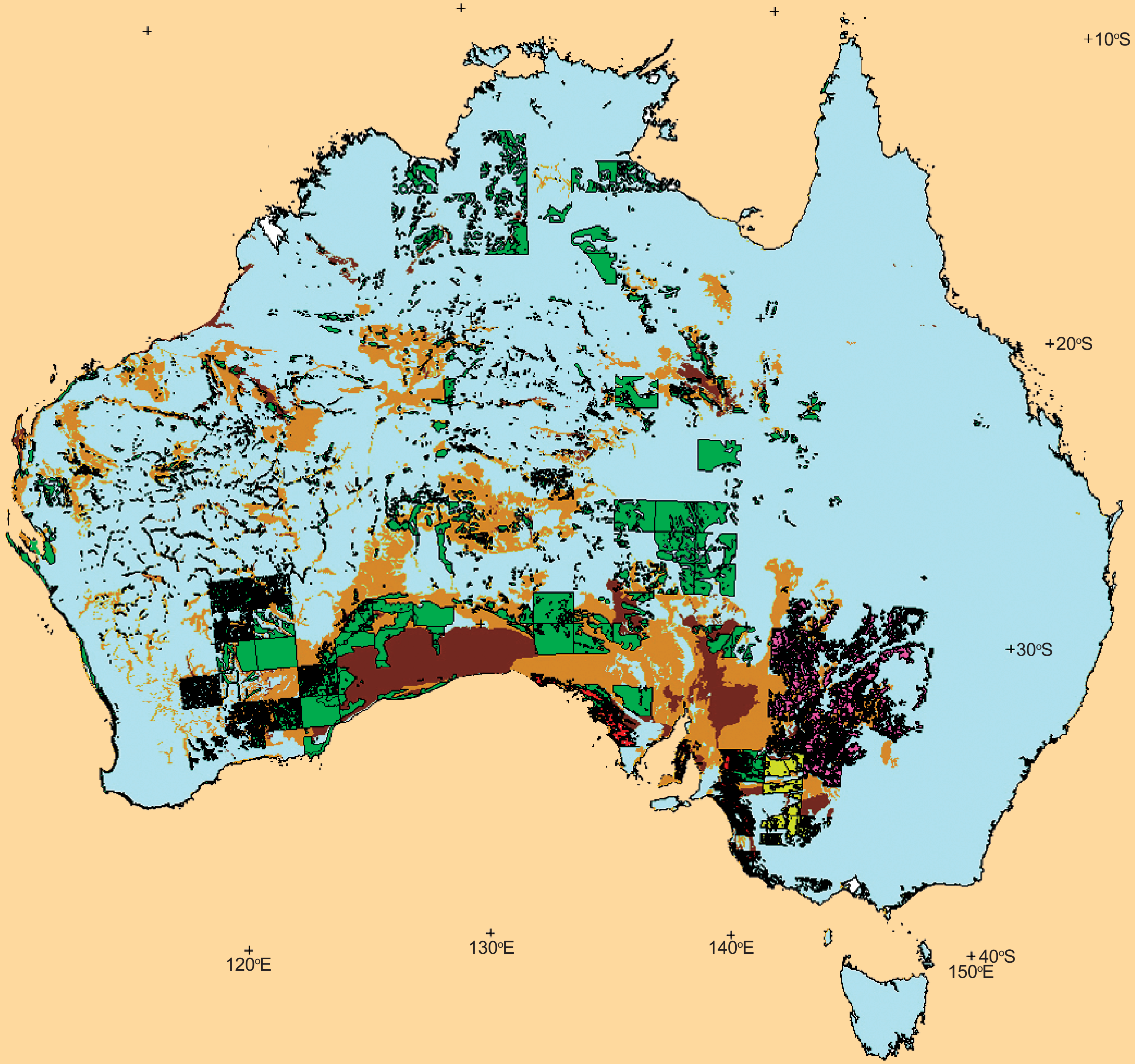


Data Sources

🟩 Digital and hand-drawn facsimiles of WA, NT, SA, Qld, NSW and Vic 1:250,000 geological maps
🟨 Victorian 1:250,000 Land Systems mapping
🟥 South Australian 1:50,000 agricultural lands calcrete mapping
🟪 NSW 1:250,000 Land Systems mapping
🟧 Digital Atlas of Australian Soils (Northcote) minor soil groups containing calcrete
🟫 Digital Atlas of Australian Soils (Northcote) major soil groups containing calcrete
Simple Conic projection with standard parallels at 18°S and 36°S

Figure 7.1.2. Map of Calcretes and Regolith Carbonates in Australia

Calcrete: characteristics, distribution and use in mineral exploration
X.Y. Chen, M.J. Lintern and I.C. Roach

CRCLEME
Cooperative Research Centre for
Landscape Environments
and Mineral Exploration

Calcrete: characteristics, distribution and use in mineral exploration

X.Y. Chen, M.J. Lintern and I.C. Roach

Calcrete: characteristics, distribution and use in mineral exploration

Editors:

X.Y. Chen
M.J. Lintern
I.C. Roach

Cooperative Research Centre for Landscape Environments and Mineral Exploration

CSIRO Exploration and Mining, Kensington, Western Australia 6151
The University of Canberra, Division of Science and Design, Australian Capital Territory 2601

The National Library of Australia Cataloguing-in-Publication Data:

Calcrete: characteristics, distribution and use in mineral exploration.
ISBN 0-9581145-0-1

Typesetting & Design: Bai, Ying

Printed by
Instant Colour Press, Belconnen ACT

Contents

Chapter 1: Introduction

X.Y. Chen and I.C. Roach

Chapter 2: Morphology and occurrence

X.Y. Chen

Chapter 3: Origins

X.Y. Chen

Chapter 4: Classification systems

X.Y. Chen

Chapter 5: Mineralogy and chemistry

X.Y. Chen and R.A. Eggleton

Chapter 6: Calcrete sampling for mineral exploration

M. J. Lintern

Chapter 7: Distribution in Australian: calcrete landscapes

X.Y. Chen, N.J. McKenzie and I.C. Roach

Maps of calcrete distribution in Australia (Full-sized maps in the attached CD)

I.C. Roach, N.J. McKenzie and X.Y. Chen

List of figures

Acknowledgments

This project was initiated by the executive committee of the Cooperative Research Centre for Landscape Environments and Mineral Exploration (CRC LEME I), particularly by Charles Butt, Graham Taylor and Tony Eggleton. As the leader of the Program, to which this project belongs, Tony provided consistent support and some very useful guidance in report writing. Graham provided very useful discussions and encouragement to Chen. Charles Butt and Ravi Anand provided very useful data and arranged logistic support when Chen visited Perth in 1997 and 2001. The visits were very important for Chen to finish his part in this project.

Mel Lintern would like to thank his colleagues in Perth for their scientific and technical contributions towards his chapter (Chapter 6). In particular, Angelo Vartesi is thanked for his patience, time and expertise in drafting most of the diagrams. The text has been greatly improved through critiques from Marian (Swanny) Skwarnecki, Matthias Cornelius, Charles Butt and Ravi Anand. Resourcing for many of the Western Australian gold case studies has been from the exploration industry through the Australian Mineral Industry Research Association, the CSIRO and CRC LEME.

Many other CRC LEME members contributed in various ways to this study. During several field trips, Chen was helped and accompanied by Matthias Cornelius and Peter de Broekert. Gill Ashton, Dale Longman, Pearl Phillips and others at Perth helped Chen in many ways, from finding his accommodation to preparing his office and necessary facilities.

Many CRC LEME members provided useful discussions, photos, slides, carbonate samples and diagrams. These include Steve Hill, Pauline English, Ken McQueen, Mal Sheard, Ravi Anand, David Gray, Ian Robertson, Annamalai Mahizhnan, David Gibson, Craig Johnston, Richard Green, John Wildman, Li Shu, Cajetan Phang and Charles Butt. For one reason or another, the materials provided by them are not all used in this report. However, their generous help is greatly appreciated.

Many CRC LEME members joined, with enthusiasm, the discussion through email on calcrete. This helped significantly to clarify some basic concepts of calcrete.

Some people outside CRC LEME provided significant help. Linda Ashton (CSIRO, Soil and Water) helped to extract the soil data concerning calcrete distribution. Richard Merry (CSIRO, Soil and Water, Adelaide) provided very useful information on available data of Australian calcretes. Jon Stirzaker (AGSO) provided information on geology of the Northern Territory. Peter O'Shea and Mark Imhof (NRE, Victoria) provided information on geology of Victoria. Greg Chapman and Mick Dwyer (Land & Water Conservation, NSW) provided information on calcareous soils in NSW. Philip Burden (DME, WA) provided data on geology of Western Australia. Dave Howe (LPEPALM, NT) provided information on geology of Northern Territory. Greg Jenkins, David Tonkin, and David Maschmedt (PIRSA) provided various information on South Australia. David Maschmedt and Andy McCord of Primary Industries and Resources of South Australia are thanked for their permission for using photos from their publications.

Although authors here made an effort, some people, who have contributed in some way to this project, may be missed out in this acknowledgment.

CRC LEME is supported by the Australian Cooperative Research Centres program.

Chapter 1

Introduction

X.Y. Chen and I.C. Roach

1.1 Objectives

Carbonate minerals, predominantly calcite and dolomite, are deposited in a wide range of environments including the oceans, estuarine waters, lakes, rivers, caves, springs and within the regolith. There is a large group of terrestrial carbonates that originally precipitate as authigenic minerals within host materials such as soils, saprolite and sediments. The abundance of these authigenic carbonates in the host materials varies widely from several percent to nearly pure carbonate. Compositions also vary, from calcium-dominant to dolomite-dominant. The morphology varies from soft and powdery to highly cemented or indurated, and from a continuous layer to discrete nodules, aggregates, coatings and fillings. These carbonates form the subject of this report because:

- they appear to have common mechanisms and processes of formation;
- they commonly occur together or transform gradationally from one to another vertically or laterally over a short distance; and,
- for practical purposes, e.g. as sampling media in mineral exploration or as an indicator of soil chemical condition, they are virtually identical.

Most of these authigenic carbonates are referred to as calcretes, although many other terms are used. They are found mainly in arid and semi-arid regions and cover approximately 13% of the Earth's land surface (Yaalon 1981). In Australia, calcrete occupies about 21% of the land surface as found in the calcrete map produced by this study (Chapter 7). This is higher than the world average, because of the much larger proportion of arid and semi-arid lands in Australia. Australian soil scientists have extensively studied calcrete (e.g., as reviewed by Milnes and Hutton 1983), because of its common occurrence and its important role in determining soil chemical and physical properties. Calcrete is also important to geologists, firstly because of its association with uranium deposits (e.g., Butt *et al.* 1977, Carlisle *et al.* 1978) and its importance as a sampling medium for gold exploration (e.g., Butt *et al.* 1991, Lintern and Butt 1993b, Hill *et al.* 1998), and secondly, because of its use as an indicator of sedimentary and diagenetic environments (e.g., Warren 1983, Semeniuk and Searl 1985, Arakel 1986a).

Some aspects about calcrete still remain confusing and unclear despite the intensive studies and a large number of publications on calcrete in Australia and elsewhere. These include :

1. nomenclature: different terms have been used by different authors to describe the same materials; conversely, the same terms have been used by different authors to describe very different materials;
2. genetic interpretations: various models have been raised but some contradictions exist between those models;
3. classification systems: similar calcretes have been differently classified by different authors using different criteria, and there is lack of overall consistency; and,
4. distribution in Australia: although a few diagrams (e.g., Milnes and Hutton 1983) have been presented to show regional distribution of calcrete across the whole continent, their accuracy and precision are far from the requirements of practical field use for any applications.

This report is a compilation and summary of information on calcretes in Australia including their morphological features, distribution, classification, genesis, role in landform evolution, and their relevance to mineral exploration.

1.2 Terminology

1.2.1 Calcrete

Many terms have been used in the literature for terrestrial authigenic carbonates, such as "caliche", "kankar", "kunkar" and "travertine", (e.g., Aristarain 1971, Goudie 1972a, 1973, 1983, Milnes and Hutton 1983). The term calcrete is probably the most widely used outside the Americas, but may have very different meanings to different authors.

Lamplugh (1902) introduced the term calcrete to describe carbonate-cemented gravels, together with the parallel terms silcrete and ferricrete for materials cemented by silica and iron oxide respectively. According to this original usage, i.e., "crete" as cementation, a calcrete should have a degree of induration. However, the term calcrete has been extended in later literature to cover a much wider range of authigenic carbonates including some soft materials, such as powdery calcrete, (e.g., Netterberg 1967, Goudie 1973, 1983).

Wright and Tucker (1991), based on Netterberg (1967), Watts (1980) and Goudie (1973, 1983), summarised a definition of calcrete as *"A near surface, terrestrial, accumulation of predominantly calcium carbonate, which occurs in a variety of forms from powdery to nodular to highly indurated. It results from the cementation and displacive and replacive introduction of calcium carbonate into soil profiles, bedrock and sediments, in areas where vadose and shallow phreatic groundwaters become saturated with respect to calcium carbonate. ...The term is not used to describe tufas, travertines, beachrock and lake carbonates."*

This definition now represents the common usage for the term calcrete and will be followed in this document. However, several points need to be discussed further:

1. Authigenic origin.
The genesis is included in the definition, i.e., carbonate minerals precipitate within host materials. This differentiates calcrete from the carbonates which deposit originally from "free water", e.g., from water in springs, caves, rivers, lakes and other water bodies. However, some calcretes and non-calcrete carbonates may be similar to each other in morphology, particularly if they have undergone common diagenetic processes (e.g., Wright and Tucker 1991).

2. Powdery types.
In the definition, cementation or induration is not regarded as an essential character for calcrete and violates the original meaning of Lamplugh (1902). The reason is probably that the soft or powdery type may occur itself but more commonly occurs as part of a hardpan calcrete (or "real" calcrete) profile, changing downward gradually from highly cemented through less cemented to soft/powdery carbonate. Powdery carbonates occur even more commonly as matrix material mixing with indurated carbonate nodules which are otherwise called nodular calcrete. It is not practical to draw a line separating "real (cemented) calcrete" from the powdery part. They are in the same profile and are formed through common processes, but probably at different stages of the development of the whole.

3. Carbonate content.
The definition does not set a minimum carbonate content for a calcrete but in the same paper, Wright and Tucker (1991) exclude "calcareous soil" from calcrete. Calcareous soil is characterised by *"small carbonate accumulations as grain coatings, patches of powdery carbonate"*. This implies that a minimum carbonate content is required for a calcrete. In comparison, the "calcified soil" has a carbonate content of 10-50% (Wright and Tucker 1991) and it is debatable whether or not it should be included as calcrete (Goudie 1983). In the USA publication Soil Taxonomy (6th edition, 1994), a calcic horizon is defined as >15% $CaCO_3$ by weight and when $CaCO_3$ is > 40% the term "carbonatic" is used. Therefore, a calcrete should have a minimum carbonate content of 10-15%, although a much higher value (> 40-50%) is commonly expected. The main consideration here should be whether the authigenic carbonate forms the dominant morphological features of the layer/horizon to be described. A calcrete should appear to be mainly characterised by its carbonate component, which is commonly the

case if carbonate content reaches 40% or more ('carbonatic horizon', Soil Taxonomy 1994). If the carbonate content is much lower, other components will be dominant and the layer/horizon should be described as, e.g. a calcic red clay, instead of a calcrete. However, to set an exact value, e.g. 40% of $CaCO_3$, as the minimum level for a calcrete is, practically, not possible. It cannot be justified why 40% of $CaCO_3$ is a calcrete but 39% is not.

Therefore, in this document, more than 40% of $CaCO_3$ in mass for a calcrete is taken for reference only, not as a restrict criterion. A lower carbonate content may be accepted if the carbonate component is the dominant feature, e.g. 20-30% of carbonate may well cement gravels forming a calcrete in its original sense (Lamplugh 1902).

4. Ratio of $CaCO_3/MgCO_3$.
It is commonly agreed that for calcrete, calcium carbonate should be the dominant carbonate mineral and the dolomite-dominant type should be referred to as dolocrete (e.g., Goudie 1983, Wright and Tucker 1991). However, the standard, e.g., a ratio of $CaCO_3/MgCO_3$, is not given. Netterberg (1980) suggested that a calcrete should have <5% dolomite in mass of total carbonate minerals. He also suggested a classification of the transitional forms from calcrete to dolocrete based solely on the ratio of calcite and dolomite contents (see Section 4.4).

The discussion above shows that the division between calcrete and non-calcrete authigenic carbonates is vague. This probably reflects the fact that authigenic carbonates form a gradational sequence, changing from typical calcrete (a hardpan type) to nodular and powdery types, and to non-calcrete authigenic carbonates. In practice, it is impossible to draw a clear line to separate them. Therefore, the definition adopted from Wright and Tucker (1991) remains broad and generalised, without clear-cut criteria.

1.2.2 Regolith carbonate

A more general term is required to describe the numerous types of authigenic carbonates because of the wide-ranging objectives described in Section 1.1. One option is to re-define and further expand the term calcrete. However, if the understanding of this term becomes too broad, e.g., including dolomite-dominant carbonates, or sediment layers with a few scattered carbonate nodules, or with a few percent of diffusing powdery carbonate, it will not be acceptable within the Australian or international community. To expand the definition of calcrete from those commonly used (e.g., Goudie 1983, Wright and Tucker 1991) would cause significant confusion.

Another option is to use a term having a broader sense than that of calcrete. Recently, Hill *et al.* (1999) used "regolith carbonate" to include calcrete and those materials which fall outside the calcrete definition, e.g., including magnesium-rich authigenic carbonate (dolomite). Their definition for regolith carbonate is *"secondary carbonate minerals within the regolith"*. This new term has been adopted to cover all of the authigenic carbonate deposits described earlier (Section 1.1), i.e., including all the authigenic carbonates in regolith, soil and the voids of bedrock which vary:

- from a very small amount in host materials to a nearly pure carbonate layer;
- mineralogically from calcite-dominant carbonate to dolomite-dominant ones; and,
- morphologically from soft and powdery to highly indurated and from a continuous layer to discrete nodules, aggregates, coatings and fillings.

Therefore, all calcretes are regolith carbonates but not vice versa. The advantages of using the term regolith carbonate include:

- \- it has been rarely used before and does not have any stereotypical meanings.
- the term has a very broad sense, covering numerous carbonate minerals, and has no limitations on carbonate content or the degree of cementation.

Hill *et al.* (1999) sought to remove any confusion associated with different understandings of the term "calcrete" by substituting terms like "carbonate hardpan facies" for "hardpan calcrete". To continue in this line, however, may cause difficulty in communicating the true nature of materials because calcrete is currently the most widely used term for the authigenic carbonate deposits in Australia and in the world. Moreover, as a newly introduced term, its widespread acceptance by the scientific community will take time.

1.2.3 Summary

The term "calcrete" will be used in this document, under circumstances without uncertainties, i.e., following the definition of Wright and Tucker (see above). In comparison, the term "regolith carbonate" is only used in places where uncertainties may occur for differentiating calcrete from "non-calcrete" authigenic carbonate (as described above and in Section 1.1).

In Chapters 6 and 7, which summarize case studies from a wide range of literature, other two terms are used necessarily in order not to distorting the meanings of various authors:

Carbonate. This has broader sense than regolith carbonate, including both authigenic and non-authigenic carbonates (e.g. marine limestone). It is short and convenient to use in field and some authors may use it in the sense defined for regolith carbonate, e.g. ‘red clay with trace carbonate powders’, ‘quartz gravels with thin carbonate coating’. However, it describes the mineral feature without any genetic implications as the term regolith carbonate.

Pedogenic carbonate. In most literature this is commonly used for authigenic carbonate found in soil profiles, mostly within 1 m, up to several meters, from land surface. This excludes limestone and ground-water calcrete (See chapter 3), assuming that the carbonate precipitated during soil forming processes. There may be some vagueness because of the difficulties for defining soil forming processes (see Chapter 3).

If regolith carbonate is not evenly distributed and forms aggregates or nodules, the individual aggregate/nodule can be described, e.g. as a calcrete nodule, if its carbonate content is high enough. In this case the layer/horizon may be described as 'red sandy clay with calcrete nodules'. However, if the carbonate content is low and occurring as dispersed powder or thin films on coarse grains (coating), it cannot be described as 'red clay with calcrete powder/coating' but can be 'red clay with regolith carbonate powder/coating'. The term ‘regolith carbonate powder’ emphasizes both the authigenic origin and the morphology of the carbonate. If the origin is not important for the description, particularly in the field, the term can be, e.g. ‘red clay with carbonate powder’, or ‘red clay with carbonate’, if the carbonate morphology is unimportant either.

The above calcrete/dolocrete differentiation may not be applicable to field use because the ratio of calcite/dolomite cannot be determined in the field. Some texts describe a test that may distinguish calcite from dolomite but often they are not suitable for field use as they may require warm and/or concentrated acids. Also, the tests are sensitive to the crystallinity and morphology of the carbonate. Therefore, the term calcrete may be used in the field for both calcrete and dolocrete and in cases where the ratio of calcite/dolomite is unknown.

1.3 Methods

The form of this study is essentially that of a literature review. The descriptions and data presented in this report are based on various published and unpublished papers and reports from Australia and elsewhere. However, because of the nature of the objectives, this study concentrates more on the literature concerning regolith carbonates in Australia. Members of Cooperative Research Centre for Landform Evolution and Mineral Exploration (CRC LEME) contributed to this report by way of discussions with the authors and by providing photographs depicting various types of calcretes and regolith carbonates at different sites across Australia. Various geological and soils maps of different scales have been compiled to produce the map showing the distribution of regolith carbonates for this study. The details of the source maps and the compilation procedure are included in Chapter 7.1.

Chapter 2

Morphology and occurrence

X.Y. Chen

2.1 Morphological types

Calcrete, dolocrete and other regolith carbonates occur in a wide range of morphology. The principal types of calcretes are described below:

Powdery calcrete occurs as fine, usually loose particles of calcite in a continuous body with little or no nodule development (Wright and Tucker 1991). Powdery calcrete is commonly found as part of a calcrete profile, as illustrated in Figure 2.1.1 (page 154), underlying hardpan calcrete with a gradual boundary. Some powdery carbonate concretions may be excluded from this type and classified by their more distinctive morphology, e.g. as tubular calcrete.

Nodular calcrete consists of discrete soft to very hard concretions of carbonate-cemented and/or replaced soil (Wright and Tucker 1991). The shape of the nodules is commonly irregular but approximately equal in three dimensions. This type exclodes the round carbonate concretions with concentric structures and those significantly extended in one or two dimensions.

The morphology of individual carbonate nodules may widely vary in:

- size, ranging from assumed minimum size, e.g., 2 mm (Hill *et al.* 1999), to tens of centimetres;
- degree of cementation, from highly indurated to relatively soft;
- content of carbonate, from nearly pure to containing significant amounts of other materials; and
- internal structures, from structureless, to containing clasts in the centre, to laminae near the surface, to internal voids and coalesced nodules.

The nodular calcrete illustrated in Figure 2.1.2 (page 154) consists dominantly of irregularly shaped carbonate nodules and some carbonate pisoliths in a matrix of powdery carbonate and clayey sands.

Pisolitic calcrete is similar to nodular calcrete but the carbonate concretions are mostly rounded and have well-developed concentric structures, commonly with massive carbonate and/or detrital grains in the centre. The pisolitic concretions are highly indurated and range in size from several millimetres to larger than 10 cm. For the concretions less than 2 mm in diameter the term ‘ooid’ is used by some authors (e.g., Read 1974, Arakel 1982). Figure 2.1.3 (page 154) shows a profile with a 15 cm layer of carbonate pisoliths underlain by nodular carbonate layers. Figure 2.1.4 (page 154) shows some of the internal structures of carbonate pisoliths.

Tubular calcrete forms as tube-shaped carbonate concretions, from indurated to soft and powdery. The concretions may be discrete/separated or connected and vary in size and content of carbonate. Some are hollow but others are solid or filled with various materials other than carbonates. Tubular calcrete can be further classified (e.g., Klappa 1980) and the most common sub-type is carbonate rhizoliths, or root casts/tubules. A single tube-shaped carbonate concretion can be termed as a carbonate tubule. Figures 2.1.5 (page 154) and 2.1.6 (page 154) show carbonate rhizoliths in a Pleistocene coastal dune. Figure 2.1.7 (page 155) shows a mixture of carbonate tubules and nodules, with the tubules shorter in length than those of the coastal dune.

Laminar calcrete occurs as indurated sheets of carbonate, typically, but not always, overlying hardpan calcrete or other hard surfaces (Wright and Tucker 1991). The laminae may be as thin as < 1 mm and the total thickness of a laminar calcrete is commonly less than 25 cm. However, laminar calcrete may occur as a relatively thick (e.g., > 1 m) layer without any underlying hard surfaces (e.g., Figure 2.1.9, page 155). Figure 2.1.8 (page 155) shows a thin laminar carbonate layer overlying a massive carbonate. Laminar regolith carbonate may occur within planner voids of a host (e.g., Figure 2.1.10, page 155).

Boulder/cobble calcrete varies from discrete to coalesced hard boulders and cobbles of carbonates within a calcareous or non-calcareous matrix (Figure 2.1.11, page 155). Dissolution features and thin laminar structures may develop on the surfaces of the boulders.

Hardpan calcrete occurs as an indurated sheet-like horizon, typically with a complex internal fabric, a sharp upper surface and a gradational lower surface (Wright and Tucker 1991).

The morphology and occurrence of hardpan calcrete varies widely. The thickness ranges from several centimetres to tens of metres and the lateral extent ranges from tens of square metres to hundreds of square kilometres (e.g., Butt *et al*. 1977). The internal fabrics can be highly complex, including coalesced nodules, re-cemented brecciated carbonate fragments, various voids and floating clasts of other materials. Carbonate-cemented gravels (conglomeratic calcrete) are regarded as a particular type of hardpan calcrete (Goudie 1983). Figure 2.1.12 (page 155) shows a hardpan calcrete profile which consists of three layers with the degree of induration decreasing downwards. The third layer (150-205 cm, Figure 2.1.12, page 155) consists of patches of carbonate and clay and is only weakly cemented. Figure 2.1.13 (page 156) shows the complex internal fabric and structures of a hardpan calcrete.

Honeycomb calcrete has a fabric of partly coalesced hard nodules with interstitial areas of less-indurated calcareous materials (Wright and Tucker 1991). The nodules seem to coalesce by the development of overlapping lamellar rinds. This type is rarely described and reported in Australian literature.

The term '*Carbonate mottles*' refers to a mottled zone in a calcrete profile, termed by some authors as *mottled calcrete* (e.g., Read 1974, Arakel and McConchie 1982). It commonly underlies hardpan and powdery calcrete zones. In this zone, carbonate micrites occur as mottles in the host sediments/soils. The mottles are irregular and from 1 cm to >10 cm in size (e.g., Arakel and McConchie 1982). The mottles consist of relatively pure carbonate but may contain some 'floating' sands or gravels of the host sediments. The carbonate mottles are soft and rarely cemented, in which respect they differ significantly from calcrete nodules. The lowest layer (150-205 cm) of the calcrete profile in Figure 2.1.12 (page 155) is of this type.

The above morphological types of calcrete are also applicable to dolocrete, e.g., 'nodular dolocrete', 'hardpan dolocrete', etc. A layer of regolith/soil with low content of authigenic carbonates, eg. < 10-15%, is not a calcrete or dolocrete, and may be described as, e.g., 'a sandy clay layer with a small amount dispersed powdery regolith carbonate'. If a concretion in such a soil/regolith layer has a much higher carbonate content, the concretion can be termed as a carbonate or calcrete/dolocrete nodule/pisolith/tubule.

2.2 Calcrete profiles

Calcretes occur in soil or regolith profiles that may range in thickness from tens of centimetres to tens of metres. Within such profiles, there can be more than one morphologic type of calcrete, either within a layer or as separate layers.

The simplest profile, i.e., with a single layer of calcrete consisting of only one morphological type (e.g., Figure 2.1.5, page 154), is rare. Calcrete profiles tend to be more complex, as follows:

1. A single layer of calcrete which is a mixture of at least two different morphological types (e.g., Fig 2.1.2). This calcrete profile can be named by the dominant morphology, e.g., nodular calcrete, shown by Figure 2.1.2 (page 154).
2. A layer of calcrete may consist at least of two sub-layers in a sequence of different morphologic types (e.g., Figure 2.1.3, page 154). Some authors (e.g., Milnes and Hutton 1983, Arakel 1996) have used the term 'multi-layered (calcrete) profile' to refer to such a calcrete profile.
3. As above, but in one or more sub-layers there are at least two morphological types.

4. Multiple calcrete layers occurring in a profile, interbedded with sediment layers. Each calcrete layer may be either a simple calcrete with only one morphologic type or a complex one with two or more morphological types. Good examples are aeolianite sequences, which consist of many calcrete layers interbedded with dune sands, in the coastal region of Western Australia (e.g., Read 1974) and in South Australia (e.g., Milnes and Hutton 1983).

In practice, when describing a calcrete or a sediment/soil profile with regolith carbonate, it may not be necessary to differentiate the above four types clearly. However, for a detailed description, the following data may need to be included:

- the regolith/soil profile, the number of relatively homogeneous layers, their thickness, colour, texture and structure;
- within the profile, number of layers of calcrete or sediments containing regolith carbonates;
- estimates of the relative abundance of carbonate and other soil/regolith materials for each layer;
- within each calcrete layer (or layer with regolith carbonates), the number of morphological types;
- details for each morphological type, e.g., size of nodules, degree of induration, structure;
- reaction to cold 0.1N HCl.

Chapter 3

Origins

X.Y. Chen

3.1 Sources of calcium and magnesium

3.1.1 Bedrock

Table 3.1 shows that the contents of Ca and Mg vary in various rocks, with much higher Ca contents in basalts than in granites and in some sedimentary rocks. When interpreting the close association of calcrete with greenstones in the Mt Gibson region, Anand *et al.* (1997) concluded that the weathering of bedrock is one of the major sources of calcium for the calcrete in the region.

Table 3.1. Concentrations of selected elements in selected igneous and sedimentary rocks (Wedepohl 1971).

Rocks	SiO_2%	Al_2O_3%	CaO%	MgO%
Alkali olivine basalts	48.4	15.0	9.1	0.19
Tholeiitic basalts	50.6	14.9	10.1	0.2
Granites	73.1	13.9	1.1	0.42
Granodiorites	67.4	15.8	3.6	1.6
Greywackes	67.1	14.4	2.3	2.1
Clays and shales	58.9	16.7	2.2	2.6

Some sedimentary rocks and sediments contain Ca/Mg salts and/or carbonate. These may be dissolved and re-distributed by groundwater, contributing eventually to calcrete/dolocrete formation. Limestones and dolomites are not regarded as calcrete or dolocrete, but weathering of these rocks may be major sources of Ca and Mg for calcrete/dolocrete formation. Moreover, these rocks may be converted to calcrete/dolocrete by weathering through dissolution, re-precipitation and brecciation (e.g., Arakel 1982).

3.1.2 Aeolian dust and rainwater

Aeolian dust (aerosols) is an important source of carbonate. Dust may be derived from coastal beaches and dunes, inland dry salt lakes, alluvial plains and top soils of the arid zone where vegetation cover is sparse. These sources may originally contain some carbonates, providing the materials for calcrete formation. In some areas near the coast, e.g., the Eyre Peninsula, dust originating from the calcareous beach sands and fore-dunes is believed (e.g., Crocker 1946, Milnes and Hutton 1983) to be the major carbonate source for the calcrete in the region. As presented later (Section 7.2.6), aeolian dust deposits may reach up to several meters in thickness in south-eastern Australia. Carbonate nodules commonly occur and are likely to have originated from the carbonate brought in with the aeolian dusts.

Rainwater is another source of calcium. The influence of the sea is significantly stronger close to the coast, but decreases inland (Hutton and Leslie 1958). This is indicated by the significant decline in Cl^- content of rainwater with increasing distance from the coast (e.g., Keywood *et al.* 1997). In Victoria, from about 300 km inland, bicarbonate ions replace chloride as the dominant anion in rainwater (Hutton and Leslie 1958, Hutton 1982a).

The annual accession of Ca^{2+} from rainwater and dusts to various sites in Western Australia ranges from 0.8 to 35 kg/ha, and HCO_3^- from 1 to 105 kg/ha (Hingston and Gailitis 1976). If the highest value for Ca^{2+} (35 kg/ha) is taken, the accumulation rate of carbonate will be 3.2 mm/1000 years, assuming that all Ca^{2+} will deposit as calcium carbonate. This rate seems to be very low, but re-distribution and concentration by surface-water and groundwater may result in much higher rates in run-on areas. Moreover, since the climate and dust activities varied significantly during the Pleistocene (e.g., Bowler 1976), a much higher aeolian accession of Ca^{2+} may be expected for the colder and drier glacial periods in the past (e.g., Butler 1956).

3.1.3 Groundwater

Saline groundwater is another important source of Ca^{2+}, Mg^{2+} and CO_3^{2-} and is dominantly responsible for the formation of calcrete in some trunk valleys of ancient drainage systems in Western Australia (e.g., Butt *et al.* 1977, Carlisle *et al.* 1978) and in some coastal dunes (e.g., Semeniuk and Meagher 1981). The groundwater is, of course, only a transport agent responsible for the re-distributing and concentrating Ca^{2+}, Mg^{2+} and HCO_3^-, compared to the more original sources from bedrock, connate salts and aeolian dusts. Similarly, shallow groundwater and soil water re-distribute carbonate through the processes of leaching and vertical and lateral water flows within soils and sediments. For a calcrete in a particular area, the Ca^{2+} and Mg^{2+} may be derived from more than one source (e.g., Anand *et al.* 1997).

3.2 Mechanisms and processes of carbonate precipitation in host materials

3.2.1 Calcium carbonate precipitation

Calcium carbonate precipitates if Ca^{2+} and HCO_3^- concentrations in a solution become sufficiently high. The solution may be open water in the sea, in a lake, in a spring or groundwater and soil water.

The processes of calcium carbonate precipitation and dissolution can be simplified as follows (e.g., Leeder 1982):

$$H_2O + CO_2 \qquad [1]$$

$$\downarrow\uparrow$$

$$CaCO_3 + H_2CO_3 \rightleftharpoons Ca^{2+} + 2HCO_3 \qquad [2]$$

As indicated by the above equations, precipitation of calcium carbonate (equation [2]) can be promoted by:

- increasing of the concentrations of Ca^{2+} and/or HCO_3^- in the solution; and,
- removal of CO_2 from the solution.

These can be achieved through the following mechanisms (e.g., Wright and Tucker 1991):

1) evaporation and evapotranspiration. These are regarded as major processes responsible for the formation of calcretes in semi-arid and arid zones and rhizoliths in coastal dunes;
2) degassing of CO_2 from solution, by raising the temperature and/or pH of the solution;
3) organic activities. Some bacteria take up CO_2 from soil air and solution (e.g., Krumbein and Giele 1979). Fungi are particularly important in triggering carbonate precipitation (e.g., Phillips *et al.* 1987) by taking up CO_2; and,
4) common-ion effects. These may cause addition of Ca^{2+} to a solution, e.g., when groundwater moves towards playa lakes and encounters saline groundwaters.

3.2.2 Replacement and displacement

As carbonates precipitate in soil or regolith, they replace and displace other regolith components.

During replacement, some host components are dissolved and/or removed and are replaced by calcium carbonates. The replaced components may include silicate minerals (e.g., Goudie 1983), gypsum (e.g., Chen 1997b), plant materials such as tree roots (e.g., Klappa 1980) and nodular Fe oxides (Anand *et al.* 1997).

Displacement is probably a more common process and commonly occurs with replacement. The amount of carbonate in a calcrete profile tends to exceed the original pore space of the host. This produces an increase in volume and physical displacement of the original host components. The feature of 'floating grains' is directly attributable to this process (e.g., Wright and Tucker 1991).

The valley calcrete or groundwater calcrete of Western Australia (Section 7.2.1) is probably formed by precipitation of carbonate near the water-table and by displacive growth (e.g., Carlisle *et al.* 1978), resulting in relatively pure and very thick carbonate layers. Mann and Horwitz (1979) believe that this upward displacive growth explains some features of valley calcrete such as small anticlines, diapir structures and inverted stratigraphy.

The mechanism of displacive growth may be explained (e.g., Wright and Tucker 1991) by calcite crystals preferentially forming cohesive bonds with other carbonate crystals, reflecting the chemical affinity of the ionic bonding of calcite. In other words, existing calcite is a more favoured site for further precipitation than non-calcite surfaces. The inability of carbonate to form adhesive bonds with non-carbonate grains results in the displacement of these grains.

3.3 Diagenic processes

Diagenesis of calcrete or regolith carbonates includes all those processes that act on these carbonate minerals after their initial precipitation. In general, physical, chemical and organic processes begin acting on regolith carbonates immediately after precipitation in the hosts. The most common diagenic processes are as follows.

Dissolution and re-precipitation

The solubility of calcium carbonate (calcite) ranges from 0.01 to 0.05 g/l in water at a temperature of 25°C (e.g., Krauskopf 1967), and depends on the CO_2 concentration of the water. When exposed at the surface, calcrete or regolith carbonates are slowly dissolved by rainwater and karst features may develop (e.g., Carlisle 1978, Arakel 1991). Within the soil/regolith (vadose zone), dissolution is also very common when percolating rainwater interacts with regolith carbonate.

Water with dissolved carbonate may flow away, transporting Ca^{2+} and HCO_3^- to other locations. Re-precipitation occurs when the solution becomes more concentrated and reaches saturation for carbonate, through evaporation or degassing of CO_2. The re-precipitated carbonate minerals tend to concentrate on the surfaces and within the voids of existing carbonate due to the preferential cohesive bonds between carbonate crystals (e.g., Wright and Tucker 1991).

Pisolitic and laminar calcretes result from dissolution and re-precipitation (see Section 3.4). Some hardpan calcretes consist of re-cemented carbonate breccias, indicating a stage dominated by brecciation followed by a stage dominated by re-precipitation. Features of re-cemented breccias can be seen in Figure 2.1.13 (page 156).

Dissolution and re-precipitation may occur many times during the development of a calcrete profile. In many cases, it may be difficult to identify features of 'original precipitation' and re-precipitation.

Silicification

Silicification is very common in groundwater calcrete (e.g., Butt *et al.* 1977, Arakel *et al.* 1989). Conditions favouring the replacement of calcite by silica include relatively low pH, low temperature and the saturation of the pore solution with silica (Blatt *et al.* 1980). The silicification reaction may be represented symbolically (Blatt *et al.* 1980):

$$CaCO_3 + CO_2 + H_4SiO_4 \longrightarrow SiO_2 + Ca^{2+} + 2HCO_3^- + H_2O$$

Silicification of calcrete appears to be most pronounced within the phreatic zone, but it also occurs, less commonly, in the vadose zone (Arakel *et al.* 1989). Silica may occur in many forms such as thin grain coatings, veins, pore and cavity linings, spherules and massive precipitates. Figure 3.3.1 (page 156) shows authigenic silica as massive and irregular aggregates within a calcrete.

Silicification of calcrete may produce either an opaline silica in filling of solution pipes and other voids in calcrete, or as a replacement involving simultaneous dissolution of carbonate and precipitation of opaline silica. Silicification may be initiated within incipient carbonate mottles, where micropores provide loci for the nucleation of opal-CT from Mg-rich alkaline pore solutions (Kastner *et al.* 1977). Within the carbonate mottles, progressive replacement of sparry cement by silica and eventual coalescence of spherulites may ultimately give rise to the development of a massive replacement chert (Arakel *et al.* 1989).

Brecciation

Brecciation features are very common in calcrete profiles (e.g., Figure 2.1.13, page 156), reflecting the disturbance probably caused by the displacive growth of carbonate, wetting and drying cycles, thermal expansion, swelling clays and tree root activity (e.g., Wright and Tucker 1991). Boulder or cobble calcrete appears to be formed by the brecciation of hardpan calcrete.

Cementation and hardening

Cementation in carbonate rocks normally refers to the growth of crystals into pore space from carbonate rock surfaces (e.g., Blatt *et al.* 1980). The new crystal occupies space that was formerly occupied by water or air. This process may also occur in the vadose zone and is probably responsible for the hardening of the upper part of a calcrete profile, where dissolution/re-precipitation occur more commonly.

3.4 Formation of different morphological types

Powdery calcrete

The formation of powdery calcrete is not well understood. Some authors (e.g., Goudie 1983) have suggested that the paucity of nodules may be because the host material is too fine grained to act as nuclei for nodules to develop. However, large carbonate nodules were commonly found within very clay-rich sediments, such as parna deposits (e.g., Beattie 1972).

In most calcrete profiles, the degree of induration (cementation) decreases downward, with powdery calcrete most commonly occurring in the lower part. This is probably because the lower part represents a relatively early stage of development beyond the reach of most percolating rainwater. Therefore, cementation by dissolution/re-precipitation has not taken place.

Nodular calcrete

The formation of carbonate nodules probably involves two different processes: *in situ* precipitation of micritic carbonate, and breakdown of massive calcrete. The *in situ* precipitation of carbonate may occur either near the water-table or within the illuviated horizon of a soil. Such precipitation is not evenly distributed within the host materials, but tends to concentrate at a nucleus, forming aggregates or nodules. In addition, in the near-surface, large masses of calcrete tend to be brecciated into smaller fragments. Mechanical movement and transport of these fragments may also be involved in the formation of nodular calcrete.

Pisolitic calcrete

Carbonate pisoliths are found generally in the upper part of a calcrete profile and close to the land surface (in the soil moisture zone). In this zone, water infiltration and the dissolution/re-precipitation of carbonate commonly occur. The concentrically-laminated layers of the pisoliths may be interpreted as coatings formed by periodic precipitation of carbonate on the surface, as the percolating soil water brings carbonate-saturated solutions to the existing carbonate nodules or other nuclei. The precipitation of carbonate may occur on all faces of a nodule/pisolite as soil water (or soil solution) gradually dries out. This explains why the thickness of a lamina of a carbonate pisolith is relatively constant.

Tubular calcrete

Rhizoliths are the most common type of tubular calcrete. They are interpreted to form by accumulation and/or cementation around, within, or by replacement of, plant roots by carbonate (e.g., Klappa 1980). Carbonate may precipitate within the voids left by dead roots, or around living roots as the concentration near the roots rises due to removal of water by the roots (e.g., Klappa 1980).

Honeycomb calcrete

This may be developed from nodular and pisolitic calcretes by continued precipitation of authigenic carbonate in the matrix between carbonate nodules and pisoliths, leading to the cementation of them together. The nodules also coalesce by the development of overlapping lamellar rinds.

Hardpan calcrete

This is regarded as a calcrete that has reached a relatively mature stage of development, in which replacive and displacive accumulation of micritic carbonate in the host materials has resulted in a continuous, cemented layer. Complex fabrics and structures are common as the result of brecciation, dissolution and re-precipitation (e.g., Figures 2.1.8, page 155 and 2.1.13, page 156).

Laminar calcrete

Laminar calcrete rarely exceeds 25 cm in thickness and commonly caps hardpan calcrete or other hard surfaces. It may be formed by precipitation of carbonate from soil water (or soil solution) ponded over a relatively impermeable surface. Some laminar carbonate may be biogenic (e.g., Wright 1989). Laminar calcrete may also form by carbonate precipitation within planner voids of a host material which has developed laminar structures (Figure 2.1.9, page 155).

Boulder/cobble calcrete

This is interpreted by most authors to result from disrupted hardpan calcrete by fracturing and brecciation caused by swelling and shrinking of underlying clays, tree-root disturbance, thermal expansion or colluvial processes.

Carbonate mottles

These are formed as carbonate precipitates within the host material, initially filling voids and then expanding to form larger aggregates (or carbonate mottles).

3.5 Models of calcrete formation

Various models and mechanisms of calcrete formation have been proposed (e.g., Goudie 1973, 1983, Carlisle *et al.* 1978, Wright and Tucker 1991). These are related to different hydrological and geohydrological settings (Carlisle *et al.* 1978), which can be classified into: surface water; soil-moisture zone; gravitational water zone; capillary fringe; and phreatic (or groundwater) zone (Figure 3.5.1).

1) Surface water

Shallow surface water with high concentrations of Ca^{2+} and HCO_3^- may infiltrate and cause carbonate precipitation within the top part of sediments, such as gully bed cementation, case hardening and fluvial laminar crusts (e.g., Carlisle *et al.* 1978, Wright and Tucker 1991, Figure 3.5.2A). However, these are barely within the definition of calcrete/regolith carbonate because carbonate precipitated in this manner is transitional between authigenic carbonate and the carbonate precipitated from surface water.

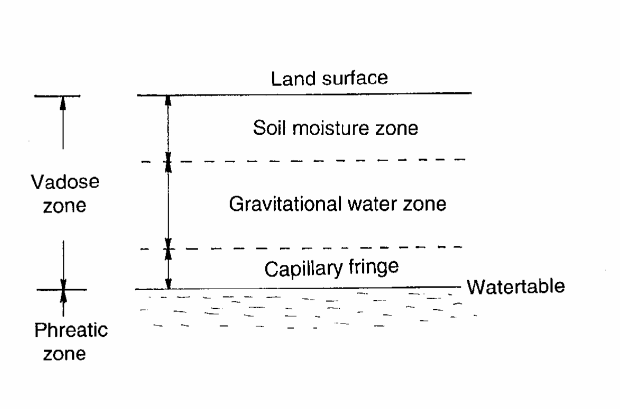


Figure 3.5.1. Geohydrological zones below the land surface.

Carbonate grains/debris may be transported mechanically by fluvial and colluvial processes. Transported carbonate debris may be deposited as a layer, loose or re-cemented, which can be referred to as 'reconstituted and/or detrital calcrete' (Carlisle *et al.* 1978, Figure 3.5.2B).

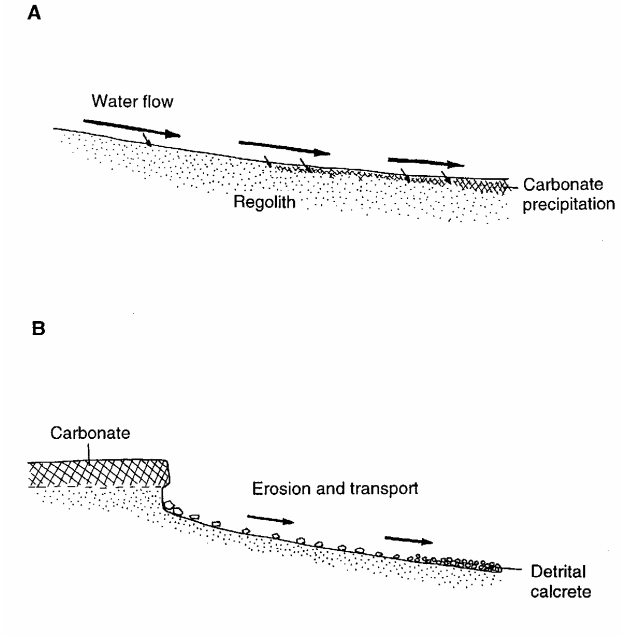


Figure 3.5.2. Calcrete (regolith carbonate) formation in the surface water zone (adapted from Carlisle *et al.* 1978)

A Surface water with high concentrations of Ca^{2+} and HCO_3^- may cause carbonate precipitation in the top part of the soil/sediment.

B Fragments of carbonates may be transported mechanically to form a detrital calcrete. Dissolution and re-precipitation may occur and cause cementation.

2) Soil moisture zone

This zone extends from the land surface down to the normal depth of rainwater infiltration. Within this zone, soil water may move downwards, e.g., during rainfall, and upwards, by evaporation and capillary rise during dry, hot period. In this zone, calcrete or regolith carbonate may form by transport and concentration of carbonate by soil water movements (Goudie 1983):

a. *per descensum model*: downward leaching (or eluviation/illuviation processes), resulting in concentration of carbonates within the lower part of the soil moisture zone (Figure 3.5.3A). The Ca and Mg may be derived originally from dust, rainfall, vegetation litter, surface runoff or calcareous sediments. These are brought to the lower part of the soil moisture zone by rainwater and precipitate as authigenic carbonate; and,

b. *per ascensum model* : in this model, carbonate does not precipitate in lowest part of the soil moisture zone. Soil water may infiltrate to depth but then moves upward under the capillary effect bringing dissolved carbonate to a higher level (Figure 3.5.3B).

Some aspects of these models can explain the relative accumulations of authigenic carbonate at a certain depth within the soil moisture zone. The depth of the carbonate accumulation is determined by the rainfall regime, generally being deeper with increasing rainfall (e.g., Jenny 1941, McFadden and Tinsley 1985).

Another model, the *in situ alteration* of non-authigenic carbonate, explains the alteration of, e.g., limestone, by brecciation, dissolution and re-precipitation (Figure 3.5.3C). This *in situ* alteration may occur on the land surface or at a depth, but more commonly within the soil moisture zone (e.g., Arakel 1982).

