, by removing much pre-existing regolith. Thereafter, humid conditions during the Mesozoic and early Cainozoic gave rise to extensive deep weathering, with modification occurring in response to subsequent arid periods dating from the Miocene. The accumulative effect of these processes has been to produce the low relief characteristic of the Yilgarn Craton. This general model for landscape evolution of the Yilgarn is examined in the light of studies in the Merredin region and discussed in terms of the implication to diamond exploration.

3.2 Tectonics

Tectonically, the Yilgarn Craton has been relatively stable since the Permian, although along the western and the southern margins two major tectonic events have affected the landscape evolution of the Merredin region. Firstly, and most significantly, the break-up of Gondwana in the Early Cretaceous, which led to the formation of the Perth Basin in which marine and non-marine sediments accumulated over 14 000 m.

Secondly, during the Cretaceous, a shallow sea opened up to join the southern Indian Ocean to the Eucla Basin immediately south of the craton. A long tensional phase resulted in a very gentle downwarping of the southern margin of the craton, followed by subcrustal thinning. This eventually led Australia to split away from Antarctica in the Early Eocene (Veevers, 1971).

The continental riftings have many effects on the subsequent landscape evolution of the western Yilgarn. First of all, during continental rifting and plate drift, transgression takes place under extensional stress or strike-slip motion along pre-existing lineaments, followed by rupture and marginal upwarps (Falvey, 1974; Kinsman, 1975; Fairbridge and Finkl, 1980). Thus, a significant surface uplift of the western margin of the Yilgarn Craton, or a rift flank uplift, probably occurred immediately adjacent to the newly formed Perth Basin. Such uplift would cause changes to existing drainage patterns; its effect on the development of the Yilgarn River System will be discussed in Section 3.4.6.

Libby and de Laeter (1979) reported a decrease in biotite Rb-Sr dates, which measure the time elapsed since cooling below a closure temperature, from about 2 500 Ma near Meckering to about 500 Ma near the Darling Fault. Similar results were obtained along another traverse across the Darling Fault from Harvey to Kulin (see Figure 1; Libby and de Laeter, 1993). The younger ages toward the Darling Fault were attributed to cooling as a result of erosional unloading following the upwarp along the western margin of the Craton prior to the Eocene.

The magnitude of uplifts in the Yilgarn since the Eocene is a subject of controversy. Based on shallow Eocene marine sediments, now about 270 - 300 m above sea level at Mt Ragged, the Stirling Range, Lake Cowan, and the Kennedy Range (Figure 1), Johnstone *et al.* (1973) suggested that the whole shield area has been uplifted by approximately 300 m since the Eocene. However, Eocene sediments, preserved at the 270 - 300 m levels on the western margin of the Yilgarn (see Section 3.4), do not have any marine components. Therefore, the post-Eocene uplift of the Merredin region must be within 250 m.

3.3 Climatic changes

The Merredin region has had at least three major climates since the Permian. During the Mesozoic, integrated palaeo-drainage systems were formed in the whole of Western Australia (Van de Graaff *et al.*, 1977), in which Eocene sediments were deposited. A pluvial climate must have prevailed then because development of large drainage systems requires large amounts of run-off. In the Eocene, rainfall over southwestern Australia was sufficiently great and reliable to enable the development of the pan-Australian mesophytic flora including *Cinnamomum*, *Nothofagus*, *Podcarpus*, *Casuarina*, and *Banksia* (Crocker and Wood, 1947; Wood, 1959). The presence of *Araucaria*, *Banksia*, *Nothofagus* and *Gleichenia* in sediments of Eocene origin also suggests that the region was wet (McWhae *et al.*, 1958). For instance, well-preserved microfloras in sediments of late Eocene or early Oligocene age at Coolgardie have abundant *Nothofagus* (Balme and Churchill, 1959), and in the catchment of the Yilgarn River System at West Dale, the Eocene sediments have typical, broad-leaved rainforest species observed in Eocene-Oligocene rainforest of eastern Australia (Hill and Meerifield, 1993).