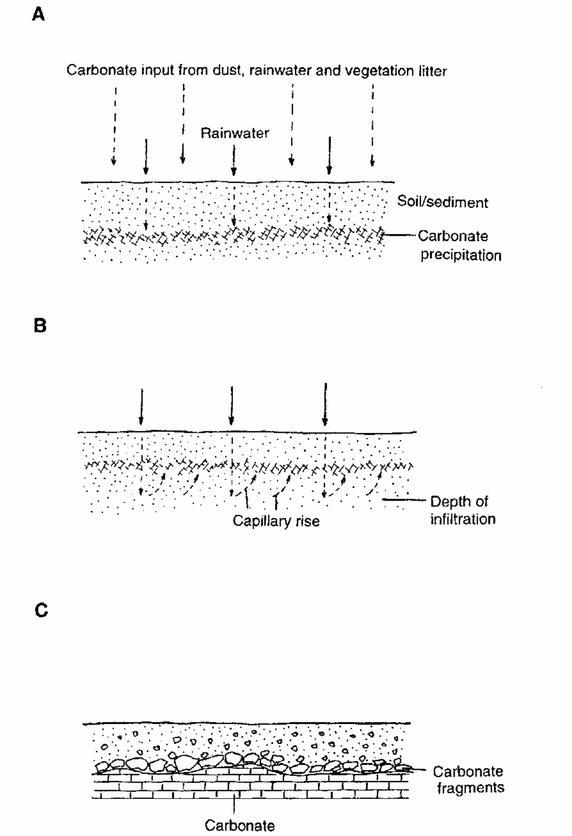


Figure 3.5.3. Calcrete (regolith carbonate) formation in the soil moisture zone (adapted from Goudie 1983).

A. Authigenic carbonate accumulates in the lower part of the soil moisture zone as a result of eluviation/illuviation. The carbonate may have a variety of sources.

B. Authigenic carbonate may accumulate at a higher position in the soil moisture zone. Capillary rise may bring dissolved carbonate upwards.

C. Carbonate fragments may result from brecciation of a non-authigenic carbonate, e.g., a marine limestone. These fragments may form a calcrete through the processes of partial dissolution, re-precipitation and cementation.

3) Gravitational water zone

This is below the soil moisture zone and above the capillary fringe of the groundwater table. This zone may be absent if the watertable is close to the land surface and the capillary fringe reaches the soil moisture zone (Figure 3.5.1).

Infiltrating rainwater may reach this zone through irregular channels (with higher permeability), such as holes resulting from animal activities and plant roots, or during heavy rains and floods. Groundwater may also reach this zone through upward transport by deep-rooted trees. Both rainwater and groundwater can bring in dissolved carbonate, producing calcrete (or regolith carbonate).

4) Phreatic water zone and capillary fringe

In a catchment area, groundwater flows may transport Ca^{2+}, Mg^{2+} and HCO_3^- towards the low-lying locations, e.g., to the drainage axis, where the water-table becomes closer to the land surface. In this location, carbonate may precipitate within the phreatic zone or in the capillary fringe (Figure 3.5.4) if the concentrations of Ca^{2+}, Mg^{2+} and HCO_3^- reach saturation. Precipitation may be promoted by evaporation/transpiration, degassing of CO_2, and the common ion effect, particularly when groundwater flows close to salt lakes (Section 3.2).

Although groundwater flow and lateral transport of dissolved $CaCO_3$ are commonly involved, this may occur at very different scales. Figure 3.5.5 (page 156) shows an example of small-scale lateral transport, i.e., carbonate accumulation in a lower topographic location, which may be due to lateral transport by shallow groundwater (or soil water in a perched watertable). Conversely, lateral transport can occur at a much larger scale, such as in the groundwater calcretes in the ancient trunk valleys of Western Australia and Northern Territory. The trunk valleys range from tens of kilometres to over one hundred kilometres wide, with groundwater calcrete in the central part (e.g., Butt *et al.* 1977, Arakel 1986b and 1991). The distance of lateral transport of Ca^{2+}, Mg^{2+} and HCO_3^- in this case may reach tens of kilometres.

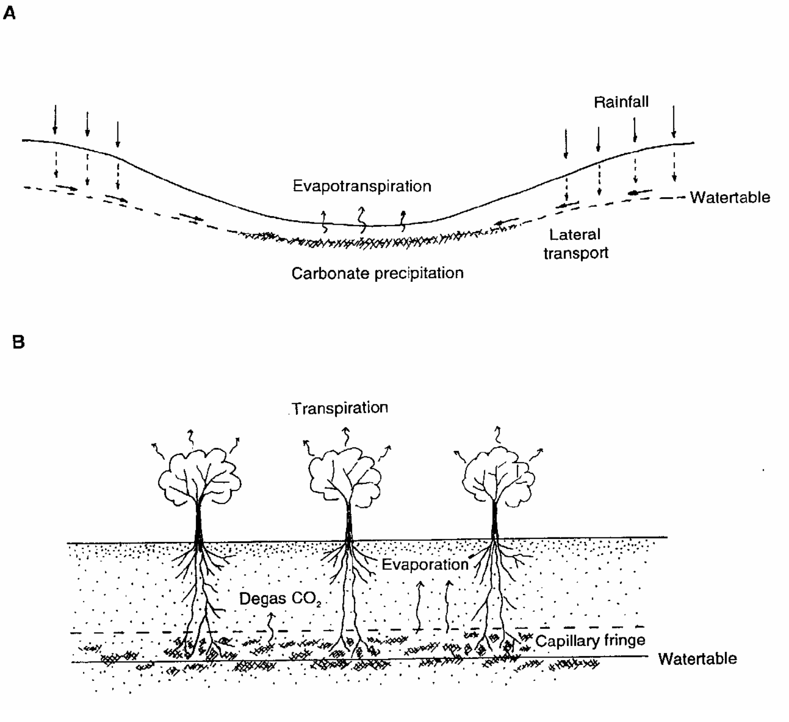


Figure 3.5.4. Calcrete (regolith carbonate) formation in the phreatic zone and the capillary fringe (adapted from Carlisle *et al.* 1978).

A. Dissolved carbonate is transported by groundwater towards topographically low areas. This can occur at different scales, from tens of metres to tens of kilometres laterally, and from deep groundwater to shallow perched water.

B. Where the watertable is close to the surface, authigenic carbonate may precipitate near the watertable. This is due to increasing concentrations of Ca^{2+} and HCO_3^- from evaporation/transpiration and degassing of CO_2.

Chapter 4

Classification systems

X.Y. Chen

4.1 Morphological classification

The morphological classification scheme is based only on visible features, which can be described mostly in the field, without consideration of genesis or other interpretations. The morphological types described earlier (Chapter 2.1) can be used as categories in a classification system. This classification scheme appears simple and objective in its application, although some difficulties may be encountered, as discussed below.

Discrepancies

Different morphological classification systems are used by different authors. Some are only nominal, in that the same morphological types are referred to using different terms. For example, the 'glaebular calcrete' of Netterberg (1980) is basically the same as the 'nodular calcrete' of Goudie (1983). However, there are some significant differences in the case of those soils and regoliths with relatively low contents of authigenic carbonate. This again involves the problem of differentiating calcrete from a 'non-calcrete' regolith carbonate. Wright and Tucker (1991) use the following two categories for the regolith carbonate with low carbonate content:

- Calcareous soils: 'very weakly cemented or uncemented soil with small carbonate accumulations as grain coatings, patches of powdery carbonate including needle-fibre calcite (pseudomycelia), carbonate-filled fractures and small nodules'; and
- Calcified soil: 'a firmly cemented soil, just friable, few nodules, 10-50% carbonate'.

A soil/regolith layer with <10% carbonate, which occurs as scattered nodules, can be classified as 'calcareous soil' according to Wright and Tucker (1991). On the other hand, this can also be classified as 'nodular regolith carbonate' according to Hill *et al.* (1999). However, the above classification categories of 'calcareous soil' and 'nodular regolith carbonate' only have a small overlap in their definitions. Moreover, 'calcified soil' is regarded by some authors as a calcrete because its carbonate content may be high (up to 50%) and it may be highly indurated (Goudie 1983).

To avoid such discrepancies, this report recommends the following solutions :

- the objective to be classified, e.g., a layer/horizon of regolith/soil containing carbonate, can be considered at two scales, the whole layer/horizon and the carbonate in it;
- if the layer/horizon satisfies the definition of a calcrete (Section 1.2), e.g., dominated morphologically by carbonates (>40% in mass as a reference), it can be classified as a calcrete layer, e.g., 'nodular calcrete';
- if the layer/horizon has too low carbonate content, it should be described as 'a regolith/soil containing carbonate'. The carbonate itself can be classified morphologically (see Chapter 2.1); and
- the result would be, e.g. 'nodular (or pisolitic or powdery) carbonate'. Thus the whole layer/horizon can be describe as 'a soil/regolith with nodular (or pisolitic or powdery or tubular) carbonate'.

Transitional forms

In morphological classification systems, only specific 'end-member' types are described, yet, in reality calcretes commonly occur as a continuum between the end-members. For example, Figure 2.1.1 (page 154) shows a transitional form between hardpan and powdery calcretes and Figure 4.1.1 (page 156) a transitional form between nodular and hardpan calcretes. Transitional forms may be found between other typical morphological types as well, eg. between nodular and pisolitic calcretes, between nodular and powdery calcretes, and between hardpan and boulder calcretes.

Most calcretes are mixtures of two or more morphological types (e.g., Figure 2.1.2, page 154), but there is no systematic scheme dealing with transitional types and/or mixtures of two or more morphological types. A few authors add adjectives to the major morphological types, e.g., 'brecciated hardpan calcrete' for a transitional form between hardpan and boulder calcretes (Milnes 1992). This is probably an appropriate solution. This report does not intend to establish a system but suggests the following:

- for a mixture of two morphological types, both types may be included in the name but with the minor one as an adjective. For example, a 'pisolitic-nodular calcrete' refers to a calcrete as a mixture of carbonate nodules and minor carbonate pisoliths;
- for a mixture of more than 2 morphological types, the word 'complex' may be added to the dominant type. For example, a 'complex nodular calcrete' may refer to a calcrete with nodular morphology dominant and mixed with other two or more minor morphological types. For a detailed description, all morphological types should be included although the name follows the dominant type only; and,
- in the case of a calcrete in a transitional form between two typical morphological types, an adjective can be added to the dominant type, e.g., 'nodular-structured hardpan calcrete', 'weakly-indurated hardpan calcrete' or 'powdery nodular calcrete'.

Calcrete profiles

Different morphological types commonly occur as distinct layers in a sequence, forming a calcrete profile consisting of several morphological types. Most authors classify each layer by its morphology and do not classify the whole profile. However, some morphological types may occur regularly in a sequence forming recognisable calcrete profiles. For example, very similar 'mature' calcrete profiles have been recognised by Crawford (1965), Read (1974), Arakel (1982) and Milnes and Hutton (1983) at many locations from South Australia, Western Australia and central Australia. Each profile consists, from top downwards, of distinct pisolitic, laminar, hardpan and mottled calcrete layers/horizons. There are many other calcrete profiles with sequences of various morphological types (e.g., Watts 1980, Milnes and Hutton 1983, Milnes 1992). Some authors (e.g., Milnes and Hutton 1983) refer to such profiles as 'multi-layered' calcrete.

Although there are no systems to classify calcrete profiles, a description of such complex profiles should include:

- the number of calcrete layers in a soil/regolith sequence;
- the number of distinct sub-layers/horizons in each calcrete layer; and,
- the morphological types of each sub-layer/horizon.

Further classification

Each morphological type (see Chapter 2.1) may vary significantly in terms of:

- carbonate content (the ratio of carbonate to other soil/regolith materials);
- size and internal fabric of the carbonate nodules;
- degree of induration of discrete nodules and cementation of the whole layer,
- thickness of the layer; and,
- distribution pattern of the nodules.

Despite such variations, there are no well-developed or commonly accepted systems for further classification, although some have been suggested for pisolitic calcrete (Hay and Wiggins 1980) and tubular calcrete (Klappa 1980).

It is not intended here to establish a scheme for further classification based on calcrete morphology, because calcretes may differ significantly from one region to another, according to climate, landform history and geological settings. Therefore, it may be too difficult to establish a very detailed classification scheme suitable for whole world or the whole of Australia. However, this does not preclude the development of further morphological classification for specific-purposes, for a particular area, or for a particular project using particular criteria.

4.2 Genetic classification based on hydrologic settings

Calcrete genesis includes several aspects: sources of Ca^{2+}, Mg^{2+} and HCO_3^-, and then transportation in the hosts, and the precipitation and diagenesis of authigenic carbonates (see Chapter 3). Many authors (e.g., Arakel 1982, 1986a, Klappa 1980, Goudie 1983, Wright and Tucker 1991) have suggested genetic models for various calcretes, but have not developed classification systems based on the models.

The most systematic genetic classification has been compiled by Carlisle (1980), based on the hydrological settings of calcrete formation (Figure 4.2.1). The classification categories of his system are clearly divided into two groups: ‘pedogenic’ and ‘non-pedogenic’ calcretes. Pedogenic calcrete results from the relative accumulation of carbonate in the soil moisture zone (Carlisle 1980), by movement of percolated rain water and/or soil water, such as eluviation/illuviation or as a product of biological activity such as a root respiration. Among the various non-pedogenic calcretes, phreatic (or groundwater) calcrete contrasts the most with the pedogenic type. It forms by the absolute accumulation of Ca^{2+} and HCO_3^- which are transported laterally by groundwater flow.

Pedogenic calcrete seems to occur more widely and has been studied more thoroughly. Several genetic models for pedogenic calcrete were summarised by Goudie (1983) as the *per descensum model*, *per ascensum model* and *in situ alteration* of calcareous but non-calcrete material, e.g., limestone (see Section 3.5). However, no classification systems have been developed to further classify pedogenic calcrete using these models.

The most representative phreatic or groundwater calcrete is the ‘valley calcrete’ which occurs as sheets along the central tracts in some ancient trunk valleys in Western Australia and central Australia ” (e.g., Butt *et al.* 1977, Carlisle *et al.* 1978, Mann and Horwitz 1979, Arakel 1986a). This type of calcrete is formed due to the precipitation of authigenic carbonate near the water-table when groundwater flows towards the valley axis and becomes carbonate-saturated.

Between the two extremes (pedogenic calcrete and groundwater calcrete) there can be many intermediate types, forming a series from more groundwater-related types to more soil-water-controlled. For example, in the gravitational zone between the capillary fringe and the soil moisture zone (Figure 4.2.1), calcrete may form under:

- either meteoric/soil-water-dominant conditions, with downward transport of carbonate along irregular higher permeability channels; or
- groundwater-dominant conditions, with upward transport and accumulation of carbonate by deep-rooted plants.

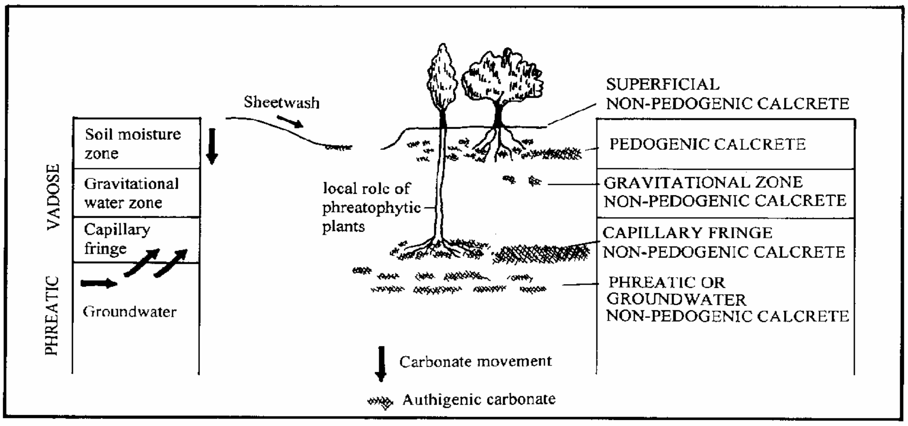


Figure 4.2.1. Classification of calcretes by hydrologic settings (adapted from Carlisle 1980, Wright and Tucker 1991).

It is, however, difficult, both conceptually and practically, to define and classify the intermediate types. For example:

- if the water-table is close to the land surface and the capillary fringe overlaps the soil moisture zone, carbonate deposited within the capillary fringe may be regarded as either groundwater calcrete, because the Ca^{2+} and HCO_3^- come from the groundwater, or pedogenic calcrete, because it forms within the soil moisture zone;
- it is difficult to differentiate the soil moisture zone from the gravitational water zone and to determine the maximum depth that pedogenic processes can reach. Therefore, pedogenic calcrete cannot be clearly differentiated from the non-pedogenic calcrete of the gravitational zone; and
- soil water and/or percolated water may also transport dissolved carbonate laterally, although at very different scales compared to regional groundwater flow. More carbonate may accumulate in topographically-low locations, due to the lateral flow of soil water (Figure 3.5.5, page 156). Indeed, percolated rainwater, soil water, perched groundwater, shallow groundwater and deep groundwater have some overlaps and cannot be clearly differentiated. They may all flow both vertically and laterally, causing both relative accumulation and absolute accumulation, although the scales are very different for different types of water.

In addition to the above conceptual difficulties, there are no morphological features that provide a clear differentiation between four genetic categories of calcrete (Carlisle 1980) listed above. Similar morphologies, e.g., hardpan and tubular calcretes, may occur in both pedogenic and groundwater calcretes (e.g., Semeniuk and Meagher 1981, Arakel 1996, McCord 1995). The tubular calcrete (carbonate rhizomorphs) of coastal dunes, for example, may form through both the up-take of groundwater and downward leaching of calcareous sands by meteoric water (Klappa 1980, Semeniuk and Meagher 1981). Moreover, the present hydrological setting may have changed and differs from that under which the calcrete originally formed. This eliminates the possibility of using present hydrological settings to determine the original situations of any calcrete.

These difficulties explain the lack of sophisticated genetic classification systems using hydrological settings. In general, only the typical types of the two extremes, pedogenic calcrete and groundwater calcrete, may be distinguishable to some degree. Although the two have some common morphological features, they also show some differences in the following aspects:

- thickness. They both vary significantly in thickness but the maximum thickness of a single layer may be quite variable. A single layer of groundwater calcrete commonly reaches a great thickness, e.g., >10 m. A single layer of pedogenic calcrete is commonly <2 m and rarely over 5 m thick, although many interbedded layers of pedogenic calcrete in a regolith sequence can reach a much greater total thickness;
- morphological types. Nodular, pisolitic and powdery forms are commonly found in pedogenic calcrete, but are either absent or occur only at the top of a groundwater calcrete as a result of exposure at the land surface and alteration by diagenesis (see Chapter 3.4);
- occurrence. Pedogenic calcrete may form at or near the surface and in many different landforms. Groundwater calcrete occurs more commonly along drainage axes and near salt lakes. Modern groundwater calcrete forms at the water-table but old groundwater calcretes may be far from the present water-table; and,
- silicification. This is very common for groundwater calcrete and much less so in pedogenic calcrete. Silicification can be so intense that a silcrete may form, interbedded with or transforming laterally to a groundwater calcrete, e.g., in Western Australia (Butt *et al.* 1977) and in central Australia (Arakel *et al.* 1989).

It can be concluded that, based on the present knowledge, a genetic classification using hydrological settings has not yet been developed sufficiently to classify calcretes in any detail. Only the two extreme types in this system, pedogenic calcrete and groundwater calcrete, may be differentiated.

4.3 Classification according to stages of calcrete formation

Classification based on theoretical models of calcrete profile development are also genetic, relying on the degree of ‘maturity’ instead of hydrological setting. Among various models (e.g., Read 1974, Mann and Horwitz 1979, Warren 1983, Arakel 1982), that developed by Gile *et al.* (1966) and modified by Machette (1985) and Wright and Tucker (1991) is the most commonly adopted. According to this model, a calcrete can be classified into six stages of development using specific diagnostic features (Table 4.3.1). The model classifies the whole calcrete profile, which may consist of several sub-layers of different morphological types. In the initial or lower stages (stage 1 to stage 3), the gravel content of the host has significant influence on the features of the calcrete, but at higher, more mature stages, this influence is diminished. There is no close correlation between development stages and the absolute time period of calcrete formation, e.g., a mature calcrete profile (stage 4 and above) may develop in several thousand years, but a Jurassic calcrete has been reported as only stage 3 (Wright and Tucker 1991).

Table 4.3.1, Classification of pedogenic calcretes based on stages of development. From Machette (1985) and Wright and Tucker (1991). High gravel content refers to >50% gravel and the low is less than 20%. The per cent $CaCO_3$ refers to <2mm fraction. (K is a carbonate soil horizon; m refers to induration)

Stage	Gravel Content	Diagnostic feature	$CaCO_3$ distribution	Maximum $CaCO_3$ content
1	High	Thin discontinuous coatings on pebbles, usually on undersides	Coatings sparse to common	Trace to 2%
	Low	Few filaments in soil or faint Coatings on ped surface	Filaments sparse to common	Trace to 4%
2	High	Continuous, thin to thick coatings on tops and undersides of pebbles	Coatings common, some carbonate in matrix	2-10%
	Low	Nodules, soft 5-40mm in Diameter	Nodules common, generally non-calcareous to slightly calcareous	4-20%
3	High	Massive accumulations between clasts, fully cemented in advanced forms	Continuous in matrix to form K fabric	10-25%
4	Any	Thin (<2mm) to thick (10mm) laminae capping hard pan (Km)	Cemented, platy to tabular structure. Km horizon is 0.5-1m thick	>25% in high gravel content, >60% in low gravel content
5	Any	Thick laminae (>10mm); small to large pisolite above; Laminated carbonate may coat fracture surfaces	Indurated, dense, strong, platy to tabular. Km horizon is 1-2m thick	>50% in high gravel content, >75% in low gravel content
6	Any	Complex fabric of multiple generations of laminae, brecciated and recemented, pisolitic. Typically with abundant pisolites in fractures	Indurated, dense, thick, strong tubular structure. Km horizon is commonly >2m thick	>75% in all gravel contents

It should be noted that this classification system is only applicable to pedogenic calcrete and is probably not applicable to groundwater calcrete. Some authors (e.g., Mann and Horwitz 1979, Semeniuk and Meagher 1981) have suggested development stages as models in groundwater calcrete, but have not used them for classification.

Developmental classification systems are based on a theoretical model that assumes simple conditions, such as continuous downward leaching of carbonates from a calcareous parent material, steady environmental conditions without significant climatic and hydrological changes, and no erosion/deposition. The real situation may be different, and a calcrete may have a complex history, involving variations in climate and hydrology, change of landscape position, as well as erosion and deposition (Gile *et al.* 1966). As a result, some calcrete profiles may show more diverse features than those mentioned in the system (Table 4.3.1). Such profiles cannot be classified, e.g., carbonate pisoliths as a sole morphologic type in a regolith profile without any hardpan calcrete beneath, simply are not considered at all by the system (Table 4.3.1). Therefore, this classification system cannot be applied to every calcrete profile.

4.4 Classification based on carbonate minerals

Calcretes and regolith carbonates can be classified according to the ratio of two carbonate minerals, calcite and dolomite. Other authigenic carbonate minerals, if any, are very rare in the regolith (see Chapter 5). Aragonite is locally abundant in some groundwater calcretes, especially in deltaic facies towards salt lakes in Western Australia (C. Butt, personal communication). However, it has not yet been considered in any calcrete classification systems. A classification scheme suggested by Netterberg (1980) is shown in Table 4.4.1.

Table 4.4.1. Classification of calcretes and dolocretes based on dolomite content (after Netterberg 1980).

Name	% dolomite by mass of total carbonate	Approx. equivalent % $MgCO_3$*
Calcrete	<5	<2
Magnesian calcrete	5-10	2-5
Dolomitic calcrete	10-50	5-25
Calcitic dolocrete	50-90	25-40
Dolocrete	>90	>40

* % $MgCO_3 = 100 * MgCO_3 / (MgCO_3 + CaCO_3)$

This system is straightforward, but laboratory analysis is needed to determine calcite and dolomite contents and so is not suitable for field usage. In the field, cold 0.01M HCl acid may be used to find out whether there is a significant amount of dolomite in the carbonate, but is not sufficiently precise for determining the dolomite content required by the classification.

Gypsum ($CaSO_4.2H_2O$) and authigenic silica commonly occur with calcrete or dolocrete. It should be possible to devise classifications for gypsiferous and siliceous calcrete/dolocrete, but there seems little need for this.

4.5 Classification based on biogenic features

Biological activities are important in the formation of some calcretes (Chapter 3) and some biogenic features can still be recognised, including the following types.

Carbonate rhizoliths. Morphologically classified as tubular calcrete, carbonate rhizoliths may be either biogenic or sedimentary in origin. Carbonate can precipitate around living plant roots as the roots extract water and increase the concentration of Ca^{2+} and HCO_3^- in a solution (e.g., Semeniuk and Meagher 1981). Authigenic carbonate can also precipitate in channels left by decayed roots, forming root casts (e.g., Klappa 1980). A detailed classification on rhizoliths, made up of carbonate or other materials, has been developed by Klappa (1980).

Biogenic laminar calcretes. Many laminar calcretes are interpreted as being formed from the periodic ponding of surface, soil or ground water on relatively impermeable surfaces (see Chapter 3.4).

However, some laminar calcretes have been recognised to be biogenic in origin, including:

- laminar structured carbonate crusts formed on the land surface in deserts as a result of activities of cyanobacteria; these may be referred to as 'subaerial stromatolite' (e.g., Krumbein and Giele 1979, Wright 1989);
- calcified root mats (horizontal root systems) (Wright 1989); and,
- other laminar calcareous crusts originated from activities of algae and fungi.

Biogenic micro-fabrics in various calcretes. At a micro-morphological scale, various biogenic fabrics have been recognised, including:

- small peloids interpreted as calcitized fecal pellets (Wright 1989);
- needle-fibre calcites (calcific filaments). These are mainly formed as a result of bio-activities particularly relating to communities of fungi (e.g., Wright 1989, Phillips *et al.* 1987); and,
- other biogenic features mostly at a micro-fabric scale, such as microbial tubes, alveolar septal fabric and microcodium (Wright and Tucker 1991).

Some of these biogenic features are easily recognised in the field, but others can only be identified by micro-morphological studies. Some biogenic origins are based on interpretations which are not always easy to differentiate, e.g., the biogenic and non-biogenic laminar calcretes.

The calcrete classification system using biogenic features is not well-developed and essentially only recognises the two end-members: with and without significant biogenic features (e.g., Wright and Tucker 1991). Further classification is possible but micro-morphological data are necessary and a system has yet to be established. Therefore, it is unlikely to be suitable for field usage.

4.6 Conclusions

Morphological classification is the most favoured classification scheme. It uses visible features without genetic or other interpretations. Most morphological features can be described in field. Therefore, this system seems to be objective and easy to use. Additionally, the morphological types of calcrete described in the Australian literature are basically the same as those reported from other parts of the world.

The genetic classification system based on hydrological settings is restrained by both theoretical and practical difficulties in differentiating the various transitional types between the two recognizable extremes, namely groundwater and pedogenic calcretes. Even these two extreme types are not always easily differentiated by morphological or other visible features. The genesis of a calcrete cannot therefore be used for any detailed classification and, in any case, can only be regarded as an interpretation rather than an objective classification. However, this interpretation has important applications, e.g., for exploration of gold, uranium and groundwater resources (see Chapter 6).

Three other classification systems, based on developmental stages, carbonate minerals and biogenic features, have been used much less commonly for the reasons discussed earlier (Sections 4.3, 4.4 and 4.5).

Chapter 5

Mineralogy and geochemistry

X.Y. Chen and R.A. Eggleton

5.1. Introduction

The mineralogy and chemical compositions of calcrete and regolith carbonates can be complex. Most contain both authigenic and matrix minerals. The matrix component may have a wide range of mineral and chemical compositions and is incorporated into a calcrete as relict and/or intruding particles from the host materials, that will not be considered further. This chapter will summarise general mineral and chemical characteristics of Australian calcretes and regolith carbonates. Some specific chemical and mineral features particularly relevant to mineral explorations will be presented in Chapter 6.

5.2. Carbonate minerals

5.2.1 Calcite, aragonite and dolomite

Although there are in total more than 60 carbonate minerals (e.g., Degens 1965), calcite, aragonite and dolomite are the most common carbonate mineral species in all marine and terrestrial carbonates (>99% of all, Berner 1971). Aragonite and calcite have the same chemical compositions ($CaCO_3$) but are different in their crystal structures (Table 5.1).

Table 5.1. Comparison of the 3 major carbonate minerals (from Blatt *et al.* 1980, Leeder 1982, Boggs 1987).

	Crystal system	Specific gravity	Solubility product*
Aragonite ($CaCO_3$)	Orthorhombic	2.93	$6.3 * 10^{-9}$
Calcite ($CaCO_3$)	Hexagonal (rhombohedral)	2.72	$4.0 * 10^{-9}$
Dolomite ($CaMg(CO_3)_2$)	Hexagonal (rhombohedral)	2.85	$1.0 * 10^{-17}$

* in sea water at 25°C

Calcite and aragonite can form both inorganically and organically. Aragonite is more soluble than calcite (Table 5.1) at ordinary pressures and temperatures, and will commonly precipitate first from solutions. Calcite may precipitate from solutions as well depending on salinity, biological factors and temperature (e.g., Degens 1965). In both limestones and regolith carbonates aragonite is rare compared to calcite because it is thermally unstable and will transform to calcite. This process is more rapid in hydrous environments and at higher temperatures (e.g., Degens 1965). At ordinary temperatures the transition only takes place by dissolution of aragonite and precipitation of calcite.

The term dolomite refers to both the mineral species dolomite, $CaMg(CO_3)_2$, and the carbonate rock that contains more than 50% of the mineral (eg. Blatt *et al.* 1980). The mineral dolomite has a structure derivative from the calcite (or magnesite) structure, in which the planes of cations are alternately Ca^{2+} and Mg^{2+}. Natural crystals of dolomite commonly depart significantly from the ideal composition. At ordinary temperatures, formation of protodolomite, which contains up to 10 mole per cent excess of $CaCO_3$, is much more common, (e.g., Degens 1965).

Although dolomite rocks and dolocrete are common, there are only rare examples of modern dolomite deposition and dolomite has never been synthesised in the laboratory under conditions analogous to common sedimentary environments (Berner 1971). Modern dolomite presently deposits in a few salt lakes (e.g., summarised by Degens 1965), including the Coorong Lagoons in South Australia. Most dolomite in carbonate rocks is believed to be diagenetic products through a process of ‘dolomitization’. Some (e.g., Degens 1965) believe that even the modern and recent dolomite deposits are mostly a product of early diagenetic metasomatism of calcite.

The dolomitization process is unlikely to be a solid-state reaction and some solutions may be involved, occurring by the simultaneous dissolution of calcium carbonate and precipitation of dolomite (e.g., Blatt *et al.* 1980). High salinity (hypersaline environments) and sufficiently high Mg^{2+}/Ca^{2+} ratios of the solution are favourable conditions for dolomitization (e.g., Degens 1965, Blatt *et al.* 1980).

A reverse process, dedolomitization, has been noted by some (e.g., Blatt *et al.* 1980), i.e., dolomite is replaced by calcite. It commonly occurs in association with gypsum or oxidised pyrite under near surface conditions where meteoric water falling on gypsum beds generates a solution with a very high Ca^{2+}/Mg^{2+} ratio (Blatt *et al.* 1980).

A carbonate rock or a regolith carbonate may contain both calcite and dolomite. Similar to the classification of the calcrete-dolocrete series (Table 4.4.1), there is a simple classification of carbonate rock based on calcite and dolomite contents (e.g., Boggs 1987): limestone (0-10% dolomite), dolomitic limestone (10-50% dolomite), calcareous dolomite (50-90% dolomite), and dolomite (90-100% dolomite). The mineral calcite containing less than 4 mole % of $MgCO_3$ is referred to as low-Mg calcite (Boggs 1987).

5.2.2 Carbonate minerals in calcretes

The mineralogical and geochemical features of calcretes and regolith carbonates in South Australia have been summarised by Milnes and Hutton (1983), Milnes *et al.* (1987) and Milnes (1992). The calcrete developed on the calcarenites of the barrier ridges near the coasts of South Australia are chemically similar to the underlying calcarenites, characterised by calcite and low-Mg calcite (Figure 5.1A). However, the calcretes and regolith carbonates from the carbonate blanket of some inland regions of South Australia have an important dolomite component (Figure 5.1B). In some occurrences, dolomite is the dominant carbonate mineral (Figure 5.1B) and these should be referred to as dolocrete instead of calcrete (Chapter 1).

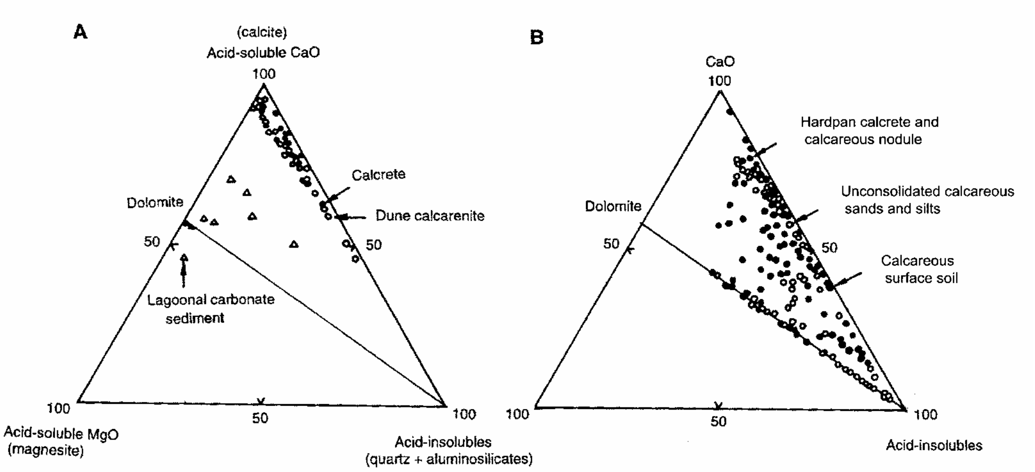


Figure 5.1. Chemical compositions and inferred mineralogical compositions of carbonates from
A) the coastal province, and
B) inland regions of South Australia. (from Milnes and Hutton 1983)

One of the origins of this dolomite component is probably the seasonally dry salt lakes in which dolomite is actively precipitating during the wet phase (Milnes *et al.* 1987). However, an origin by dolomitization may be more important, particularly in explaining the distribution of dolomite in many regolith carbonate profiles of South Australia, a general trend of increase in dolomite/calcite ratio towards lower part (Hutton and Dixon 1981, Milnes and Hutton 1983, Phillips and Milnes 1988). Dixon (1994) also examined the distribution of dolomite in regolith carbonates along a soil catena of a hill slope in the St Vincents Basin of South Australia and found a significant enrichment of dolomite in the regolith carbonate from the top to the base of the catena. These distribution patterns of dolomite in regolith carbonate profiles are regarded (Wetherby and Oades 1975, Milnes and Hutton 1983, Dixon 1994) as an effect of dolomitisation, involving *in situ* leaching of an original calcareous deposit, and vertical and lateral transport of Mg^{2+} by soil water. The processes include: a) carbonate dissolution, b) subsequent disequilibrium precipitation of calcite in preference to dolomite in the surface zones with further leaching of magnesium, and c) precipitation of dolomite in lower zones due to a progressive enrichment of magnesium relative to calcium in the solution. Magnesium-rich groundwater from a more distant source may also play an important role in the formation of dolomite at depth (McQueen *et al.* 1999).

Similarly, in central and western Australia, low-Mg calcite is the main carbonate species in regolith carbonates, but high-Mg calcite and dolomite are also common (e.g., Arakel 1986b, Jacobson *et al.* 1988, Arakel *et al.* 1989, Anand *et al.* 1997). In general, dolomite content increases with depth in calcrete and regolith carbonate profiles (e.g., Jacobson *et al.* 1988, Anand *et al.* 1997). A recent study at Broken Hill in New South Wales (Hill *et al.* 1999, McQueen *et al.* 1999) reported the same trend.

However, there are more complex situations. In a regolith carbonate profile on the Yilgarn Plateau, Mann and Horwitz (1979) found an increase of dolomite and decrease of calcite from near surface down to 3.5 m (about 1 m above the watertable), then a reversed trend around the watertable with a significant decrease of dolomite/calcite ratio. Mann and Horwitz (1979) also pointed out that at some other sites on the Yilgarn, where groundwater salinities and Mg^{2+} concentrations are high, dolomite is more abundant near the watertable.

Similar distributions of carbonate minerals in regolith carbonates have been found in other parts of the world. Calcite and low-Mg calcite are the dominant carbonate minerals (e.g., Goudie 1972b), but dolomite also occurs (Watts 1980, Goudie 1983). In the Kalahari of southern Africa (Watts 1980) high-Mg calcite and dolomite occur more commonly in the regolith carbonates developed on Mg-rich host materials and in the lower levels of the regolith carbonate profiles developed in and around saline depressions. Precipitation of high-Mg calcite and dolomite is believed to relate to the high Mg/Ca ratio of vadose and groundwaters (Watts 1980, Arnaud and Herbillon 1973).

5.3 Clay minerals

Clay minerals are very common in calcrete and regolith carbonates and may be divided (e.g., Watts 1980) into three groups, although clear differentiation of them may not be always possible:

1. a component derived physically from the host soil/regolith materials;
2. an authigenic component, not closely related to calcrete formation, occurring as alteration products of the host materials and formed during general pedogenesis; and,
3. an authigenic component formed as part of the processes of calcrete formation.

The common clay minerals in soils and regolith, including illite, smectites, kaolinite and randomly interstratified clay minerals, have all been found in calcrete and regolith carbonates (e.g., Milnes and Hutton 1983, Wright and Tucker 1991, Dixon 1994). They are mostly formed during general processes of weathering and soil formation, and may not necessarily related to calcrete formation.

However, two other clay minerals, palygorskite (attapulgite) and sepiolite, which are not common in soil/regolith, commonly occur in calcrete and regolith carbonate. These magnesium-rich clay minerals are regarded by many (e.g., Watts 1980, Goudie 1983, Wright and Tucker 1991, Dixon 1994) as authigenic minerals closely related to the processes of regolith carbonate formation. Some palygorskite and sepiolite may have been inherited from calcareous sediments (e.g., Goudie 1983). However, most probably formed in magnesium-enriched soil water or groundwater, the result of preferential removal of Ca^{2+} due to precipitation of low-Mg calcite and/or from conversion of high-Mg calcite to low-Mg calcite (Watts 1980, Wright and Tucker 1991).

In Australia, the clay mineralogy of regolith carbonates appears to be related to their provenance. The dominant clay minerals are illite, kaolinite, smectite and interstratified clay minerals (Milnes and Hutton 1983, Phillips and Milnes 1988, Anand *et al.* 1997). However, palygorskite and sepiolite have also been found, and locally are the dominant clay minerals, e.g., at Tailem Bend, Monteith, Murray Bridge and Black Hill in South Australia (Hutton and Dixon 1981). The origin of these Mg-rich clay minerals was ascribed to Mg-rich sediments and weathered Mg-rich bedrock on which the regolith carbonate has developed (Hutton and Dixon 1981, Milnes and Hutton 1983). In Western Australia, palygorskite has also been found in regolith carbonates, particularly in samples rich in dolomite (Anand *et al.* 1997). Because of the restriction of dolomite and palygorskite to regolith overlying Mg-rich rocks in the Mt Gibson area, the source of Mg^{2+} for formation of the palygorskite is likely to be the bedrock (Anand *et al.* 1997). In central Australia, sepiolite and possibly also palygorskite have been found in regolith carbonates, particularly towards the lower parts of profiles, and their occurrence is again related to Mg-rich groundwater solutions (Arakel 1986b).

5.4 Other authigenic minerals

In addition to carbonate minerals and authigenic clay minerals, other authigenic minerals may also occur in calcretes and regolith carbonates. Authigenic silica and gypsum are the most common ones.

Authigenic silica

It has been noted by many authors (e.g., those reviewed by Goudie 1972b) that authigenic silica commonly occur in calcretes. Its origin was believed (e.g., Goudie 1972, Arakel *et al.* 1989) to be due to calcrete silicification, during which silica replaces calcite. Authigenic silica may occur at any ratio to carbonate minerals, forming a continuum from calcrete to siliceous calcrete, calcareous silcrete and to silcrete (Goudie 1972b). Authigenic silica commonly occurs as opaline silica and chalcedony, as cement infilling voids (Goudie 1972b, Watts 1980).

In Australia, authigenic silica occurs commonly in groundwater calcretes in Western Australia (e.g., Butt *et al.* 1977, Arakel *et al.* 1989) and central Australia (Arakel 1986b, 1991). In contrast, authigenic silica is rarely found in pedogenic calcretes. The minerals of the authigenic silica are dominantly opaline silica, chalcedony, opal-CT and rarely cryptocrystalline and fibrous quartz (Arakel *et al.* 1989). They occur in both the phreatic and vadose zones, but more commonly in the phreatic zone. They generally occur as void fillings and pore linings, indicating that the precipitation of authigenic silica post-dates calcrete formation (Arakel *et al.* 1989).

The chemical conditions and the processes of silicification are described in Section 3.3.

Gypsum

Gypsum ($CaSO_4.2H_2O$) is another relatively common authigenic mineral found in calcretes (e.g., Goudie 1972b), but typically in quantities less than 10% (Mann and Horwitz 1979). In some gypcretes of arid inland Australia, a small quantity of carbonate has also been found (e.g., Arakel 1991, Magee 1991, Chen 1997b).

Carbonate and gypsum are unlikely to precipitate simultaneously from solution because they have very different solubilities. Therefore, the gypsum in regolith carbonates and the carbonate in gypcrete are most likely to have originated from later replacement processes. In the central Namib Desert, replacement of carbonate by gypsum occurred in calcretes, probably due to offshore sulfurous eruptions and/or sulfate-rich fogs (Goudie 1972b). In Australia, the carbonate in gypcrete shows replacement features, such as voids-fillings, and generally occurs at or near surface landform positions (e.g., Magee 1991, Arakel 1991, Chen 1997b), indicating that rainwater is involved in the replacement of gypsum by carbonate.

5.5 Geochemical features

The geochemical compositions of calcrete and regolith carbonates reflect both their authigenic and host components, because the two cannot be easily and totally separated in the pre-treatment before analysis.

5.5.1 Major and minor elements

In Australia, most geochemical data for calcretes and regolith carbonates has been obtained from South Australia where the occurrence of calcretes is most common and abundant (Chapter 7).

Milnes and Hutton (1983) summarised the chemical compositions from more than 200 samples of calcretes and regolith carbonates in South Australia. The compositions of major elements are compiled and presented (Figure 5.1) as three groups: MgO, CaO, and acid insolubles (SiO_2, Al_2O_3 and Fe_2O_3). In general, these reflect the major mineral compositions. The Ca/Mg ratio indicates the relative amounts of calcite and dolomite, and the acid insolubles show the impurities in the calcretes and regolith carbonates, mainly quartz and aluminosilicates. Based on the chemical data, Milnes and Hutton (1983) recognised two distinct geochemical provinces of calcrete formation in South Australia: the Bridgewater Formation associated with Pleistocene coastal dune complexes and aeolianites, and a continental province with diverse bedrock (Figure 5.1). The Ca/Mg ratio in many regolith carbonate profiles of the continental province decreases downwards, indicating an increase of dolomite at depth (Milnes and Hutton 1983).

Dixon (1994) listed the major element chemistry of 36 typical calcrete samples from the Murray Basin and Yorke Peninsula of South Australia. The calcretes from Yorke Peninsula have higher CaO (ranging from 22.8% to 51.1%) and lower MgO (1.1% to 8.5%) than the calcretes from the Murray Basin (CaO 12.6% to 40.9%, and MgO 2.5% to 20.4%). As pointed out by Milnes and Hutton (1983) and Dixon (1994), there is considerable variability in the chemistry of regolith carbonates in South Australia. This is related to the location, underlying substrates, profile position, depth and the morphology of regolith carbonates.

There is relatively little published geochemical data for regolith carbonates from other parts of Australia, particularly for groundwater calcretes. Arakel (1986b) presented five major element analysis (Ca, Mg, Si, Al, and Fe) of groundwater calcretes from Lake Napperby area in central Australia. As for the pedogenic calcretes of South Australia, the Ca/Mg ratios are high in upper parts of the profiles (up to 15.7), indicating the dominant occurrence of low-Mg calcite (Arakel 1986b). However, Ca/Mg ratios decrease significantly downwards in the profiles, indicating the increase of dolomite and Mg-rich clay minerals at depth. Similar features have also been found in groundwater calcretes at Curtin Springs in central Australia and Wiluna area in Western Australia (Arakel *et al.* 1989). Geochemical data for a few samples from groundwater calcretes of Western Australia have been also reported by Mann and Deutscher (1978) and by Kern and Commander (1993), showing significant amounts of Mg (dolomite) in the regolith carbonates.

There is relatively very little published data for the minor element contents of regolith carbonates in both Australia and in the world. Milnes and Hutton (1983) listed data for Zn, Ti, Sr and Zr for more than 20 calcrete samples from South Australia. They illustrated and pointed out that minor elements were potential indicators of the provenance of detrital materials in regolith carbonates and may show the relationships of regolith carbonates and the host soil, sediments and underlying bedrock.

It should be noted that minor elements in calcretes and regolith carbonates have significant applications in mineral exploration. For example, uranium is concentrated to an economically significant level in some groundwater calcretes in Western Australia, and geochemical data on U in calcretes and grounders has been published by Butt *et al.* (1977), Mann and Deutscher (1978), Carlisle *et al.* (1978), and Butt (1988). Studies in Western Australia (e.g., Butt *et al.* 1991) and at Broken Hill in NSW (McQueen *et al.* 1999) provided both major and minor elements of some calcrete profiles and illustrated their implications for gold exploration. Unpublished geochemical data for both major and minor elements of regolith carbonates is held by mining companies. These data and the applications of calcrete geochemistry to mineral exploration are presented in Chapter 6.

5.5.2 Isotopes

The three most common carbonate minerals, calcite, aragonite and dolomite, are composed of the four light elements: carbon, oxygen, magnesium and calcium. All of these elements contain at least two stable isotopes that are relatively abundant (e.g., Degens 1965). Carbon has an isotope ^{14}C that is a radioactive tracer constituent with a half life of 5730+/-40 years.

Stable isotopes in regolith carbonates are mainly studied for purposes of interpreting palaeo-environments and identifying the sources of the carbonates (e.g., Milnes and Hutton 1983, Wright and Tucker 1991). The stable isotopes of Ca (^{40}Ca and ^{48}Ca) and Mg (^{24}Mg and ^{26}Mg) are much less studied than those of carbon and oxygen, because they have much less variation in various natural systems (e.g., Degens 1965).

Stable carbon isotopes

The terrestrial ratio of the two stable carbonate isotopes ^{12}C and ^{13}C is about 90 to 1 (e.g., Rosler and Lange 1972). However, this ratio varies significantly in water, air, plants and carbonate rocks as a result of fractionation. The most significant fractionation occurs during the photosynthesis of plants, resulting in an enrichment of ^{12}C and a depletion of ^{13}C in the plant bodies. However, the magnitude of this fractionation depends on the plant species (e.g., Bradley 1985).

The concentration of ^{13}C in a sample is commonly expressed as δ^{13}C:

$$\delta^{13}C = (R/Rs - 1) * 1000$$

where: $R = {}^{13}C / {}^{12}C$ ratio in the sample,
$Rs = {}^{13}C / {}^{12}C$ ratio in the standard (the PDB Chicago belemnite standard)

Terrestrial plants have very low δ^{13}C values (Table 5.2). Ocean water and marine limestone have similar δ^{13}C values and are much higher than those of terrestrial plants (Table 5.2). Both surface water and groundwater on land have a wide range in δ^{13}C values (Table 5.2) because of the complex interplay between air, plants, groundwater and dissolved components (e.g., HCO_3^- from limestone).

Table 5.2. Selected δ^{13}C values in some natural systems (from Degens 1965). It should be noted that different δ^{13}C values have been reported from other sources, e.g., Rosler and Lange (1972).

Natural systems	δ^{13}C
Atmosphere	-10 to –7
Ocean water	-4 to +4
Marine limestone	-4 to +4
Terrestrial plants	-28 to –22
Fresh waters (surface and ground waters)	-18 to +3

The HCO_3^- to form regolith carbonates may come from biogenic CO_2 in soil air with low δ^{13}C values, or from dissolved limestone with relatively high δ^{13}C values. Therefore, the δ^{13}C values of regolith carbonates may be in a wide range. The more negative δ^{13}C values, e.g., as low as –10, may indicate high input from biogenic CO_2 in soils, and less negative or even positive values may reflect contamination from pre-existing carbonate in the substrates (e.g., Wright and Tucker 1991). However, there are many other factors that can influence the calcrete isotopic composition and make interpretations very difficult. These include elevation, latitude, temperature, the type and amount of vegetation cover, its seasonal activity, rainfall composition, the degree of evaporation, proximity of the sea, monsoonal effects and seasonal variation in rainfall isotopic composition, degree of contamination from pre-existing soil carbonate, and many others (Wright and Tucker 1991).