Lateritization is generally considered to be the product of weathering under sub-tropical to tropical conditions with seasonal variations in rainfall, similar to those of the present-day wetter savannas, although there is some evidence that it may occur under temperate climates (Butt, 1981; 1989; Butt *et al.*, 1997). As sediments of Upper Eocene age are the youngest rocks lateritized extensively (Van de Graaff *et al.*, 1977), wet conditions must have prevailed in the region, forming a mantle of lateritic materials from the Late Eocene to Middle Miocene. In the flanking basins, there is a change from terrigenous to carbonate sedimentation since the late Mesozoic, which is probably associated with the dominance of chemical weathering and limited erosion.

From the Middle Miocene onward, the climate became more arid and gradually the modern climate was established. Alluvial sediments in palaeo-river valleys, such as in the Yilgarn River System, contain Miocene pollen, suggesting that at some time after the Middle Miocene, run-off became insufficient to clear the trunk valleys of the sediments supplied by tributaries.

3.4 Development of the Yilgarn River System

3.4.1 Introduction

One of the major driving forces behind the landscape evolution in most places is drainage development. The concepts of river incision and channel aggradation are keys to understanding landscape evolution. River incision or aggradation, however, is dictated by a base level, either the sea

level (*i.e.*, the ultimate base level) or a local geological barrier (*i.e.*, local base level), toward which erosion constantly progresses and below which a river can not incise further. Lowering of the channel beds provides energy for the tributaries to be able to erode the land surface of their catchments and supply sediments to the trunk channels. As a result of either prolonged tectonic stability or climatic changes, main rivers can lose their erosive power. Consequently, chemical weathering of a land surface, headward erosion of tributary streams and infillings of major valleys take over in shaping the landscape of a region. These concepts are applicable to the Merredin region.

The Yilgarn River System, including the Yilgarn, Salt, Avon, and Swan rivers, was once a main drainage system in the Western Yilgarn Craton but is now rather discontinuous (Section 1.5). Its development is of major importance for the landscape evolution in the Merredin region. In the following section, the evolution of the Yilgarn River System is subdivided into four major episodes: (i) establishment of an ancestral river system and erosion of the Yilgarn Craton (Permian to Middle Cretaceous), (ii) drainage development and land planation (Late Cretaceous to Eocene), (iii) development of a sluggish river (Plageocene to Miocene) and (iv) disintegration of the river system (Pliocene to Present).

3.4.2 Establishment of an ancestral river system and erosion of the Yilgarn Craton (Permian to Middle Cretaceous)

As pointed out by Van de Graaff *et al.* (1977), the Early Permian glaciation, which affected the whole state of Western Australia, would have modified any pre-Permian drainage system. The glacial event establishes a maximum age of palaeo-drainage development in the western and central parts of the Yilgarn Craton. Soon after the Permian glaciation, drainage development started on the Yilgarn Craton. Terrigenous clastic sediments, derived primarily from the Yilgarn Craton in the Triassic, are 3 km thick in the Perth Basin. To deliver such a large volume of sediments, large drainage systems must have been developed by that time. Sedimentation in the Perth Basin continued. Marine sediments of the Late Cretaceous in the lower parts of some present-day river valleys in the Perth area indicate that drainage patterns had been established and rivers had downcut to the present levels by the Early Cretaceous in the western parts of the Yilgarn block (Van de Graaff *et al.*, 1977).

3.4.3 Drainage development and land planation (Late Cretaceous to Eocene)

In the Perth Basin, terrigenous sediments of the Late Cretaceous are thin and interbedded with carbonates, with only a minor influx of terrestrial clastics. This suggests that supply of detrital sediments from the hinterland is minor, partly due to a low relief formed on the Yilgarn Craton by previous erosion. Beard (1998) attributed this to a rise in the sea level, which would have prevented further downcutting by the rivers and had given rise to the general levelling of the land surface on the Yilgarn. In turn, the levelling provided a relatively inert surface on which erosional material accumulated and beneath which deep weathering took place. As a result, a gently undulating plateau had formed on the Craton by the Middle Cretaceous, which was covered largely by the products of its own erosion.