The $\delta^{13}C$ values of regolith carbonates from various sites in Australia range from –9.6 to +3.4 (Milne and Hutton 1983). Although some uncertainties exist, the $\delta^{13}C$ data suggests different sources of carbon, particularly marine and terrestrial sources (Milnes and Hutton 1983). However, there seem to no be regular relationships between $\delta^{13}C$ values, age and Ca/Mg ratios of regolith carbonates.

A study in South Australia and Victoria (Quade *et al.* 1995) showed that a marine source for some soil carbonates is insignificant, based on $\delta^{13}C$ values ranging between –11 and –8.7. Bowler and Polach (1971) found that the $\delta^{13}C$ values of carbonate in soils at six sites in Victoria are in a relatively small range of –8.9 to –2.3, despite variations in soil types, carbon sources, vegetation cover, climate and carbonate mineralogy. They suggested that the observed $\delta^{13}C$ values resulted from post-depositional fractionation processes in the calcretes which effectively masked any effects due to carbon source and primary pedogenic processes.

Jacobson *et al.* (1988) obtained $\delta^{13}C$ values, ranging from –7.05 to 4.33 without systematic variation with depth, from groundwater calcretes of central Australia. Compared with the $\delta^{13}C$ values of groundwater in the region (-8.6 to –7.2), they interpret that the $\delta^{13}C$ values of the calcretes are consistent with the precipitation of dissolved carbonate in groundwater.

Radiocarbon isotope (^{14}C)

The radioactive isotope of carbon, ^{14}C, has been studied thoroughly by many because of its applications in dating carbon-bearing materials. There is a huge accumulation of literature on ^{14}C and the dating method.

^{14}C is produced in the upper atmosphere by neutron bombardment of atmospheric nitrogen atoms. By various processes, such as assimilation, absorption and exchange at the air-water interface, ^{14}C can be incorporated into plants, animals and waters. Because of the relatively fast decay (half life of ^{14}C : 5730 years), ancient carbon-bearing rocks, e.g., most limestones, do not have any ^{14}C.

During deposition, regolith carbonate may incorporate some ^{14}C, leading to the possibility of dating the regolith carbonate if it is within the limit of the ^{14}C decay (about ten ^{14}C half-lives or about 50,000 years). However, two major processes may cause complexities and misleading ^{14}C ages for a regolith carbonate. Firstly, post-depositional pedogenic activities may input young/modern ^{14}C to an existing regolith carbonate, resulting in ^{14}C ages that are too young. Secondly, incorporation of old or radioactively dead carbon from groundwater with dissolved HCO_3^- from limestone may give ^{14}C ages that are too old.

Bowler and Polach (1971) obtained ^{14}C ages from pedogenic calcrete layers in Victoria and found that these ages were variably younger than the ages of the host sediments and some were even younger than the main phase of pedogenesis of the host soils. This was explained by carbon exchange with the atmosphere long after the initial segregation of the carbonates (Bowler and Polach 1971).

In the Lake Torrens area of South Australia, Williams and Polach (1969, 1971), on the other hand, obtained ^{14}C ages from regolith carbonates in paleosols which were significantly older than the coexisting organic carbon. They concluded that the pedogenic carbonate had not equilibrated with ^{14}C in the soil atmosphere at the time of its segregation but incorporated dead carbon from circulating groundwater.

Mann and Horwitz (1979) obtained three ^{14}C ages from a profile of groundwater calcrete on the Yilgarn Craton: 25 ka at 0.5 m depth, 36.5 ka at 3.5 m, and 21 ka at 5.5 m (1 m below watertable). Two possibilities were suggested and both included possible contamination with modern carbon, either from rainfall for the top sample or from recent groundwater for the sample below the watertable (Mann and Horwitz 1979). Therefore, these figures indicate the minimum ages of the original carbonate precipitation.

Ten ^{14}C ages of a profile of groundwater calcrete in central Australia (Chen and Polach 1986, Jacobson *et al.* 1988) vary irregularly, i.e., 27 ka for the surface sample, 16.6 ka at depth 6.8 m, 30 ka at 9.1 m, 17.1 ka at 10.7 m, and background ^{14}C concentration (or >40-50 ka) at depths 9.1 m and 11.1 m. This variation is significantly less systematic than the ESR ages obtained from same profile (Jacobson *et al.* 1988), showing complex contaminations possibly from both modern and dead carbon.

The above examples illustrate the uncertainties of using ^{14}C for dating regolith carbonates because of their vulnerability to contaminations from modern carbon and dead carbon. Great caution should be taken when interpreting ^{14}C ages for regolith carbonates.

Oxygen isotopes

Oxygen isotopes (^{16}O, ^{17}O and ^{18}O) have been intensively studied for their value in determining palaeo-temperatures. The method has been particularly successful in studies on global systems such as the ocean and the icecap in the Antarctica, mainly because the mechanism of fractionation of oxygen isotopes and the controlling environmental factors of these large systems are relatively simple and well known (e.g., Bradley 1985). Another major application of oxygen isotope studies is to identify the sources of sediments, because oxygen isotope compositions in some minerals can be used as a 'signature'. An example is the identification of the aeolian dust deposits on the Southern Tableland of southeastern Australia by using the oxygen isotope signature of quartz grains (Chartres *et al.* 1988).

However, studies on the oxygen isotopes of regolith carbonates are relatively rare, probably because of poorly understood, more complex influences due to various local factors on regolith carbonate formation. Despite this, there seems to be some general agreements between climatic regime and oxygen isotope composition of calcrete (Talma and Netterberg 1983, Wright and Tucker 1991, Dixon 1994).

There are very few studies of oxygen isotopic compositions of regolith carbonates in Australia. Jacobson *et al*. (1988) obtained some $\delta^{18}O$ values, ranging from –6.60 to –4.32, from a profile of groundwater calcrete in central Australia, comparable with those of the regional groundwater (-6.42 to –6.03), suggesting a groundwater origin for the calcrete (Jacobson *et al*. 1988).

Chapter 6

Calcrete sampling for mineral exploration

M. J. Lintern

6.1 Introduction

6.1.1 Background

Terminologies aside, there are basically two types of calcrete that have been used in mineral exploration: pedogenic and groundwater. In most of the case studies that follow, it is the pedogenic form, found in the top one or two meters of the soil profile, that is being discussed. In many of the case studies, the detailed morphology of the calcrete is not known and is, therefore, not described; however, where such information is available it is included in the site description. The calcrete types that have been sampled vary between powdery and nodular to more indurated forms such as laminar and boulder (massive) and this distinction is made where possible.

According to McGillis (1967), the use of calcrete as a geochemical guide to metal deposits may have begun in Russia during the late 1950s. However, its potential may have been recognised earlier by Cuyler (1930) who suggested Ca-rich (and other metals?) waters, rising under hydrostatic pressure, deposit calcrete in faulted areas. Outside of Russia, the value of calcrete as a specific geochemical sampling medium was not fully recognised until the early 1970s. One of the early records of calcrete as a geochemical sampling medium appears to have been in the Yilgarn Craton, WA (Western Australia) when it was investigated as a means to explore for Ni deposits. Initially, it was considered as a geochemical diluent (Mazzuchelli 1972) and other media such as the residual soils themselves were sampled instead or efforts were made to upgrade the metal content of samples by dissolving the calcrete away and analysing the residue, e.g. Garnett *et al.* (1982). However, Cox (1975) gave further consideration to its specific use when looking for Ni in the Kambalda area (Yilgarn Craton, WA). Other base metal studies in South Africa and Australia followed during the next decade, some of which are documented in the case studies that follow. Exploration companies, however, never systematically used calcrete as a sample medium of choice during these early years. As with many other geochemical techniques such as the collection of soil, rock chip or stream sediments, calcrete sampling has recently benefited from analytical laboratories providing low-cost, rapid chemical analyses with low detection limits.

Mineral deposits have been discovered directly as a result of their association with calcrete for centuries. Early mineral discoveries were often made by untrained people such as shepherds or farmers tending their herds and crops and finding evidence of mineralisation at the surface or in animal burrows and scrapes. Copper was one of the first metals found in this manner. Bright green Cu carbonate minerals, which visually contrast with the paler colours of the calcrete, were often the first indications of Cu mineralisation. For Au, the colour contrast with calcrete is not so marked but, nevertheless, according to anecdotal evidence from early mining documents, the lustre was conspicuous enough for the discovery of Au in "limestone cement", road base material and in the calcareous "soil" of the Eastern Goldfields of WA. Most of these early discoveries relate to the fortuitous presence of Cu or Au within calcrete rather than any specific or systematic exploration technique. If the soil in which the Au nuggets were found happened to contain calcrete then an association was documented in historical records irrespective of it being accidental. Furthermore, there are no known geological, chemical or physical reasons why Au nuggets should be found in calcrete, except that both Au and calcrete are found in the same surficial environment. Prospectors using metal detectors are just as likely to detect Au nuggets at the surface whether there is calcrete present or not. Conversely, calcrete does not always contain Au. Bright yellow and pale green U minerals in groundwater calcretes are another example of visually contrasting secondary mineralisation occurring in calcrete.

Calcrete had a major impact as a specific sample medium for Au exploration in Australia in the late 1980s until the present as a result of CSIRO and later CRC LEME research. In 1987, the CSIRO commenced a research project with a consortium of exploration companies through AMIRA (Australian Mineral Industries Research Association Ltd) to improve geological, geochemical and geophysical methods for mineral exploration that would facilitate the location of blind, concealed or deeply weathered Au deposits. In late 1987, the first detailed research on calcrete above a Au deposit commenced at Bounty (120 km S of Southern Cross, WA; Lintern 1989) with spectacular results! For the first time an economically important metal was demonstrated to be highly correlated (not merely associated) with Ca (calcrete); this was strong evidence indeed for the soluble and mobile nature of Au in the soil. The results showed not unexpectedly that Fe and many other elements had been diluted by the calcrete, consistent with the earlier base metal studies, and so were not correlated with Ca or Au. The correlation was widespread at the Bounty Deposit in soils which were typical of those found throughout the auriferous greenstones of the Eastern Goldfields of WA. Thus the potential for the widespread use of calcareous soil (calcrete) for exploration was enormous. In fact, results from further research and company exploration at several other deposits between 1988 and 1993 confirmed the relationship to be common in the southern Yilgarn and indicated that calcrete was a robust geochemical sample medium that could be used with confidence, pending certain important provisos.

Calcrete sampling reached a significant milestone as an exploration technique when its use was publicly acknowledged to have found the Challenger Gold Deposit (Gawler Craton, South Australia) in 1995. Subsequently, in a series of conference proceedings, company reports, magazine reviews and newspaper articles describing Au exploration on the Gawler Craton, calcrete was highlighted and recommended by many as the principal sampling technique to be used. Indeed, "calcrete" became a household word for mineral explorers in South Australia (SA). So why was it so vigourously acclaimed in SA rather than WA where it was first recognised? There appear to be several reasons for this:

1) Calcrete appears to be ubiquitous throughout much of the Gawler Craton, whereas it is mostly restricted to the SE portion of the Yilgarn.
2) In WA, other technologies and sampling media had been successful including ferruginous lag and lateritic residuum.
3) Calcrete is more prominent in SA (greater thicknesses, more indurated, and commonly highly visible on the surface) compared with WA where it is generally present in powdery forms and sub-surface; calcrete has been used as a housing, fencing and road-making material in SA. Blocks of calcrete have been piled up in many farm paddocks in SA as it is a hindrance to agriculture.
4) Calcrete found the first significant gold deposit (Challenger) in a new exploration province.
5) The confidential, industry-sponsored nature of CSIRO research on calcrete sampling initially stifled the dissemination of the technique beyond the borders of WA. In fact Mr K. Wills, then with Metana Metals (an AMIRA sponsor), is credited with applying the WA calcrete research to SA.

Interestingly, by the end of the 1990s, calcrete was being acclaimed as the sampling medium of choice in the Yilgarn Craton by a much wider audience of exploration companies than in the early 1990s, many of whom were not familiar with the earlier WA research, but had been convinced by the successes in SA. Clearly the technique has taken several years to filter through to the junior explorers even in the area where it was first recognised! As with many other geochemical sampling media, such as soil, rock chip or stream sediments, the popularity of calcrete has benefited from analytical laboratories providing low-cost, rapid chemical analyses with low detection limits. Calcrete has now gained a foothold in many other parts of the world for mineral exploration including North and South America, southern and northern Africa, and parts of the former USSR, and no doubt will increase in popularity as new discoveries are made with it.

6.1.2 Advantages and disadvantages of calcrete as a sampling medium

Calcrete has both advantages and disadvantages for mineral exploration as described by Butt (1992). The presence of calcrete may be advantageous to exploration in the following circumstances:

1) Calcrete may represent a pH contrast to underlying neutral to acid regolith and may cause the precipitation and concentration of mobilised metals, hence forming epigenetic anomalies.

2) The re-location of some of the Au to the calcareous horizons of soils appears to be primarily governed by the processes of meteoric water infiltration and evapotranspiration. This may give rise to or enhance a near-surface expression to concealed primary or secondary mineralisation.
3) Groundwater calcrete in particular may be the aquifer and host rock for the transport and precipitation of potentially economic U concentrations.
4) Calcrete represents a consistent, easily identified, sampling medium (generally corresponding to a B or illuvial horizon) for exploration purposes.

The principal disadvantages are:

1) Many pedogenic calcretes represent absolute additions to soils developed on pre-existing deep weathering profiles, which, in many instances, have been partly or almost fully truncated prior to soil and calcrete formation. The concentrations of many mobile elements associated with economic mineralisation may have been already reduced by leaching during the initial deep weathering and later pedogenesis, so that the addition of calcrete causes dilution and depresses anomaly contrasts still further. The replacement of primary and secondary minerals by carbonates may lead to the mobilisation and loss of some elements, including Pb and Zn.
2) The high pH prevailing in calcrete reduces chemical mobility of many elements (but, significantly, not complexed Au in the soil) and hence restricts the development of epigenetic anomalies.
3) The addition of calcrete acts as a diluent to other well-established sample media, e.g. laterite or skeletal soils developed on bedrock.
4) Calcrete may occur in different forms and/or positions in the soil profile representing different ages, stages of development or climatic episodes that may have different levels of metal concentration or dilution. For example, calcrete many metres thick might not be particularly useful as a sample medium nor would calcrete developed high in the profile of an aeolian dune.
5) The presence of non-pedogenic carbonates e.g. groundwater, that may be difficult to distinguish from pedogenic varieties, and do not have the Au association.

6.1.3 Regolith classification

With any geochemical sampling technique, knowledge of the regolith, geomorphology, style of mineralisation, geology, and present climate is crucial to the process of finding mineral deposits. This knowledge, in turn, guides us towards the most appropriate sample media to use, the grid size for sampling, the elements to be analysed and the choice of analytical technique. To assist the process, several sets of regolith classification models have been suggested to help provide a framework for stratigraphy, relief, climate and understanding landscape evolution. This approach has enabled particular exploration case histories to be "pigeon-holed" according to criteria determined for a particular model to facilitate our understanding and to make valid comparisons between case histories. One of the more useful models for (sub-) tropical terrains has been proposed by Butt and Zeegers (1992) who broadly divided the regolith into three Types (A, B and C) based on the degree of preservation of the "complete" weathering profile. A complete weathering profile is one that has saprock, saprolite, mottled zone, soil and a lateritic duricrust. These types were further divided according to modifications of the pre-existing profile, e.g. alteration, or the presence of calcrete, gypsum, silica and/or transported material. Type A models are those in which the profile is complete i.e. fully preserved. The uppermost residual horizon is commonly lateritic duricrust, or soils developed over or from it. Type B models are those in which the profile is partially truncated by erosion (lateritic duricrust absent), so saprolite with quite different geochemical characteristics from the ferruginous horizon forms the uppermost horizon and the parent material of residual soils. Type C models are those in which the earlier regolith has been entirely eroded and bedrock is either buried by transported overburden, outcrops at surface or has thin or skeletal residual soils forming directly from it. A simplified and modified version of this approach is used for the case histories presented below.

Although it has been widely recognised by mineral explorers that in deeply weathered terrains, the degree of regolith truncation (if any) and the presence of lateritic duricrust are important, insufficient emphasis has been placed on the importance of transported overburden. This is an important consideration that has ramifications for the type, interpretation and cost of a geochemical sampling programme, including those involving calcrete. Ideally, the depth and type of transported material should be known since this may have a bearing on the ability of metals to migrate vertically to the surface, but this is not always possible, particularly for regional soil surveys where drilling is limited. The presence of even a thin layer of transported material can have enormous effects on the use of calcrete as a sampling medium. Exploration companies have used two basic strategies to explore in regolith dominated by transported overburden.

The first approach has been to drill through the overburden and into the underlying bedrock (itself usually weathered and leached of elements of interest). This approach is expensive but low-risk and is commonly used on the prospect scale when there has already been one or more areas of mineralisation identified, and the odds are in favour of finding more of the same.

The second approach involves the collection of materials (including calcrete) at or near the surface, and is high risk, poorly understood and relies on the premise:

(i) that because the sediments are old and have undergone either diagenesis or post-depositional weathering, there has been time for pathfinder or target elements to migrate towards the surface;
(ii) that there is active dispersion of such elements (e.g., vapour phase), thereby revealing the presence of any buried mineralisation; and/or
(iii) that in cases where there is thin transported overburden, bioturbation can mix sediments and physically re-locate particles to the near-surface.

For Au, the surface expression of mineralisation through many tens of metres of transported overburden is the subject of much controversy. It has been apparently demonstrated by some explorers, doubted by many geochemists and believed by many others. The initial research undertaken by CSIRO and others suggested that calcrete developed in transported overburden appeared to accumulate Au (or reflect the geochemistry) of underlying mineralisation even where the combined overburden (both the transported component and leached saprolite) was up to 40 m thick. However, recent follow up work by CSIRO and CRC LEME shows that only in certain cases does surficial calcrete appear to be able to accumulate metal ions vertically transported, and only if the transported overburden is less than 10 m (Butt *et al.* 1997). However, more comprehensive case studies are required in this area.

To reflect the emphasis on the substantial effect transported overburden has on the exploration geochemistry of weathering mineral deposits, it is proposed to introduce a "T" Type model to the system suggested by Butt and Zeegers (Figure 6.1). Thus, the simplified and modified models of Butt and Zeegers (incorporating the lower pedolith and mottled zone in Type B, and ignoring the alteration and genetic themes) and the new Type T model can be summarised below:

Type T: transported overburden present.
Type A: weathered bedrock host with lateritic profile.
Type B: weathered bedrock host with no lateritic profile.
Type C: saprock-bedrock host with thin mainly residual soil.

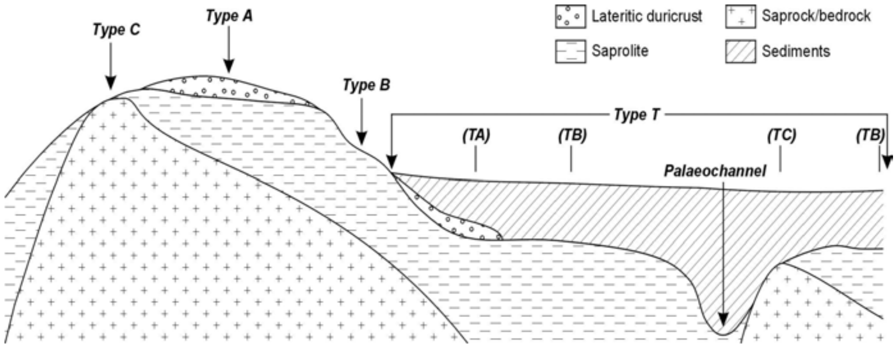


Figure 6.1: Schematic diagram showing regolith models. Type T: transported overburden present. Type A: weathered bedrock host with lateritic profile. Type B: weathered bedrock host with no lateritic horizon. Type C: saprock-bedrock host with thin mainly residual soil. Type TA, TB or TC refers to transported overburden lying over laterite, weathered bedrock or saprock-bedrock, respectively (if known).

This model system can be further modified. If transported overburden is overlying residual regolith then the annotation Type TA, TB or TC may be used; however, while this degree of detail may be important for general exploration, it does not appear necessary when discussing the use of calcrete as an exploration medium. The approximate depth of overburden, if known, is important and may be incorporated in the annotation such as Type T5 or T5-10, signifying the presence of 5 m or 5 to 10 m of overburden, respectively. This detailed nomenclature has not been included in the case studies below because of insufficient data.

6.1.4 Paleochannels

A special case of transported overburden is the palaeochannel, which is a feature of the Australian continent, particularly in the cratons, the Tasmanian Fold Belt and their margins. They have formed partly as a result of deep weathering, tectonic stability and long periods of humid followed by dry climatic conditions. In Australia, many of the palaeochannels are probably of mid-Eocene age and have been filled with fluvial and lacustrine sediments of Cainozoic age. Their presence is not easily detected and the course they follow is commonly poorly defined, even after drilling. They are of particular importance in the southern Yilgarn Craton (WA) where they have been shown to host, or be related to, significant Au mineralisation, commonly within the basal sands or in underlying saprolite. They present a special problem for exploration because barren sedimentary units, 15 to over 50 m thick, usually conceal them. Nevertheless, surficial anomalies have been reported by exploration companies directly above buried mineralisation in some locations, often associated with calcrete. In many cases, the immediate origin of the mineralisation in the palaeochannel has not been determined. Locally, sub-economic mineralisation occurs within the palaeochannel sediments but the highest grades seem to occur at the unconformity between the basal sands and the underlying weathered units. In addition, high-grade mineralisation has been identified below the unconformity, but even this appears to follow the course of the palaeochannel probably following structural features in the bedrock.

6.1.5 Regolith history

Calcrete is an overprint or secondary accumulation on an existing profile. The particular geochemical signature of calcrete may therefore be largely dependent on the original geochemical signature of the host material (i.e. transported overburden, weathered or fresh bedrock). A basic understanding of the geochemical processes and elemental distributions within the soil (pre-calcrete formation) is therefore desirable. Thin residual soils developed directly on partially weathered mineralised bedrock would be expected to produce strong geochemical anomalies in the surrounding soil. Residual soils developed on deeply weathered and leached rocks are more complex. For Au in a Type A weathering profile, a pre-existing enrichment of Au in the lateritic duricrust would be expected. If there is no duricrust present (Type B), then the geochemistry may be more complex and may require information on, for example, the degree of stripping and/or leaching, development of supergene deposits at relict water tables or redox fronts, presence of relict auriferous quartz veins or other partially-weathered rock clasts; the reader is referred to Butt and Zeegers (1992) for a full discussion of these points. Gold is unusual, as the case histories will demonstrate, in that there is usually a strong relative accumulation of the metal, derived from the original host material, in the calcrete.

In its weakest or youngest expression, calcrete occurs as fine powdery accumulations or coatings of pedogenic carbonate that maybe indistinguishable from the host regolith except with the aid of acid. In these situations, the tenor of the host regolith geochemistry imposed on the calcrete appears to be strongest. Progressively, calcrete will replace and displace host materials until the original regolith host or even bedrock becomes unrecognisable. Ultimately, as the calcrete develops into a separate component of the regolith, the influence of the host regolith geochemistry becomes gradually diminished or lost entirely, so that the uppermost calcrete in a profile will mostly reflect the geochemical signatures of underlying calcrete layers rather than the original host. For example, the Bridgewater Formation is a sequence of Quaternary aeolian sediments (calcarenites) found on the coastlines of Southern Australia. It unconformably overlies rocks of Proterozoic and Archaean age and can reach up to 200 m in thickness; in such circumstances, it is extremely unlikely to reflect at its surface the characteristics of these older rocks.

6.1.6 Landforms

The type of landform, relief or topography can have a series of complex effects on the dispersion of geochemical anomalies in the soil whether they be chemically (hydromorphic) or clastically (mechanically) controlled (Figure 6.2). In this respect, calcrete behaves no differently from other soil components. Calcrete, however, is an unusual sample medium as it can be either readily dissolved and/or mechanically transported as dust, nodules, pisoliths or fragments. For Au, it appears that calcrete provides a host for both (i) hydromorphically-mobilised forms probably occurring as organic ligands, and (ii) mechanically-mobilised Au particles of various size ranges ((m to cm) that become re-located within the re-mobilised Ca. Thus Au anomalies in calcrete may be found in a variety of landscape positions relative to the ore body source.

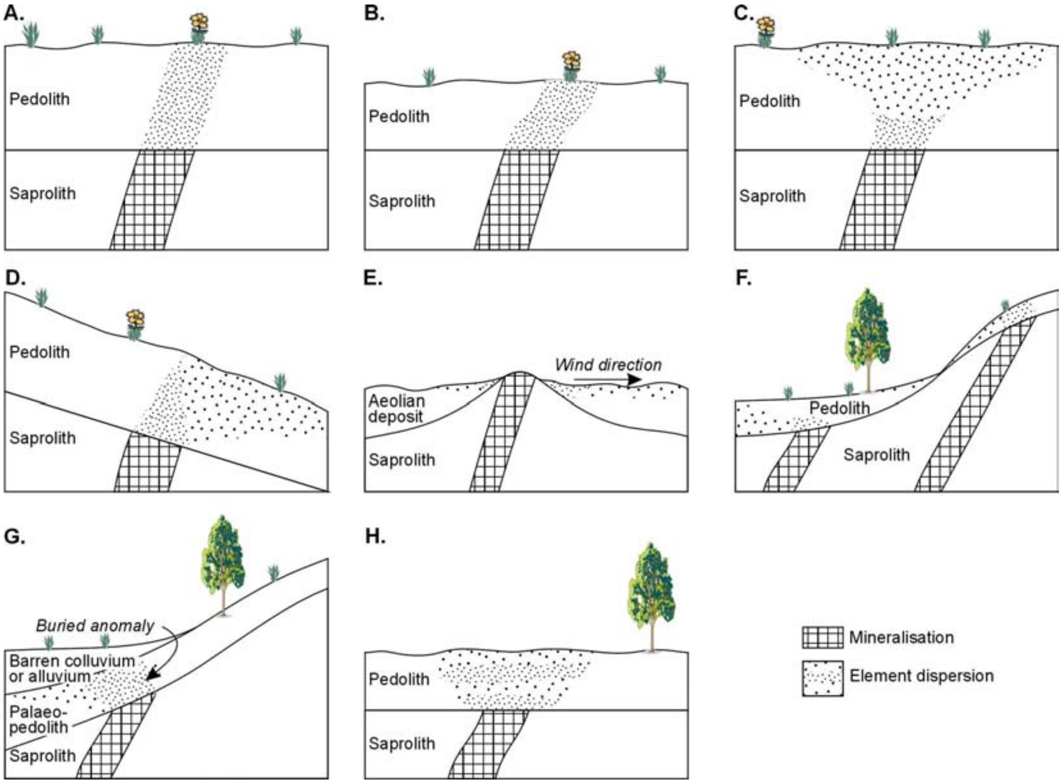


Figure 6.2: Schematic diagrams showing mechanisms for chemical and mechanical dispersion into calcrete (modified from Joyce 1984, pp 48-51). A) Residual clastic dispersion. B) Residual clastic dispersion pattern displaced by eluviation. C) Residual clastic dispersion enlarged by physical/biological mixing. D) As for C but displaced by soil creep. E) Aeolian clastic dispersion. F) Clastic and chemical dispersion down slope. G) As for F but further complicated by presence of transported overburden. H) Chemical dispersion due to upward movement of soil moisture during dry periods.

Sand dunes present some of the most difficult environments for the application of geochemistry. The presence of calcrete within sand dunes and aeolian sand sheets is evidence of the mobile nature of carbonate within the landscape during the Quaternary. In simplistic terms, the calcrete forms and, with vegetation, serves to partly-stabilise the dunes during wetter climatic periods, but becomes exposed and begins to fragment (physically weather) during drier periods. Importantly, the exhumed calcrete may then be re-located down slope to swale areas. However, in either the dune or swale, surficial calcrete is likely to be of limited use as a geochemical indicator of underlying rocks as it has relatively little time to acquire any possible signature (including mineralisation) from the underlying rock. However, the calcrete found *at depth* within the swale soil sequence is a more effective sample since it is more likely to reflect the geochemistry of the underlying rocks, e.g., through capillarity and bioturbation. Obviously, other techniques such as sieving to remove aeolian sand are beneficial in "upgrading" the calcrete sample. A related problem is that caused by relief inversion (Figure 6.3). Differential erosion of calcareous material and overlying soil and alluvial layers exposes harder calcrete layers (laminar, massive and breccia forms) that are more resistant. These in turn become topographic highs and their eventual dismantling leads to mechanical movement of calcrete down slope from breakaways.

6.1.7 Biota

The role of biota in the re-cycling of elements such as Cu, Au and Ca at the surface is confirmed by the presence of these elements in plant tissues, although the magnitude of the role in the Au-calcrete association is possibly only minor. Elements are absorbed via roots, enter the plant tissue, and are ultimately returned to the soil surface as plant litter. In the solum, biological processes take place involving the conversion of plant litter into an enormous variety of organic and inorganic compounds through the action of soil invertebrates, fungi, bacteria and other microorganisms. The biochemical processes involved in the conversion of metallic organic and inorganic complexes from plant litter into those that reside in the soil is poorly understood mainly due to the low concentrations involved.

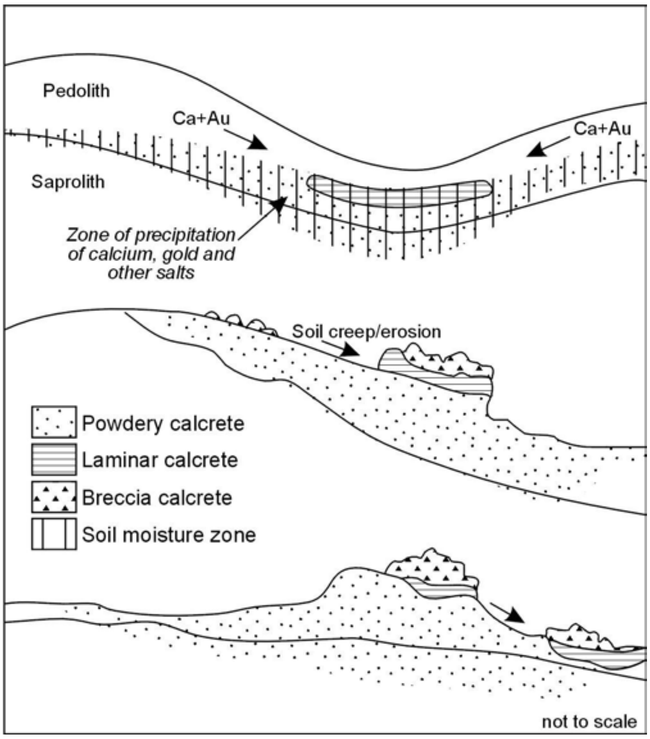


Figure 6.3: Relief inversion through calcrete formation (after Arakel 1995).

Gold is possibly mobilised in soil solution as an organic complex and deposited as an evaporite in this complexed form, with the calcrete. It has been speculated that Au and other elements of economic interest have been brought to the surface from great depths by root systems, thereby providing a mechanism by which anomalies can form in soils developed in transported material. There is no doubt that plants, particularly trees, have extensive root systems particularly in dry areas. However, at least for Au in the Eastern Goldfields (WA), strong evidence for the role of plants translocating material from depth to the surface is lacking: (i) the absence of long (greater than 15 m) vertical roots within open cut mines, (ii) the presence of highly saline ground water unsuitable for plant growth, and (iii) the generally poor correlation between concentrations of Au found in vegetation, soil and underlying mineralisation.

6.2 Case studies

6.2.1 Introduction

The case studies that follow have been derived from research conducted by CSIRO Exploration and Mining, CRC LEME, industry and universities, and were reported in academic journals (particularly the Journal of Geochemical Exploration), reviews in published texts, books and company reports. As can be seen from Figure 6.4, many of the case studies originate from WA, an area dominated by deeply weathered terrains, and most familiar to the author. The emphasis is primarily on Au but other commodities have been included where information is available. Only brief descriptions of the case studies are provided and the reader is referred to the original reference for complete description and discussions. The regolith profiles have been described as Type A, Type B (based on Butt and Zeegers, 1992) and the new Type T in accordance with the arguments presented above; Type T case studies are described in order of increasing depth of transported overburden. No Type C (fully truncated profile or bedrock) case study samples involving calcrete has been described in the literature. In reality, regolith profiles are usually complex and many of the deposits and prospects described in the case studies have examples of more than one type of regolith. Many gold and base metal anomalies in calcrete are now being found throughout Australia forming the basis for further case studies. This will help further refine the models and improve understanding of the processes of formation of geochemical anomalies.

6.2.2 The Menzies Line

The Menzies Line is an important environmenal and geological boundary relating to the distribution of calcrete and hence exploration techniques in the Yilgarn Craton, WA. It is a narrow (~5-100 km) EW transitional zone, stretching across the southern Yilgarn Craton where there are marked changes in soil types, vegetation associations and groundwater quality (Butt *et al.* 1977; Figure 6.4). The changes are

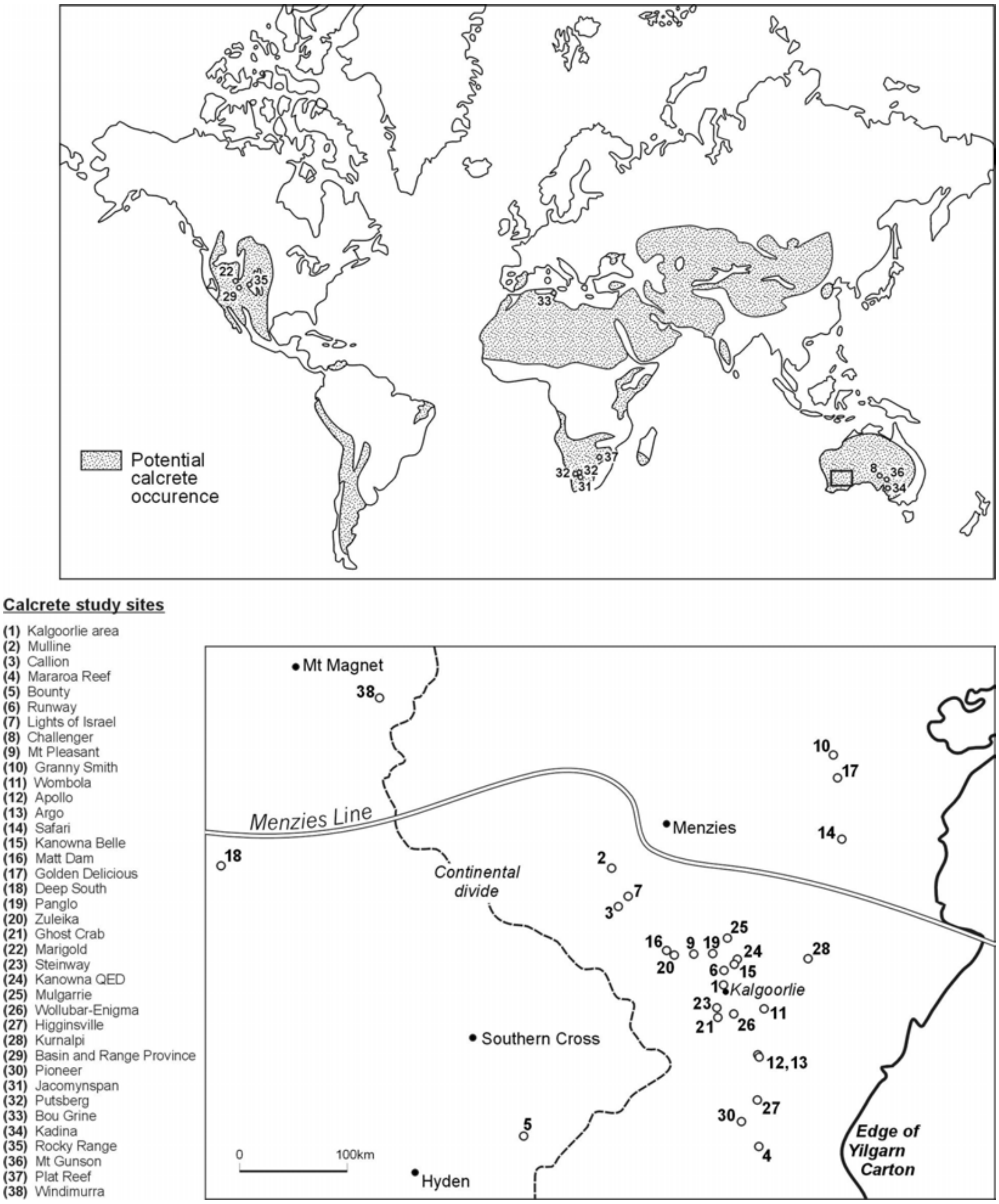


Figure 6.4: Location of case studies and the Western Australian Menzies Line. Australian calcrete distribution map from D.J. Gray (CSIRO, July 2001, written communication) derived from Northcote *et al.* (1975). South Africa calcrete distribution after Netterburg (1971). World distribution of arid and semi-arid terrains after Dregne (1983).

probably a response to climatic factors, although the sharpness with which the changes occur is more abrupt than any climatic gradient. South of the Menzies Line, soils are predominantly neutral to alkaline, orange to red loams, with extensive development of pedogenic calcrete. Non-calcareous earthy sand soils occupy high landscape positions, principally over granitic rocks. Groundwaters tend to be saline, neutral to acid. Average annual rainfall generally exceeds 225 mm, mainly in winter; annual evaporation is less than 2500 mm and the annual mean temperature is less than 19^{o}C. Vegetation immediately S of the Line is typical of that within the Coolgardie Botanical District, comprising woodlands of mixed eucalypts, especially salmon and gimlet gums (*Eucalyptus salmonophloia* and *E. salubris*) and shrublands of mulga (*Acacia*), *Grevillea*, mallee (*Eucalyptus*) and sheoak (*Casuarina*). North of the Menzies Line, soils are predominantly neutral to acid, red, non-calcareous earths, sands and lithosols, with extensive development of red-brown siliceous hardpans. Groundwater (or valley) calcretes are common in major drainages. Groundwaters are less saline than in the S, and are neutral to alkaline. Annual rainfall is generally less than 225 mm, falling mainly in the summer, with annual evaporation exceeding 2500 mm and annual mean temperatures exceeding 19^{o}C. The vegetation is typical of that found within the Austin Botanical District, comprising shrublands dominated by mulga, with eucalypts, such as the river red gum (*E. camaldulensis*) common only along water courses and some valley calcretes.

6.2.3 Gold case studies

6.2.3.1 Lateritic residuum host (Type A)

The presence of calcrete in lateritic residuum-capped weathering profiles has not often been described. It occurs in Mauritania (Nahon *et al.* 1977) and southern Australia (Anand *et al.* 1989, Anand *et al.* 1997), and is probably present in equivalent regions elsewhere. The paucity of data may be due to lateritic residuum, formed during humid climates, being already modified or destroyed by calcrete during an arid phase. Continued calcrete accumulation is a strong factor involved in the destruction of indurated lateritic horizons both physically, by growth of carbonate segregations, and chemically, by replacement of existing minerals. The calcrete, containing lateritic residuum, forms a fragmentary surface horizon or calcareous soil subject to erosion and mechanical dispersion. Lateritic residuum and calcrete can co-exist but there are many instances where its presence and associated soil appear to restrict the accumulation of the alkaline earths, possibly due to the acidic nature of the ferruginous material. Thus, we may have a landscape where lateritic residuum is present in a soil devoid of calcrete adjacent to a soil containing calcrete but no lateritic residuum. This can present particular problems for interpretation of geochemical sampling data. In such terrains, it is recommended that Fe and Ca are routinely analysed as part of the analytical suite.

(1) Kalgoorlie area, WA. (Mazzucchelli and James 1966, Butt and Zeegers 1992)
Carbonate dilutes the concentration of many elements in the soil profile especially those retained or concentrated in Fe oxides, including certain pathfinders (chalcophiles, siderophiles) for Au mineralisation, and, consequently, it has been avoided during sampling programs. In the Kalgoorlie region (WA), Mazzucchelli and James (1966), exploring for Au mineralisation, found that As is concentrated in lateritic fragments (220 ppm) compared to calcrete (40 ppm). Arsenic anomalies can be enhanced by preferentially sampling either the surface ironstone fragments (lag), mostly free of carbonate coatings, or the coarse (>840µm) soil fraction, in which these fragments are most concentrated; whole samples or the <175µm fraction are diluted by calcrete (Figure 6.5).

The surface fragments also give a wider anomaly, due to dispersion by sheetwash, as is the case for pisoliths and lags.

(2) Mulline, WA. (Lintern and Butt 1991)
The Peach Tree Gold Prospect is situated in the Mulline area, approximately 50 km W of Menzies and about 140 km NW of Kalgoorlie (WA). The Mulline township (now abandoned) is located near Peach Tree and close to the site of an underground Au deposit mined earlier in the century. The deposit occurs in basalt and hornblende-schist zones with mineralisation controlled by quartz veining and shears. Alteration of the primary deposit includes silicification and the formation of hydromica. Minerals associated with Au include pyrite, galena, sphalerite and chalcopyrite. Production figures reported were 4.2 tonnes of Au, mined from a grade of 25.3 g/t (Geological Survey 1990). The region is characterised by the local preservation of complete lateritic regolith profiles, especially over mafic rocks. Gold and Fe are enriched in lateritic gravels and duricrusts, and along sub-surface redox boundaries, over primary mineralisation and form small Au deposits. One such deposit (Peach Tree)

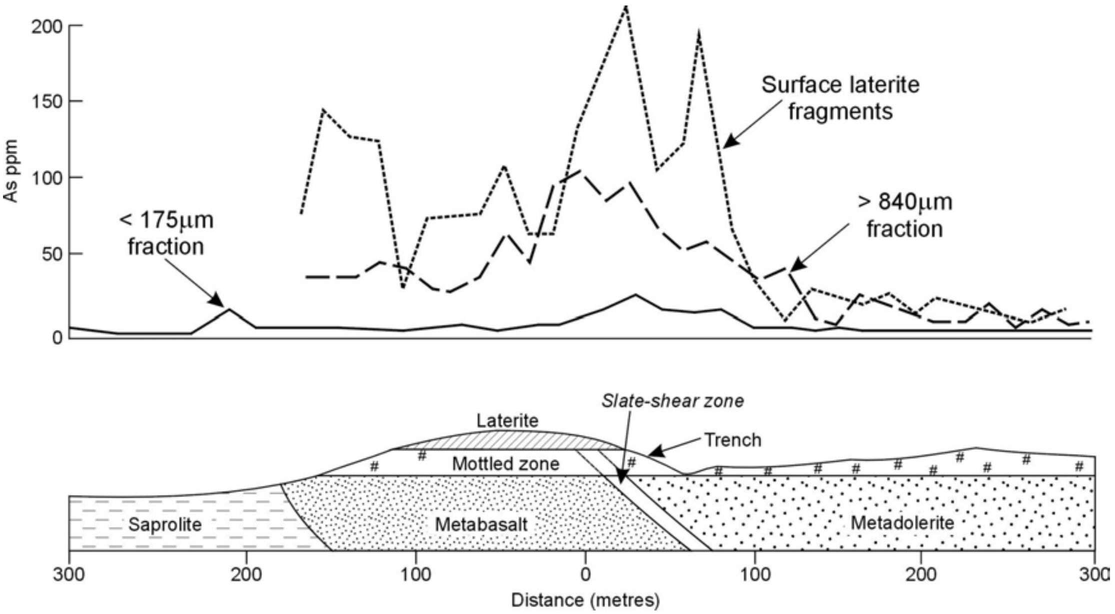


Figure 6.5: Lateral dispersion of As in laterite (surface ironstone fragments), coarse soil and fine soil fractions (modified after Butt 1992, Mazzucchelli and James 1966).

was investigated (Lintern and Butt 1991). The thickness of the deposit (with grades >0.5 ppm Au), and the locations of drill traverses and trench profiles are illustrated in Figure 6.6A.

Mulline is situated just S of the Menzies Line. The soils are alkaline, with strong development of pedogenic carbonates invading the pre-existing lateritic gravels; the vegetation is an open eucalypt woodland (predominantly *E. salmonophloia*) with a sparse shrubby understorey of *Acacia* and *Melaleuca*. The area is thus fairly typical of conditions S of the Menzies Line. Locally, however, the soils and vegetation relate closely to the geological setting; eucalypt woodlands are present mainly on the mafic rocks of the greenstone belts and pedogenic calcretes only appear to be abundant close to specific source units. Indeed, the Menzies Line here extends unusually far N, following the Davyhurst-Mt. Ida greenstone belt to beyond Bottle Creek, 65 km to the N.

Sampling sites were selected from data supplied by Pancontinental Mining Ltd. A trench exposed the top 1 to 2 m of the regolith, and several profiles were sampled (Figure 6.6B). Profiles were sampled by vertical channel sampling from the surface to the base of the trench. Deeper samples were collected by sub-sampling drill cuttings from two grid lines on traverses that extended from mineralisation to background zones low in Au. Adjacent traverses were selected (25 m apart) to examine differences due to sub-sample or spatial inhomogeneities. Samples were taken from bagged RC cuttings for depths of 0-1 m and 3-4 m.

A typical soil profile at Mulline is described below:

0-0.4 m	Red calcareous clay-rich loam with Fe oxide and calcrete pisoliths and nodules
0.4-0.6 m	Orange loam with Fe oxide pisoliths and calcrete nodules. Some calcrete nodules enclose Fe oxide-rich pisoliths
0.6-0.95 m	Similar to 0.4-0.6 m; Fe oxide-rich pisoliths more abundant
0.95-1.2 m	Pseudo-bedded calcretes enclosing Fe oxide-rich pisoliths
1.2-1.5 m	Fe oxide-rich pisoliths with some calcrete layers

Lateritic gravels and duricrusts host the Au mineralisation at Peach Tree prospect and contain pedogenic carbonate in their upper 2 m. The zone of Au enrichment (as shown by the isopachs in Figure 6.6A) trends approximately EW and has well-defined southern and western boundaries that parallel the occurrence of the lateritic materials. Thus, to the S, soils are developed directly from saprolite, with little or no lateritic gravel, and to the W there are outcrops of fresh rock. From the S in particular, the lateritic materials are seen to form a low mound with an EW trend. The shallow N-S trench cut in the centre of the anomaly shows that carbonates are abundant in the near-surface horizons. A massive "bar" of calcrete cross-cuts the trench, striking approximately EW along the axis of the Au

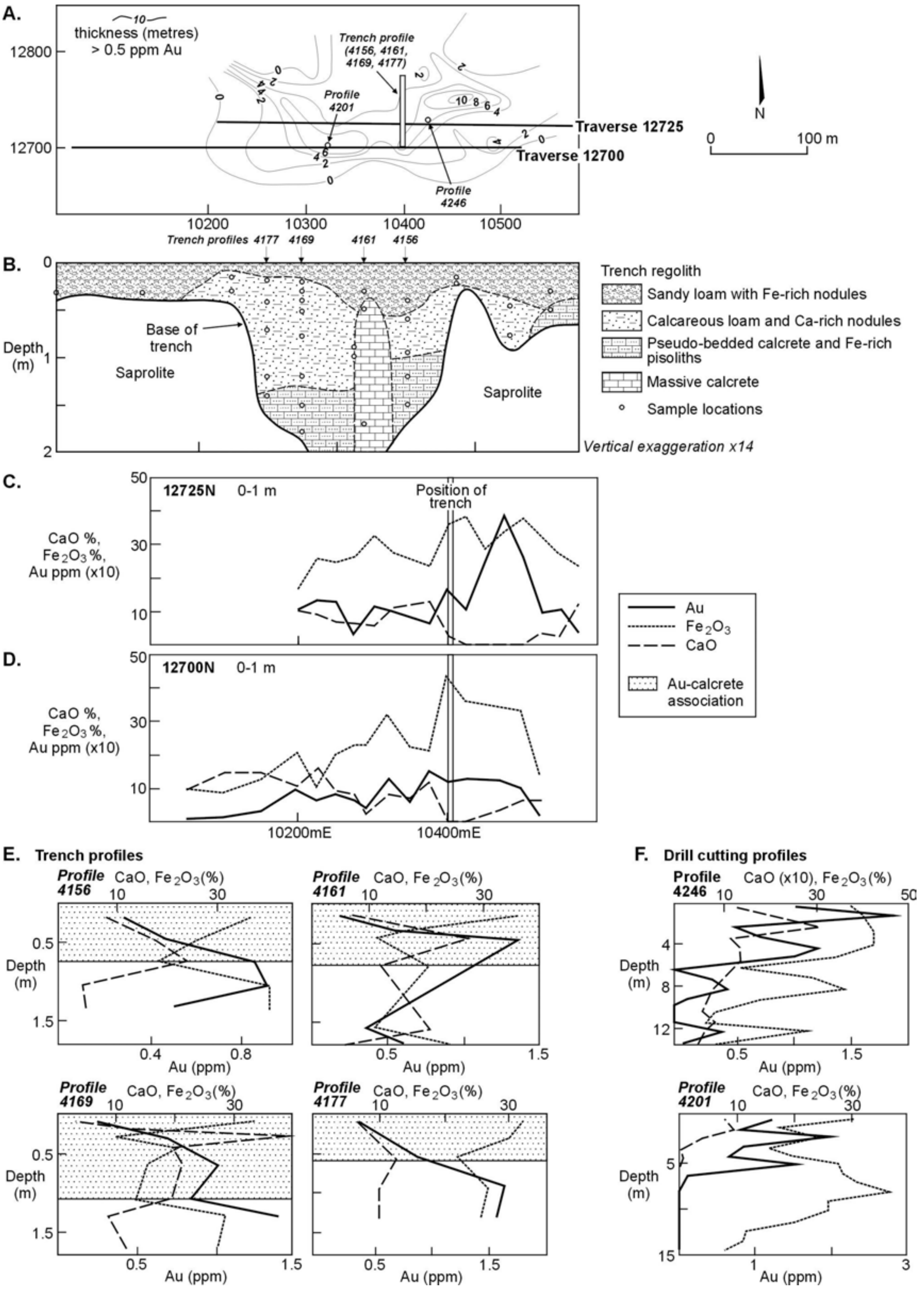


Figure 6.6: Geochemistry and regolith stratigraphy at Peach Tree, Mulline (WA). A) Plan showing location of traverses, trench and Au anomaly in ferruginous material. B) Section through trench showing regolith facies. C), D) Geochemical traverses of 0-1 m material taken from drill cuttings. E) Geochemistry of selected profiles taken from trench. F) Deeper geochemical profiles taken from drill cuttings from two holes.

anomaly. The amount of carbonate enrichment appears to decrease away from this bar and the lateritic gravels, exposed at the S end of the trench and nearby drill holes, are carbonate-free. It appears that the primary source of the Au has an EW strike, parallel to lineaments interpreted from aerial photography. This source may be related to the carbonate bar exposed in the trench. Indeed, the bar may also reflect a Ca-rich rock (e.g. carbonate alteration) and hence represent the local source unit for much of the pedogenic carbonate. Similar massive calcrete about mineralisation is found at Callion (see below; Glasson *et al.* 1988) and other prospects. Gold is present in both carbonate-rich and Fe oxide-rich soils and gravels and there are no simple correlations between Au concentrations and their abundances (Figure 6.6C-E). Thus, in some samples, the ferruginous pisoliths contain 1.5-3.0 ppm Au whereas the associated calcrete contains 0.7-1.5 ppm Au. The carbonates possibly dilute the initial Au content of the lateritic materials but have themselves been Au-enriched. The association between Au and Ca is strongest in the top 0.5-1.0 m, where carbonates are more abundant and occur as coatings and within the soil matrix. Deeper in the profile, where carbonate does not occur, there is a clear association of Au with Fe peaking at a series of old redox boundaries (Figure 6.6F).

(3) Callion, WA. (Glasson *et al.* 1988; Butt 1992)
Callion is a now abandoned mining centre 100 km NNW of Kalgoorlie (WA) which was worked intermittently between 1899 and 1956. Gold occurs in quartz-filled shear zones within a sequence of metamorphosed (amphibolite facies) basalts, interflow sedimentary rocks and acid tuffs within the Archaean Wiluna-Norseman greenstone belt (Glasson *et al.* 1988). The area has a subdued relief with low laterite-covered hills rising to a maximum of 20 m above colluvial-alluvial plains. Weathering commonly extends to depths of 40-60 m and, where it has not been eroded on the hills of metabasaltic rocks, the profile consists of:

1) red brown clay loam soil, up to 0.3 m thick;
2) coarse pisolitic laterite, 1.0-3.0 m thick, with pisoliths to 50 mm diameter, commonly including a pedogenic calcrete horizon;
3) mottled zone, with ferruginous nodules and fragments in a kaolinitic and commonly silicified matrix;
4) saprolite, bleached and kaolinitic in the upper 10-20 m and passing downwards to yellow to red-brown and pale green clays, probably smectitic in part.

A soil sampling survey on parallel traverses across each of the thirteen laterite-covered hills on the tenements was undertaken (Figure 6.7A). One kg samples of soil and pisoliths were collected at 50 m intervals. Two adjacent samples on the first traverse were highly anomalous (530 and 350 ppb Au) compared to the background of 60 ppb Au. A detailed soil survey on a 25 x 50 m grid outlined a 200 x 600 m anomaly, defined by the 100 ppb contour, and parallel to the N-S structural trend. The 1000 ppb contour of the anomaly, 70 x 340 m in size, defines the lower cut-off grade of the small lateritic Au deposit. This deposit was outlined by drilling to the base of the mottled zone (5 to 10 m) on a 25 x 25 m grid, locally infilled at 12.5 m intervals (Figure 6.7B). Reserves were estimated to be 71000 t at 2.0 g/t, with an average thickness of 3 m. Gold occurs as the free metal, associated mostly with Fe oxides, and includes some clearly secondary forms. The highest concentration of Au (16.1 ppm) was associated with the inferred position of Au-rich quartz veining and massive pedogenic calcrete, (exposed in a trench) near the centre of the anomaly (Figure 6.7C). In general, the Au contents of the soils were about 50% of those of the underlying laterite deposit, probably due to dilution (e.g. by transported clays and sand). The coincident distributions of Au, As and, to a lesser extent, Pb in soils reflects the occurrence of arsenopyrite and galena in the primary mineralisation.

Subsequent drilling resulted in the discovery of the primary mineralisation underlying the soil anomaly and lateritic deposit. A quartz-veined shear was located by deep diamond drilling after initial drilling to 30 m depth had been unsuccessful. Thereafter, drilling on 25 m centres proved a saprolite resource of 104,000 t at 7.9 g/t Au using a 2 g/t lower cut-off. The 3 m wide ore zone was found to occur over a strike length of 300 m and to extend to the base of weathering at 60-70 m. According to Butt (1992), although the deposit is very small, the Au distribution illustrates many of the features typical of supergene Au deposits in semiarid lateritic terrains:

1) There is a "mushroom-like" dispersion of Au into the mottled and pisolitic horizons of the profile.
2) Gold is largely depleted between 3 and 9 m in the upper saprolite.
3) Gold in the saprolite is more or less confined to the shear, with some very high values (e.g. up to 54 g/t) suggesting enrichment, possibly at an old water-table level. However, as the primary mineralisation is vertically zoned and is poorly developed in the unweathered zone despite the continuation of the shear, the degree of enrichment cannot be estimated.
4) There is an increase in Au fineness towards the surface, from 81% below 40 m to 92% above.
5) Secondary forms of Au, including crystals, are present in the lateritic horizon.

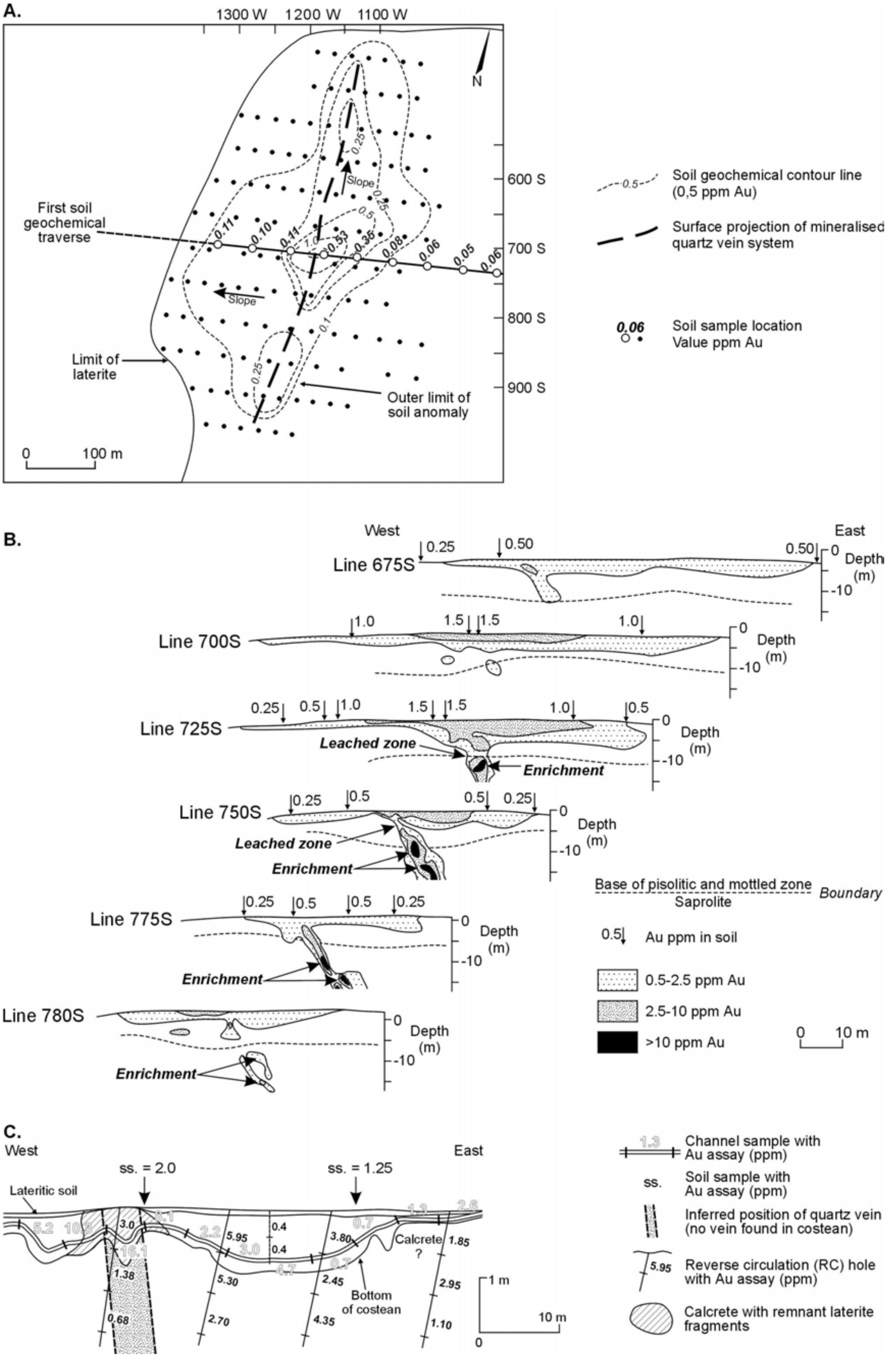


Figure 6.7: Geochemistry of the Callion Gold Deposit (after Butt 1992, Glasson *et al.* 1988). A) Plan of Au anomaly and location of soil traverses. B) Sections through the main ore body showing dispersion of Au to form an anomaly in the calcrete. C) Section through trench over main ore shoot.

Although dispersion processes generally dilute the tenor of anomalies, Au concentrations in calcrete associated with lateritic residuum at Callion are still high enough to assist exploration by providing a larger target.

6.2.3.2 Pedolith or saprolith host (Type B)

These examples include sites where there are thin (<2 m thick) predominantly residual soils developed directly on mottled zone, saprolite or above saprock where lateritic residuum (if ever developed) is not present.

(4) Mararoa Reef, Norseman, WA. (Smith and Keele 1984, Butt 1992)
The effects of dilution by calcrete, sand or clastic material (aeolian or colluvial) may be reduced by data manipulation. For example, analytical data for As may be adjusted according to variations in Fe content because As is generally concentrated in ferruginous material. At Norseman, WA, As- and Au-bearing quartz reefs occur in shear zones cross-cutting an Archaean greenstone belt. Smith and Keele (1984) showed that the geochemical expression of known mineralisation could be distinguished in the calcrete-rich surface (0-1 m) horizon by normalising As data with respect to Fe (Figure 6.8A). However, such normalisation may be neither applicable nor necessary if As dispersion is still active, for in calcareous soils, it may be trapped by carbonates rather than Fe oxides (Frick 1985). At Mararoa, Au is concentrated in surficial material (probably calcareous, see Figure 6.8B), with maximum values (>30 ppb) directly over the mineralisation itself, rather than over the barren subcrop of the shear, so there is actually no need to sample the ferruginous material for As (Figure 6.8A). Smith and Keele (1984) recommend that samples should be taken from a common horizon of in situ material below the highly calcareous horizon; this may be appropriate for collecting Fe-rich material for As determination but is in contrast to other work from this area (e.g Higginsville case study) that indicates it is the carbonate horizon that should be sampled and analysed for Au.

(5) Bounty, Southern Cross, WA. (Lintern 1989, Lintern *et al.* 1990)
The first study ever to demonstrate the strong correlation between Au and carbonate was commenced at the Bounty Gold Mine area in 1988, prior to mining activity. The Bounty Gold Mine is located about 440 km E of Perth (WA). The major landform of the area is a series of undulating plains averaging about 440 m ASL with about 50 m of relief. The principal mineralised zone (Bounty Zone) is situated on the eastern flank of a broad gently sloping hill. Drainage is poor but generally E from the Bounty Zone to a broad valley about 400 m away, where it drains gently N and E for approximately 10 km into a salt lake system. The climate is semi-arid with an estimated annual average rainfall (falling mostly in the winter) of 400 mm.

The nature and density of the vegetation is largely controlled by the two main soil types (see below) and topographic location, and consists of a mosaic of distinctive plant communities. Over the calcareous clay soils, sclerophyll woodland is dominant consisting of a eucalypt canopy (up to 10 m in height) with locally larger salmon gum (*Eucalyptus salmonophloia*), and a lower and semi-continuous shrubby horizon up to 1-2 m in height where tea-tree (*Melaleuca*) is prominent. In lower-lying areas to the N of the Bounty Zone, eucalypts are mainly of a mallee form (up to 4 m in height) with a sparse understorey. Vegetation controlled by lateritic soils is also of two forms, namely scrub heath consisting of vegetation no more than a metre in height characterising an area to the NW of the Bounty Zone, and broombush thicket consisting of a mixture of very dense *Acacia*, *Casuarina*, *Hakea* and minor mallee *Eucalyptus* up to 4 m in height growing over the southern portion of the Bounty Zone.

The Bounty Gold Deposit is situated in the Forrestania Greenstone Belt, the southern extension of the Southern Cross Greenstone Belt (Chin *et al.* 1982). According to Smith (1987), Au mineralisation at Bounty is hosted by a steeply dipping, semi-conformable shear system near the contact of a mafic intrusive and a komatiitic flow sequence. Mineralisation cropped out with no obvious leached zone. The main area of interest, the Bounty Zone, has an ore reserve of 5.6 Mt grading 4.6 g/t (Maxey 1997). Mining of the site commenced in late 1988 and is continuing.

Soils in the vicinity of the Bounty Zone fall into two broad types:

1) Calcareous clay soils are developed within a heavy red clay loam consisting of an almost homogeneous material (both in colour and texture) with gravelly ironstones (ferruginous granules a few mm in diameter). Additional features include a veneer of organic litter and the presence of

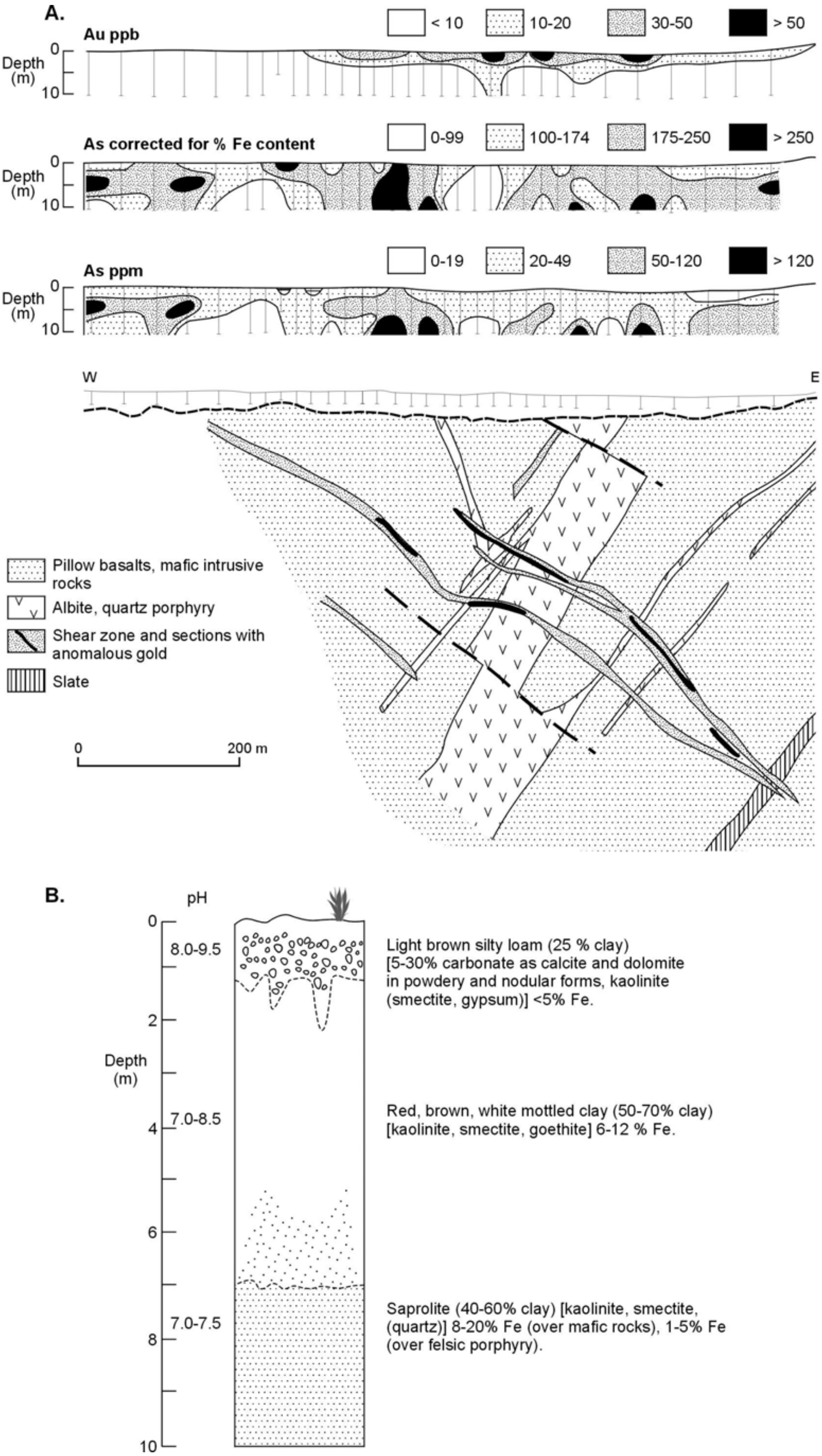


Figure 6.8: A) Distributions of Au and As above mineralisation in section at the Mararoa Reef. B) A regolith profile over the Mararoa Reef showing location of calcareous material above mottled clays. (After Smith and Keele 1984).

sheetwash containing sand and minor rock fragments mainly of quartz. Near the surface, and contained usually within the top 2 m, is a prominent horizon of frequently lighter coloured, friable to nodular clay-rich material composed of kaolinite, calcite and dolomite. Invariably the calcite occurs above the dolomite to form a continuous carbonate horizon.

2) Gravelly, lateritic soil profiles consist of yellow mottled (goethitic) nodular ferruginous material with zones of induration and loosely agglomerated material. Ferruginous nodules vary in size but are generally less than 30 mm in diameter. Decaying vegetation litter overlying sandy material (as for calcareous clay soils) occurs at the surface. There is little carbonate in the lateritic soils, although they are often located adjacent to calcareous clay soils.

The study consisted of (i) the multi-element analysis of 1060 augered samples from ~0-1 m, (ii) the excavation, description and geochemistry of 7 soil pits and (iii) the construction of a regolith-landform map of the area. The northern part of the study area is shown in Figure 6.9A. The highest Au concentration in the augered samples (1020 ppb) occurs directly over the main Bounty Zone. Gold and carbonate are highly correlated vertically within the soil profile. There is an anomalous plume of Au from the Bounty Zone downslope (Figure 6.9C). Where there are thin transported sands (<0.2 m) overlying the red clays (duplex soils), the calcrete and Au are located slightly deeper in the soil profile (Figure 6.9B, profiles 6 and 7). Whereas there is excellent vertical agreement between Au and the alkaline earth metals as demonstrated by the soil profile data, the correlation is not apparent in a lateral sense when the augered sample geochemistry is plotted along a traverse (Figure 6.9D); obviously not all the calcrete is equally rich in Ca and Au. (Profile 4 was collected on the edge of remnant calcrete-poor lateritic residuum, which would explain the low Ca and Mg contents reported for the corresponding augered samples).

The studies conclusively demonstrated that Au has being mobilised hydromorphically, since the alkaline earth metals and Au are highly correlated (Figure 6.9B). In conclusion, auger sampling is clearly successful in collecting the Au-rich calcrete horizon.

(6) Runway, Kalgoorlie, WA. (Lintern 1996a)

The Runway prospect is located ~10 km N of Kalgoorlie in the Archaean Wiluna-Norseman greenstone belt. The deposit is hosted by sedimentary rocks of the Black Flag Group that dip steeply to the W, and trend N-S. The lithology is comprised of four EW orientated units: volcanic sandstone, interbedded conglomerate-sandstone, black shales and siltstones, and massive sandstone. Runway is situated on a flat plain with areas of sub-cropping saprolite. The climate is semi-arid with average annual rainfall of 280 mm. Vegetation consists of open eucalypt woodland over residual terrain, and small shrubs including bluebush dominate depositional areas.

Mineralisation at Runway occurs as a thin, sub-horizontal zone of supergene Au enrichment close to the weathering front, beneath 50 m of leached or barren saprolite (Figure 6.10A). Primary mineralisation occurs as sporadic, narrow quartz veins. Minor sulphides, including pyrite, arsenopyrite, sphalerite and galena, are present and As, Ag, Cu, Zn and Pb are associated with Au mineralisation. The veins appear to be generally restricted to the interbedded conglomerate-sandstone unit, which exhibits pervasive carbonate-sericite alteration and disseminated pyrite and arsenopyrite.

The saprolite at Runway is thinly covered by semi-residual, calcareous, red, sandy clay soils. The saprolite is within 1 m of the surface in places. Reddish-brown sandy clay extends from the surface to about 0.25 m depth, and contains small (to 10 mm) carbonate nodules. Orange silty sandy clays are present between 0.25-1 m and contain carbonate nodules of varying size, but becoming smaller (<1 cm) with depth. Calcareous, orange and yellow, clayey silt, at 1-2 m depth has friable lithic nodules derived from underlying saprolite.

A geochemical study of the near surface (0-1 m) was undertaken at the Runway prospect (Lintern 1996a; Figure 6.10A). The study was concentrated adjacent to a geochemically anomalous area in Au (maximum of 270 ppb) outlined by an earlier survey of the 0.3-1.3 m interval. In both studies, regolith material (principally calcareous soil) was sampled by augering on an EW traverse over the thinly covered mineralised basement. In the follow-up study, Au (maximum of 0.094 ppm), As (405 ppm), Sb (8 ppm) and W (11 ppm) were anomalous compared to backgrounds of <0.01, <20, <1 and <2 ppm respectively (Figure 6.10C). Over mineralisation, samples below 0.5 m were moderately more concentrated in Au and carbonate compared with samples above 0.5 m. A soil profile directly over mineralisation was analysed to a depth of 2 m. Here, there is a weak association between Au, Ca and

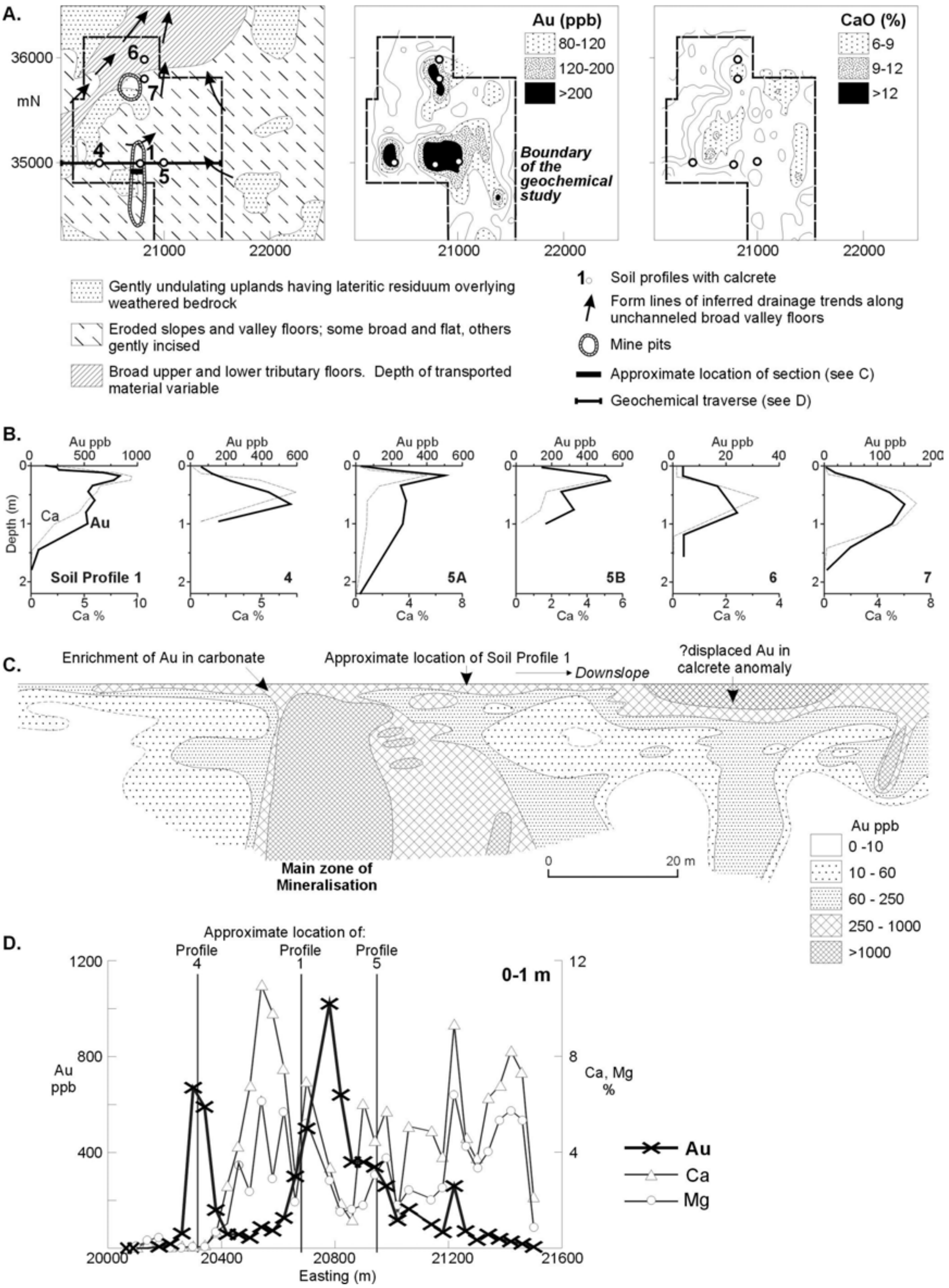


Figure 6.9: Geochemistry and regolith-landforms at Bounty. A) Regolith landform map and geochemical distributions around the Bounty mine pits. B) Geochemical profiles from several soil pits. C) Distribution of Au in the top 20-30 m across the Bounty mineralisation (after Smith 1987). D) Geochemical traverse from drill cuttings prior to the excavation of the Bounty Pit.

Mg in the top 1.3 m, but the highest Au concentrations (80 ppb) and the least Ca and Mg are found below 1.5 m (Figure 6.10B). Highly anomalous concentrations of As (2700 ppm), Sb (42 ppm) and W (45 ppm) are present between 1.75-2.00 m.

The coarse fraction (>1 mm) from three soil samples taken from over mineralisation was sub-divided into five components: calcareous nodules, green lithic fragments, assorted saprolite / mottled zone

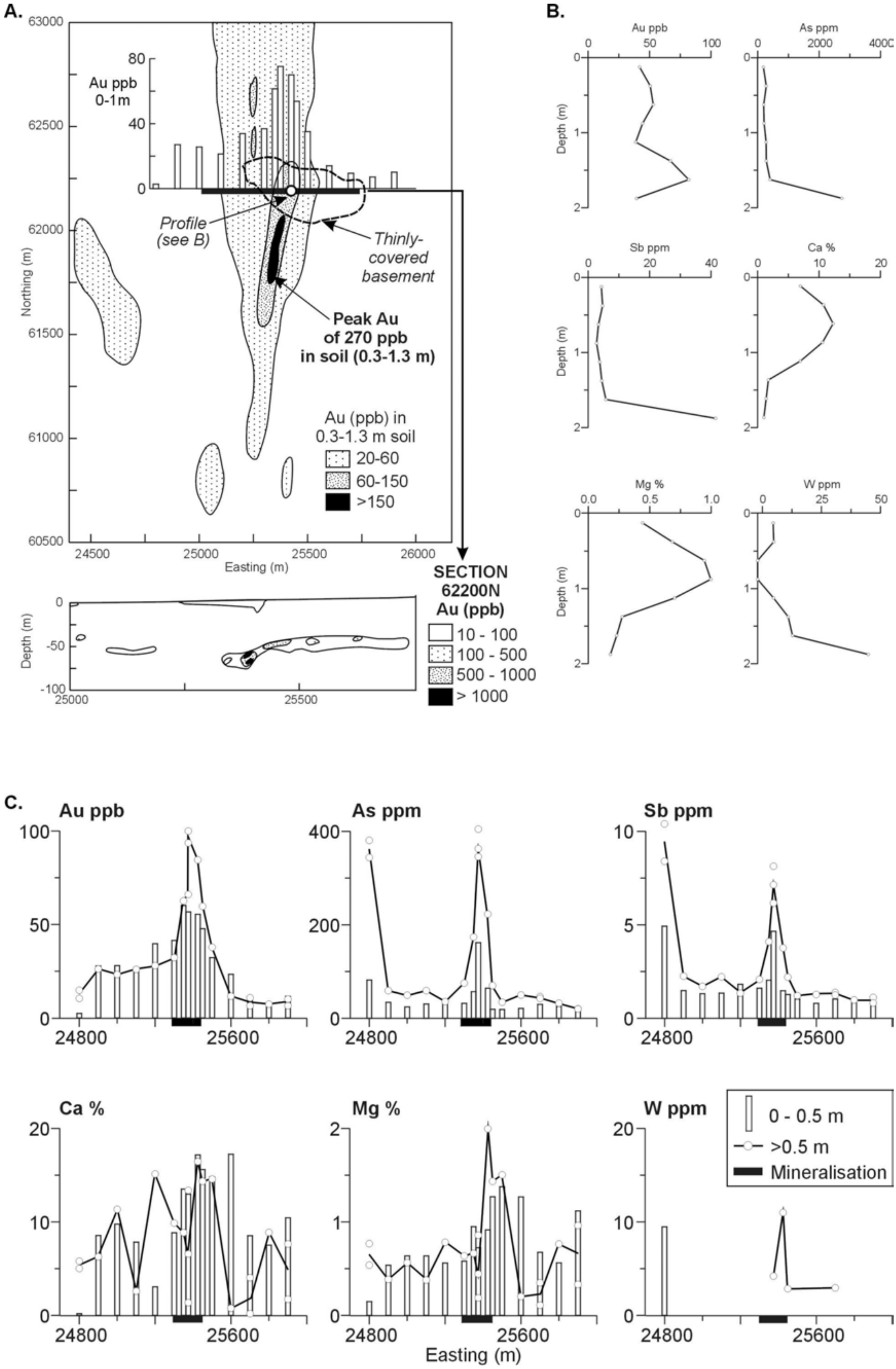


Figure 6.10: Geochemistry of the Runway Gold Prospect. A) Plan of Au distribution in soil (0.3-1.3 m), Au in soil from a traverse (0-1 m), and a geochemical section through the mineralisation beneath the 0-1 m traverse. B) Selected geochemistry of a soil profile above mineralisation. C) Comparison of 0-0.5 m soil geochemistry with deeper samples.

fragments, ferruginous saprolite, and magnetic ferruginous granules. Gold occurs in each, with the highest concentrations in the calcareous fraction (>500 ppb) and in the ferruginous granules (295 ppb).

The study demonstrates that although Au appears to be associated with carbonate in the soil, and would be effective to sample to delineate mineralisation, the probable immediate source of the Au in calcrete anomaly is relict grains of Au occurring in the saprolite. In addition, it study demonstrates that Au can still be found above mineralisation in soils developed over significant thicknesses (>40 m) of Au-poor saprolite.

(7) Lights of Israel, Davyhurst, WA. (Robertson and Tenhaeff 1992)
The Lights of Israel Gold Deposit is located about 100 km NE of Kalgoorlie (near Davyhurst). Biotite schist within metabasalt hosts mineralisation. Pre-production ore reserves of 415000 tonnes at 4.2 g/t were outlined (Hellsten *et al.* 1990). Full-scale underground production began in 1996 and was forecast to initially produce 40000 oz from 400000 tpa. The deposit is located beneath eucalypt woodland S of the Menzies Line. The weathering profile has been truncated to the mottled zone or lower. Carbonate skins cover blocks of saprolite in places. The stratigraphy of the top 2 m of the regolith showing the position of the carbonate is shown in Figure 6.11D. A limited geochemical study was undertaken at Lights of Israel mainly restricted to a traverse across mineralisation (Figure 6.11A). Gold showed the best indications of mineralisation in soils with significant anomalies (400-700 ppb) developed in a regional background of 5-7 ppb and a local background of 33-120 ppb (Figure 6.11B). The <4 (m fraction has the highest Au concentrations (750 ppb) but lesser, similar anomalies (peaking at 400 ppb) from the <75 (m fraction and the complete soil (Figure 6.11C) were found. Gold was strongly correlated with Ca in the <4 (m fraction demonstrating that much of the Au was finely dispersed. Normalising with respect to Ca content removed some of the apparently spurious anomalies to the W of mineralisation (Figure 6.11B).

(8) Challenger, Gawler Craton, SA. (Lintern and Sheard 1998)
The Challenger Gold Deposit is located in the northern Gawler Craton 750 km NW of Adelaide (SA). It was discovered in 1995 as a direct result of calcrete sampling. Calcrete is almost ubiquitous in southern SA as a variably indurated horizon up to 1 or 2 m thick just beneath the surface. It is easily sampled by digging a shallow hole and using a crowbar or a pick to remove the preferred nodular-laminar material.

The climate of the Challenger area is semi-arid with an annual rainfall of <200 mm. Vegetation consists of chenopod-dominated shrublands, with scattered open woodland groves of *Acacia*. The landscape is very subdued and consists of low rises, sand spreads and dunes, gibber plains, silcrete outcrops and ephemeral drainages. The palaeolandscape of the northern and western parts of the Gawler Craton appears to be similar to the Yilgarn Craton, as investigations have revealed a series of palaeochannel drainages in-filled with Cainozoic and earlier sediments that drain into the Eucla Basin.

The bedrock is a garnet-rich paragneiss consisting of plagioclase, perthitic K-feldspar, quartz, cordierite, garnet and biotite. Mineralisation is associated with silica and arsenopyrite alteration. Mineralisation occurs over a strike length >250 m and to a vertical depth >450 m. The high-grade ore shoots plunge 30° at 030°. Structural studies indicate that the plunge is defined by a megascopic fold closure in the gneissic foliation.

The near-surface regolith consists of variably silicified and calcreted units with underlying clays. The calcrete occurs as in several forms including coatings on sand grains (soil), laminar, massive and nodular. In adjacent areas, up to several tens of metres of variably silicified clays comprise a transported overburden which themselves overlie a deeply weathered basement profile truncated to the saprolith (Figure 6.12C). The regolith in the mineralised zone consists of a deeply-weathered profile truncated in the saprolith.

A broad Au anomaly (>5 ppb, >4 sq km) is present in the calcrete overlying the Challenger mineralisation (Figure 6.12A). This was outlined from a regional survey based on a 1.6 km square grid with a peak Au concentration of 180 ppb. Importantly, if calcrete had been sampled a few metres E or W the Au concentration would have been an order of magnitude smaller and the anomaly downgraded in importance. A later, detailed geochemical survey of calcrete revealed the full extent of the anomaly, which included a maximum concentration of 620 ppb Au. The recent investigation by Lintern and Sheard (1998) of the geochemistry of calcretes and other regolith materials along a NW-SE

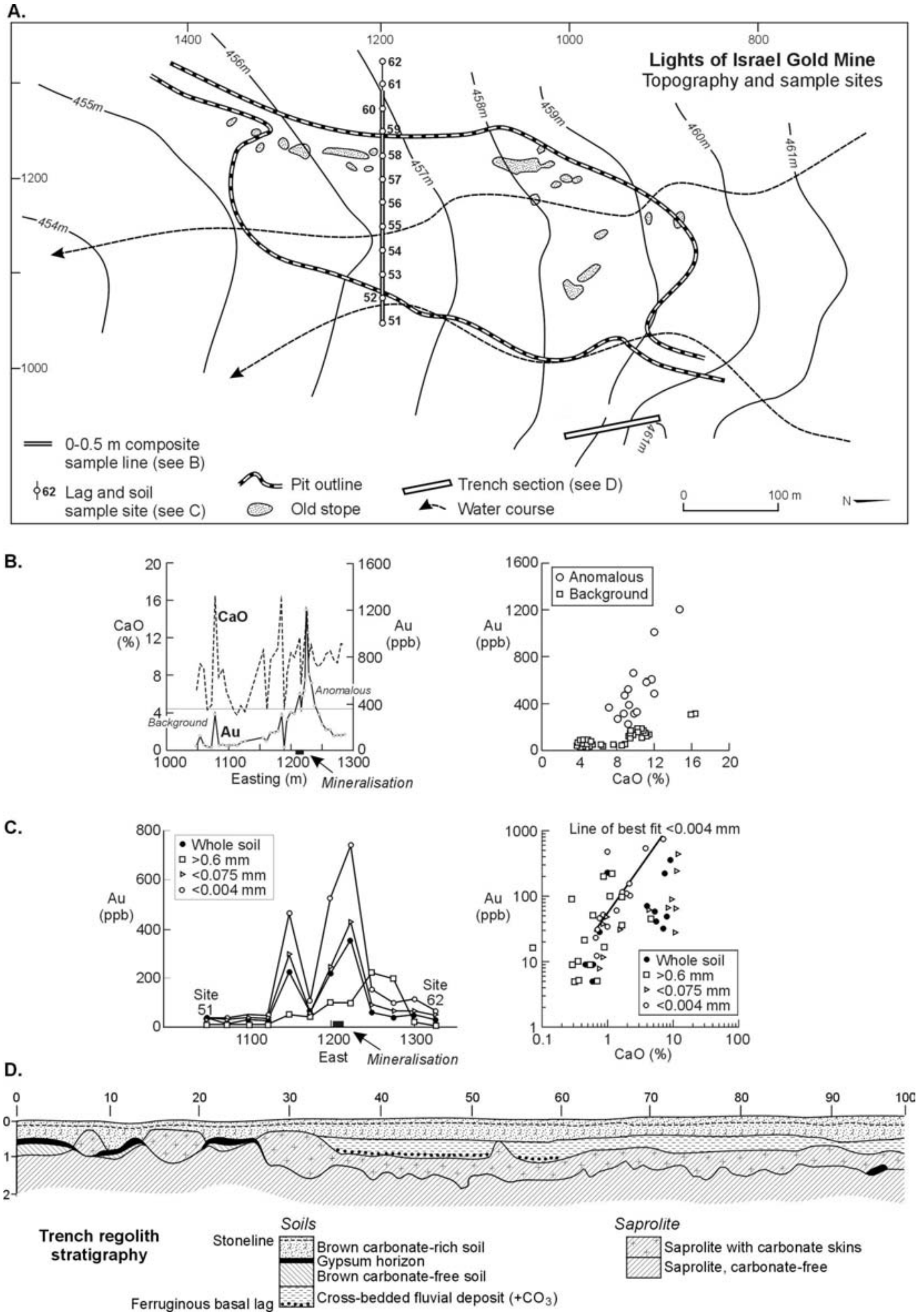


Figure 6.11: Geochemistry and regolith at the Lights of Israel Gold Deposit (after Roberston and Tenhaeff 1992). A) Plan showing topography and location of sampling points. B) Gold and Ca concentrations of 0-0.5 m composite soils across mineralisation and scatter plot showing broad association between the two elements. C) Soil size fractionation geochemical study and scatter plot of Ca and Au data.

traverse across mineralisation, reported a concentration of 2370 ppb Au in calcrete directly overlying the main mineralised Zone 1 (Figure 6.12C). Such high concentrations of Au are indicative of mineralised saprolite or native Au within the calcrete sample. The process of calcrete replacement and displacement has all but destroyed the host saprolite minerals and fabrics. However, in soil pits above mineralisation (GCP121-123) quartz veining extending within a few cms of the surface was observed. Gold concentrations as high as 100 ppm were recorded in material from 2 m in pit GCP122. East of the main lode, the presence of 20 m thick transported overburden appears to prevent any significant Au appearing in the surficial calcrete. However, the soil pit above mineralisation here (Zone 3, GCP106) indicates anomalous Au (>15 ppb) associated with sub-surface calcrete and requires further investigation (Figure 6.12B). There is a broad association between Au and Ca in the soil pits but this disappears where high Au grades associated with quartz veins occur.

The Challenger Deposit is the largest deposit found specifically using calcrete as a sampling medium although many more prospects have been located in the vicinity including ET, Tunkillia, South Hilga, Golf Bore, Birthday, Myall, Sheoak and Campfire Bore. South Australia was the scene of frenzied activity in the mid to late 1990s by exploration companies using calcrete.

6.2.3.3 Transported overburden host (Type T)

Exploration in areas of transported cover using surficial materials has been investigated at many sites. The advent of calcrete as a sampling medium provided another avenue to investigate the possibility of using surficial materials as a cheap and effective technique to explore in this type of terrain. In this context, transported overburden includes locations where the depth of transported material is in excess of a nominal 2 m and commonly considerably more; calcrete developed in thin cover often contains material derived from underlying saprolite or other residual units from pedological processes such as bioturbation. Type T also includes deposits concealed or hosted by palaeochannels which characterise ancient landscapes including many regions of Australia, e.g. the Gawler and Yilgarn Cratons. Typically the cover is Cainozoic in age for most of the case studies discussed. As more data has become available, it has become apparent that with many Type T case studies (including many of those that follow), a simple transect is normally insufficient to validate whether an anomaly developed in soil or calcrete is derived from the underlying buried mineralisation or from downslope dispersion from outcrop (Type A, B or C). Ideally, case studies require detailed four-dimensional information-encompassing factors such as regolith characterisation, landscape evolution, topography, and a study of the soils themselves.

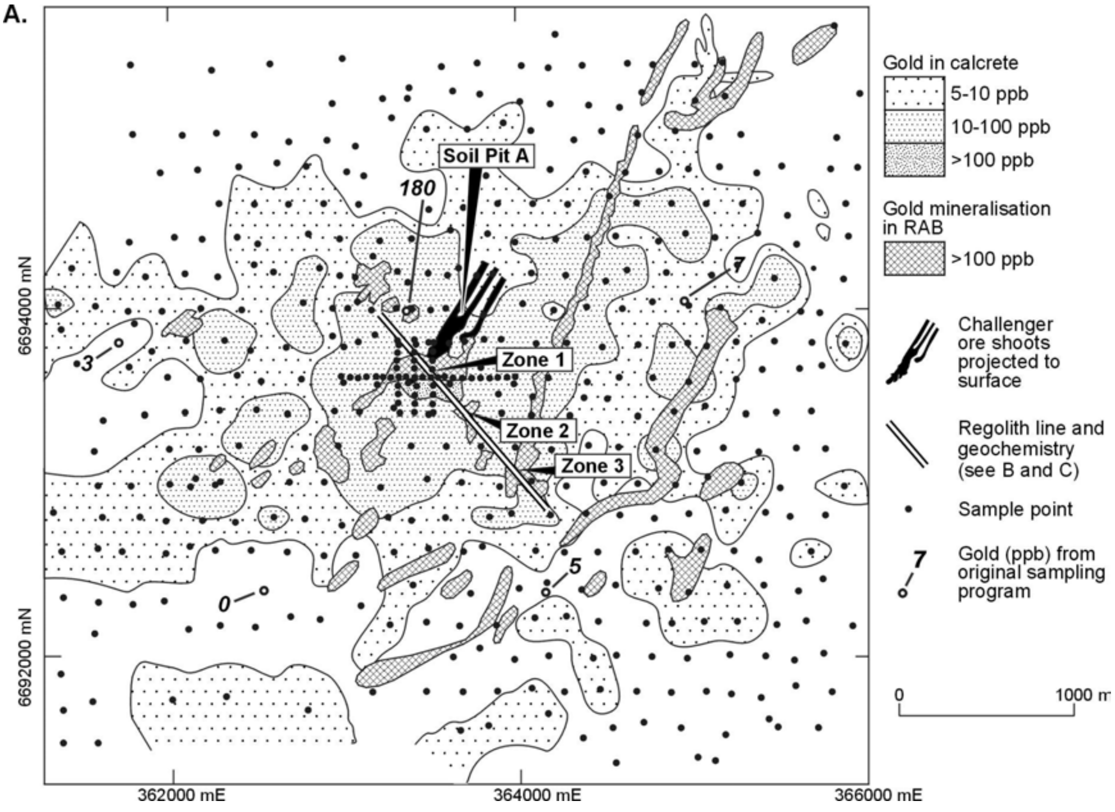


Figure 6.12: Geochemistry and regolith at the Challenger Gold Deposit. A) Plan showing Au in relation to calcrete distribution, mineralisation and the sampling line.

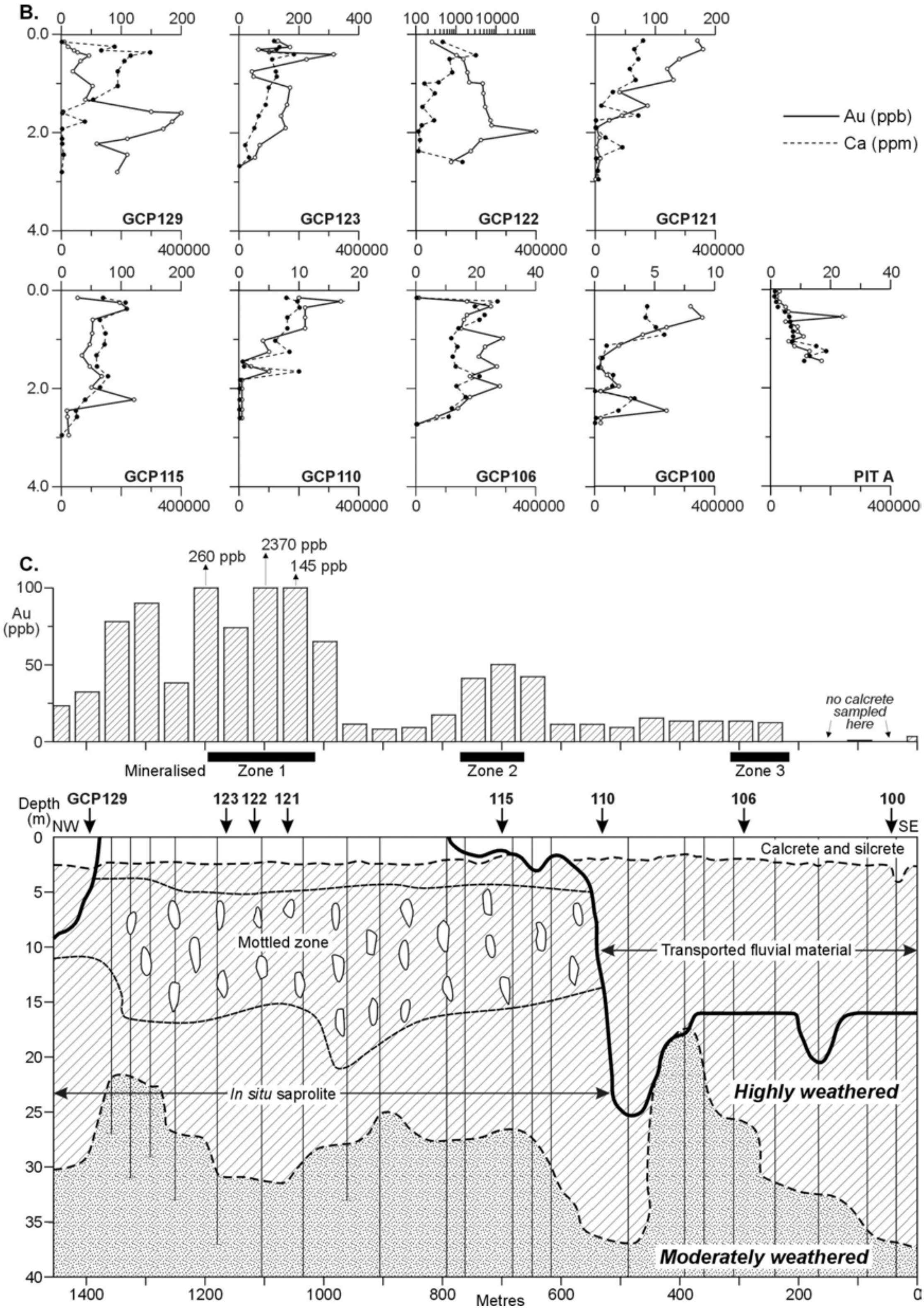


Figure 6.12 (continued): Geochemistry and regolith at the Challenger Gold Deposit. B) Soil profiles (position indicated in C) from along the sampling line. C) Gold in calcrete from the sampling line with a section through the regolith beneath.