Rainfall in the Late Cretaceous and Early Tertiary was ample, hence rivers had enough discharge and sufficient time (30 Ma) to lower their channel beds to the sea level. However, rivers had probably already downcut to their base level by the end of the Middle Cretaceous and lost their power to downcut any further. Consequently, the rivers would have collected sediments from tributaries and delivered to the sea without aggradation in channel beds. Erosion associated with the Yilgarn River System corresponds with the deposition of the Kings Park Formation in the subsurface of the Perth Basin during the Palaeocene (Playford *et al.*, 1975). The terrigenous components of the formation

were derived from the Yilgarn River System (Shafik, 1978). By the Early Eocene, a flat land surface would have been established, so that Eocene sediments were deposited in broad and shallow valleys

Eocene fluvial sediments in the western Yilgarn Craton are known at Calingiri, West Dale and Muradup (Hill and Merrifield, 1993; Wilde and Backhouse, 1977). These sediments occur on or near present drainage divides, about 270 - 300 m above sea level. At Trayning, conglomeratic sediments occur in a similar geomorphological setting (Section 2.3.1) and were probably deposited at the same time.

In the modern landscape no streams carry sediments of the grain size found in these palaeo-sediments. The river system which transported these sediments must, therefore, be older than the present salt lake system, which is approximately 40-60 m lower in the landscape than the palaeo-sediments. The sediments at Trayning underlie lateritic colluvium on the sandplains, suggesting that the palaeo-river predated the lateritization in the area. The roundness of quartzite gravel (Figure 6F) indicates a steep gradient in the longitudinal profiles of the palaeo-channels and a long distance of transportation. An alternate possibility is that the gravels were deposited in palaeo-rivers fed by waters from melting glaciers in the Permian. Although both hypotheses remain untested, the conglomerates at Trayning have many characteristics in common with other Eocene fluvial sediments in similar geomorphic settings in the western Yilgarn.

Eocene sediments, as indicated by a rich spore-pollen assemblage, also occur lower in the landscape (220-260 m) within a discontinuous valley of the Beauford River (Figure 1; Waterhouse *et al.*, 1994). These sediments are located about 60 m lower than the fluvial sediments with a basal conglomerate at an elevation of 320 m on the modern interfluve at Kojonup (Wilde and Backhouse, 1976). However, Eocene sediments are not known in the valley of the present-day Yilgarn River.

3.4.4 Development of a sluggish river (Oligocene to Miocene)

From the Oligocene to Middle Miocene the climate progressively changed towards aridity. The region nevertheless remained dominantly wet and deep weathering took place. Only towards the end of the Middle Miocene did an arid climate begin to prevail. A wet climate would normally increase the run-off into the Yilgarn River System and thus intensify its erosive power. There is, however, very little terrigenous sediment of this period in the Perth Basin, suggesting a dwindling rather than an increase of the water flow. There is also very little fluvial sediment in both the main drainage and its tributaries for valleys of this size. Vast areas of the flat valley floors have only very thin soil on saprolite exposed in many small farm dams in the Merredin region. There are also very few terrace or floodplain deposits, which are normally associated with large rivers.

Drilling by Astro Mining N.L. intersected 70 m of alluvium near Kununoppin in the main channel which is here only a few hundred metres wide. A further example is the main channel in a broad and shallow valley at Quairading, which is also only a few hundred metres wide (Salama, 1997).

The relative paucity of sediment in the main valleys is attributed to an abrupt change in water flow, possibly associated with tilting of the Yilgarn Craton. With the western margin of the Craton tilted up, the gradient of the Yilgarn River System would have been reduced and hence, had become sluggish. Similar abrupt changes in sediment types are common in palaeo-drainage from Norseman to Peak Hill. As this could have occurred in a relatively short period of time, extensive sedimentation in the Yilgarn did not take place. Coupled with climatic changes, large lakes formed in the river valley. The seismic activities in the Southwest Seismic Zone and major earthquakes at Meckering (ML6.9 on 14 October 1968 and ML5.5 on 17 January 1990; Lewis, 1990) suggest that tilting is still continuing.