(9) Mt Pleasant, Kalgoorlie, WA (Lawrance 1988, Lawrance and Butt 1992).
The Golden Kilometre Gold Mine at Mt Pleasant is situated in relatively flat terrain in the Norseman-Wiluna Greenstone Belt, about 35 km NW of Kalgoorlie (Figure 6.13A). Climate is semi-arid with mean annual rainfall of 280 mm. Vegetation is typical of the Kalgoorlie area and consists of open eucalypt woodland with a sparse under-storey.

Gold mineralisation occurs in a quartz vein system and surrounding pyrite-rich calcite-muscovite alteration zones hosted by a differentiated layered gabbro (Figure 6.13C). The mineralised zone is 1.2 km long, 5.5 m thick and extends to at least 80 m depth. The estimated total reserve is 3 Mt averaging 3.2 g/t.

The presumed original lateritic profile over the deposit has been largely eroded and is overlain by 0.5 to 5 m of alluvial and colluvial sediments. The remaining residual profile extends to 30 m depth around the lode and, away from the mineralisation, fresh gabbro occurs at the unconformity. The surface slopes very gently towards the creek to the SE. The transported overburden consists of four units:

1) Soil (0.5-1.5 m thick). Composed of ferruginous clay-rich loam. Soil is commonly weakly cemented by carbonate minerals just below the surface.
2) Sandy lateritic gravels (0-1 m thick). A layered, unconsolidated horizon of lateritic gravels and quartz sand overlies the ferruginous clays. Gravels partly comprise sub-rounded ironstone pebbles and pisoliths, some weakly cemented by carbonate minerals. This horizon also contains rare rock fragments similar to those in the basal horizon, and quartz fragments, which become more common closer to the quartz veins of the lode.
3) Ferruginous clays (0-1 m thick). Lenses of red-brown ferruginous clay, containing lateritic pebbles.
4) Basal gravels and conglomerates (0-0.5 m thick). Clast-supported horizon composed of fluvial gravels and cobbles containing rounded to angular, coarse, polymictic lithofragments, quartz and ferruginous nodular and pisolitic material in a matrix of coarse quartz sand and red-brown clay.

Gold concentrations in the transported material at Mt Pleasant vary. Up to 420 ppb Au was found in samples collected at the unconformity with concentrations reaching only 10 ppb in the soil immediately above (Figure 6.13B). Coarse Au nuggets (2-6 mm in diameter), some with quartz, suggest there has been a net concentration of Au at the old land surface (now the unconformity) by deflation, although their low Ag contents compared with the lode Au suggest some chemical re-working.

Lawrance (1988) did not document the vertical distribution of Au or Ca in the soil profile in detail (Figure 6.13C). The broad association of Au within the soil may either be interpreted as hydromorphic dispersion directly from the unconformity or chemical re-working of coarse Au from the unconformity after being displaced either from upslope or vertically by bioturbation processes. In plan, the Au anomaly more or less directly overlies the mineralisation. The strike of the mineralisation is perpendicular to the presumed flow direction of the palaeo- and present drainages.

(10) Granny Smith, Laverton, WA (Lintern and Butt 1993)
The Granny Smith Gold Deposit is 25 km S of Laverton (about 250 km NW of Kalgoorlie, WA) and N of the Menzies Line. The land surface is essentially flat and consists of thin colluvium and alluvium (about 1-3 m thick) at 410 m above sea level, with two hills of BIF rising above the surrounding plain. Deep gullies drain the flanks of the higher hill (Figure 6.14B). Vegetation is open scrub (dense along creek lines) consisting primarily of mulga (*Acacia aneura*) with a sparse understorey of shrubs including *Cassia*, *Eromophila* and *Maireana*.

The deposit lies in a major structural corridor in which several other Au deposits are also located (Figure 6.14A). The depth to mineralisation varies but is generally about 5-20 m. The regional and local geology have been described by Hallberg (1983) and Hall and Holyland (1990) (Figure 6.14A). The measured, indicated and inferred resource are estimated to total 39.4 Mt at 1.6 ppm. Mineralisation comprises three ore zones, two of which are shown in section (Figure 6.14B):
1) Goanna. Mineralisation occurs in a shear zone trending NNW and dipping 50o E with a strike length of at least 1 km and thickness that varies between 5 and 20 m. The host rocks are sedimentary (including BIF), which are weathered to depths of up to 80 m.
2) Grannys. Located 1.5 km S of Goanna, mineralisation occurs as a shallow sub-horizontal blanket along the contact between a granodiorite intrusion and overlying sediments and rocks. The

contact is sheared and brecciated. The shear has a strike length of 600 m, is up to 500 m wide, 15 to 40 m thick and dips 25^o E. The depth of oxidation is highly variable, ranging from 10 to 80m. A higher-grade zone exists in the upper part of mineralisation.

3) Windich. Located 0.8 km S of Grannys, Windich is buried beneath at least 5 m of colluvium/alluvium. No investigations were undertaken here.

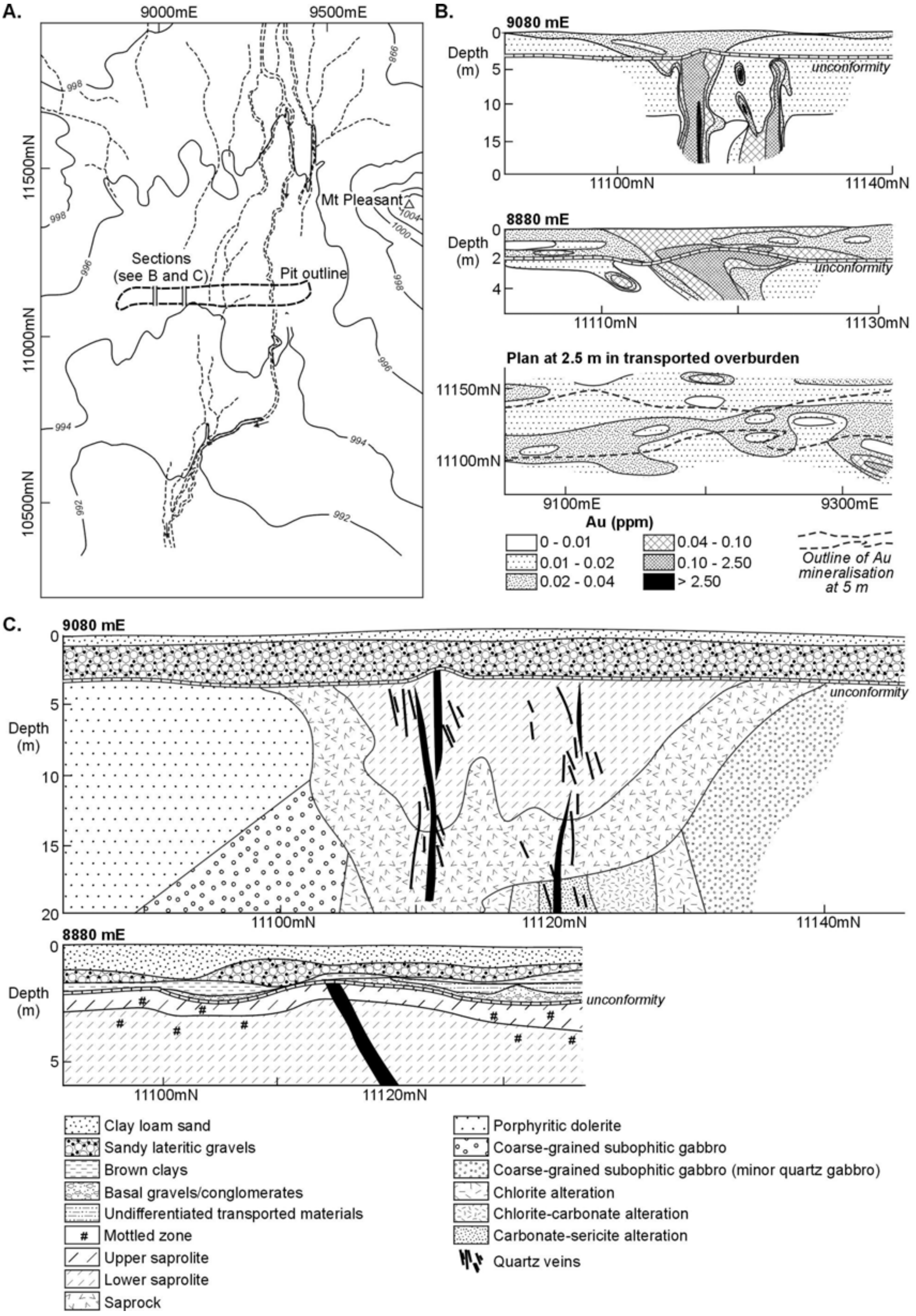


Figure 6.13: Geochemistry and regolith of the Mt Pleasant Gold Deposit (after Lawrance 1988). A) Plan showing drainage, location of open cut mine and sampling lines. B) Section showing distribution of Au in sampling lines. C) Section showing detailed geology for sampling lines.

Five upper regolith profiles were sampled from existing vehicle ramps into the Goanna and Grannys pits. They consist of three horizons, unconsolidated soil or topsoil, hardpan and brecciated saprolite:

1) Soil. Gravelly, unconsolidated, shallow, sandy, acidic (pH 4.6) colluvium varying in thickness from a few centimetres to nearly one metre. The gravels consist of coarse polymictic clasts, including BIF, ferruginous nodules and quartz.
2) Hardpan. Red-brown, indurated colluvium and residual clays several metres thick having a variable sub-texture consisting of laminated and blocky units with occasional friable silty-clay segregations. In the upper portion, manganiferous nodules and Mn staining are common. Calcareous segregations occur towards the base of the hardpan. The hardpan commonly grades into brecciated saprolite with depth.
3) Upper saprolite. This consists of sub-angular clasts of weathered bedrock in a groundmass of red-brown clays, locally mottled ochre, red and/or orange. The upper saprolite, to a depth of at least 9 m, is commonly calcareous. Carbonates (calcite) are dispersed through the clay-rich matrix as clasts and also form veins and segregations. The abundance of carbonate in the lower regolith is surprising, since usually it is found within the upper two metres of the surface, particularly S of the Menzies Line. The saprolite below 10 m was expected to be poor in secondary carbonate, as reported for other saprolites in the region.

Gold concentrations for each unit are described below and illustrated in Figure 6.14C:

1) Soil. The Au content of the soil varies from 3 to 18 ppb. The highest concentrations occur in profiles 5 and 6, and may be due to the inclusion of hardpan that is richer in Au, since the soil is very shallow in both these profiles. The unusually high Au contents in profile 3 (12 ppb) may be due to particulate Au from sub-cropping mineralisation shed from upslope, where visible Au was found (Figure 6.2). The strength of the anomaly in the soil is very weak considering that profile 6 was located only 20 m from sub-cropping mineralisation.
2) Hardpan. The highest Au concentrations occur in profile 6 (190 ppb at 1.25 m), which is close to sub-cropping mineralisation. In profiles 3, 4 and 6, the Au maxima are close to the base of the hardpan, whereas in profiles 1 and 5, the highest Au is in the upper part of the hardpan, with minor peaks lower down close to the saprolite.
3) Upper saprolite. The interface between the saprolite and the hardpan is not distinct, since the former becomes brecciated and is composed of sub-angular clasts (lithorelics) supported by a siliceous hardpan matrix. The highest Au contents of the saprolite occur closest to the contact with the hardpan and may be due to the presence of this material. The highest Au content of the saprolite occurs in profile 1 (80 ppb at 3.75 m).

The highest concentrations of Au in the upper horizons of the regolith at Granny Smith appear to be primarily related to the contact between transported and residual components of the soil profile; this commonly occurs towards the base of the hardpan and is coincident with a trend towards increasing pH. Soils have become acid as a result of leaching of cations from the upper part to the lower part of the profile. The soil and hardpan are acid, (minimum pH 4.6), whereas the upper saprolite is alkaline due to the precipitation of carbonate and other cations. Segregations of hardpan from the contact zone indicate that Au is present in lithorelics and the matrix of the hardpan, although most is found in the latter.

Most Ca (and calcite) occurs at the top of, or within, the saprolite horizon, dispersed throughout the clay-rich matrix and as veins and concretions. The above results indicate that the Au-Ca association is only weakly present, if at all, at Granny Smith, even though evidence for the association was specifically and critically investigated. Generally, Au and Ca do not follow the same pattern of mobilisation and precipitation as noted in the southern Yilgarn case studies and, therefore, the carbonates should not specifically be sought as an exploration sample medium. Pedogenic carbonate is, in general, uncommon N of the Menzies Line and it is uncertain whether its presence at Granny Smith is atypical for the region or different in origin to that in the S. The reasons for the differing behaviour of Au and Ca N and S of the Menzies Line may be due to the soil hydrology. The carbonate may well represent a transitional stage between pedogenic and groundwater forms present in the regolith.

This study indicates that prescriptions for geochemical exploration for Au in areas dominated by hardpan are more difficult than for areas S of the Menzies Line. The behaviour of Au in soils at Granny Smith should not be extrapolated to other sites that have hardpan development, since only five profiles were sampled. Nevertheless, sampling of hardpan at the contact between transported and

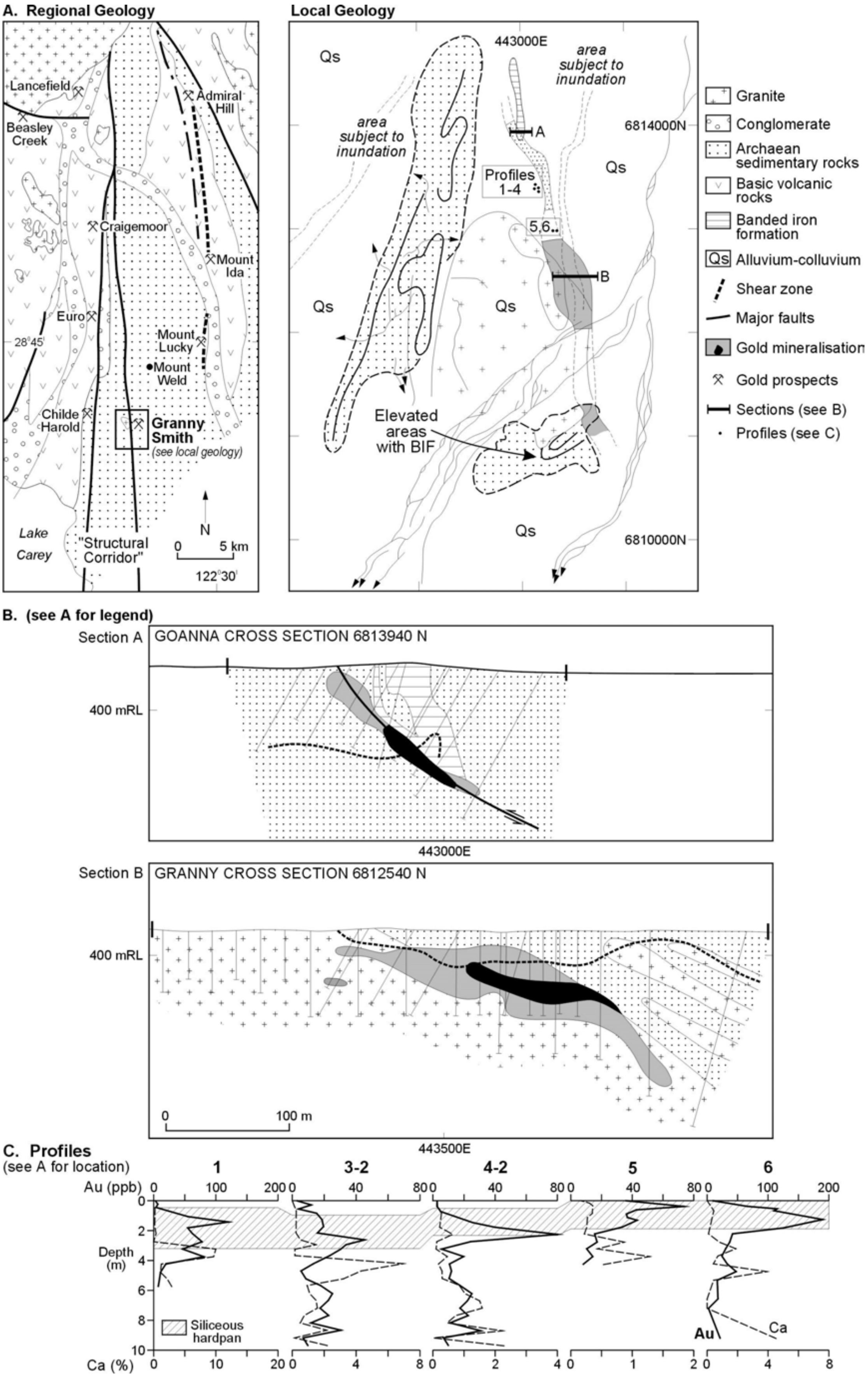


Figure 6.14: Gold distribution and regolith at the Granny Smith Gold Deposit. A) Regional and local geology (after Hallberg (1983) and Hall and Holyland (1990)). B) Sections A and B through mineralisation (see A for location). C) Geochemical profiles (see A for location).

residual components may have some general application. Furthermore, different Au-Ca characteristics may be exhibited where the hardpan is developed entirely within transported overburden, which itself may be 5-10 m thick and overlie leached saprolite.

(11) Wombola Gold Prospect, Kalgoorlie, WA (Anand *et al.* 1993)
The Wombola district is located in Archaean granite-greenstone terrain of the East Coolgardie Goldfield, about 50 km SE of Kalgoorlie. It consists of a lower unit of felsic volcanic rocks (rhyodacite, and minor basalt-andesite) overlain by a strongly deformed ultramafic-mafic sequence consisting predominantly serpentinised peridotite with subordinate gabbro, pyroxenite, felsic volcanic-volcaniclastic rocks and high Mg basalt (Ahmat *et al.* 1993). The local geology at the Wombola Gold Prospect consists of a thin belt of amphibolite, dolerite, shale, black shale and porphyry intrusions.

The Wombola district is characterised by low, rounded hills that grade gently into broad alluvial floors and salt lakes. The prospect is located in a colluvial outwash plain. The regolith stratigraphy consists of a mantle of fine to coarse polymictic lag comprising ferruginous granules and pebbles, quartz and carbonate, which overlies about 1 m of calcareous red soil with gravels and carbonate nodules. This, in turn, overlies 2 to 4 m of transported red clay with gravel. Below this is a truncated mottled zone 8 to 10 m deep with lenses of transported, loose pisoliths at the unconformity. Bleached saprolite lies beneath the mottled zone. Mineralisation occurs at 40 m depth.

A variety of near-surface regolith materials was sampled, including ferruginous pebbles, calcareous soil, loose pisoliths from the red soil, and hardened mottles from the saprolith. The highest concentration of Au is 440 ppb and occurs in one sample over mineralisation in the calcareous soil (0-1 m, Figure 6.15) there are no other data available to assist with the interpretation of the origin of the Au in the soil.

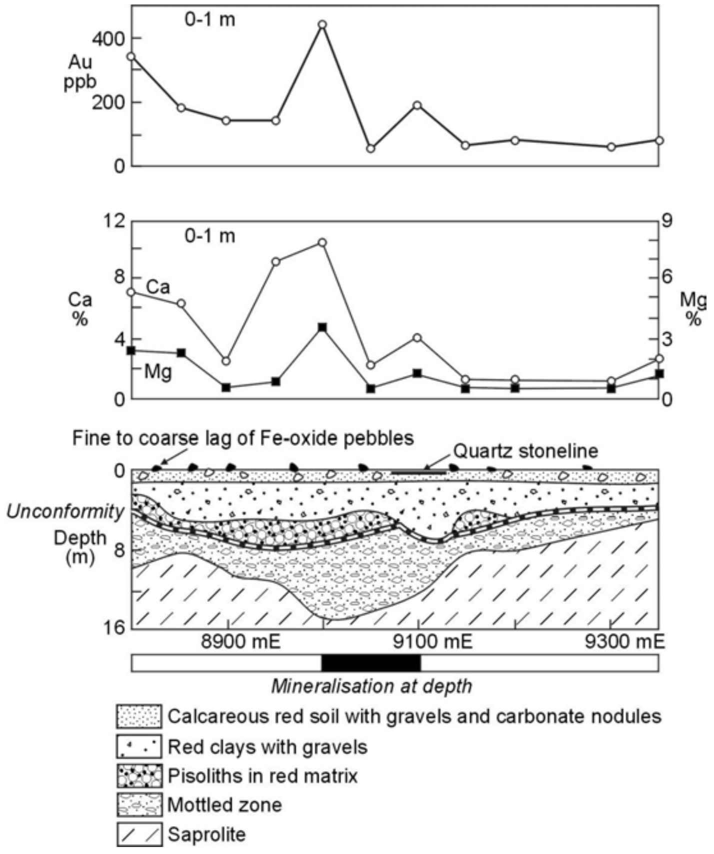


Figure 6.15: Regolith and Au distribution at the Wombola Gold Prospect (after Anand *et al.* 1993). The 0-1 m samples are drill cutting composites.

(12) Apollo, Kambalda, WA. (Lintern *et al.* 1997).
The Apollo Gold Prospect is located about 25 km SE of Kambalda, and about 500 m NE of the Argo

Gold Deposit. The two case studies illustrate the role played by thickness of overburden and depth to mineralisation, which are both greater at Argo. The climate is semi-arid with average annual rainfall of 280 mm. Vegetation is sparse and composed of open mixed woodland of *Eucalyptus*, rare *Casuarina* (she-oak), and small shrubs including *Eremophila* (poverty bush) and false bluebush (*Cratostylis conocephala*). The landscape is typical of the floodplains bordering the salt lake landscape regimes of the region. A broad colluvial plain with scarce clay pans drains the study area to the SW towards the salty and usually dry Lake Lefroy, where dunes cover large areas.

Apollo is located in the western limb of the St Ives Antiform, part of the Archaean Norseman-Wiluna belt of the Yilgarn Craton. The bedrock consists of the Paringa Basalt, the Black Flag Group and the Condenser Dolerite, all of which strike NE, dip 70-80^o SW and are weakly metamorphosed. The deposit is hosted within the Condenser Dolerite, a sill up to 400 m thick, which fractionated in situ to several zones. Gold mineralisation tends to have an affinity with a highly siliceous and Fe-rich zone. Mineralisation is encountered at about 15 m depth and can be traced down dip in excess of 760 m to the W. It is confined to bedrock and saprolite, and is associated with albite alteration products within two NNE-trending mylonitic shear zones.

The regolith is complex. Three principal sedimentary units cover the residual regolith and palaeochannel sediments in the Apollo area (Figure 6.16A). A sandy aeolian drift, generally 10 to 20 cm thick (but up to 2 m thick locally), covers a calcareous soil. It covers a calcareous clay-rich red clayey sand from 0.2-2.0 m depth, which contains a dark manganiferous horizon at ~1.5 m depth. The soil is characterised by locally abundant calcareous nodules 1-2 cm in diameter, some of which are coated rock fragments, (derived from outcrop located 1-2 km away). This covers an upper, partly calcareous red-brown sandy clay which can be further sub-divided. A unit of hard red and grey clays with variable ferruginous mottling covers the saprolite. This unit contains zones of indurated ferruginous and siliceous material, forming a cement (probably a palaeosol) of variable thickness, generally between 2-7 m depth. The residual regolith profile consists of variably coloured, dark, clay-rich saprolite. The saprolite is generally between 20-30 m thick, but is thinner beneath palaeochannel sediments which are incised into the residual regolith 250 m to the S of the Apollo prospect, cuts across the nearby Argo deposit in an approximate EW orientation. The palaeochannel has a maximum depth of 60 m and average width of 400 m.

The results from a variety of samples are variable:

(i) The mean Au content of the calcareous sandy clay (0-1 m and 1.3-1.8 m composite samples) from mineralised areas (9 ppb) and background areas (11 ppb) is similar.

(ii) Gold and carbonate appear to be weakly associated in 0-1 m composite samples (Figure 6.16D). Limited data from two soil profiles near Apollo, one from over mineralisation (L) and one from background (M) (Figure 6.16C), suggest marginally higher Au contents over the former.

(iii) For both profiles, the highest Au concentrations occur between 0.5-0.8 m and there is only a weak association between Au and Ca; profile samples from 0.0-0.1 m (Figure 6.16C) are below detection (<5 ppb).

(iv) Beneath the top 2 m of sediments and upper (ferruginous) saprolite there is a zone poor in Au (<10 ppb). However, Au contents of mineralised deeper saprolite exceed 500 ppb.

(v) For 0.05-0.15 m soils, Au was anomalous (>10 ppb) but not related to carbonate above mineralisation (Figure 6.16B).

(vi) Deeper grab samples (up to 0.8 m depth) taken from shallow soil pits over mineralisation were richer in Au compared to the surface soils (up to 37 ppb) but were not related to carbonate.

Interpretation of the geochemical results for Au is equivocal. Although there is some suggestion that higher Au concentrations in the soil may be related to shallowly buried mineralisation, on a broader local scale (including Argo), these results do not appear to be significant. Augering the top 1-2 m is the best practical sampling technique for collection of the calcrete, although this, in itself, is not effective in detecting mineralisation in this environment. The presence of recently deposited and variably thick sandy material in the Apollo area makes it difficult to locate the calcrete.

(13) Argo, Kambalda, WA (Lintern and Gray 1995b)

General information on the location, climate, vegetation and mineralisation of the Argo Gold Deposit is given in the Apollo case study. Argo is located about 500 m SW of the Apollo prospect and has thicker overburden and greater depth to mineralisation than the latter. The Argo deposit is situated on the side of an EW palaeochannel, which has a maximum depth of 60 m and average width of 400 m. The channel has been incised into a residual regolith profile of variably coloured, clay-rich saprolite. The saprolite is generally 20-30 m thick, but is thinner beneath the palaeochannel. As with Apollo, the Archaean stratigraphy has been blanketed by transported material. Primary and secondary mineralisation is confined to bedrock, saprolite and the unconformity between these and the transported material, where it appears to follow the palaeotopography downslope and along the base of the palaeochannel (Figure 6.16A). Hence, the depth to mineralisation is variable but generally commences at the Archaean-Tertiary unconformity (20-30 m depth), deepens laterally and is continuous to the base of the adjacent palaeochannel.

Seven sedimentary units infill the palaeochannel, the upper three of which appear to blanket the entire region and are as at Apollo: a red and grey clay, a clayey sand and a sandy drift, with the latter two units being variably calcareous. The four units confined to the palaeochannel consist of mottled lacustrine clays (10 m thick), consisting of kaolinite and quartz, with secondary accumulations of goethite and hematite. These overlay approximately 15 m of spongolite, consisting of pale silts and siliceous sponge spicules, about 30 m of grey clays containing carbonaceous woody fragments and lignite and, finally, a basal unit of fluvial gravels, sand and lignitic silts, up to 16 m thick.

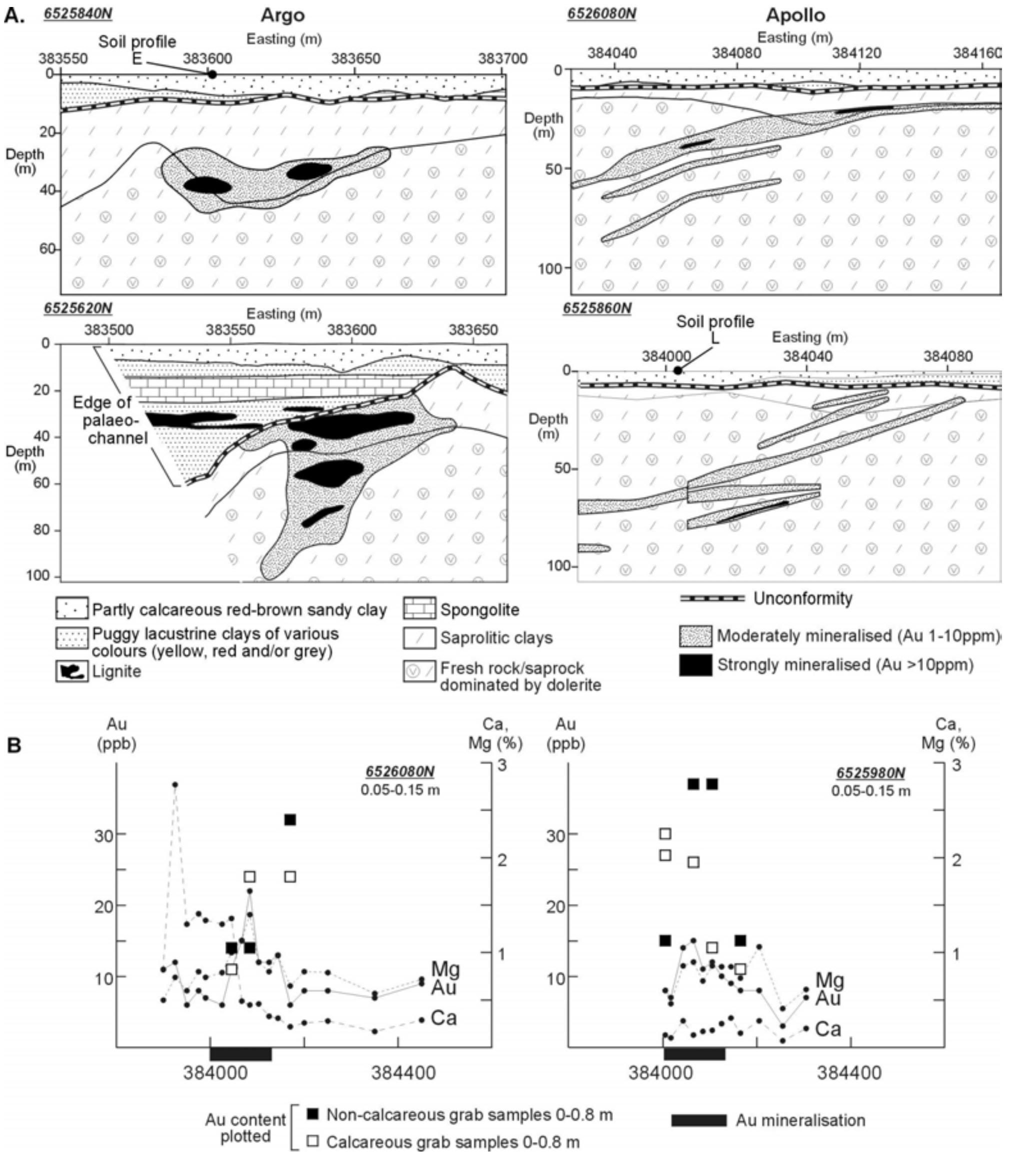


Figure 6.16: Geochemistry and regolith stratigraphy at Argo and Apollo (WA). A) Geological sections showing distribution of Au mineralisation. B) Geochemical traverses for soil (0-0.15m) and deeper grab samples.

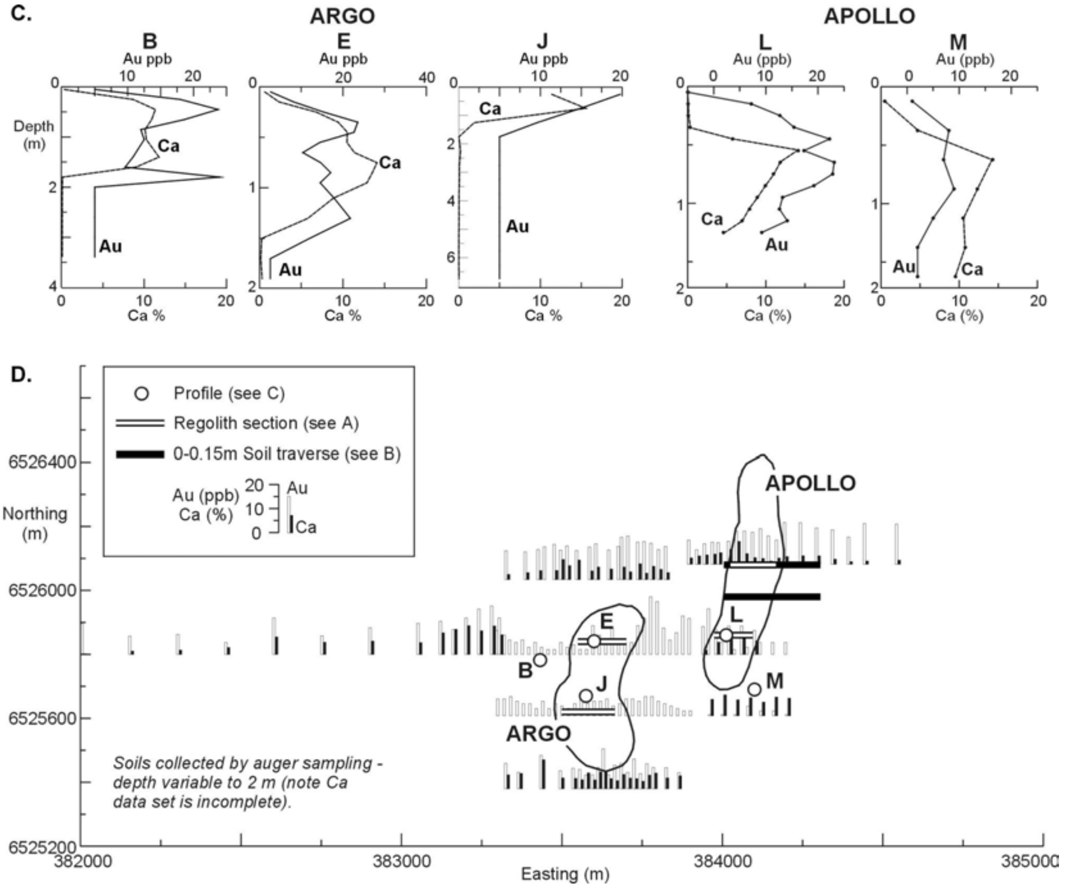


Figure 6.16 (continued): Geochemistry and regolith stratigraphy at Argo and Apollo.
C) Geochemical profiles for soil. D) Plan showing location of traverses with geochemistry, mineralisation and sections.

The distribution of Au in the soil at Argo does not appear to be related to underlying mineralisation. There are no significant differences in the distribution characteristics, or total Au content, between mineralised and background areas. The Au concentrations in the soil profiles are generally less than 10 ppb, with maxima occurring between 0.3-0.5 m (carbonate, max 23 ppb), and 1.2-1.8 m depth (Mn-rich horizon, max 24 ppb) (Figure 6.16C). The latter horizon has also scavenged As, Co, Mo, Sb, W and REE (Lintern and Gray 1995b). The Au in the top 2 m of the soil at Argo is generally associated with Ca-Mg carbonates (Figure 6.16D).

Augering the top 1-2 m remains the best regional sampling technique for collection of material containing the highest Au concentrations, although its use for detecting underlying mineralisation is not effective. The greater depth to mineralisation and the complex sediments that overlie it may prevent any Au from migrating to the surface at Argo unlike at Apollo. However, as at Apollo, the interpretation is equivocal and more samples need to be analysed.

(14) Safari (Mt Celia), Lake Raeside, WA (Bristow *et al.* 1996b)
The Safari Gold Prospect is located 200 km NNE of Kalgoorlie and 9 km NE of the margin of Lake Raeside, close to the Menzies Line. The climate is semi-arid with mean annual rainfall of 225 mm. Rain falls variably throughout the year, resulting from frontal systems in winter, or convectional storms and cyclone-related depressions in summer. The vegetation is medium to dense woodland of *Acacia* with minor *Eucalyptus*. Safari is situated on a broad, sandy, colluvial valley that slopes gently to the SW. As for Golden Delicious, three regional surface regolith units can be delineated by Landsat TM imagery. These consist of dominantly post-Archaean sediments covering over 85% of the region, residual Archaean units, and ferruginous materials developed in both the Archaean units and the post-Archaean sediments.

The Safari Prospect lies within the southern extension of the Laverton Tectonic Zone, part of the Archaean Wiluna-Norseman belt. The bedrock geology consists of a greenstone assemblage composed of a wide variety of volcanic and volcaniclastic rocks. These rocks are heterogeneously deformed and generally strike NNW. Regionally, the greenstone sequence has been metamorphosed to lower greenschist facies, but alongside large plutons of intrusive porphyritic syenite, coarse granodiorite and adamellite, the greenstone sequence has been metamorphosed to amphibolite facies. Drilling to date indicates a resource of 1.08Mt at 3.3g/t Au. The mineralisation is hosted by andesite to dacite metavolcanic rocks, now largely represented by quartz-chlorite-sericite ± carbonate schists. They are bound to the W and E by serpentinised komatiite and talcose schists. Gold is primarily associated with quartz veins within an anastomosing shear. Anomalous Au occurs in the saprolite just below the unconformity, especially where it directly overlies primary mineralisation (e.g. 1200 ppb in a quartz vein from the top two metres of the saprolite). The top metres of saprolite give is strongly anomalous over mineralisation (1000 ppb), compared to an elevated and noisy local background of 10-50 ppb Au (Figure 6.17A).

The palaeosurface is much steeper and more variable than the present land surface (Figure 6.17C). The most prominent features of the palaeosurface are a palaeohigh that meets the present land surface, and a valley draining W in the northern part of the area. The study area is completely blanketed by transported overburden, except for the small area coinciding with the palaeohigh where Archaean rocks outcrop. There is a uniform distribution of sheetwash and aeolian sand up to 1 m thick at the surface. The composition and thickness of the sediments, including the sheetwash, varies. Generally, the sediments are 5-10 m thick, reaching 20 m in the northern palaeovalley. The sediments below the sheetwash are a polymictic assemblage containing 2-10% coarse material in a matrix of sand, silt and, locally, clay. The coarse fraction commonly occurs towards the base and is comprised of angular, weakly weathered rock fragments over most of the area, including near the mineralisation. However, in the northern palaeovalley, there is a mixture of ferruginous pisoliths, nodules and lithorelics. Locally, drilling has intersected narrow lenses of coarse alluvial sand and gravel. Post-depositional modification of the sediments is widespread; most significant is the widespread calcification from about 0.5-5.0 m below the surface. Mottles of carbonate, a few tens of millimetres in diameter, occur only 0.2 m below the surface, but the carbonate morphology below 1 m depth is uncertain (probably as coatings) because the only samples are drill cuttings. Beneath the zone of intense calcification, silica and Fe oxides commonly indurate the sediments, moderately to strongly. Most of the residual regolith consists of saprolite with variable clay content, although in isolated areas in the N of the prospect, there are deep profiles with highly ferruginous upper horizons. Incipient mottling is present throughout the saprolite and the upper few metres are commonly indurated by silica and/or carbonate. Fresh rock is generally encountered 10-20 m below the unconformity. The bedrock is reasonably fresh where it subcrops, but it is subject to the same calcification as that of the upper few metres of the sediments. Calcium carbonate causes the brecciation of the subcrop and the upper few metres contain large (to tens of cm) nodular structures.

Anomalous Au (22-60 ppb) is present in the carbonate horizon, with enrichment strongest from 0.5-2.5m depth directly over mineralisation (Figure 6.17B). Concentrations of Au (over 7 ppb) above background occur in the calcareous horizon for 800 m across strike of the mineralisation. Using a cyanide leach for Au with a low detection limit (0.04 ppb), an anomaly in the top half metre, with excellent contrast, peaks directly over the primary mineralisation with concentrations exceeding 5 ppb for over 600 m across strike. Despite higher absolute Au contents within the calcrete horizon, preferentially sampled highly calcareous fragments do not increase anomaly contrast, and the Au/Ca ratio in these is consistently lower than a bulk sample from the same interval. The Au anomaly associated with carbonate at Safari accurately reflects mineralisation, with optimum sampling between 0.5 and 2.5 m depth.

The Safari case study is a convincing example of anomalous Au in calcrete within transported overburden above mineralisation. The continuous nature of the anomaly from mineralisation through about 5 m of transported units and into the calcrete has not been recorded elsewhere. Further examination of the anomaly with analyses of samples from adjacent sections is recommended to examine the shape of the anomaly in three dimensions. The anomaly has probably been formed from a combination of bioturbation, capillarity and possibly re-cycling through vegetation.

(15) Kanowna Belle, Kalgoorlie, WA (Anand *et al.* 1993)

The Kanowna Belle Gold Deposit is located about 18 km NE of Kalgoorlie. The Kanowna district forms part of a belt of NNW-trending metamorphosed ultramafic, mafic, sedimentary and felsic volcanic, and intrusive rocks of the Norseman-Wiluna Belt. The deposit is contained within a package

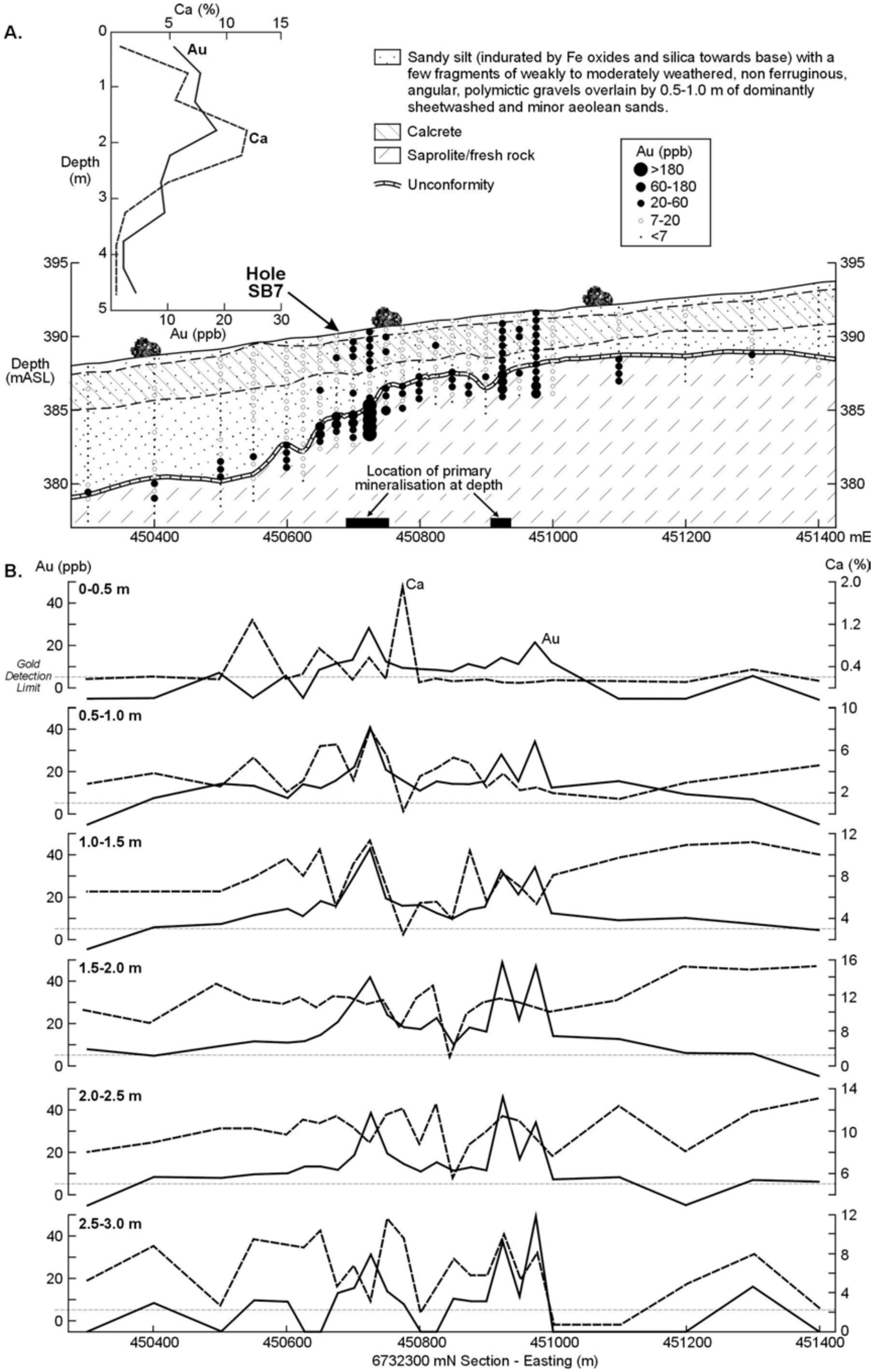


Figure 6.17: Geochemistry and regolith stratigraphy at Safari Bore, Mt Celia (after Bristow *et al*. 1996b).

A) Section showing distribution of regolith materials and Au; inset shows a geochemical profile generated from the data displayed in the section.

B) Geochemical profiles for different depths.

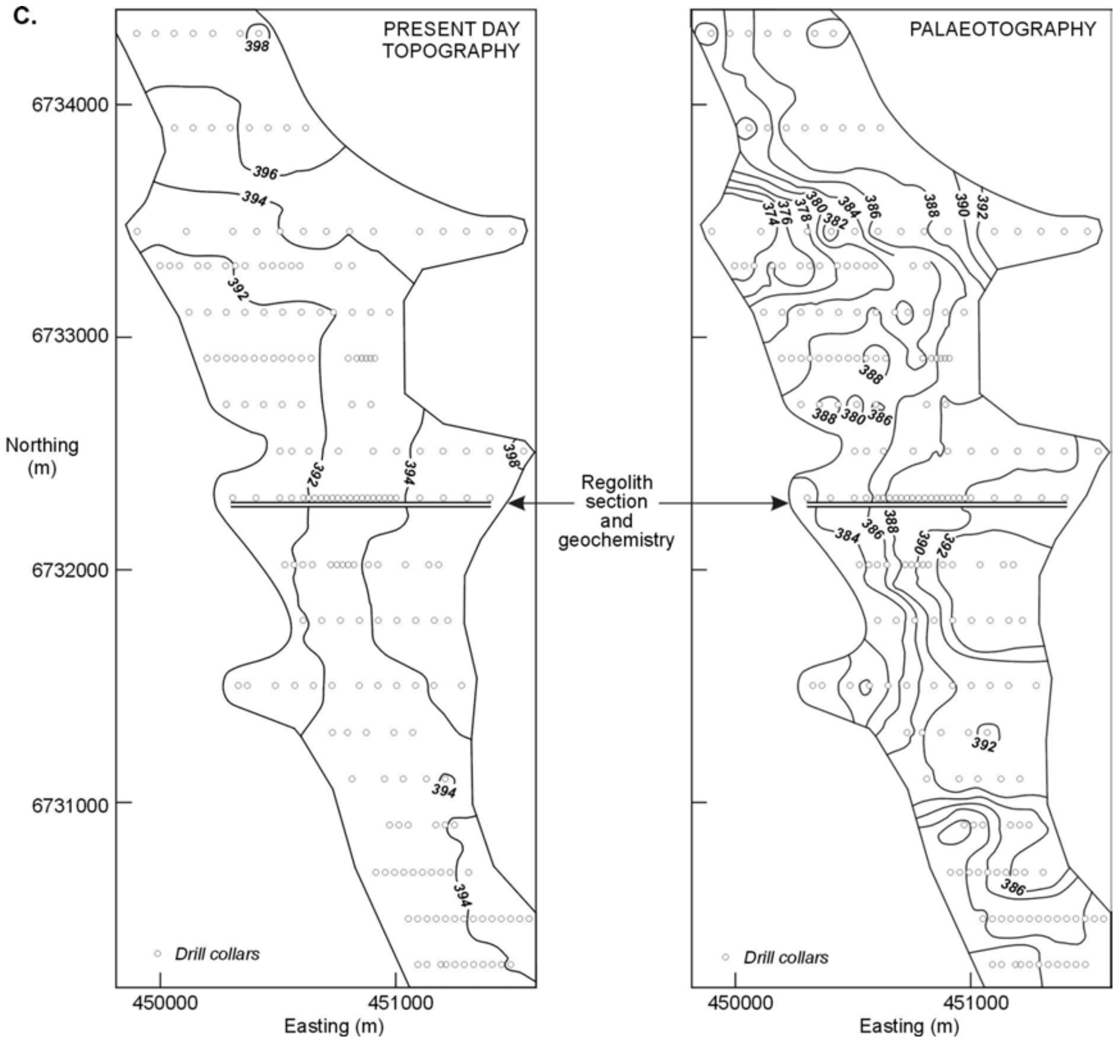


Figure 6.17 (continued): Geochemistry and regolith stratigraphy at Safari Bore, Mt Celia.
C) Section showing distribution of regolith materials and Au; inset shows a geochemical profile generated from the data displayed in the section.
D) Geochemical profiles for different depths.
E) Plan showing topography, palaeotopography and regolith section.

of NE trending, S dipping, predominantly intermediate to felsic, volcanic-derived tuffaceous mass flow units and breccias. The total resource at Kanowna Belle is 15 Mt at 5.3 g/t to a depth of 650 m (Thomson and Peachey 1993).

Kanowna Belle lies on the edge and beneath a depositional plain within a major N flowing drainage basin (Figure 6.27A). Pale orange, calcareous clay soils containing abundant black ferruginous granules form a 0.2-1 m thick mantle. Calcrete, 2 to 5 m thick, occurs as coatings on, and as soft aggregates within, the clay. Acid red clay, largely devoid of carbonate, underlies the calcareous soils and also contains abundant ferruginous granules. A mottled zone occurs at depths generally greater than 2 m. A zone of silcrete, 1 to 8 m thick and preferentially developed from the weathering of grits and feldspar porphyry, marks the base of the mottled zone above bleached saprolite; it is anomalous in Au. The silcrete is strongly silicified, commonly with a conchoidal fracture and a vitreous lustre; the transported-in situ boundary is located immediately above or within the silcrete. Beneath this zone, leached or barren saprolitic clays 20 to 50 m thick occur above mineralised bedrock. Supergene Au mineralisation is significant, with a well-developed horizon (>0.1 ppm Au) 1-4 m thick and up to 200 m wide at the base of the saprolite (35-45 m below surface); smaller (<20 m wide) pods of supergene mineralisation (<0.1 ppm) occur closer (5-12 m) to the surface.

Two traverses across mineralisation were investigated (Figure 6.18B). Ferruginous granules (highly ferruginous, hematite-rich, vitreous, hard pellets up to 5 mm in diameter) and the soil above mineralisation are anomalous in Au, Sb, As and Ce. Gold concentrations in soil (mean 90 ppb), are

10-20 ppb higher than those in the ferruginous granules extracted from the same soil (Figure 18A). Gold concentrations in the top metre range from 17 to 230 ppb and are normally in excess of 60 ppb. There is a considerable decrease in Au concentrations in samples collected from 2-3 m. The observed peak Au concentration within the calcrete conforms well to the sub-surface position of the major ore shoots (Figure 6.18C).

The appearance of anomalous Au in calcareous soils above mineralisation concealed by relatively thin sediments is not surprising. However, the strength of the anomaly (maximum >200 ppb Au) is unusual. The source of the Au may be the underlying ore body (located at 50 m depth) or more possibly from the Au enrichment in the silcrete and/or relict Au in the upper saprolite. However, the limited scope of the study does not preclude the possibility of the Au being laterally derived from upslope.

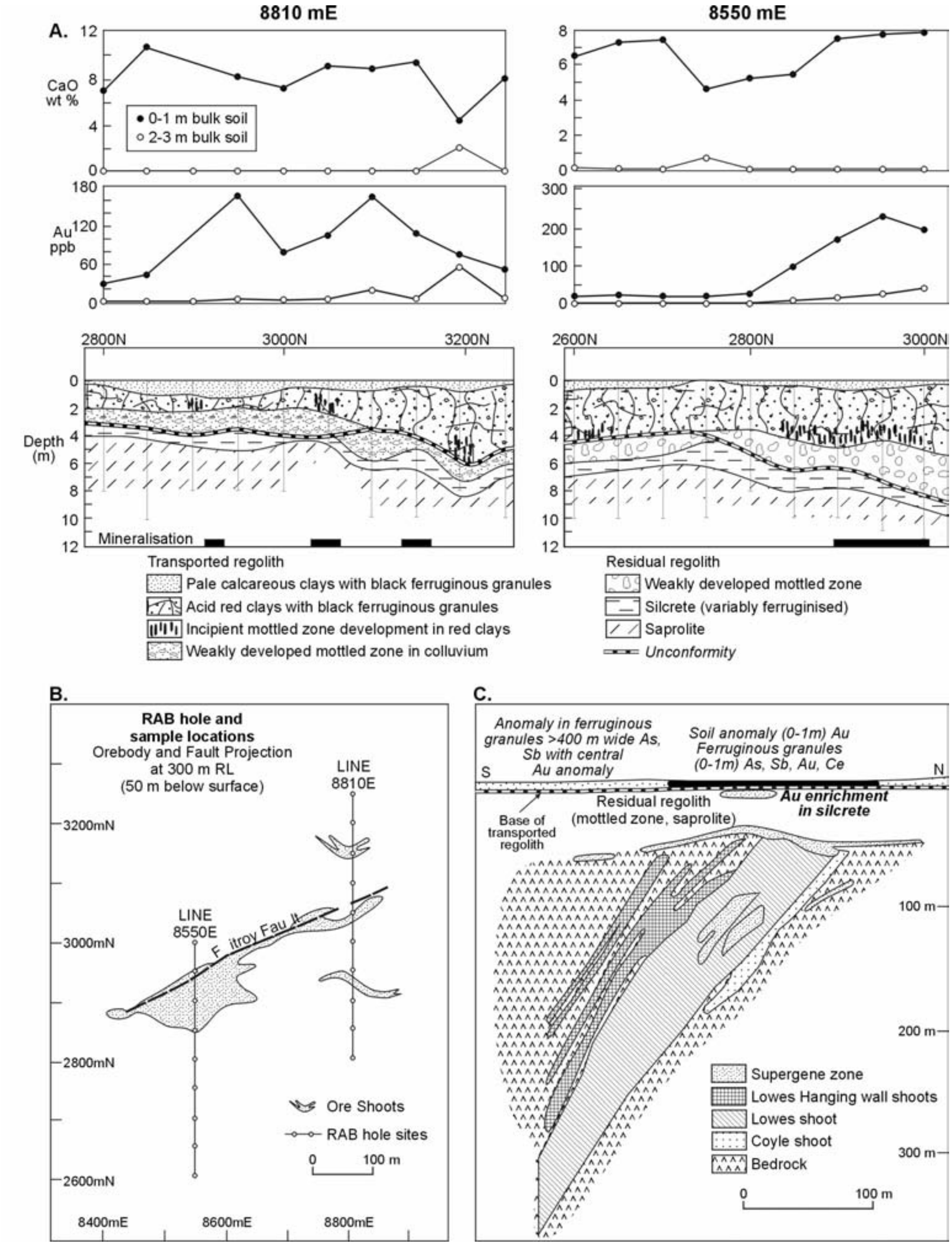


Figure 6.18: Gold distribution and stratigraphy of the Kanowna Belle Gold Deposit (after Anand *et al.* 1993).

A) Geochemistry and regolith section for the two sampling traverses.

B) Location of sampling traverses with respect to mineralisation.

C) Cartoon showing geochemical halo above mineralised shoots.

(16) Matt Dam, Kalgoorlie, WA (Anand *et al.* 1993)
The Matt Dam Gold Prospect is located about 55 km NW of Kalgoorlie and 4 km from the Zuleika Sands Deposit. Primary mineralisation is hosted by NW trending high-Mg basalts and komatiites with bands of intermediate to felsic tuffs and sedimentary rocks (Harrison *et al.* 1990). A 0-1 m soil survey over the area on a 200 by 50 m grid outlined a 3 km wide NW-trending 30 ppb contoured Au anomaly. Two lines, 7400N and 7700N, were investigated.

Matt Dam is located partly in erosional (Type B) and partly in depositional (Type T) regolith regimes. In the erosional areas, the surface is mantled by a coarse, irregular, yellowish-brown to reddish-brown, residual lag derived from ferruginous saprolite. The top 0.5 m consists of pale, orange, calcareous, sandy, clay soil containing saprolite fragments. Carbonates occur as coatings, and as nodules within the clay. The calcrete nodules are composed of irregular, pinkish material, varying from 1 to 5 cm in diameter, enclosing partially to completely replaced ferruginous saprolite fragments and hardened mottles. Saprolite occurs at depths generally >0.5 m. In depositional regimes, a black lag of ferruginous granules mantles the regolith. Fragments in this lag are generally <0.1 m in diameter and range from sub-rounded to irregular. Calcareous soils are up to 1 m thick and contain varying amounts of carbonate nodules and ferruginous granules. On 7400N, a 16 m deep palaeochannel was identified with a white, kaolinite-rich, bleached clay zone extending to 25 m under the channel (Figure 6.19). The stratigraphy of the channel consists (from the surface) of (i) calcareous clays, (ii) acid, kaolinitic, red clays with mottles, and (iii) smectite-rich puggy grey clays containing hardened mottles and fine ferruginous granules. The stratigraphy along 7700N is more complex (Figure 6.19). It has several zones of transported clays with mottling crossing the unconformity into the saprolite. Underlying interbedded tuffs, dolerites, ultramafic rocks and shales dip near-vertically to the E. Zones of white, bleached clays are evident under transported clays containing hardened mottles.

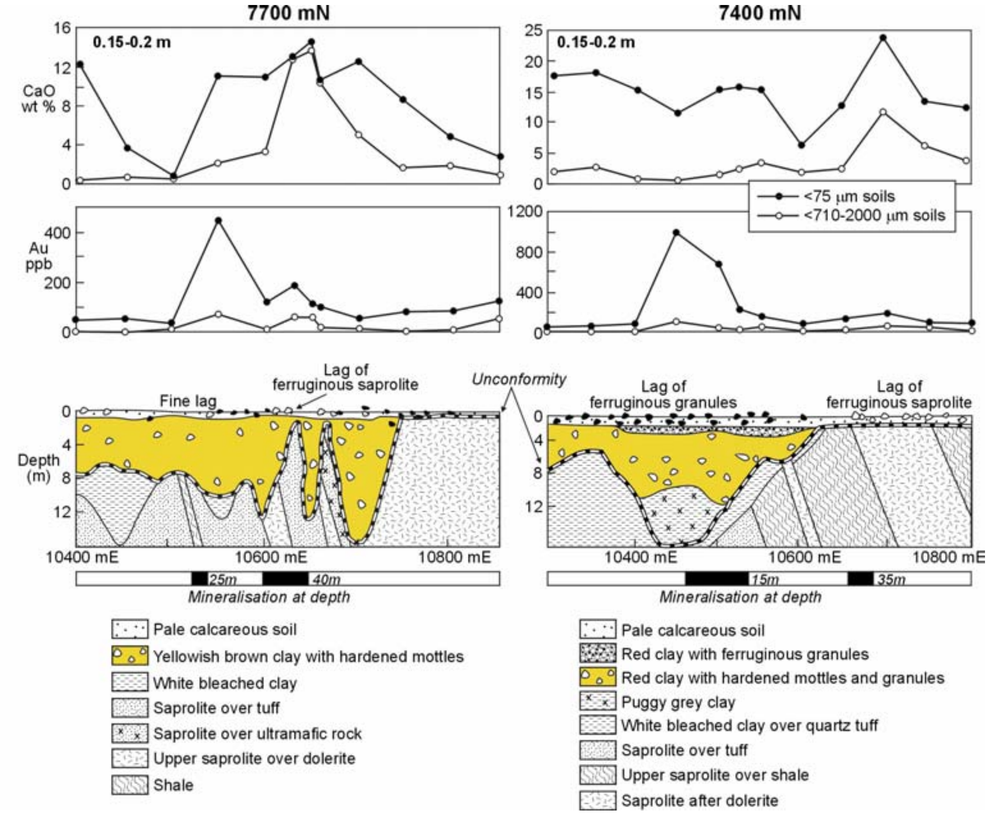


Figure 6.19: Matt Dam Gold Prospect showing Au distribution and regolith (after Anand *et al.* 1993).

High concentrations of Au in surficial materials occur on both traverses. In the palaeochannel area, where mineralisation occurs at 15 m depth on 7400 N, Au concentrations peak at 1010 ppb in the calcareous fine (<75 (m) fraction (Figure 6.19). Calcareous nodules themselves have a maximum of 160 ppb Au. Gold is also present in ferruginous granules over the palaeochannel and the saprolite, but in much lower concentrations. Gold concentrations are much weaker over the saprolite where mineralisation occurs at 35 m depth. For the fine calcareous soil on 7700N, Au concentrations appear to be higher (450 ppb) over the weakly mineralised area (740 ppb at 20 m) compared with the stronger mineralised area (150 ppb over a maximum 8 ppm at 40 m). Gold was not detected in ferruginous granules. More data on adjacent sections would assist with the interpretation of the origin of the Au in the soil.

(17) Golden Delicious, Lake Carey, WA (Bristow *et al.* 1996a)
The Golden Delicious Deposit is located 50 km S of Laverton and north of the Menzies Line. The climate is semi-arid with an annual rainfall averaging 200-250 mm. Vegetation in the area consists of sparse to dense woodland of *Acacia*, with an understorey of smaller shrubs of *Acacia*, *Cassia* and *Eremophila* (poverty bush). Golden Delicious is situated on a broad colluvial plain, and the present land surface slopes very gently towards the NW (Figure 6.20A). Three regional surface regolith units were delineated by Landsat TM imagery. These consist of dominantly post-Archaean sediments covering over 85% of the region, residual units derived from Archaean bedrock, and ferruginous materials developed in both the Archaean units and the post-Archaean sediments.

The Golden Delicious Deposit is in the Archaean Norseman-Wiluna greenstone belt, in the southern part of the Laverton Tectonic Zone. The region comprises variously faulted, folded and metamorphosed greenstone sequences intruded by granites. Gold mineralisation is hosted by volcaniclastic "greenschist" rocks on the western margin of a suite of granitoids that intrude intermediate to mafic volcanic rocks. The resource is estimated at 6.1Mt @ 1.3g/t Au. The main mineralised unit begins at about 20 m depth, about 5 to 10 m below the unconformity between the Archaean and the Cainozoic sediments, where there is also minor enrichment in Au.

The sediments are poorly-sorted, polymictic colluvium-alluvium consisting of clay, silt and gravels that generally become coarser with depth. The colluvium-alluvium can be divided into three units:

1) T1: Calcareous, hardpanised silty clays, 3-5 m thick, that are strongly indurated with silica, carbonates and Fe oxides. Secondary carbonate occurs as thin sub-horizontal laminar material and Mn oxides are present as dendritic coatings.
2) T2: A variable unit, 3-6 m thick, dominated by fine-grained sediments. Ferruginous gravels are more common than in the upper unit, and it is less strongly indurated by silica and Fe oxides. Carbonate is present, mostly as irregular masses up to 40 mm in diameter.
3) T3: The lowermost unit, up to 10 m thick, is below the watertable. It contains 25% coarse material consisting of: abundant ferruginous gravels; pisoliths and nodules which are mostly broken and abraded; and minor quartz and lithorelics, some of the later being almost fresh. Maghemite is common in the pisoliths and the upper few metres of this unit, particularly in the NE, have minor amounts of concretionary goethite, apparently formed in situ.

The sediments (transported overburden), ranging from 9-16 m in thickness, lies over a mottled zone (Figure 6.20B) and, locally, directly over saprolite. A clay-rich saprolite merges into less clay-rich saprolite between 30-50 m depth, and fresh rock is usually encountered at about 70 m depth. The weathered Archaean bedrock has a mottled zone, characterised by large (up to 200 mm diameter) hematite-rich mottles overprinting clay-rich saprolite.

The palaeotopography at the Golden Delicious Deposit, like the modern day topography, slopes to the NW but at a much steeper and more variable gradient (Figure 6.20A). Much of the transported overburden is probably derived from the greenstone uplands 5-10 km ESE. It is possible that widespread lateritic profiles once existed there, as the sediments at Golden Delicious resemble, in reverse order, the materials of such profiles.

The results of a geochemical study of the drill cuttings indicate that the basal ferruginous gravels of the lowermost sedimentary unit provide the greatest target enlargement of any sample medium at the Golden Delicious Deposit. Gold concentrations up to 107 ppb occur 400 m across strike, offset slightly downslope (Figure 6.20). Shallower sediments have much lower Au contents (less than 5-12 ppb). Gold concentrations of 12-81 ppb in the upper few metres of residual regolith occur 300 m across strike but are not offset. The Au content of the weathered Archaean increases with depth, due to either depletion from the upper part of the zone, or to the original primary distribution. The solubility of Au and the presence of dissolved Au in the groundwater (Bristow *et al.*, 1996a), suggest depletion may have occurred. Although calcrete occurs throughout the top 6 m of the transported overburden, there is no consistent association with Au, however, in some holes (002, 004, 008, 009, and 011), there is a weak carbonate-Au association in the top 2-3 metres.

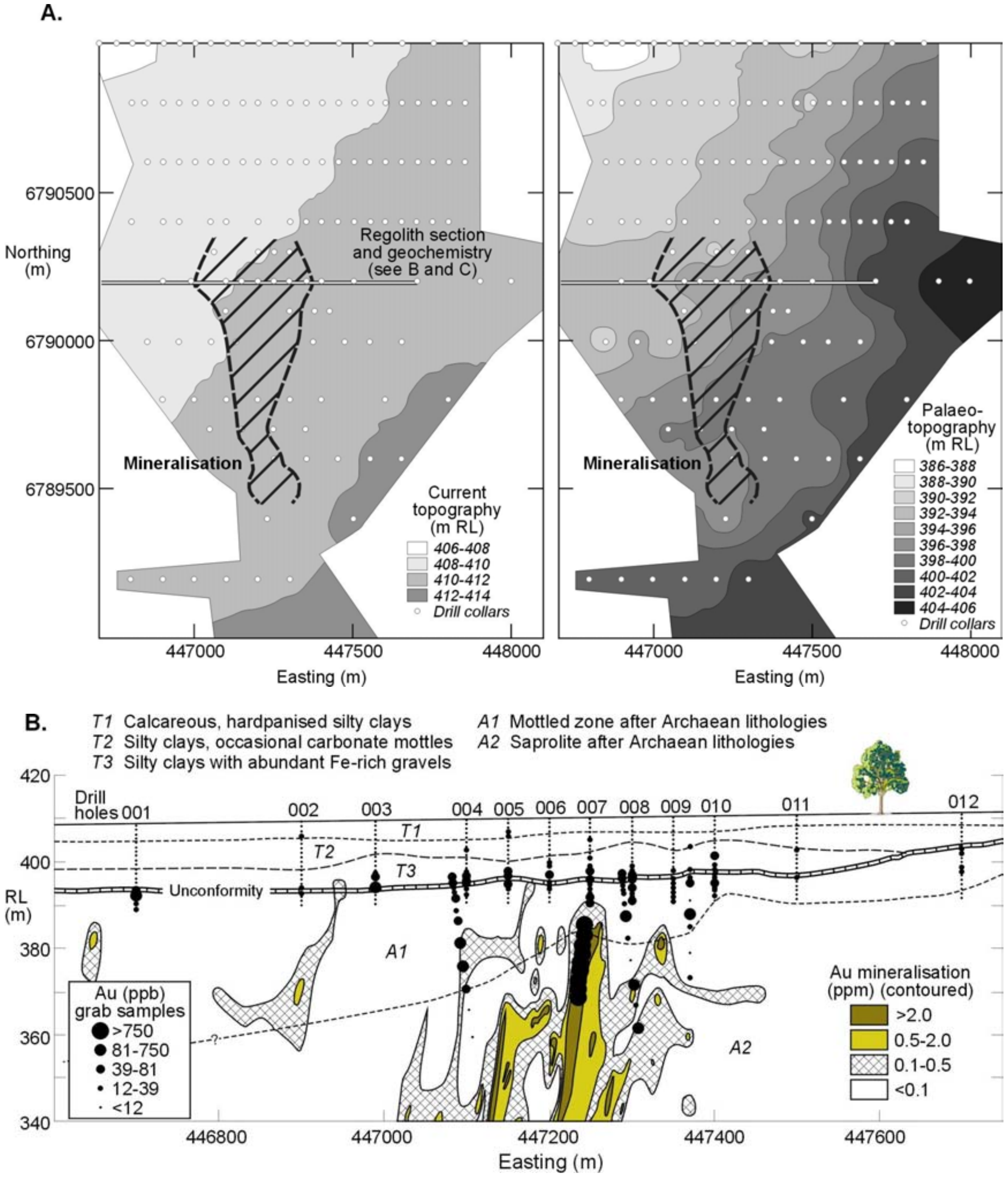


Figure 6.20: Regolith and geochemistry of the Golden Delicious Gold Deposit (after Bristow *et al.* 1996a).
A) Topography, palaeotopography and location of the sampling and regolith section.
B) Regolith section.

(18) Deep South Gold Deposit, Mount Gibson, WA (Madden 1996)

The Mount Gibson gold deposits are approximately 300 km NE of Perth, WA, in the Retaliation Greenstone Belt, Murchison Province. They lie at an elevation of 300 to 360 m on a regional divide between the Lake Moore and Lake Monger saline playa systems. The climate is semi-arid with an average rainfall of about 250 mm, most of which falls in winter. Vegetation is dominantly thickets of *Acacia* over areas of granitoid rocks and sandplain, with *Eucalyptus* woodland communities over finer-textured soils of the greenstone rocks (Anand *et al.* 1989). Deeply weathered profiles capped with laterite are widespread throughout the region with partial erosion and stripping leading to widely distributed lateritic detritus, and exposure of bedrock on hillslopes. Primary mineralisation at Deep

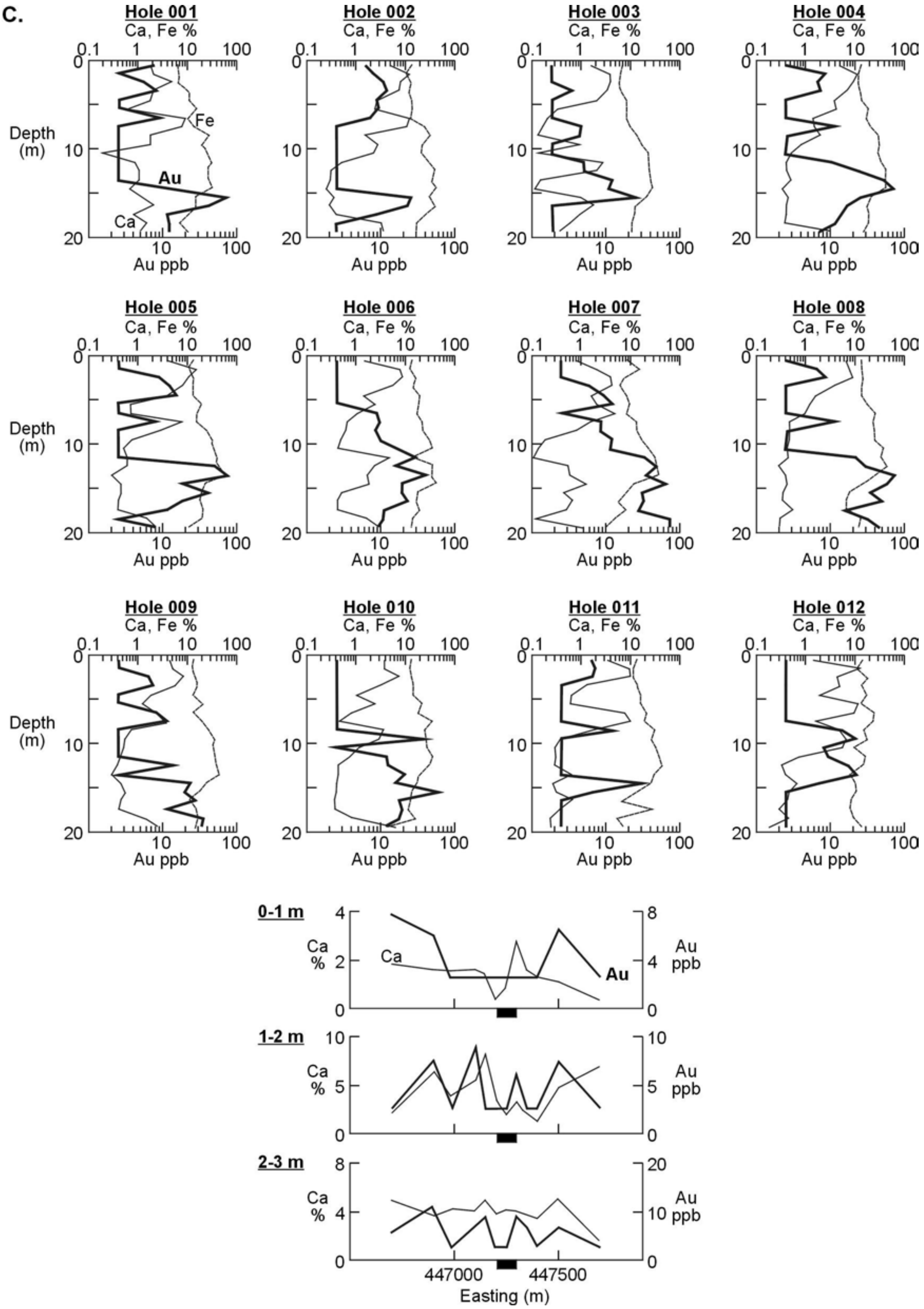


Figure 6.20 (continued): Regolith and geochemistry of the Golden Delicious Gold Deposit.
C) Selected geochemistry of drill holes.

South is hosted in felsic schists with some associated base metals probably associated with an earlier volcanogenic massive sulphide-mineralising event. Secondary Au mineralisation is present as a result of deep weathering and re-mobilisation of Au into the saprolite and during the formation of the laterite.

The Deep South regolith stratigraphy is comprised of two units (Figure 6.21A and B):

1) Sediments 10 to 15 m in thickness consisting of quartzo-feldspathic colluvium set in a kaolinite matrix becoming mottled with depth. They are capped with a siliceous and partly-calcareous red-brown hardpan a few metres thick. The sediments thin towards low hills of outcropping granitoid saprolite from which they are probably derived.
2) Saprolite, partly silicified and/or mottled in its upper portion, overlying variable lithologies including schistose mafic and felsic types and pegmatitic granitoids.

Despite the presence of 10-15 m of transported material, exploration data indicate that Au concentrations up to 360 ppb are present in near-surface materials (Madden 1996). Two profiles had Au concentrations over 250 ppb in calcareous hardpan. Separations of material from the hardpan indicated that the highest concentrations of Au were found in the carbonate but were not restricted to it (Figure 6.21).

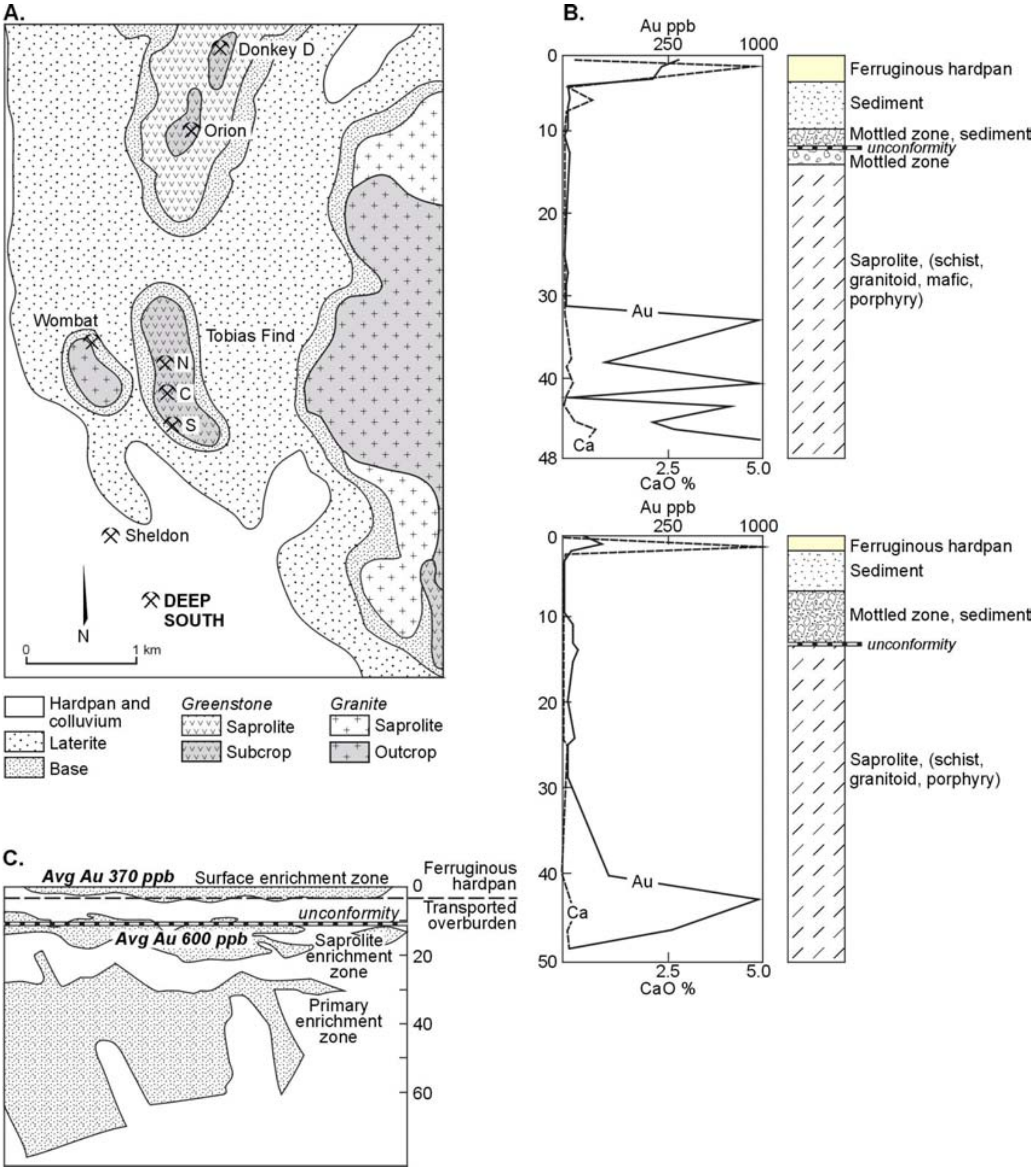


Figure 6.21: Regolith and distribution of Au at the Deep South Gold Deposit (after Madden 1996). A) Regolith map of the Deep South area. B) Regolith and geochemistry for two sets of drill hole samples from over mineralisation. C) Cartoon showing Au distribution.

The study was limited in terms of the number of samples taken and the absence of a systematic survey of the geochemistry of the hardpan over the area. However, the granitic nature of the overburden sediments, deriving from the NE rather than the auriferous laterite found directly along strike to the N, suggests the Au in the overlying calcareous hardpan may be derived from the underlying mineralisation. Madden (1996) suggested that the Au was derived from the underlying mineralisation (Figure 6.21C) via a mechanism that involved higher water tables and re-mobilisation and re-precipitation of the Au. While this may be a plausible explanation, more data on adjacent sections would assist with the interpretation of the origin of the Au and whether it, in anyway, may have originated from upslope.

Table 6.1: Element concentrations in a variety of regolith materials.

Element	Hardpan	Manganese oxide	Nodular carbonate	Laminar carbonate
Au (ppb)	137	52	200	40
Cu (ppm)	24	22	2	13
Ni (ppm)	46	53	5	39
Pb (ppm)	27	42	9	22
Zn (ppm)	18	18	8	18

(19) Panglo, Kalgoorlie, WA (Lintern and Scott 1990, Lintern 1996b)

The Panglo Gold Mine is located 30 km N of Kalgoorlie (WA). The climate is semi-arid with mean annual rainfall of 280 mm. The diversity and abundance of the vegetation are largely determined by the characteristics of the soil. Salt- and drought-tolerant species, e.g. *Maeriana* and *Atriplex*. (<0.5 m in height) with minor *Eremophila* (up to 2 m) dominate the clay-rich soils of the broad valley floor to form an open shrubland. Where soils are thin, the vegetation is sporadic and the total biomass is low. Tall *Eucalyptus* trees (up to 20 m) with an understorey of *Eremophila* (1-2 m) form open woodland over gravelly soils but are absent in the broad valley floor. There is a sharp transition between these two vegetation communities reflecting the different soil types, although individual examples of plant species occur sporadically in both communities.

The Panglo Gold Deposit is located within a 200 m wide sequence of steeply W-dipping carbonaceous shales and mafic to ultramafic volcanic rocks, within a major shear zone (Figure 6.22A). Mineralisation occurs as a relatively flat-lying, supergene deposit, up to 16 m thick between 30 and 55 m depth, over a 1 km long, N-trending zone. Underlying primary mineralisation is associated with disseminated pyrite and arsenopyrite within strongly sheared and carbonated shales and mafic volcanic rocks. Panglo was discovered in 1987, but mining did not commence until late 1994. The mineable reserves are 1.5 Mt at 2.7 g/t Au.

Most of the Panglo deposit has a covering thin (<1 m), weakly ferruginous-calcareous soil, commonly with a transported component, overlying a mottled clay and 35-40 m of leached kaolinitic saprolite, locally containing alunite. In bedrock, potassic (muscovite-rich) rocks occur with primary mineralisation. Laterally, the wall-rocks have paragonite and muscovite, instead of muscovite alone. At the southern end of the deposit, the saprolite has been eroded and is partly overlain by a palaeochannel containing up to 10 m of sediments. The soils over the Panglo deposit may be divided into two main groups:

1) Gravelly soils. These occur in high areas of the landscape (relief of 10 to 20 m) including those overlying the known southern limits of mineralisation, and are developed on sediments in a palaeochannel of presumed Tertiary age. The soils consist of an organic surface horizon containing Fe-rich gravels in a sandy matrix. Beneath this, the regolith is characterised by unconsolidated, locally-derived, Fe-rich, rounded to sub-rounded ferruginous nodules (mottled clay), varying in size from a few mm to several cm in diameter, in a sandy to loamy matrix to 2 m overlying silty clays. In certain areas, saprolite limits soil depth to a few centimetres.
2) Clay-rich soils. These are dominant in the axis of the present broad drainage that covers the northern and central sections of the deposit. They consist of a veneer of sandy loam overlying pale grey to yellow, homogeneous clays and clay-rich saprolite; saprolite is visible in shallow trenches (<1 m depth) over the deposit. Blocks of weathered rock are common within the soil profile and are either pale (clay-rich) or red (Fe-rich). Towards the S, the soils become increasingly saline as the drainage nears a playa.

Pedogenic carbonates are present in both soil types to 1 to 1.5 m depth. They are disseminated through clay-rich soils, as friable fragments and veneers on the ferruginous nodules in unconsolidated Fe-rich material, and as coatings, up to several mm thick, on indurated, shallow subcrops of saprolite.

Gold and Ca are highly correlated in soils developed over the palaeochannel (now partly a topographic high) suggesting Au has been hydromorphically mobilised (Figure 6.22D). The peak Au concentration in the soil (0-1 m, 160 ppb) appears to be accurately located above the supergene mineralisation found beneath 10 m of barren transported sediments and 30 m of poorly mineralised saprolite. However, there are also enrichments of Au (i) at the unconformity between the transported

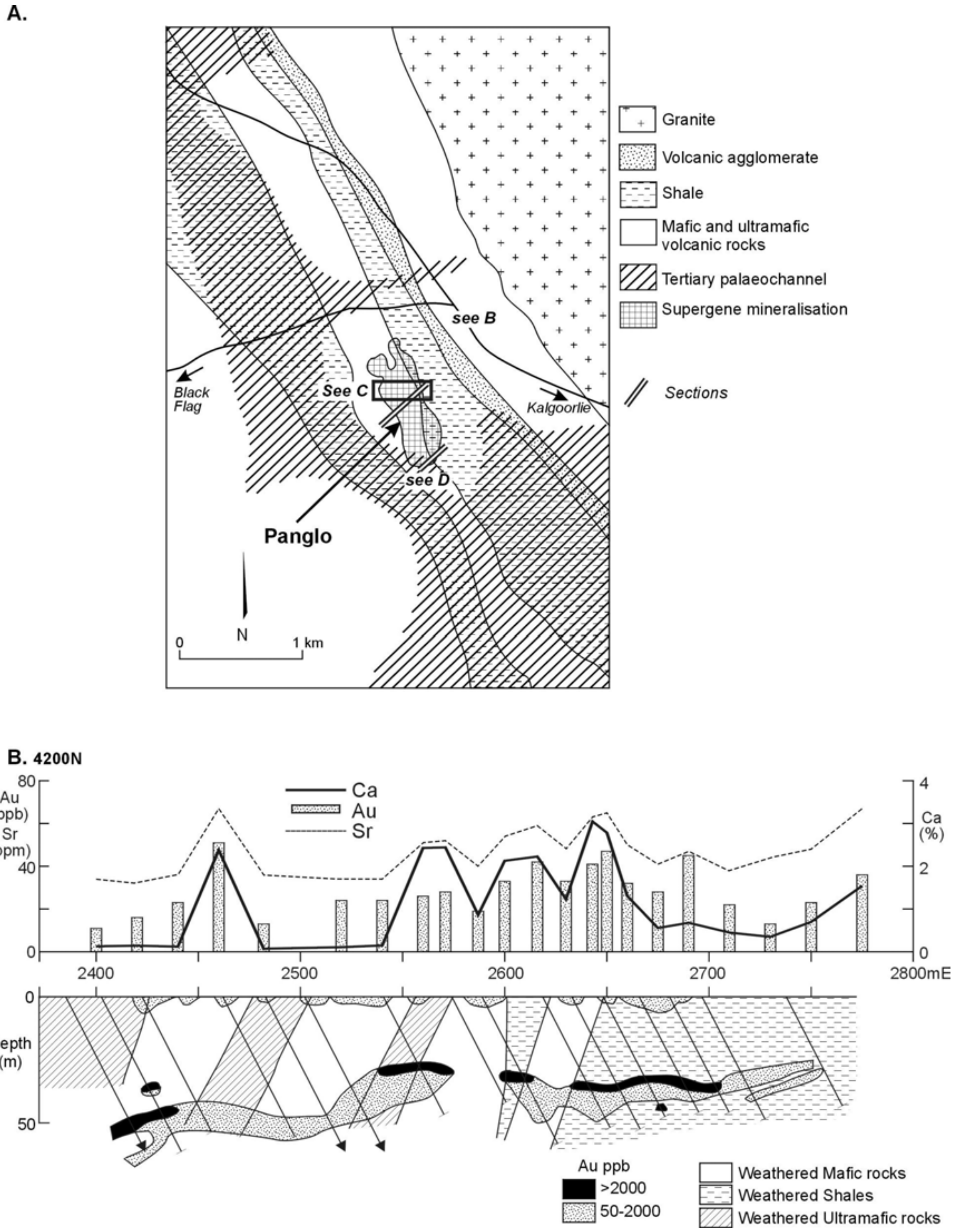


Figure 6.22: Geochemistry and geology at Panglo. A) Section 4200N showing geochemistry of soil (0-0.2 m), geology and Au distribution across mineralisation. B) Plan showing location of the study areas.

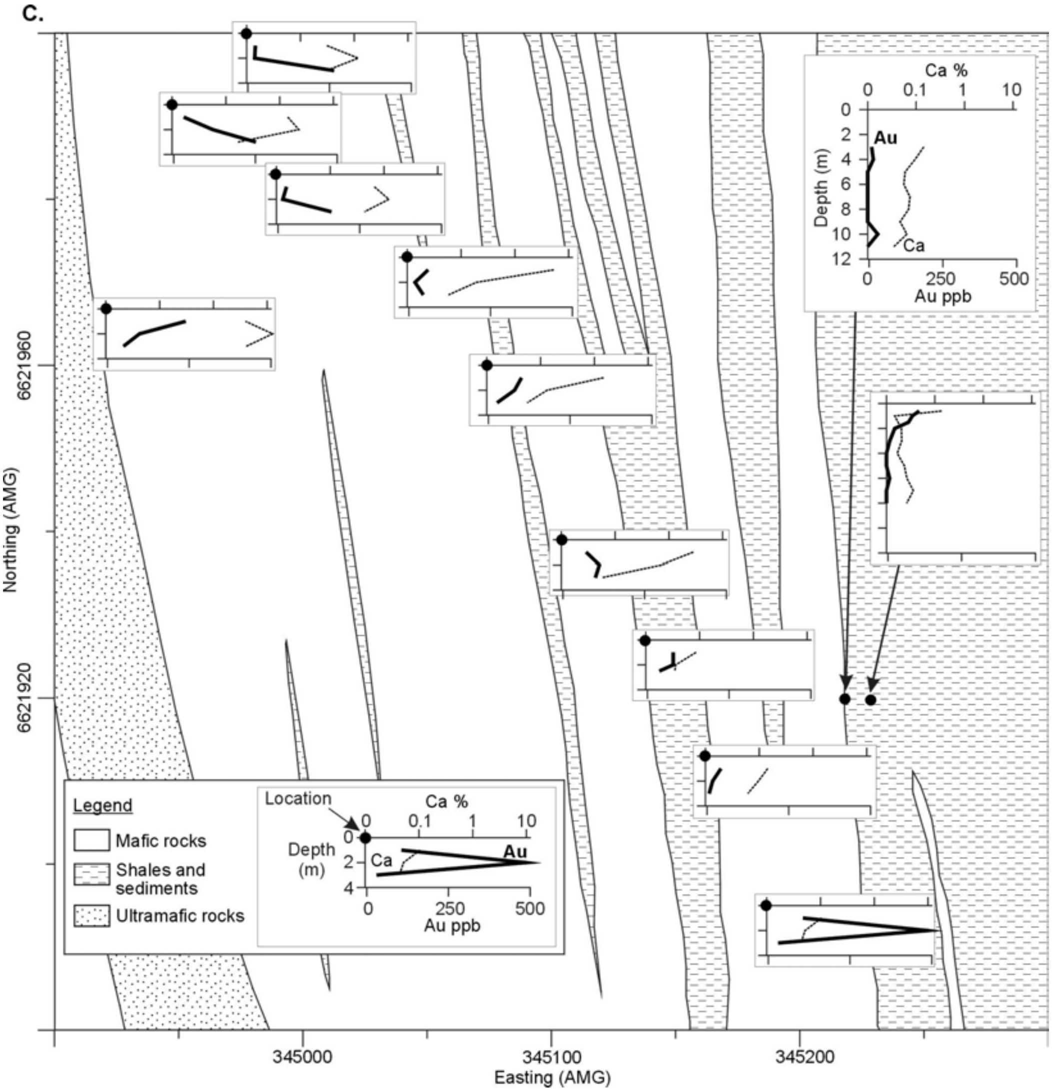


Figure 6.22 (contiuned): Geochemistry and geology at Panglo. C) Geochemical profiles of Ca and Au in relation to the geology.

material and weathered bedrock, and (ii) in nearby outcropping saprolite where Au peaks at 910 ppb (grab sample from trench). The interpretation for the source of the Au in the calcrete is equivocal, since it might be sourced from any of three locations: (i) the underlying mineralisation, (ii) the adjacent saprolite material, or (iii) the unconformity. The argument against hypothesis (ii) is that, because the saprolite in this area is mostly physically-located downslope, it cannot be the source of the Au in the soils above the palaeochannel; besides, soils directly over the saprolite are lower in Au. However, further detailed work investigating the geochemistry, three dimensional regolith structure and detailed topography of this area is required.

In other studies at Panglo (Lintern and Scott 1990, Lintern 1996b), the composition of soils and the upper regolith was examined in a Type B (saprolite) area where truncation to the mottled zone had taken place (boxed area on Figure 6.22A, and C). The strong relationship between Au and alkaline earths, noted in 0-0.01 m soils (Figure 6.22B), was examined in more detail in drill cuttings and grab samples from trenches. Data indicate that the relationship between Au and the alkaline earths is weak and is probably influenced by particulate Au present within nodular mottles or weathered rock of the saprolith, some of which has been affected by calcrete and some of which has not (Figure 6.22C). Thus samples of regolith material containing high Au concentrations (>100 ppb) when sub-sampled did not show any particular affinity for Ca or Fe (Table 6.2). The presence of Au in the upper saprolite is a relic from deep weathering that has survived leaching by being partly armoured by secondary mobilisation and precipitation by Fe and Si (c.f Runway case history). The nodular mottles and weathered rock may be an important source of Au found in the soil and calcrete.

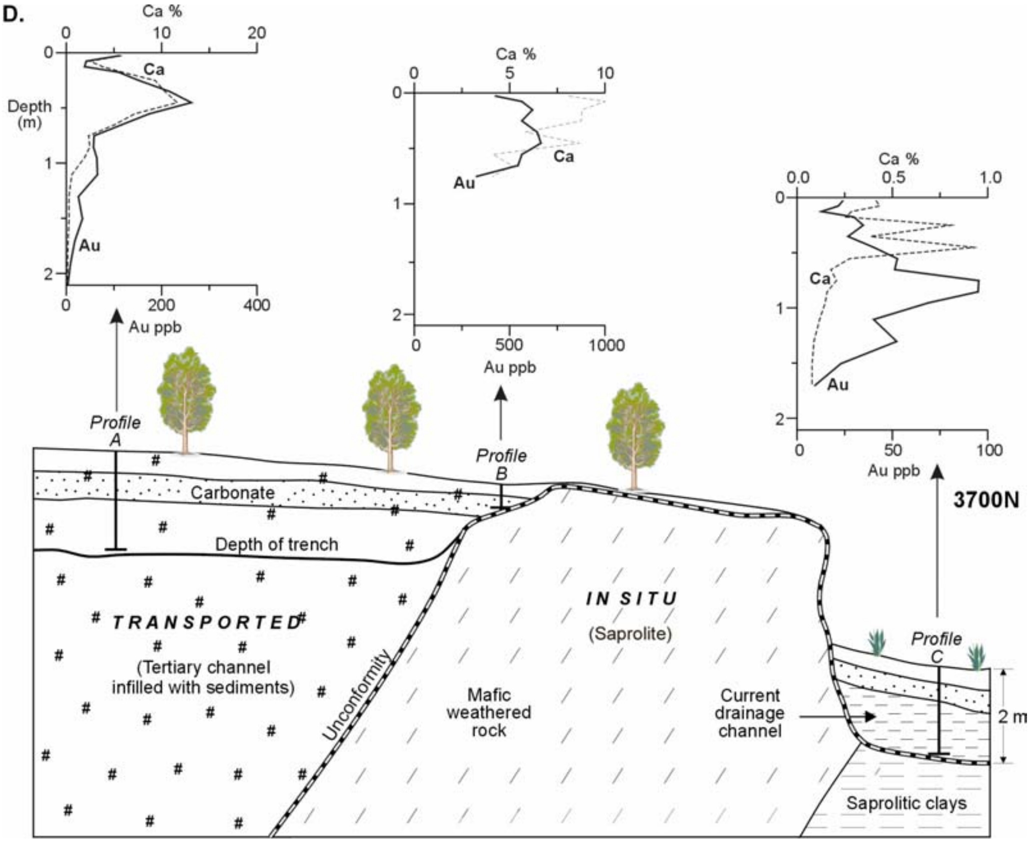


Figure 6.22 (contiuned): Geochemistry and geology at Panglo. D) Trench section showing regolith and geochemistry of profiles.

Table 6.2: Gold, Ca and Fe concentrations in the coarse fraction (>1000 (m) of selected near-surface samples collected near 4200N over mineralisation. Note the poor correlation between Au and Ca or Fe.

Sample	Number	N	E	Depth (m)	Fe (%)	Ca (%)	Au (ppb) bulk	Au (ppb) +1000 μm
09-3679	1	6621967	344920	1.5	11.4	12.58	102	75
09-3662	***2***	***6621939***	***345104***	***2.5***	***9.47***	***0.06***	***103***	***309***
09-3663	3	6621960	345074	0.5	9	1.47	105	96
09-3681	4	6621920	345228	0.3	12.6	0.14	106	14
09-3651	5	6621895	345187	0.5	10.7	0.11	110	113
09-3661	6	6621939	345104	1.5	14.5	0.72	115	260
09-3676	7	6621992	344947	1.5	13.7	2.25	123	42
09-3671	***8***	***6621983***	***344989***	***2.5***	***11.4***	***0.43***	***166***	***349***
09-3680	9	6621967	344920	2.5	3.72	3.96	241	93
09-3677	***10***	***6621992***	***344947***	***2.5***	***14.2***	***0.17***	***253***	***376***
09-3674	***11***	***6622000***	***344977***	***2.5***	***11.6***	***0.30***	***264***	***369***
09-3652	***12***	***6621895***	***345187***	***1.5***	***6.73***	***0.05***	***485***	***742***

(20) Zuleika, Kalgoorlie, WA (Lintern and Butt 1992)
The Zuleika Sands Gold Mine is located about 50 km WNW of Kalgoorlie and approximately 18 km due S of Ora Banda. The climate is semi-arid. Ora Banda has short cool winters and long hot dry summers. January is the hottest month (average maximum of 35°C) and July the coldest (average maximum of 16°C). Mean evaporation is about 3000 mm, and monthly evaporation exceeds rainfall for 10 or 11 months of the year. The annual rainfall is 275 mm but may vary from 100 mm to 500 mm, with more than half falling during winter.