The upward tilting of the western margin of the Yilgarn Craton also rejuvenated the Yilgarn River System near the coast and increased its ability to downcut. This process is progressing upstream, but has not yet reached the Merredin area. Mulcahy (1971) defined the Meckering line east of which river systems have not yet been rejuvenated and the ancient landscape is preserved. West of the line is a sharp increase in river gradients, stream erosion is intensive, and much of the ancient land surface has been removed.

3.5 Timing of deep weathering and lateritization

Laterites have developed on a number of conglomeratic deposits containing Eocene-Oligocene plant remains or pollen grains at West Dale, Calingiri, Muradup, Coolgardie on the Yilgarn Craton (Hill and Merrifield, 1993; Wilde and Backhouse, 1977; Balme and Churchill, 1959). A rich spore-pollen assemblage from the ancestral Beaufort River (Figure 1) also shows that deep weathering and lateritization of the Archaean bedrock in the southwestern part of the Yilgarn Craton post-date the deposition of Late-Middle to Late Eocene river sediments (Waterhouse, *et al.*, 1994). Lateritization of Eocene sediments places the maximum age limit for the lateritization on the Darling Plateau probably into the Oligocene. Pre-Eocene lateritization is not known in the western Yilgarn Craton.

There are no data so far to place a minimum age on laterites in the western Yilgarn Craton, but information from the Eucla and Carnarvon Basins shows that Late Eocene or older rocks were lateritized whereas the adjoining Middle Miocene formations were not affected (Johnstone *et al.*, 1973). This seems to suggest that the major episodes of lateritization must have been completed prior to the Middle Miocene.

It has long been considered that the laterites on the Darling Plateau were formed on a low-lying surface that was later uplifted and partially dissected (*e.g.* Woolnough, 1918a and 1918b). Evidence of younger laterites on newly exposed surfaces at lower elevations in rejuvenated valleys, exists in some areas such as in the York-Quairading region (Mulcahy, 1959; McArthur and Bettenay, 1960). However, there is no such evidence in the Merredin region (Bettenay and Hingston, 1964), where the major drainage has been stable for a very long period and no episodic downcutting has occurred.

3.6 Deep weathering and lateritization

Chemical weathering - Soon after the climate changed in the late Cretaceous or early Tertiary from warm and humid rainforest to seasonal and wet savanna, a period of intense weathering began. Chemical weathering of mainly granitic rocks dominated over mechanical disintegration. As a result, granitic rocks were chemically weathered to saprolite and the upper parts of the profile were mottled or indurated with Fe oxides.

Landscape lowering - During the processes of weathering and lateritization, a land surface is generally lowered, due to removal of large amounts of Si, alkalis and alkaline earths, which are transported away by water. The magnitude of terrain lowering may be constrained by the relief of the landscape.

Sandplain formation - A large portion of the Merredin region is represented by sandplains; their origin has been a topic of discussions and contradicting hypotheses for many decades. The question, whether sandplains formed in situ or have been an erosional/depositional feature, has been the topic of many presidential addresses at various occasions (*e.g.*, Woolnough, 1927; Terrill, 1956; Prider, 1966; Mulcahy, 1981).

There are two theories about development of sandplains on the Yilgarn Craton. One is residual formation of the sandplains, which has been discussed in Section 2.2.2; the other proposes the

truncation of pre-existing lateritic profiles and disintegration of lateritic materials. Mulcahy (1959) and Mulcahy and Hingston (1961) assumed that sandplains formed by separation and retention of resistant quartz sands with progressive disintegration of less resistant primary and secondary minerals in pre-existing lateritic materials. This led to a repeated formation of ferruginous gravels, followed by further weathering and stripping, which produced sandy sandplains. In their opinion, sandplains are therefore, both erosional and depositional rather than *in situ*. Hence, lateritic duricrust in the landscape may be relatively young, because the Tertiary laterites in the sandplains, along with the Tertiary land surface, have been largely destroyed (Mulcahy, 1971, p.218). Bettenay and Hingston (1961, 1964) applied this hypothesis to soil landscape studies and to the origin of the sandplains at Merredin. Mulcahy and Hingston (1961, p.31) extrapolated the hypothesis derived from their study in the York-Quairading area to the origin of the Western Australian sandplains.

This study concludes that, as shown by Profiles 1 - 5, the gravelly sandplains and the duricrusts beneath the sandy sandplains are formed largely *in situ*. There is, however, some local redistribution of quartz sand from disintegration of pre-existing laterite and therefore, both theories on sandplain formation are viable.

Chemical decomposition and physical disintegration of the gravelly sandplain on the uplands is still continuing, even though the processes involved are slow. Resistant quartz grains, encapsulated in lateritic gravels, are released with progressive disintegration of the less resistant Fe oxides. The quartz grains are then washed out and remain on the lower parts of the uplands. Some of these sands are also washed down valley sides from the edges of the uplands and form colluvium. Most sands will be retained in the upland landscape, levelling out its micro-relief and gradually changing the landform to a sandy sandplain.

3.7 Erosion of the sandplains

The Yilgarn River System remained active until the Miocene, as demonstrated by the presence of the sediments in the Salt River at Quairading. Regular flow, however, would have ceased during this time, due to the increasing aridity, which would also have slowed the rate of chemical weathering.

Rainfall was generally insufficient to cause run-off and therefore, erosion is assumed to have been slow, especially given the very minor relief and the protective duricrust. Erosion has, however, modified the valley sides due to their greater slopes.

At first, erosion formed escarpments or breakaways on upper slopes. Where breakaways are capped by resistant duricrust, the disintegration of the breakaways mostly starts with the breakdown and removal of their duricrust cappings. The breakaways will, therefore, remain as a morphological feature during their retreat further back into the sandplains. This process is demonstrated in Profile 6 (Figure 7E). There, retreats of the breakaway, with a few loose nodules and pisoliths on the top surface, form an amphitheatre. The process is also shown in Profile 2, where a large block has been left standing on the erosional plain, created by parallel retreats of the breakaways.

With headward erosion of the tributaries, their channel gradients decrease, resulting in a loss of erosive power. Unless the major drainage incises further, tributary streams stop eroding once their longitudinal profiles reach equilibrium in receiving and delivering sediment supplied to the tributaries. The main streams in the Merredin region lack the power to incise their channels due to the stability of the base level and the greatly reduced water flow. Accordingly, tributary streams become less erosive, facilitating preservation of deep laterite profiles and relative stability of the sandplains.

3.8 Denudation

3.8.1 Introduction

Denudation is the sum of the processes that result in the progressive lowering of the land surface by weathering, erosion, mass wasting and transportation. The overall rate of erosion since the time of emplacement of a kimberlite pipe is thus an important parameter that determines the preservation and size of any pipe. Various techniques, including radiometric dating, sediment volume balance calculation and morphologic observations, have been applied to estimate how much material has been removed from the Yilgarn Craton over a certain period of time (Finkl and Fairbridge, 1979; van de Graaff, 1981; Lowry, 1975; Clarke, 1994a and 1994b, Libby and de Laeter, 1979; Killick, 1998). The results from these studies vary by an order of magnitude and it, therefore, becomes necessary to review briefly previous work on denudation of the Yilgarn Craton.

3.8.2 Denudation rates from radiometric dating

Denudation rates are calculated using radiometric techniques by estimating the amount of material removed since a mineral was subjected to a particular temperature. These techniques assume an average thermal gradient, for example, 25°C/km, and take into account the thickness of material necessary to overlie the dated mineral in order to maintain this average gradient.

However, it is not known how much palaeo-thermal gradients differ from the assumed modern average gradient, which shows significant lateral and vertical variations itself. The application of these techniques to denudation therefore is difficult and probably premature.

Fission track chronology - When apatite or zircon are cooled to 100°C, fission tracks form on the mineral. By counting the tracks, the time since the mineral was unearthed to 100°C can be obtained. Following extensive work carried out in the eastern States of Australia, Kohnl *et al.* (1998) reported a total thickness of 6 - 8 km of exhumation of the Yilgarn Craton since the Late Palaeozoic, assuming a geothermal gradient of 12 - 50°C/km.

Rb-Sr chronology - This dates the time when a mineral is cooled to 300°C. Libby and Laeter (1979a) estimate a rate of 4 to 6 m per million years for the Yilgarn.