Vegetation is mainly comprised of open woodland. The floodplain has patchily distributed *Eucalyptus salmonophloia* (salmon gum), with some specimens over 15 m in height, and other eucalypts less than 15 m. The groundcover is comprised mainly of chenopod shrubs, e.g. *Maireana* (bluebush) of less than 0.5 m height. A thickly vegetated area of closed woodland of *E. salmonophloia, E. salubris* (gimlet), *Acacia* (mulga), and *Casuarina* (sheoak) occurs on 4200N (Figure 6.23A). It is several hundred metres in length and breadth and comprises a topographic low where run-off probably collects and remains for longer periods than on the surrounding floodplain. The inferred abundance of soil water enables the development of a larger vegetative biomass. The ground is covered by considerable quantities of mull ranging from decaying leaves and branches to whole trees.

Primary mineralisation in the Zuleika Mining Centre about 1 km to the N of the Zuleika Sands Gold Deposit is hosted by high-magnesian basalts and commonly associated with shear zones, e.g., at the Zuleika South Pit. Strong soil Au geochemical anomalies occur in clay- and/or carbonate-rich soil developed on at least ten metres of poorly mineralised and depleted saprolite overlying primary mineralisation. The regional geology has been described by Harrison *et al.* 1990. Investigations were undertaken at the Zuleika Sands palaeochannel deposits to the S of the Zuleika South Pit. The source of the supergene mineralisation in the palaeochannel has not been determined, although the mineralisation at Zuleika South is an obvious candidate (Figure 6.23A). Some sub-economic mineralised zones exist within the palaeochannel sediments, but the highest grades seem to occur at the unconformity between the basal sands and the underlying weathered units. In addition, some high grades of mineralisation have been identified well below the unconformity.

The palaeochannel at Zuleika Sands runs approximately parallel to the regional strike. The base of the palaeochannel at the study location is between 15 and 20 m below the present land surface, which is in an active floodplain. A subdued spur of saprolite marks the western limit of the residual regolith, and a simple projection to the axis of the channel indicates that the palaeochannel has a very steep eastern "bank". The palaeochannel is infilled by sands and clays that have been weathered since deposition (Figure 6.23B).

The total study at Zuleika involved the description and collection of drill cuttings, soils, vegetation and lags from four traverses 500-600 m in length and spaced 170-290 m apart, and soils from a series of soil pits. All four traverses crossed W to E from transported overburden in the floodplain (Type T) and underlying palaeochannel to saprolite-dominated regolith (Type B) on the margins. Only results for the traverse on 4200N are reported here.

The soils of the floodplain have been studied in the most detail. They are predominantly red to red-brown clay, ranging in texture from sandy-silty in the top-soil (0 - 10 cm) to uniform platy-blocky clay in the sub-soils. Within the top two metres, there are one or more distinct sedimentary lenses, each a few centimetres in thickness, consisting of rounded (transported) ferruginous gravels and other material (e.g., quartz, basalt). Modification of the top metre (at least) of the sub-soils has taken place to varying degrees by recently-deposited carbonate. The carbonate takes on the form of powdery coatings (<1 mm thick) on soil particles and, where the sub-soil is indurated, as precipitates on partings (>1 mm thick). Denser pockets of carbonate do occur and can be spatially related to the sedimentary, ferruginous gravel horizons. In addition, within the first five metres of the profile, there are indurated (lateritized) horizons consisting of hard, homogenous clay and ferruginous segregations. A prominent feature of the sub-surface clays (2 - 5 m) is the presence of dark grey-green and some paler mottling. This suggests the clay is partially reduced and indicates that percolating rainwater has been de-oxygenated, possibly by respiration of micro-organisms. The soils of the subdued spur are comprised of a heterogeneous mix of residual sands, silt and gravels that grade into saprolite within the top two metres. Soils are pale coloured and have been highly modified by carbonate which commonly occurs as large indurated nodules often containing a core of saprolite. There is a considerable segregation of the sub-soil which is comprised of ferruginous and siliceous nodules and fragments. Further east of the spur, residual soils consist of sandy topsoil and a brown clay-rich loam sub-soil. The top metre has been modified by introduced carbonate that occurs as coatings on, and soft segregations within, the clay. The soil grades into ferruginous segregations similar to those in the sub-soils of subdued spur, which suggest the two soils have similar origins and have developed on a similar substrate.

Sampling of drill cuttings indicates that there is no clear or discrete Au anomaly over the mineralisation in the palaeochannel, and the highest concentrations (90 ppb) are present in residual soils developed in saprolite E of the channel, probably over minor mineralised zones (Figure 6.23C). Detailed investigations of these soils, (e.g. profile K), indicate that Au concentrations (200 to 300 ppb) are directly related to those of Ca and Mg in calcrete. However, such correlations between Au and the alkaline earth metals are not apparent in soils developed on the floodplain sediments (profiles G, H, I and J). In the floodplain, where there is less calcrete and generally much lower Au, some of the Au appears to be associated either with other soil components, or be randomly distributed. In profile H, for example, a highly anomalous concentration of 910 ppb Au is probably due to particulate Au.

For soils in the floodplain, directly overlying mineralisation, the origin of Au is uncertain but could realistically come from two possible sources: (i) the relatively high Au contents in residual soils to the E (e.g. profile K), and (ii) the Au mine approximately 1 km upslope to the N. Both represent sources

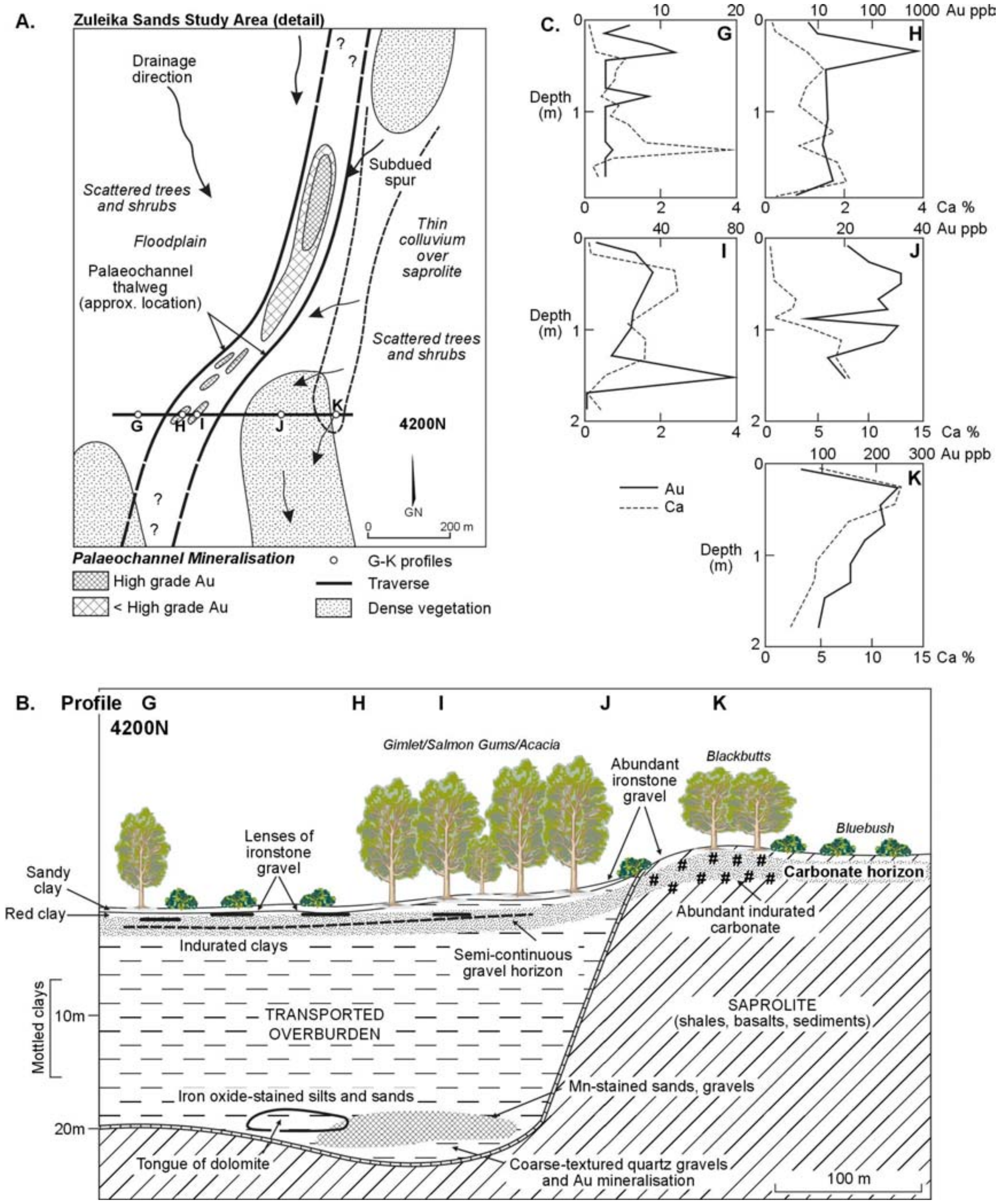


Figure 6.23: Gold distribution and regolith stratigraphy of the Zuleika Sands Gold Deposit. A) Plan showing location of sampling traverse. B) Section through palaeochannel showing mineralisation, regolith and profile location.

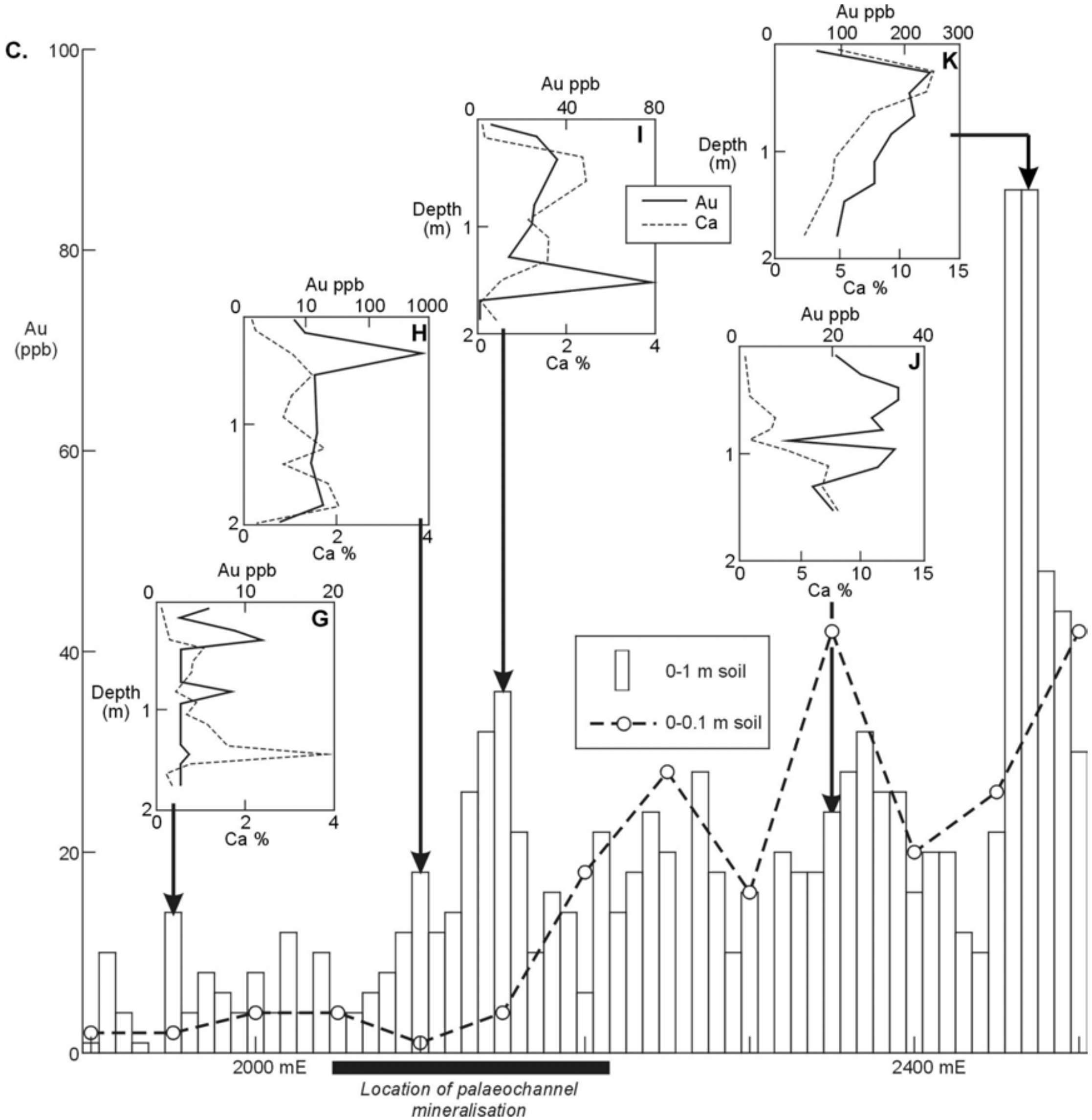


Figure 6.23 (continued): Gold distribution and regolith stratigraphy of the Zuleika Sands Gold Deposit. C) Geochemistry of soil profiles, soils and 0-1 m drill cuttings.

for detrital Au-rich materials that may have been deposited in the floodplain. The poor correlation between Au and Ca in the soils may be partly explained by the recent deposition of these materials, so that chemical re-working of the Au dispersed in the soil to the calcrete has not yet occurred. The case study is similar to Steinway and Higginsville in that the origin of the Au is probably from upslope. At Zuleika, much weaker "Au in calcrete" anomalies are developed despite the shallow depth to mineralisation.

(21) Ghost Crab Gold Deposit, Kalgoorlie, WA (Miller *et al.* 1999).
The Ghost Crab Gold Deposit is located about 15 km SW of the Steinway Gold Prospect. Transported material reaches thicknesses of about 25 m. Initially, a Au anomaly (defined by the >20 ppb contour) in the soil associated with mineralisation peaked at 57 ppb with a N-S strike length of 1.1 km (Figure 6.24). More detailed sampling of the soil was undertaken using a power auger and targeted the calcrete horizon. The maximum Au concentration in calcrete was 550 ppb Au about 200 m to the NE of the current pit boundary (Miller *et al.* 1999). The contoured soil anomalies changed their shape and direction as the density of sampling is increased, and the mineralised trend (N-W) became known from the aeromagnetic data. The final maximum concentration of Au over mineralisation was 134 ppb and was located in residual soils in what is now the SE of the open cut (Figure 6.24).

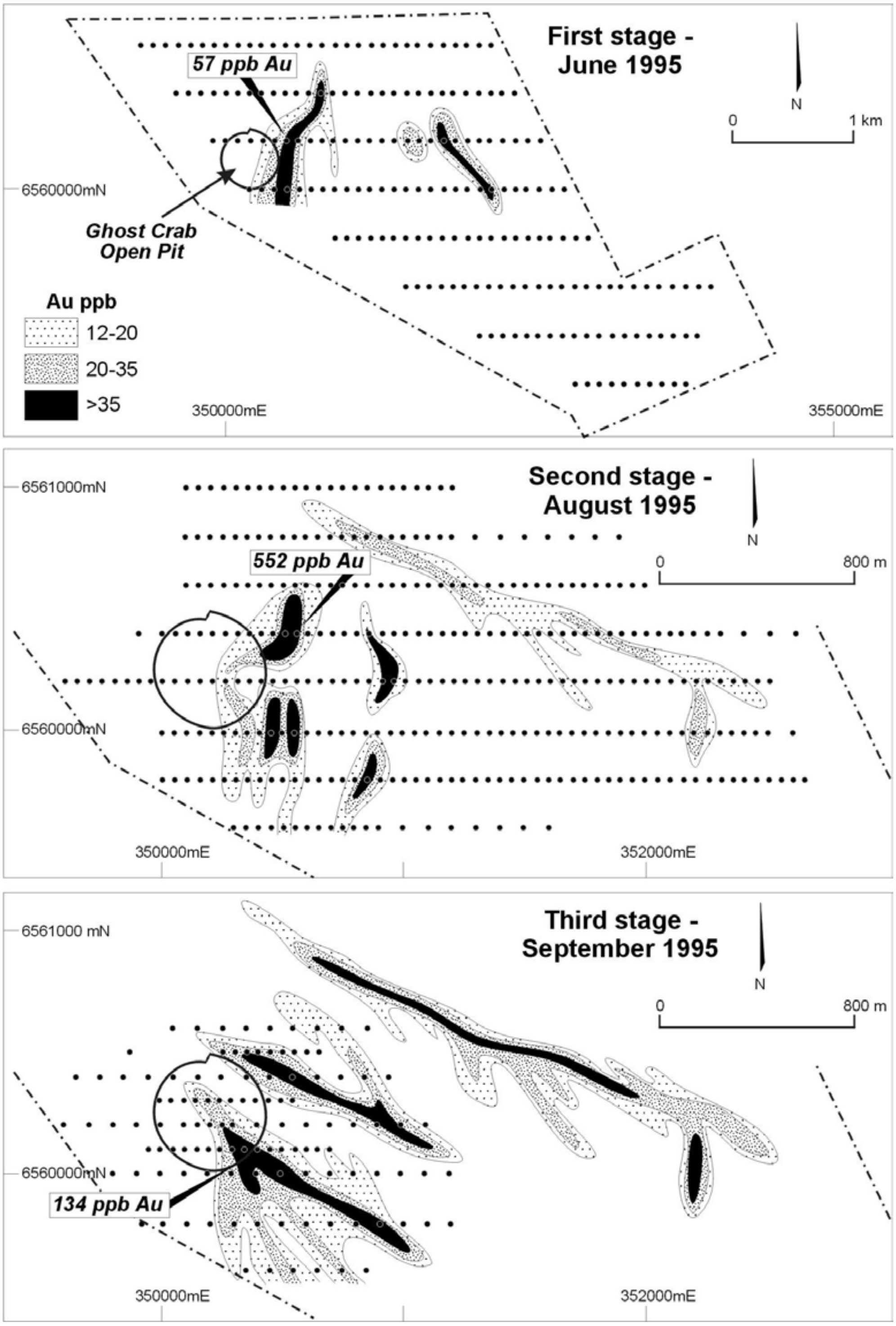


Figure 6.24: Series of plans showing the evolving location, shape and orientation of the Au anomalies as sample density increases at Ghost Crab Gold Deposit (after Miller *et al.* 1999).

No detailed research into the nature of the anomaly has been undertaken, but it is understood that Miller and colleagues have interpreted the surface expression as due to mechanical/chemical dispersion from upslope residual soils that lie on the same mineralised trend as the Ghost Crab Deposit itself. Part of the anomaly extends over the deposit buried beneath in excess of 25 m of Cainozoic sediments. The terrain is very similar to that found around Steinway, where results suggest the anomaly is due to detrital Au and not produced from the underlying mineralisation. In addition, as with the Steinway area, not all the anomalies drill-tested have mineralisation beneath them.

(22) Marigold Gold Deposit, Nevada (Smee 1998).

The Marigold Mine is located in Nevada, 30 km NW of Battle Mountain (Figure 6.25A). The Marigold deposits lie within the Basin and Range physiographic province of NW USA, a region of generally N-trending mountain ranges separated by broad alluvium-filled valleys. The area is semi-arid with an annual rainfall of 150 mm. Smee (1998) reported that the tan to grey silty sandy matrix shows little horizon development, with the exception of a poorly developed pedogenic carbonate layer. The valleys are sparsely vegetated with mesquite, greasewood, bunchgrass and shadscale.

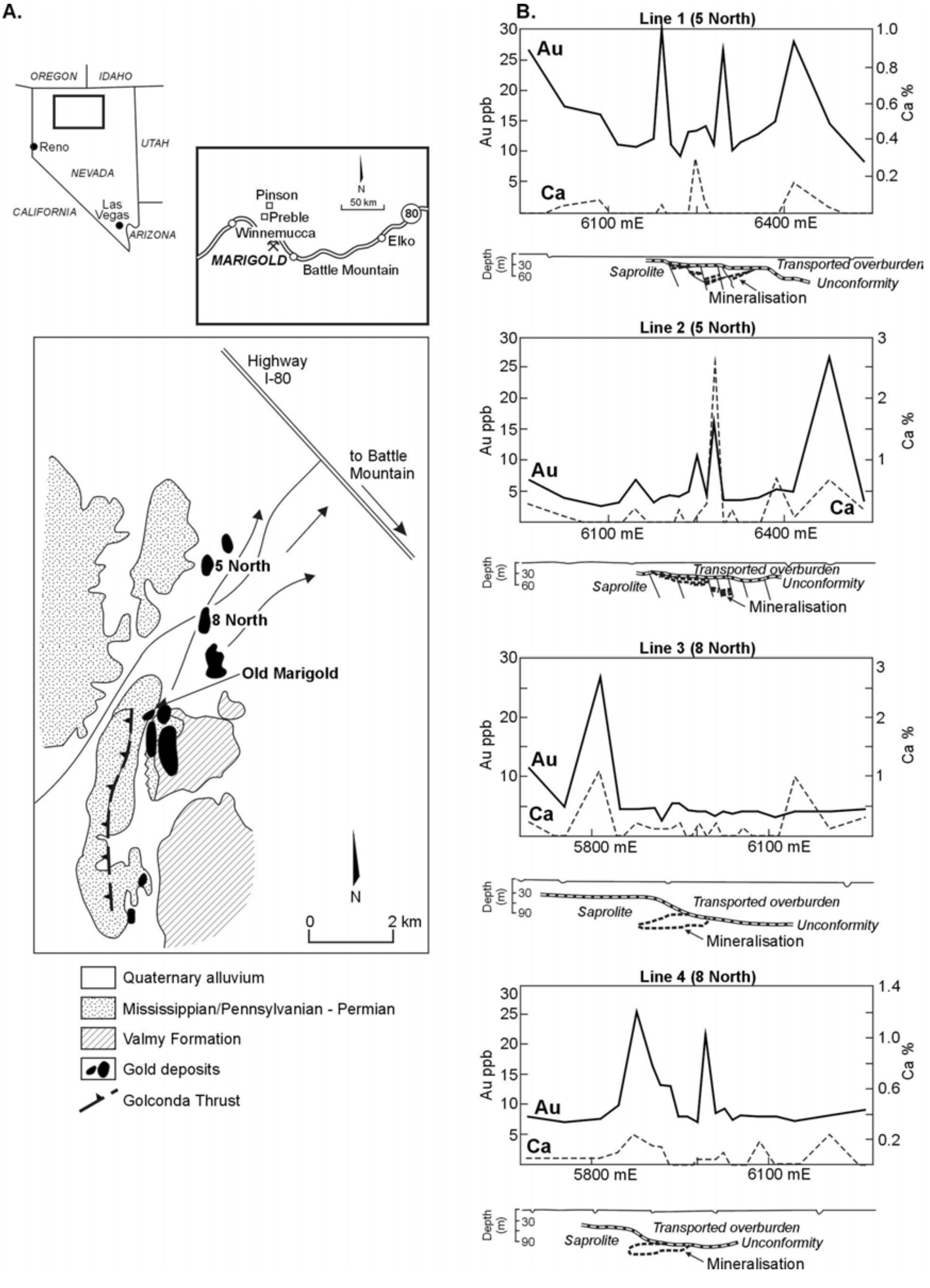


Figure 6.25: Gold distribution and stratigraphy at the Marigold Gold Deposits (after Smee 1998).

Clastic rocks of the Valmy and Antler sequences host the Marigold deposits, which are orientated approximately N-S. The Antler sequence is of Permian age, hosts the 8 North and 5 North deposits, and is composed of coarse conglomerates and sandstone that grade upward into limey mudstone, shales, siltstone and sandstones. Mineralisation is controlled by N-trending faulting and NW striking zones of fracturing. The 8 North mineralised body is approximately 300 m by 170 m in plan view. Overburden, consisting of alluvial and fluvial outwash of Tertiary age and inter-layered lacustrine clay, covers the 8 North deposit to a depth of about 100 m. The 5 North body is covered by 20-50 m of alluvium and is hosted by debris flows and siltstones, with minor limestone.

A geochemical survey involving four traverses (two over each deposit) was conducted at 8 and 5 North. A variety of partial extraction, "total" element digestion and other chemical techniques was used to identify whether there is a surface expression to mineralisation. Calcium and Sr are correlated with total soil Au and produce positive one-sample anomalies, in some cases over mineralisation (Figure 6.25B). Double peak or "rabbit ear" anomalies for total Sr and acetate-extractable Ca occur over mineralisation (Smee 1998). Smee proposes that the alkaline earth distributions may be attributable to an element migration involving the release of H^+ ions (during sulphide oxidation) and migration of H^+ or CO_2 (after reaction of the acid with carbonate wall rock) to the surface. At the surface, these components react with carbonate and Fe/Mn oxides causing disequilibrium and subsequent migration of elements away from the stimuli and towards ambient pH. At the margins of the stimuli the mobilised elements are re-precipitated forming the "rabbit ears".

Smee (1998) concluded that the analysis of Ca, Au, As and Sr in closely spaced soil samples in alkaline environments is recommended for these types of buried deposits. In a follow-up article Smee (1999) provided data suggesting that the pH of hydroxylamine extracts of soils could be used as an indicator of buried mineralisation. The data indicated that higher pHs are recorded for the "rabbit ear" samples. The author visited the site in 1999 and was of the opinion that further testing should be undertaken,e.g., to test sample site variability, carry out detailed regolith landform mapping and sample further traverses to form a grid. This would help to exclude other plausible explanations for the observed variation in the data, for example drainage from the ranges and mine areas.

(23) Steinway, Kalgoorlie, WA (Lintern and Gray 1995a, Lintern and Craig 1996)
Steinway is located about 27 km SSW of Kalgoorlie. The climate is semi-arid with mean annual rainfall of about 280 mm. Vegetation consists of open woodland of *Eucalyptus* and a sparse understorey that includes *Maireana* (bluebush). The Steinway Au prospect is located beneath a depositional plain, with few areas rising 5 m above it. To the S, an erosional area composed of mafic saprolite hosts the nearby Penfold Gold Mine, and to the SE a palaeochannel hosts the Greenback Gold Deposit. Present day ephemeral channels cross the depositional plain, generally flowing N to White Lake, a playa about 10 km distant. Ephemeral channels split the Steinway-Penfold Au anomaly found in soil (Figure 6.26A).

The Steinway prospect is located adjacent to the regional contact between mafic-ultramafic rocks of the Saddle Hills Greenstone Belt, and the overlying intermediate to felsic volcanic and sedimentary rocks of the Black Flag Group. Mineralisation at Steinway is buried beneath at least 25 m of Cainozoic sediments and is of two types: supergene mineralisation located below a palaeochannel, and deeper primary mineralisation associated with quartz stockwork veining within mafic andesites/amphibolites (Figure 6.26B).

The regolith consists of an uppermost unit of calcareous, clay-rich red soil with abundant ferruginous granules overlying a non-calcareous red clay containing large amounts of ferruginous granules between 2-5 m depth (Figure 6.26B). Beneath this, massive clays between 5-25 m depth containing strongly mottled zones of Fe-rich material occur. These in turn overlay a basal sand and silty-clay unit, between 25-30 m depth. The residual regolith profile consists of saprolite, becoming more clay-rich towards the top, and is about 20 m thick. Fresh rock is encountered at about 50 m depth.

Analysis of a soil profile located above mineralisation shows that Au concentration gradually increases with depth, whereas Ca and Mg concentrations sharply increase and then decrease (Figure 6.26E). Gold and Ca are probably associated in the upper horizons. Iron concentrations gradually increase with depth and, below 0.5 m, Au and Fe appear correlated. The Au anomaly (>24 ppb) in the 0-1 m composite samples from Steinway reaches 150 ppb against a background of less than 20 ppb (Figure 6.26C). The anomaly is over 150 m wide in an EW direction and stretches over 1 km to the NW,

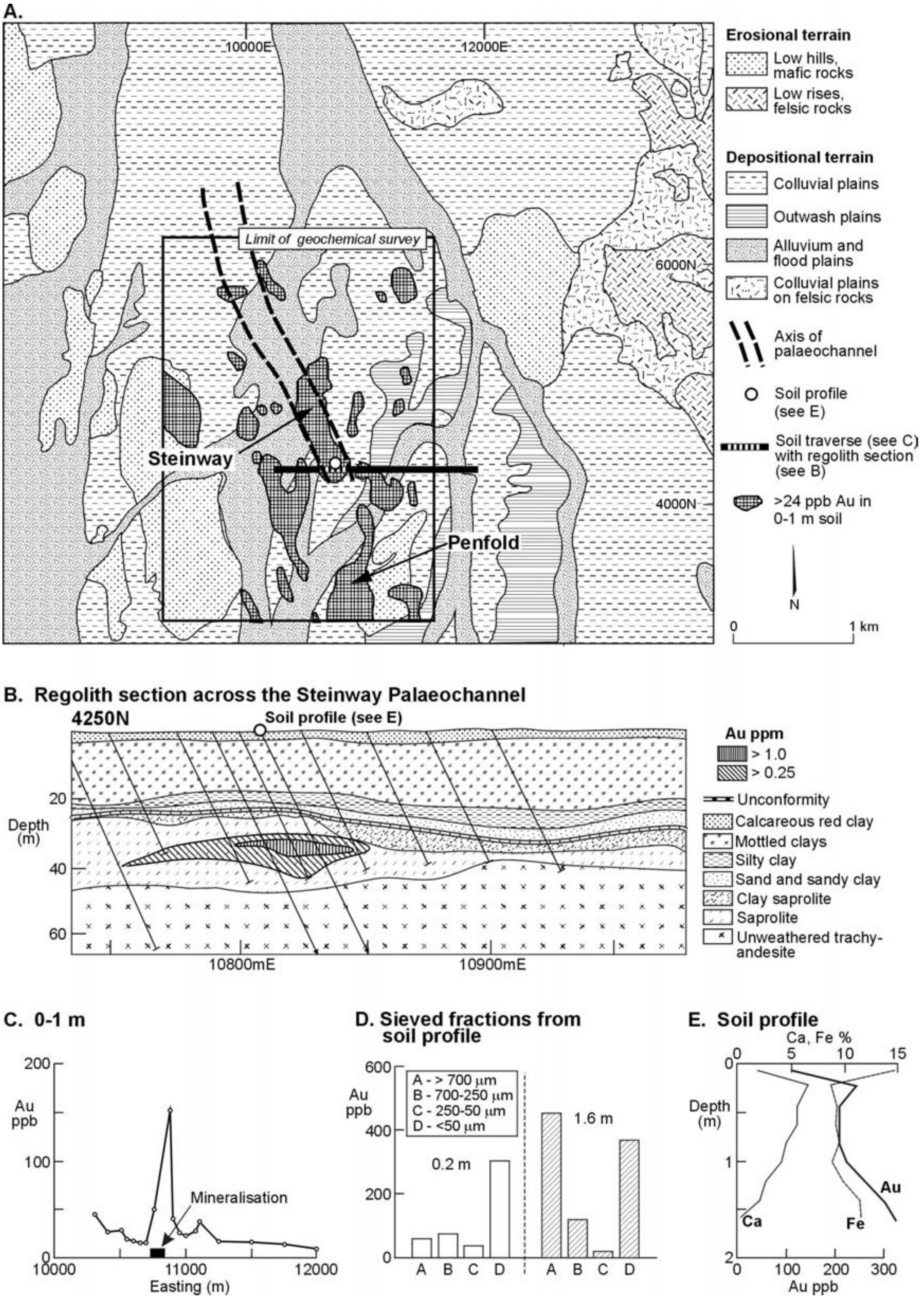


Figure 6.26: Geochemistry and regolith at Steinway. A) Plan of regolith landforms. B) Regolith section across the Steinway Palaeochannel. C) Distribution of Au across Steinway mineralised zone. D) Gold concentration in different size fractions for two samples taken from the soil profile. E) Soil profile geochemistry.

following the direction of the palaeochannel. There are also high concentrations of Au (maximum 107 ppb) in the coarse, ferruginous fractions of the soil in the same area. The distribution of Au in 0-1 m composite soil samples appears, at first, to be related to underlying mineralisation. However, broken pisoliths and other transported fragments from upslope, and the random concentration of Au in the ferruginous granules, suggest that the apparent association may be coincidental. This was investigated further. Ferruginous granules from 1.6 m depth were wet-sieved into four size fractions: > 710 µm, 710-250 µm, 250-53 µm and < 53 µm. The coarse fraction (> 710 µm) representing 10.6% of the total weight of the sample had the highest Au concentration at 450 ppb, 17% of the total mass of Au. Most of the Au (80%) is found in the fine fraction (> 53 µm) (Figure 6.26D). The ferruginous granules had lithic fabrics (related to basement rocks) suggesting a transported origin. Individual ferruginous granules had visible Au and concentrations up to 15 ppm. Paradoxically, at Greenback Gold mine about 400 m to the W, containing about 50000 ozs of Au, Au is located higher in the profile (in the sediments themselves, and with a palaeochannel stratigraphy similar to Steinway), but there is no Au anomaly in the soil above it.

The Steinway case study is similar to that at Higginsville. At both sites, the results suggest that the ferruginous granules are the immediate source of Au in the soil, and that the Au and the granules are sourced via mechanical dispersion from laterally upslope, rather than vertically from underlying buried mineralisation. The Au in the calcareous unit of the soil is probably derived from either (i) the ferruginous granules, which have weathered and released Au that has migrated by capillary action over 1 or 2 metres vertically, or (ii) direct chemical dispersion from a similar upslope source as the ferruginous granules themselves. In regolith dominated by thick palaeochannel sediments, such as Steinway, results indicate that there is probably no causal link with underlying mineralisation and that sampling of soil including calcareous material, at best, may indicate the exploration potential of the (sub)catchment. It is suggested, therefore, that for such landscape regimes, wider auger sampling intervals should be used (to indicate the potential of mineralisation in the catchment). Deeper samples, including basal sediments and/or ferruginous saprolite, should be collected when exploring for palaeochannel-related mineralisation.

(24) Kanowna QED, Kalgoorlie, WA (Dell 1992, Anand *et al.* 1993)
To the N of the Kanowna Belle Gold Deposit is an area known as QED (Figure 6.27A). This is the locality of many of the famous "deep leads" palaeochannel deposits that were mined by individual and small groups of miners in the late 19th and early 20th centuries. The ore they were chasing was located in the quartz boulders, gravels and sands found at the base of the palaeochannels. Recently, these deposits have been mined in open cuts to supplement the reserves from nearby underground operations mining primary Au.

A regolith profile from the NLP9 pit located in the palaeochannel system was studied. The regolith consists of 0.2 to 0.4 m of red to brown calcareous soil overlain by a medium to fine polymictic lag of abundant ferruginous gravels, vein quartz and lithic fragments. The soils lie above a 1 to 4 m thick horizon of pale orange calcareous clay. The unit contains multiple lenses of bedded and graded alluvium from streams that have cut channels in an underlying clay unit (2 to 5 m thick), also containing polymictic gravels. Bleaching and incipient mottles are developed within the Fe-rich clays and mark the transition into the (mini-)mottled zone (Figure 6.27B). A zone containing larger mottles 10 to 25 cm long with black ferruginous granules in turn underlies this (mega-mottled zone). The mottled zone becomes completely bleached with depth. A pisolitic greenish-grey clay, coarse quartz-rich basal gravels (unconformity) and weathered Archaean saprolite occur beneath the bleached zone (Figure 6.27B).

Gold is concentrated in the calcareous clays (up to about 200 ppb) and in the mottled zone (about 300 ppb) (Figure 6.27B). No further work was performed on the soils to identify which fraction hosted the Au. The concentrations are similar to those found at Kanowna Belle to the S but the depth to mineralisation is only 30 m in the sediments at NLP9 (the deep lead) compared with 50 m for the former. The thickness of transported material is also much greater at NLP9. Unlike Kanowna Belle, there is no shallow source of Au (such as the silcrete at 8 m depth at Kanowna Belle). It is unlikely that the soil Au enrichment is derived from the mottled zone as concentrations are similar. A lateral source of Au is more probable.

(25) Mulgarrie, Kalgoorlie, WA. (Gray 1992).
The Mulgarrie Gold Deposit is located 40 km N of Kalgoorlie. The climate is semi-arid with average rainfall of about 250 mm predominantly occurring in winter. Pan-evaporation at 2700 mm is well in excess of rainfall. Vegetation is open woodland of eucalypts with a sparse understorey including *Acacia*, *Eremophila* and *Casuarina*. The landscape relief is subdued with ephemeral drainage.

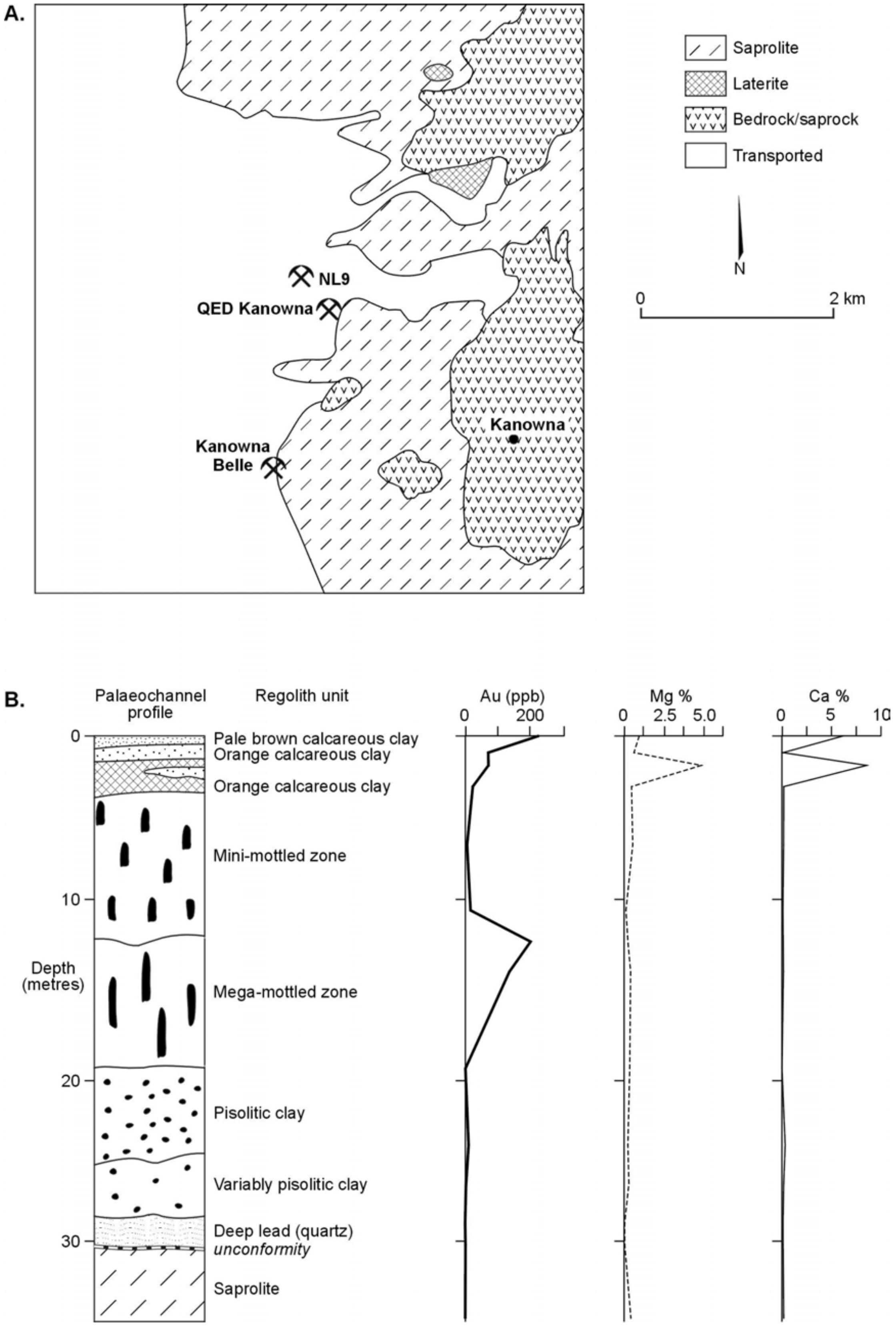


Figure 6.27: Gold distribution and regolith at the NL9 pit, Kanowna QED Gold Deposits (after Dell 1992). A) Regolith map showing location of QED an NL9 Au deposits. B) Regolith profile showing Au, Mg and Ca concentrations.

The main deposit occurs within mafic and ultramafic rocks of the Mulgarrie-Gordons greenstone belt on the eastern side of a granitic batholith. The regional strike is NW, dips are steeply E and metamorphic grade is lower greenstone facies. Locally, the stratigraphy consists of massive blocky tholeiitic basalts, overlain by a thinner pile of komatiites that show a highly variable mineralogy both laterally and vertically. Two open pits access the mineralisation. South of the Palm Pit, strong serpentinisation of the komatiites has occurred, whereas the upper, komatiitic basalts have been intensely carbonated. In the Palm Pit, high-grade Au mineralisation (5-100 ppm) is associated with quartz vein sets trending NE and dipping between 40-70^{o} NW. The quartz sets consist of a high density network of narrow, 1-10 cm sub-parallel quartz veins and stringers, hosted by an intensely carbonated talcose ultramafic rock. The host rock is also weakly mineralised, but Au concentrations rarely exceed 1 ppm in one metre samples. In the Trial Pit (located 200 m NW and downslope ofPalm), weathered ultramafic rocks are covered by a palaeochannel with 35 m of transported overburden. The transported overburden is typical of palaeochannels in the Kalgoorlie area, consisting of a sequence of a calcareous red-clay soil, variably mottled zone of clay-rich alluvium/colluvium, quartz sands and quartz-rich basal conglomerates.

Three holes were drilled between the two open pits. RAB cuttings were sampled and analysed for Au and alkali earth metals. Gold concentrations exceed 400 ppb in hole MC500. In the upper 5 m, there is a strong correlation between Au, Ca and, to a lesser extent, Mg (Figure 6.28). Varying proportions of carbonate occur as calcite, dolomite and magnesite in the upper regolith. The top metre is dominated by calcite whereas dolomite is more prevalent in the next 2-3 metres. Below this, magnesite is present particularly in hole MC 529 where Au is present in minor amounts.

The origin of the Au present in the upper regolith is equivocal since the study was limited to just three drill holes. The surficial Au is probably laterally sourced from the upslope Palm Pit area. However, vertical mobilisation from the underlying basement mineralisation at 25-40 m depth (including the interface between the transported and the basement) though unlikely cannot be discounted.

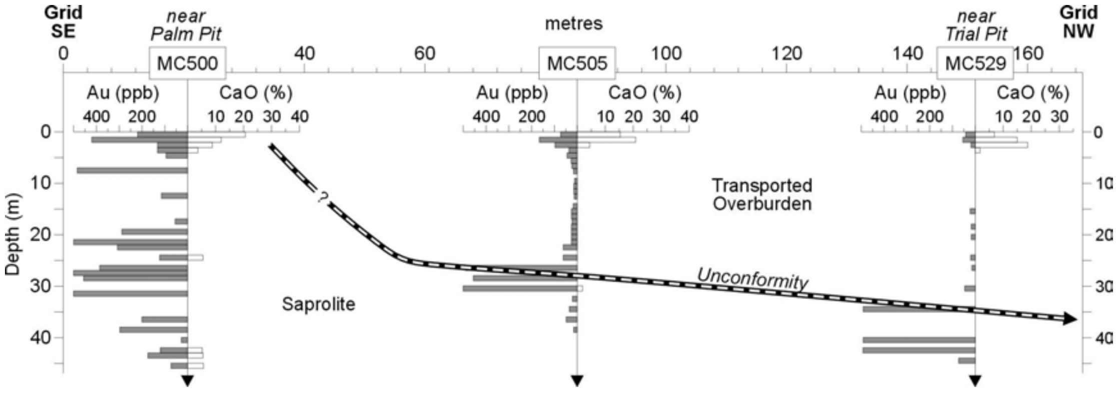


Figure 6.28: Gold and alkaline earth concentrations of 3 drill holes from the regolith at Mulgarrie (after Gray 1992).

(26) Wollubar-Enigma, Kalgoorlie, WA (Lintern and Gray 1995d)
Wollubar-Enigma is located about 35 km SSE of Kalgoorlie. The climate is semi-arid with an average annual rainfall of about 280 mm. Vegetation is sparse and consists of open woodland of *Eucalyptus* with *Eremophila* (poverty bush), bluebush and other small shrubs. The area has been extensively de-forested in the past, and there is a considerable groundcover of grasses. The site is on a flat, depositional plain with some development of ephemeral drainage in the W of the study area.

The deposit is located within part of the Archaean Wiluna-Norseman Greenstone Belt. Bedrock consists of high Mg basalts, some with pillows and variolitic textures, and sedimentary, felsic volcanic and volcaniclastic rocks of the Black Flag Group. Bedrock has been regionally metamorphosed to upper greenschist - lower amphibolite facies. The N-S trending Mt Hunt fault runs though the prospect, and the Au-bearing Boulder-Lefroy Shear occurs 4 km to the W. Primary Au mineralisation at the Wollubar-Enigma prospect is associated with sericitic schist. Supergene mineralisation is present in sub-horizontal enrichment zones in sands at the unconformity between the transported overburden and residual materials.

The study area is located in the large Wollubar Palaeochannel, which is infilled by clays and sands. Within the channel, the largely stripped residual weathering profile is covered by some 55 m of sediment. From the top of the regolith profile, reddish clays occur between 0-15 m depth. The soil consists of a sand-rich upper horizon (0.1 m thick) containing abundant ferruginous granules. Carbonate infuses the top 1-2 m of the red clays. The clay-rich horizon contains Fe-rich granules and pisoliths. Pale (cream, yellow and pink) clays occur from 15 m depth to the base of the palaeochannel, with some grey-coloured reduced clay present below 35 m depth. Rounded to sub-rounded sand grains may be sieved from the clays from 20-55 m depth. The saprolite is clay-rich beneath the unconformity, and is increasingly indurated with depth, with saprock at about 90 m depth.

A limited geochemical study was undertaken at Wollubar-Enigma, targeting soil, vegetation, ferruginous components in the transported cover, and material from saprolite and saprock. Soil was sampled by augering to a depth of 1 m on an EW traverse over mineralisation. Sediment, saprolite and saprock samples were collected from RC drill cuttings. Only soil data are reported here.

There is no evidence of anomalous Au at the surface across mineralisation. In general, Au concentrations are low for the region, averaging about 12 ppb (Figure 6.29). The maximum Au concentration is 25 ppb and several samples, some directly over mineralisation, are below detection (less than 5 ppb). Calcium and Mg are evenly distributed over most of the traverse, with the highest concentrations of Ca towards the W. Normalising Au with respect to Mg or Ca does not produce any significant trends. The results of this case study provide further evidence for the masking of buried mineralisation beneath thick overburden.

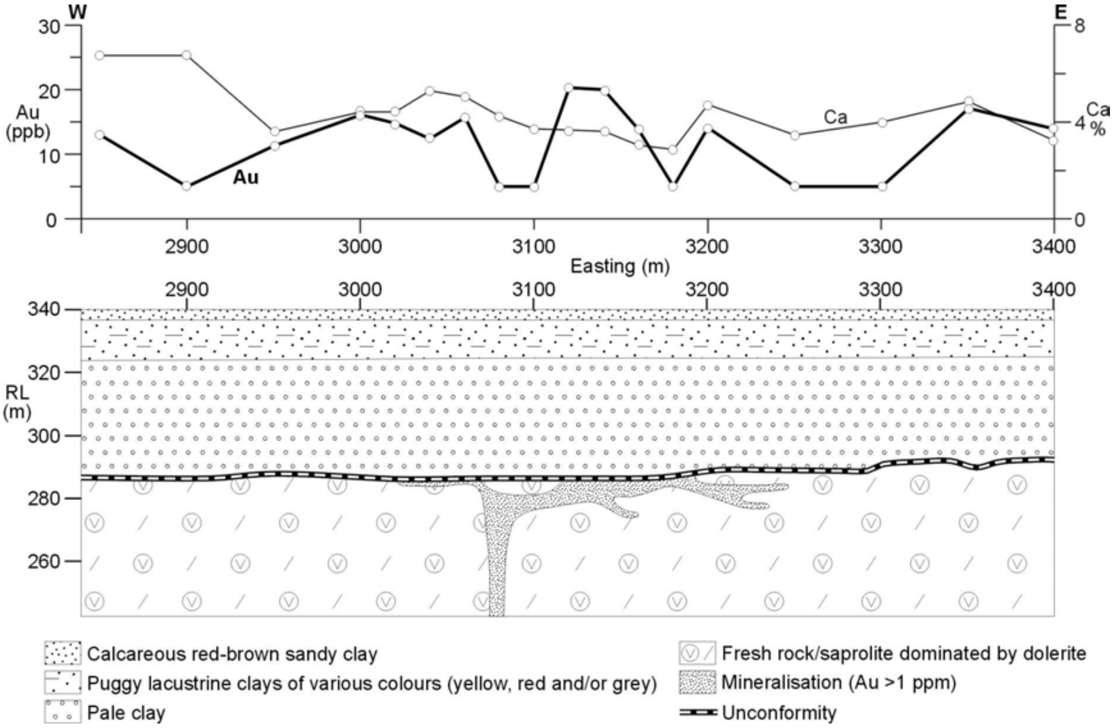


Figure 6.29: Geochemistry and regolith stratigraphy of the Wollubar-Enigma Prospect.