3.8.3 Denudation rates from sediment volume balance

Sediments deposited in the basins surrounding the Craton can be used to calculate how much material has been removed. However, several assumptions have to be made:

(i) The boundaries and geometries of the basins need to be delineated, for example by deep drilling.

(ii) The provenance and the age of the sediments have to be ascertained. In the Early Ordovician, the initial subsidence of the Canning and Carnarvon/Perth Basins marks the complete outlining of the Tethyan margin (Veevers, 1976). Greater India dispersed from Antarctica/Australia in the Early Cretaceous, and Australia dispersed from Antarctica in the Early Cainozoic (Veevers *et al.*, 1975; Veevers, 1984). Any calculations thus have to estimate the relative contributions from Antarctica and Great India in order to calculate the amount derived from the Yilgarn Craton.

(iii) The effects of isostatic rebound due to erosion, compaction of sediments, loss due to chemical weathering, and addition to the sediments of carbonates and silica from sea water have to be considered.

Nevertheless, the Perth Basin contains as much as 10 km of Permian to Lower Cretaceous sediments (Lowry, 1975). Much of this material must have come from the Yilgarn Craton. Using sediment volume balance, van de Graaff (1981) demonstrated an average of 350 m was eroded from the western Yilgarn Craton to generate the amount of clastic sediments in the Perth Basin. Lowry (1975) estimated that about 300 m have been stripped from the least eroded parts of the Collie Basin on the southwestern edge of the Yilgarn Craton. The denudation rates from these studies are within 4 to 5 m per million years. More recently, using all available data from the surrounding basins, Killick (1998) showed that about 4.09 km of material has been removed from the Craton over last 490 Ma, a rate of approximately 8 m per million years. Most of this occurred prior to the Eocene, as the Cainozoic sediments in the basins are dominantly calcareous.

3.8.4 Denudation rates from morphologic observations

The techniques discussed above provide estimates of indirect denudation rates based on various assumptions. Morphological approaches involve interpretation of features observed in the modern landscape. For instance, early Cainozoic drainage is preserved on the Yilgarn Craton (van de Graaff *et al.*, 1977; see Section 3.4), indicating that very minor denudation took place in the last 65 Ma. Remnants of Permian glacial deposits are also found, mainly along the eastern margin of the Craton. Their implications for the denudation rate of the craton need to be further investigated.

Based on morphologic observations, Finkl and Fairbridge (1979) show that there has been little erosion of the Yilgarn Craton since the Proterozoic, about 25m of removal over 250 Ma. However, this was based on the interpretation of sediment at Kirup as being Permian. Later work indicated, however, that the conglomerates may be as young as the Eocene. From morphological studies and work on the sediment volume balance for the Kambalda region in the eastern Yilgarn Craton, Clarke (1994a, 1994b) estimated that about 400 m had been eroded between the Middle Jurassic and the Early Eocene to infill the Eucla and Great Australian Bight Basins; this is equivalent to 3 m/Ma.

The wide range of rates illustrates the uncertainties in the calculations. An overall rate cannot indicate regional variations (Ritter, 1986). However, for the Yilgarn, the bulk of the sediments occurs in the Perth and Carnarvon Basins, and as Permian sediments are preserved in drainage in the east, most of the erosion must have occurred in the western half of the craton.

4. CONCLUSIONS

4.1 Preservation of kimberlite pipes

The extent of preservation of a kimberlite pipe not only is an important economic parameter, but also has implications for geochemical and indicator mineral exploration as it determines the target size and diameter of the geochemical halo.

There are many ancient features in the landscape of the Merredin region, such as sandplains, abandoned drainage on the sandplains, and underfit drainage with streams too small to have produced the wide valleys. These streams have not been rejuvenated since at least the beginning of the Tertiary and therefore the region has experienced prolonged chemical weathering but only minimal erosion. Recent work by Killick (1998) has also shown, that erosion of the Yilgarn Craton occurred dominantly pre-Cainozoic. The antiquity of the landscape favours the preservation of any potential young (post-Cretaceous) kimberlite pipe.

Morphological modelling shows that the Merredin area is close to a north to south hinge, by which the western part of the Craton has been tilted up and the eastern part down. The hinge follows

approximately the continental drainage divide to the east of the Merredin area. Due to the tilting, much more material has been removed from the western margin of the Craton than from the area along the hinge. Furthermore, minor denudation and in some areas sedimentation, might have occurred in the eastern part of the Craton.

Assuming a medium denudation rate of about 5m/Ma for the Yilgarn Craton, and little denudation in the Cainozoic (last 65 Ma), the average erosion rates for kimberlite pipes of different ages are shown in Table 13.

Table 13 Calculated erosion of kimberlite pipes of various ages on the Yilgarn Craton.

Pipe emplacement	**Cambrian (564 Ma)**	**Triassic (242 Ma)**	**Cretaceous (135 Ma)**	**Late Cretaceous (65 Ma)**
Denudation period (Ma)	499	177	70	65
Denudation rate (m/Ma)	5	5	5	0.25
Denudation depth (m)	2495	885	350	16

At a rate of 5m/Ma, any kimberlite pipes emplaced in the Precambrian would have been eroded down to the hypabyssal facies. However, the possible tilting of the craton may in fact have led to significantly higher denudation rates in the western part, and consequently much lower rates along the hinge and in the eastern part of the craton. It therefore appears premature to discount the possibility of preservation of diatreme facies kimberlite of a Proterozoic pipe in the Merredin region.

4.2 Geochemical sampling media

Lateritic gravels on sandplains

This study has confirmed that the extensive sandplains in the Merredin region are relict features, resulting from prolonged weathering and the inability of the main drainage to entrain sediments. Lateritic gravels have developed largely in situ and have only been redistributed locally. These gravels form a part of the lateritic residuum and generally reflect the local bedrock composition. They are, therefore, the preferred geochemical sampling medium.

Clay-rich soil on saprolite

Clay-rich soil on saprolite is the main regolith unit in erosional regimes and the principal parent material of preserved soils. Compared to lateritic gravels, such soils may more closely represent the composition of the bedrock so that soil geochemistry will be effective for investigation of local geophysical anomalies in erosional regimes.

Th-rich soil on proximal colluvium-alluvium

Thorium-rich soils may develop on colluvium-alluvium, proximal to lateritic duricrust due to the presence of small fragments of lateritic gravels. In most cases, the provenance of the gravels is identifiable on radiometric images, even though the original lateritic material may have been removed. As these gravels are probably within 2-5 km of the source, these soils provide an alternative medium for geochemical sampling, although their composition may be diluted due to mixing with colluvium.

4.3 Indicator mineral dispersion

The drainage in the region has been sluggish since the beginning of lateritization, probably in the early Tertiary. There is no evidence showing that significant amounts of sediments have been transported through or into this drainage during the past 20 - 40 million years. Most of the sediments, especially those close to surface, are infillings, derived from local valley sides. Alluvial sediments from upstream in the catchment have been buried at depth. The drainage in the Merredin region therefore is fundamentally different from active streams in which indicator minerals are also derived from upstream in the catchment areas. Loam sampling in an inactive drainage yields indicator minerals from surrounding valley sides and as such, is a local rather than regional test.

4.4 Regolith mapping

An understanding of regolith stratigraphy and regolith distribution is essential for the design of sampling programs and subsequent data interpretation. Studies of regolith stratigraphy have given insights into the nature and origin of the materials present and, together with mineralogical and geochemical studies, have indicated which media are most useful for sampling. In depositional regimes, accurate drill logging can lead to more efficient and relevant data interpretation.

Detailed regolith mapping is necessary in order to determine the areas where lateritic profiles are preserved. Radiometric images show various regolith units and hence, are a very important tool for regolith mapping, although some limitations have been noted. For instance, lateritic gravels formed on Th-poor parent rocks have very weak Th responses. Conversely, colluvium derived from lateritic materials may have a similar Th response to areas of lateritic duricrust. Thick sands with underlying lateritic gravels are also easily confused with thick sands on saprolite, because both have little K and Th, and therefore, show no difference on radiometric images. There are some cases in which radiometric data indicate lateritic materials but the materials are not residual. The origin of lateritic materials can, therefore, ultimately be established only by fieldwork accompanying the regolith mapping.

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