(27) Higginsville, Kambalda-Norseman, WA (Lintern *et al.* 1996).
The Higginsville Gold Deposits are located 120 km S of Kalgoorlie. The climate is semi-arid with an average annual rainfall of 270 mm. The vegetation at Higginsville consists of open woodland dominated by Eucalyptus and Melaleuca. Small shrubs including *Maireana* (bluebush), *Cratystylis conocephala* (false bluebush), *Atriplex* (saltbush) and *Eremophila* (poverty bush) comprise the understorey. The study area is situated within mostly depositional terrain, and outcrop is generally poor.

The study area is located within the Archaean Norseman-Wiluna greenstone belt. The Zuleika Shear runs through the area and mineralisation is associated with second order splays. Two of these structures, the Poseidon South Fault and the Mission Fault, bound steeply dipping, NNW trending, sedimentary rocks of the Black Flag Group. To the E and W of the sedimentary units, high Mg basalts and ultramafics with minor interflow sedimentary rocks, intruded by gabbros, dolerites and acid porphyries, represent the limbs of a regional syncline.

The Mitchell Palaeochannel drains the old Higginsville mine area. To the east and running parallel is the Challenge-Swordsman Palaeochannel (Figure 6.30B). Estuarine, marine and lake sediments filled these during marine incursions in the Eocene. Gold mineralisation is present in basal sands, grits and conglomerates (Figure 6.30A). The palaeochannels overlie major shears and significant alteration zones in the Archaean and intersect patchy primary mineralisation. This indicates that the Au deposits in the palaeochannels are probably a chemical supergene deposit remobilised from a proximal Archaean source. However, it is also possible that the Au was washed into the rivers from an unknown source(s), or that Au-bearing fluids were injected up underlying basement faults into the sandy sediments. Extensive ferruginised, calcareous soils, aeolian sands, and remnant Tertiary sediments overlie deeply weathered Archaean basement. The resulting regolith is complex, with fresh rock occurring below 80 m depth. A typical section over the palaeochannel mineralisation consists of:

0-2 m	Dense red calcareous clays with abundant ferruginous gravels. The calcrete occurs as powdery segregations in clay and coatings on, and replacement of, ferruginous granular material.
2-6 m	Red, non-calcareous clays with some grey mottling.
6-10 m	Multi-coloured clays with abundant ferruginous nodules and some pisoliths.
10-18 m	Red and khaki puggy clays with some Fe-rich nodules, becoming paler with depth.
18-34 m	Cream to white silty sandy clays
34-40 m	Sandy clays with carbonaceous (including fossil wood) and sulphidic material.
40-80 m	Clay saprolite consisting of variably coloured clays, quartz and rock fragments.

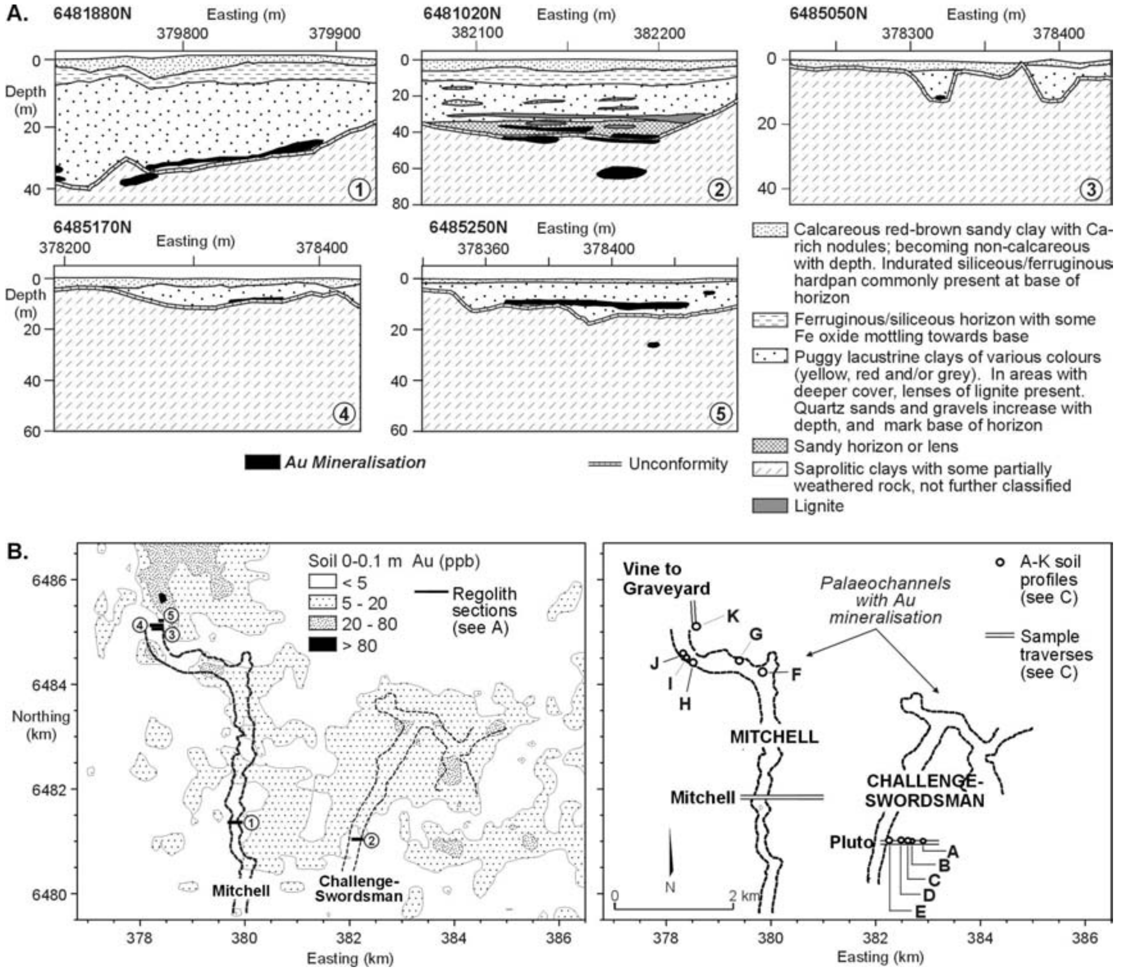


Figure 6.30: Geochemistry and regolith of the Higginsville Palaeochannel Gold Deposits. A) Stratigraphy across palaeochannels. B) Gold and Ca concentrations for soil traverses and profiles.

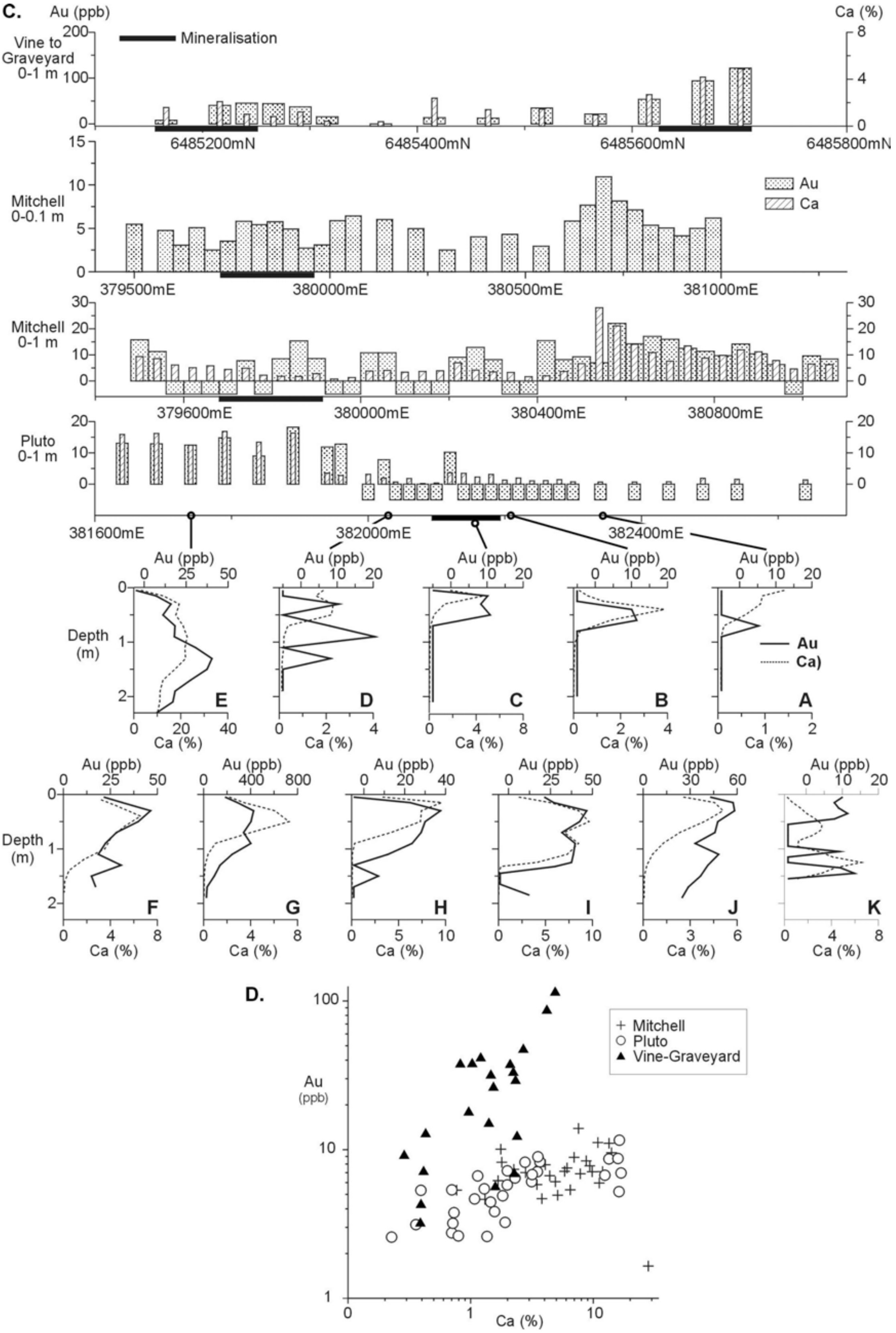


Figure 6.30 (continued): Geochemistry and regolith of the Higginsville Palaeochannel Gold Deposits. C) Plan showing regional Au anomaly, location of palaeochannels and stratigraphic sections. D) Scatter plot showing Au and Ca relationship in soil (0-1 m).

Soil samples were collected from three auger traverses (0-1 m): (i) across the Pluto deposit (Challenge-Swordsman Palaeochannel), (ii) across the Mitchell-4 deposit (Mitchell Palaeochannel), and (iii) downslope from the outcropping Vine deposit to the buried North Graveyard deposit (upper reaches of the Mitchell Palaeochannel). In addition, near-surface soils (0-0.1 m), eleven soil profiles, and ferruginous materials from selected soils and drill cuttings were collected (Figure 6.30B); the latter two sampling media are not reported here.

For the 0-1 m samples, there is a strong anomaly and an association between Au, pedogenic carbonate and mineralisation in residual soils at the Vine deposit (Type B) (Figure 6.30C). The anomaly possibly extends to the shallowly-buried (<10 m) North Graveyard deposit (Type T), although the latter anomaly is possibly related to higher carbonate contents. Importantly, however, the Au content of the soils from over the Mitchell-4 and Pluto deposits (Type T) is not related to underlying mineralisation. In fact, no Au (<5 ppb) was detected in any samples directly overlying the mineralisation at Mitchell and Pluto. Of all the soils collected, the highest Au concentration (425 ppb) was found within a soil profile located downstream of the Aphrodites pit (profile G, Figure 6.30C). Soils from 0-0.01 m have lower Au concentrations (<5-11 ppb) than the 0-1 m soils (<5-20 ppb), with neither sample type reflecting the occurrence of mineralisation at Mitchell. Gold and Ca concentrations in 0-1 m soils are correlated (Figure 6.30D).

In order to examine the associations of Au with other components of the soil in more detail, fifty individual ferruginous granules were randomly selected from a soil profile adjacent to the Graveyard-Aphrodites pit located in the Mitchell palaeochannel. The results show ferruginous granules have highly variable Au contents. One granule contained 51 ppm Au, while other granules had Au contents below detection (100 ppb). Petrological investigations of Au-rich granules (over 250 ppb) confirm they are pervasively ferruginised, with some partly-preserved primary lithic fabrics. Silver-free Au grains up to 10 µm size were found in sectioned granules.

It is probable that Au released from the detrital ferruginous granules is the immediate source of much of the Au in the calcrete. As the granules weather they release Au and this becomes associated with the carbonate under soil conditions. The ferruginous granules containing high concentrations of Au are presumably derived from upslope auriferous ferruginous saprolite (Type B regolith) or lateritic duricrust (Type A). The study demonstrates how significant amounts of Au found in calcrete can be displaced from mineralisation by many tens or hundreds of metres.

(28) Kurnalpi Palaeochannel, Kalgoorlie, WA (Lintern and Gray 1995c)
The Kurnalpi Palaeochannel Gold Prospect is located about 70 km NE of Kalgoorlie. The climate is semi-arid with an annual rainfall of 280 mm. Vegetation is dominated by *Acacia*, some *Casuarina*, and on higher ground, stunted *Eucalyptus*. Small shrubs are scarce due to the impact of grazing sheep. The Kurnalpi Prospect is located on the edge of a broad floodplain. There is a range of hills to the E and NE, and Mt Parkin rises 100m above the floodplain 2.5 km to the SE. Present day ephemeral streams, some choked with ferruginous lag, generally flow in a SW direction, draining to a side branch of Lake Yindarlgooda about 4 km to the S. The landscape is typical of floodplains E of Kalgoorlie.

The Kurnalpi Prospect is situated in the Archaean Norseman-Wiluna greenstone belt. Komatiite and variolitic basalts, mafic schists and (minor?) intrusions of gabbro, dolerite and felsic porphyry of the Mulgabbie Formation form the bedrock (Figure 6.31A). The rocks are strongly deformed and metamorphosed to greenschist facies. Two main shears cross the study area, one trending approximately NW and the other NE. Mineralisation is associated with quartz veining hosted by weathered meta-basalts. The Kurnalpi Prospect occurs beneath a deep palaeochannel, which appears to be influenced by the two shears that cross the study area. The northern part of the palaeochannel follows the NE trending shear, but where the shears cross, the southern section follows the NW trending shear. Four sedimentary units infill the palaeochannel (Figure 6.31B):

1) 0-5 m: clay-rich red soil containing abundant ferruginous granules, with pedogenic carbonate, principally as calcite, in the top 2 m.
2) 5-20 m: mottled pale and pink clays, with abundant ferruginous granules.
3) 20-30 m: variably coloured puggy clays with occasional pisoliths, which are most abundant in the grey reduced zones of the puggy clay.
4) 30-60 m: clayey sand, with some coarser gravel.

Beneath the transported cover, the thickness of the saprolite is variable. Fresh rock is generally present by 80 m depth, although the depth to fresh rock is shallower on the margins of the palaeochannel. Buried lateritic residuum is locally present, on the channel margins.

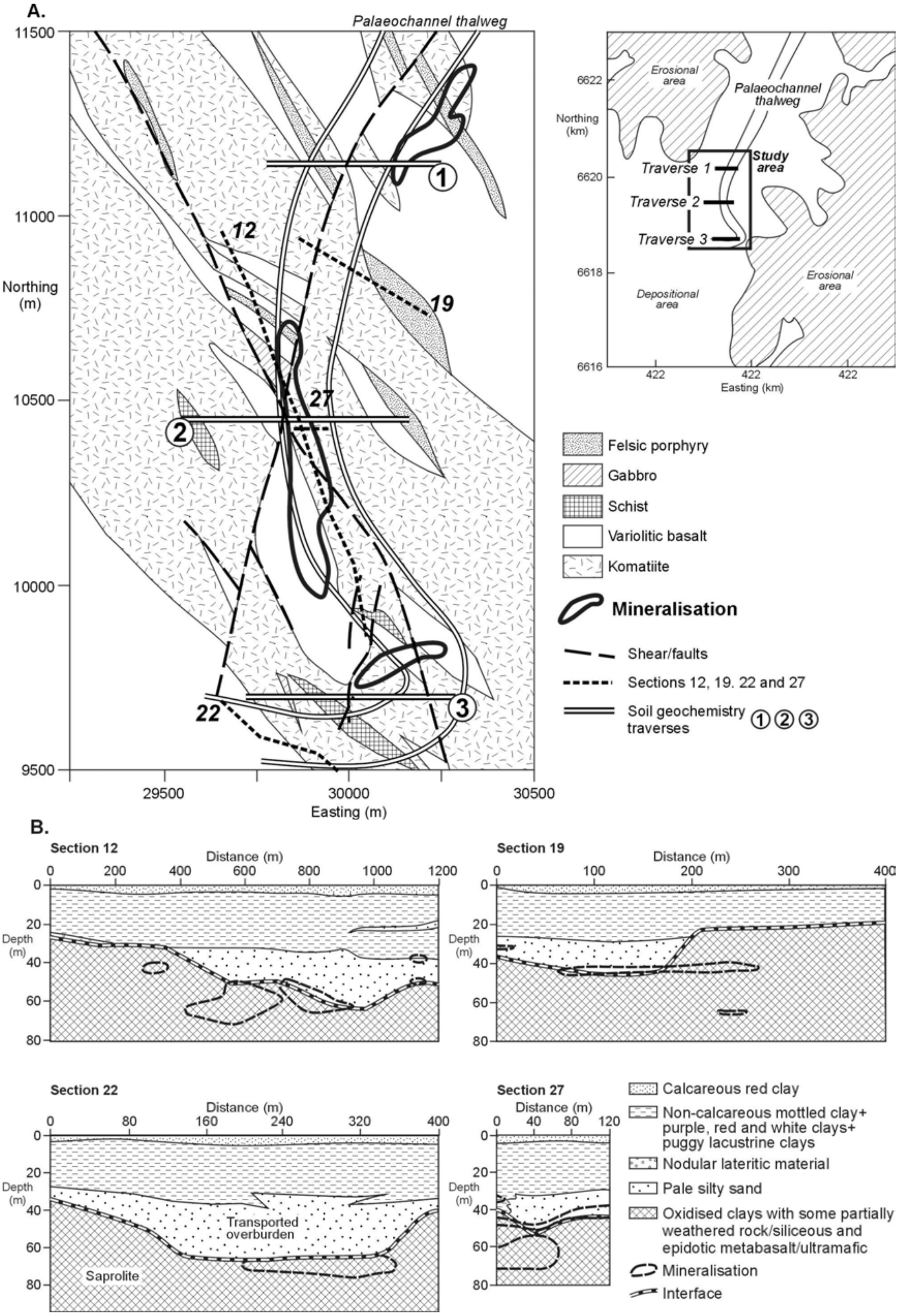


Figure 6.31: Geochemistry and regolith at the Kurnalpi Palaeochannel Gold Prospect. A) Plan showing geology, location of regolith sections and sampling lines. B) Regolith sections

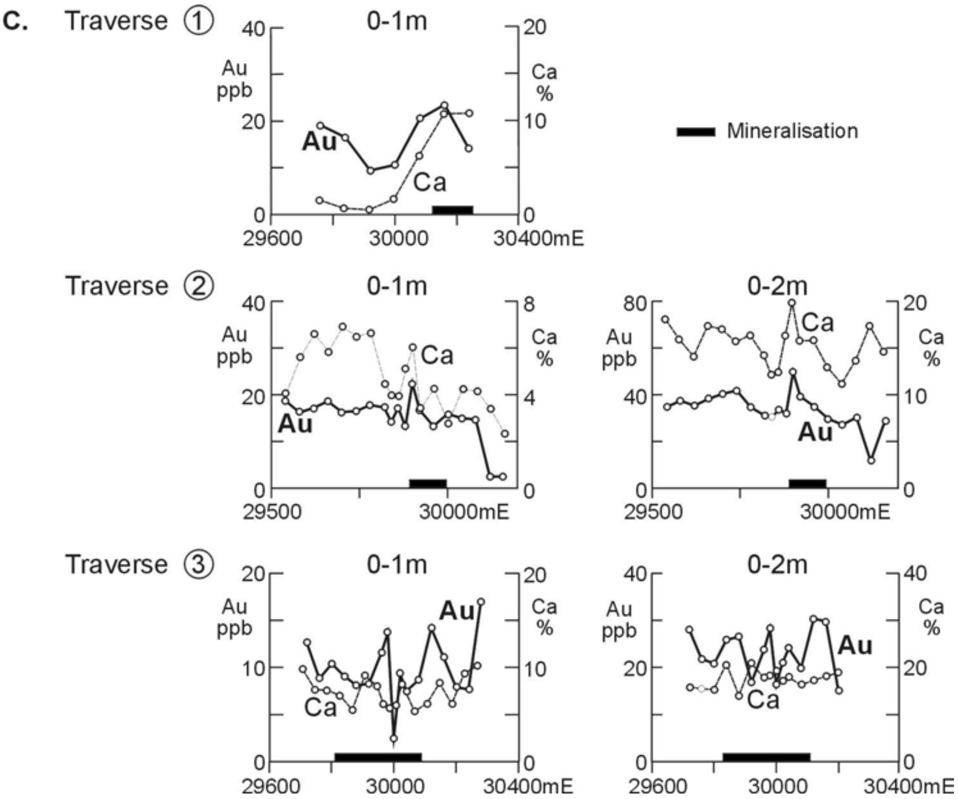


Figure 6.31 (continued): Geochemistry and regolith at the Kurnalpi Palaeochannel Gold Prospect. C) Geochemistry of soils (0-1 m and 0-2 m).

A limited geochemical study was undertaken at Kurnalpi, targeting soil, ferruginous components in the transported cover, and material from saprolite and bedrock. Soil was sampled by augering to a depth of 2 m over three traverses sited over the palaeochannel, downstream, over and upstream of mineralisation. Sediment, saprolite and bedrock samples were collected from RC drill cuttings. Only the soil traverse data are reported here.

Gold in the soil at Kurnalpi is largely confined to the calcareous horizon, which drill cuttings tend to indicate generally occurs within 2 m of the surface. There appears to be no correlation between Au distribution in the soil and the position of the palaeochannel mineralisation (Figure 6.31C). The mean Au concentration is 10 ppb for the 0-1 m depth material, with Ca concentrations (6-12%) relatively constant across the traverse. Soils in the traverse directly overlying the mineralisation have marginally higher Au concentrations (mean 19 ppb) than those downstream. Although soils located "upstream" of the mineralisation are considered background, Au concentrations (mean 16 ppb) are similar to those over mineralisation.

At Kurnalpi, augering appears to be effective in sampling the calcrete but the great depth to mineralisation and generally elevated background concentrations of Au mask any possible vertical movement of Au from buried mineralisation. The most probable source of elevated background Au concentrations in the calcrete is from the old Kurnalpi mine site 5 km to the NNE. The study demonstrates the importance of collecting sufficient samples, both from background and mineralised areas, to determine the source of the Au adequately.

(29) Basin and Range Province, Nevada (McGillis 1967).
Secondary dispersion haloes of Ag in calcrete on alluvial fans around eighteen Ag and Au mining districts were studied by McGillis (1967) as a possible guide to precious metal deposits in the Basin and Range Province of Nevada. He noted that Erickson *et al.* (1964) had previously found Ag in calcrete near the Getchell Mine, Humboldt County, Nevada. For these studies, the detection limit for Au was presumably too high and so only Ag was determined. McGillis (1967) found anomalous concentrations (mean of 3.1 ppm) of Ag downslope of all the districts sampled. The range of 0.1-4.8 ppm was recorded against backgrounds and thresholds of 1.3 ppm and 2.5 ppm, respectively.

McGillis assumed that the calcrete would act as a chemical pH barrier to any mobilised Ag with precipitation of Ag carbonate on contact with the calcrete. Samples were taken from the underside of rock fragments and their interstices from locations in intermittent stream channels that cut into the alluvial fans exposing the calcrete.

The study found that there was no significant difference in Ag content immediately above or below zones of mineralisation but that concentrations were lower in background areas. This suggests that Ag in calcrete alone cannot specifically locate mineralisation but that it may be useful as a regional tool. In contrast, the Ag content of stream sediments appeared to decrease with increasing distance from mineralisation; however, poor precision and large concentration ranges suggested contamination from mining activity. The Ag content of buried calcrete layers appeared to be no different from surface calcrete layers, indicating either there was no anthropogenic contamination from mine sites or that all the samples were similarly affected by mining activity, the former probably being the case. The study suffers from lack of data on Ag concentrations in other regolith materials or outcrop. It is possible that Ag concentrations are higher, or provide a better vector to mineralisation, in soils or weathered bedrock rather than calcrete or stream sediments.

6.2.4 Base metals case studies

6.2.4.1 Pedolith or saprolith host (Type B)

(30) Pioneer Nickel deposits, WA (Cox 1975, Butt 1992)

The Ni-Cu sulphide deposits at Pioneer, 85 km SSW of Kambalda (WA), are small bodies of massive pentlandite, pyrrhotite and chalcopyrite situated at the base of serpentinised ultramafic rocks in the Archaean Kalgoorlie-Norseman greenstone belt (Figure 6.32B). Soils are mainly residual, 0.1-1.0 m deep and developed over partly truncated profiles 25-100 m deep (Cox 1975). A calcrete horizon, 0.5-1.5 m thick, is developed below about 0.2 m depth, across the soil-saprolite transition, and consists of calcrete-coated lithorelics in a white matrix of calcareous smectitic clays. The mineralisation subcrops as a gossan, also overlain by calcrete and soil. Traverses across it showed that metal concentrations in sieved soil (<180µm) and the calcrete horizon were greatly reduced compared to those in saprolite and gossan (Figure 6.32A). Nevertheless, the maximum Ni, Cu, Co and Zn contents and Ni/Cr ratios in soils were found to be coincident with those in saprolite but had a greater lateral spread, particularly downslope. Metal concentrations were higher in the calcrete horizon than the soil but lateral dispersion was less. Dispersion in the weathered bedrock was minimal. The <180µm fraction was appropriate since Ni and Co were incorporated in Mn oxides, Zn and Cu in smectites (which comprise the fine fraction), and the coarse fraction contained clastic diluents such as quartz.

This contrasts with the finding in other case studies described in this chapter, where gossanous and/or ferruginous fragments (granules) present in the soil as a lag component increase the metal contents of coarse soil fractions. Soil profile samples indicated a gradual change in concentration with depth in Ni, Cu, Zn, Co and Cr; this suggests that metal concentrations in the saprolite are being diluted by the calcrete and soil components (Figure 6.32C).

(31) Jacomynspan Farm Copper and Nickel deposit, South Africa. (Danchin (1972), Vermaak (1984) and Tordiffe *et al.* (1989))

As with southern Australia, vast areas of the semi-arid and arid regions of southern Africa are covered with thick calcrete that often masks the underlying geology. At Jacomynspan Farm, calcrete covers migmatitic, porphyroblastic, biotite-garnet gneiss hosting Cu-Ni sulphide mineralisation occurring in a sill-like, pre-tectonic mafic intrusion. The ore body is zoned with the main horizon consisting of chlorite-biotite-tremolite schist containing disseminated chalcopyrite, pyrrhotite and pentlandite with 1-3% total sulphides. The area is located on a flat to gentle rolling pediplain with a weakly developed drainage to the N. The calcrete layer is <3 m thick and consists of various types including massive, nodular, powdery and laminar. A thin layer of sand that is rarely more than 10 cm thick generally covers it.

About 90 samples of mainly soil and calcrete were collected for a geochemical study. Results indicate that anomalies of Cu, Ni and Co in the calcrete are strong but limited in size, reaching background concentrations within 30 m of sub-cropping mineralisation (Figure 6.33B). However, as at Pioneer Ni deposits (see above), Tordiffe *et al.* (1989) found that soil and calcrete both defined the subcrop of mineralisation and retained the elemental association that reflects the host rocks (in this case mafic rocks rich in Fe-Mn-Co-Cu-Ni) and the association with secondary Fe oxides (Figure 6. 33A).

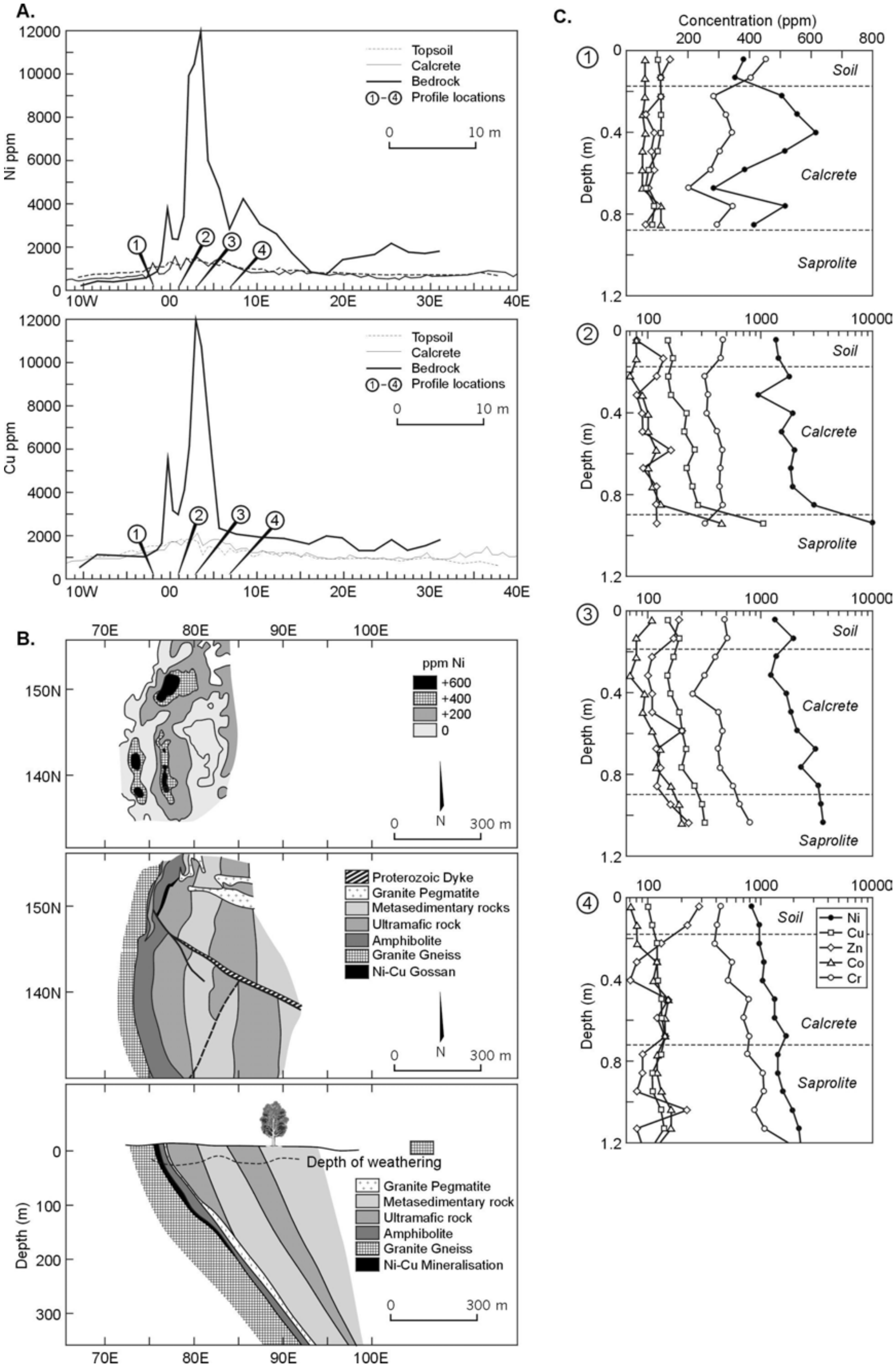


Figure 6.32: Copper distribution in various sample media at Pioneer (after Cox 1975). A) Traverse across mineralisation comparing Ni and Cu response in topsoil, calcrete and bedrock. B) Plan and section of Ni distribution and local geology. C) Profiles through the calcrete showing concentrations of various elements.

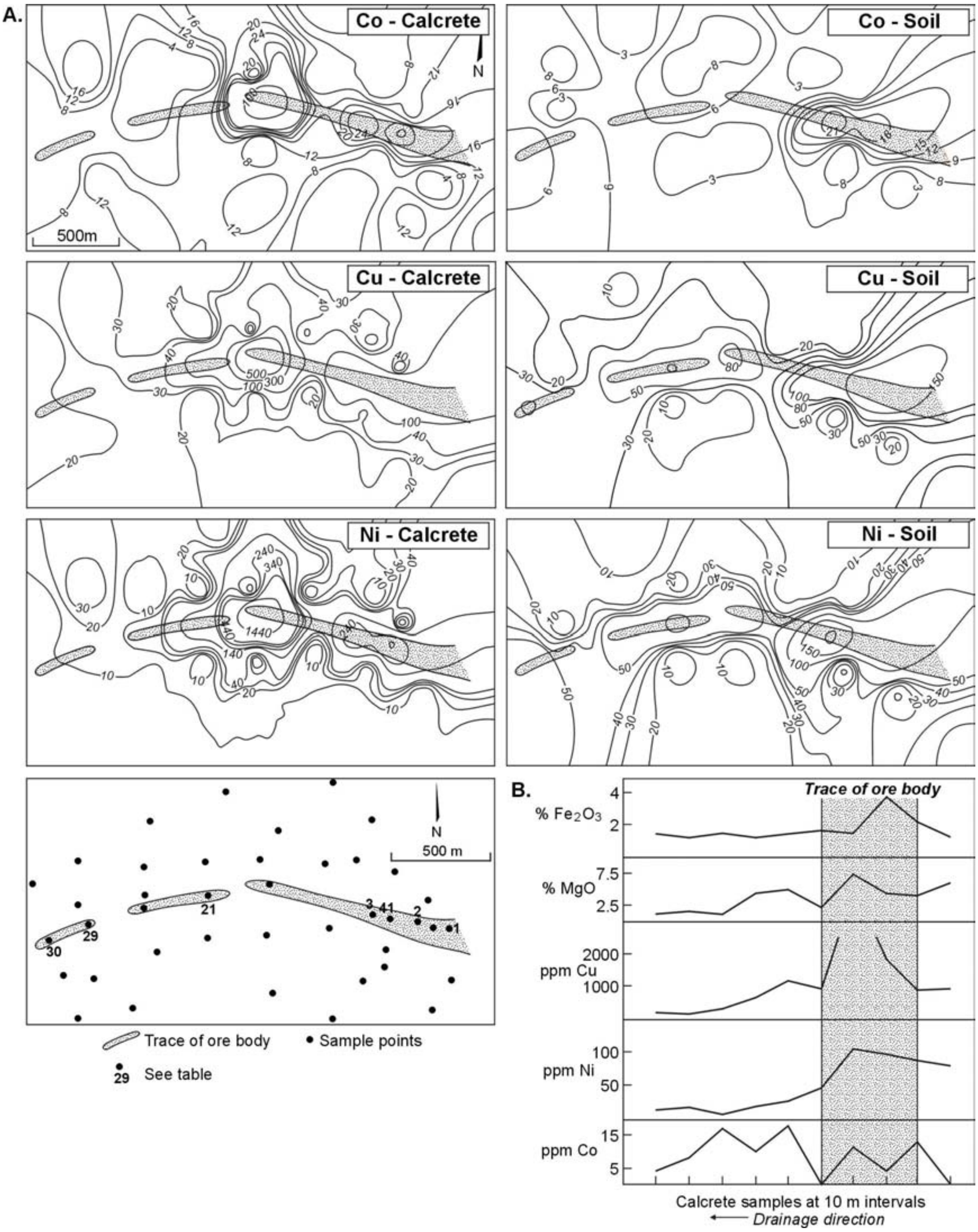
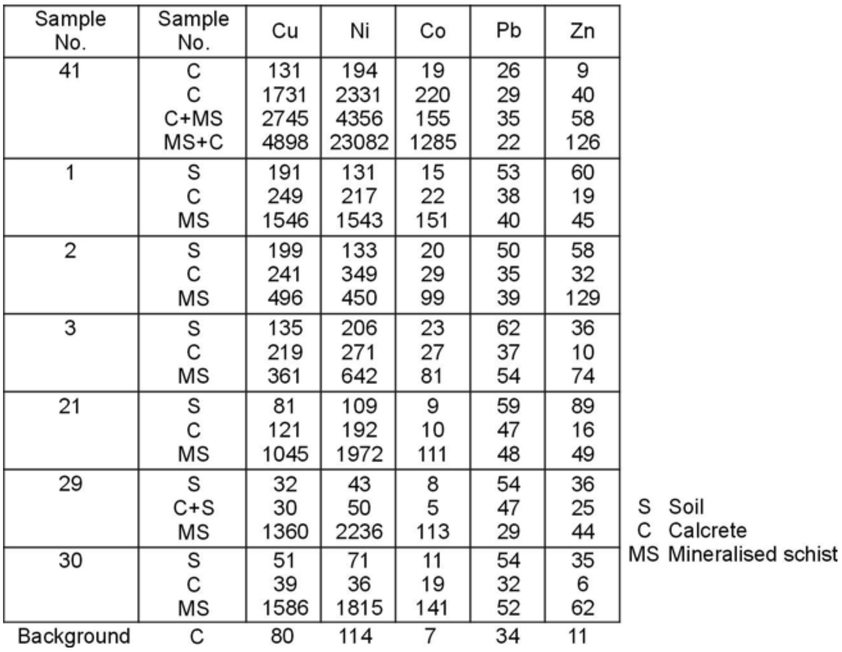


Figure 6.33: Copper, Ni and Co distributions at Jacomynspan (after Tordiffe *et al.* 1989).
A) Element distributions about the ore body.
B) Selected element concentrations in calcrete across mineralisation.

The latter are presumed to have formed by earlier weathering event(s) under more humid conditions prior to calcrete formation. In an earlier study, Vermaak (1984) found that metal concentrations in soil (30-200 ppm Cu, 45-205 ppm Ni) and calcrete (40-1730 ppm Cu, 45-2330 ppm Ni) were greatly reduced relative to mineralised schist (0.10-0.49% Cu, 0.15-2.30% Ni) (Table 6.3).

The results suggest that both soil and calcrete can be used to determine the location of the ore body. Copper, Ni and Co concentrations are nearly always higher in the calcrete than in the soil. Tordiffe and colleagues interpreted this as an indication that the elements are relatively immobile and precipitate readily in the carbonate under high pH conditions. Another possibility is that metals are greatly diluted in the soil by the presence of the aeolian sand.

Table 6.3: Element concentrations in different regolith materials from profiles (written communication Tordiffe 2000; background data from Vermaak 1984).



Sample No.	Sample No.	Cu	Ni	Co	Pb	Zn
41	C	131	194	19	26	9
	C	1731	2331	220	29	40
	C+MS	2745	4356	155	35	58
	MS+C	4898	23082	1285	22	126
1	S	191	131	15	53	60
	C	249	217	22	38	19
	MS	1546	1543	151	40	45
2	S	199	133	20	50	58
	C	241	349	29	35	32
	MS	496	450	99	39	129
3	S	135	206	23	62	36
	C	219	271	27	37	10
	MS	361	642	81	54	74
21	S	81	109	9	59	89
	C	121	192	10	47	16
	MS	1045	1972	111	48	49
29	S	32	43	8	54	36
	C+S	30	50	5	47	25
	MS	1360	2236	113	29	44
30	S	51	71	11	54	35
	C	39	36	19	32	6
	MS	1586	1815	141	52	62
Background	C	80	114	7	34	11

S Soil
C Calcrete
MS Mineralised schist

(32) Putsberg Copper Deposit, South Africa (Garnett *et al.* 1982)
The Putsberg Copper Deposit is located within the high-grade metamorphic terrain of the Namaqualand Metamorphic Complex. It is found in supracrustal rocks of the Bushmanland sequence (quartzites, ferruginous quartzites, aluminous schists, pink gneiss, amphibolite and calc-silicate rocks). Trenches across the area revealed the stratigraphy and provided access for sampling the soils and underlying material.At Putsberg, calcrete is commonly 2 to 7 m thick, but locally can extend to as much as 15 m depth, and is developed on and within bedrock. The upper contact of the calcrete is well defined in most cases, but the base is gradational. The ore zone itself is concealed by calcrete only 0.4 m thick. Immediately upslope of the ore body, the calcrete consists mostly of boulders and nodules (up to 0.5 m diameter), having calcareous silty cores and laminated carbonate skins, in a silty calcareous groundmass, but this changes to both nodular and finer calcrete further upslope and downslope (Figure 6.34D). The calcrete horizon is abruptly overlain by a sandy soil that has residual, aeolian and colluvial components. Over mineralisation, gossan fragments are present within calcrete nodules, soil and surface lag. Both coarse (1-2 mm) and fine (75-180µm) soil and calcrete samples gave a response over mineralisation (Figure 6.34A). The background values for Cu in the soil were considered to be of the order of 25 ppm or less, with the upper part of the calcrete having slightly higher concentrations, at about 60 ppm (coarse fraction) and 80 ppm (fine fraction). Near the ore zone, the strength of the geochemical response was found to be significantly greater in the calcrete than in the soil, particularly in the samples overlying the downslope section of the mineralisation (compare soil and calcrete graphs in Figure 6.34A). However, the overall width of the anomaly was probably greatest in the fine fraction of the soil. Thus, the mineralised zone was anomalous at 40 ppm, with scattered maxima greater than 200 ppm. Nevertheless, Cu, Zn and Pb contents were still greatly depleted relative to bedrock, and Cd and Ag were anomalous only in the coarse fraction.

Most of the decrease in base metal contents from saprolite to calcrete and calcrete to soil can be explained by dilution of mineralised saprolite and derived gossanous fragments by carbonates and quartz float, although some leaching may have occurred during calcrete formation. The association of Cu and Zn with heavy minerals and ferruginous fragments at Putsberg and nearby Kantienpan was also clearly demonstrated (Figure 6.34B and C). Garnett *et al.* (1982) and Vermaak (1984) both recommended the upper part of the calcrete horizon for regional sampling, because of (i) the higher metal content of the calcrete, and (ii) locally, the soil may either be absent or composed entirely of transported material. Garnett *et al.* (1982) demonstrated that the Zn anomaly could be enhanced by removal of the carbonate diluent using an acidic ammonium acetate leach and analysing the residue (Figure 6.34A). This wet chemical technique may not, however, be practical for routine exploration.

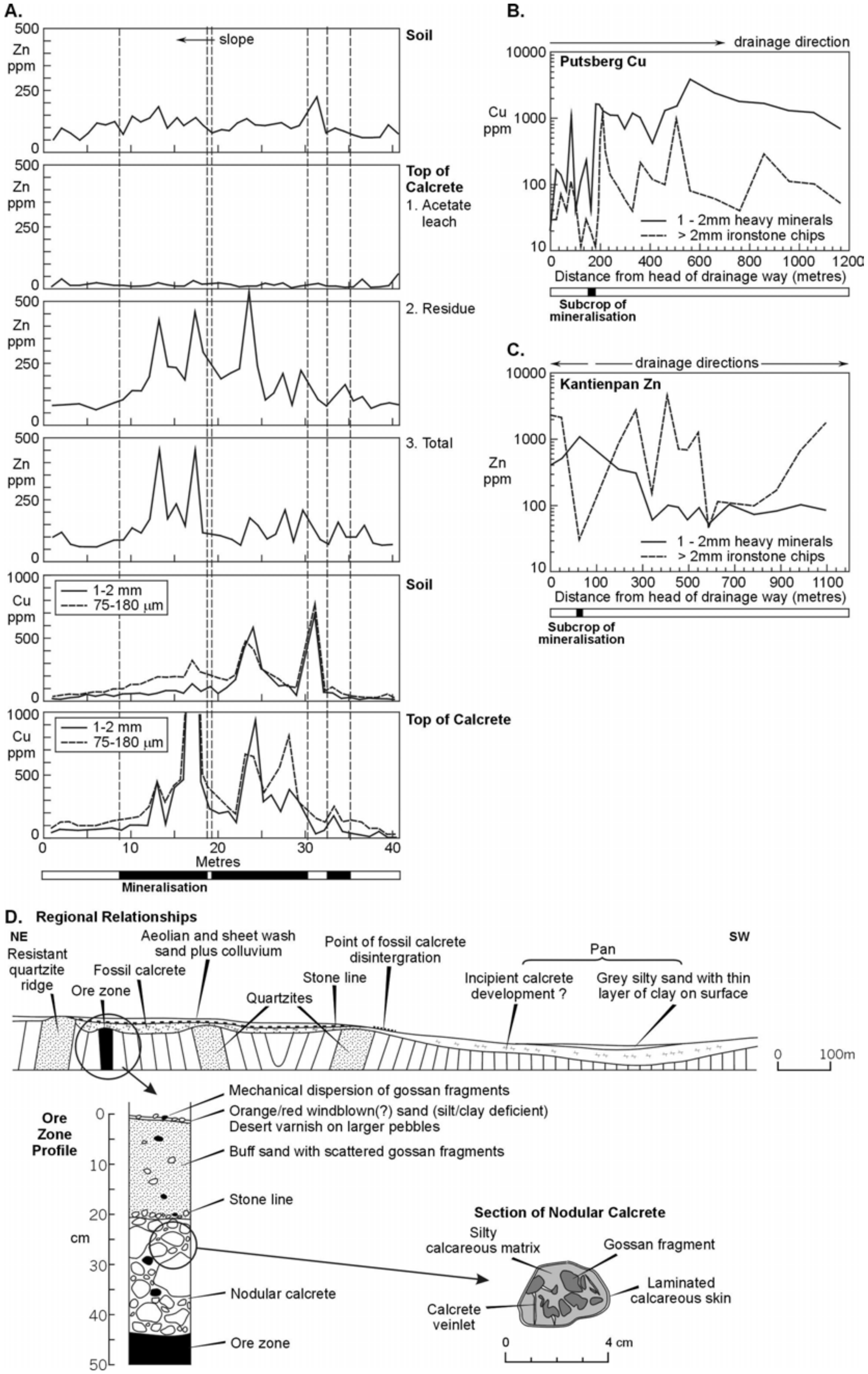


Figure 6.34: Copper and Zn distribution and regolith stratigraphy at Putsberg and Kantienpan (after Garnett *et al.* 1982). A) Concentrations of Zn and Cu in different sampling media across mineralisation. B) Concentration of Cu in heavy minerals and ironstone chips (ferruginous granules) at Putsberg. C) Concentration of Zn in heavy minerals and ironstone chips (ferruginous granules) at Kantienpan. D) Regolith section and profile at Putsberg.

(33) Bou Grine Lead-Zinc Deposit, Tunisia. (Leduc 1986, Guedria *et al.* 1989)

The Bou Grine Lead-Zinc Mine is located at the edge of the Lorbeus diapir about 150 km SW of Tunis, Tunisia. The stratigraphy consists of Triassic claystone, gypsum and sandstone rocks overlain by Cretaceous marls and limestones (Figure 6.35A). Three styles of mineralisation occur: (i) lenticular sulphides (sphalerite, galena and pyrite) associated with celestite and barite at the contact between the Triassic and Cretaceous rocks; (ii) disseminated sulphide mineralisation in Cretaceous limestones; and (iii) a semi-massive sulphide body that cross-cuts the Cretaceous sediments and is characterised by high Zn contents (> 20%). The reserves at 4% cut-off grade were estimated at 7.3 Mt @ 2.4% Pb and 9.7% Zn, and represent one of the largest base metal deposits in North Africa. Regional geomorphology is characterised by gentle slopes descending from the diapirs. Mean altitude is 500 m, the climate is semi-arid with an annual rainfall of 500 mm, and the natural vegetation consists of small trees and shrubs that have been heavily grazed.

The regolith stratigraphy consists of five units (Figure 6.35B):

1) surficial horizon containing colluvial material composed of parent rock, disseminated quartz and re-worked fragments of calcrete. Thickness increases downslope to 1 m. There is commonly asharp contact between this unit and underlying units;
2) two 0.1-0.4 m thick calcrete sub-horizons consisting of thinly-bedded lamellae separated by friable material resembling saprolite. The lower lamellar sub-horizon is of white to pinkish sub-horizontal sheets that are about 2 cm thick, slightly indurated with carbonate, and alternating with thin beds of saprolite. The upper indurated sub-horizon consists of calcareous material, is micro-grained (micrite) and hard, and displays light and dark bands;
3) nodular calcrete 0.5-1 m thick consisting of calcareous nodules about 0.5 cm in diameter, weak to medium hardness, white to pink, and a fine-grained texture. The nodules generally have a hard core of saprolite;
4) thin saprolite (0.25 m) developed directly on Triassic or Cretaceous parent rocks.

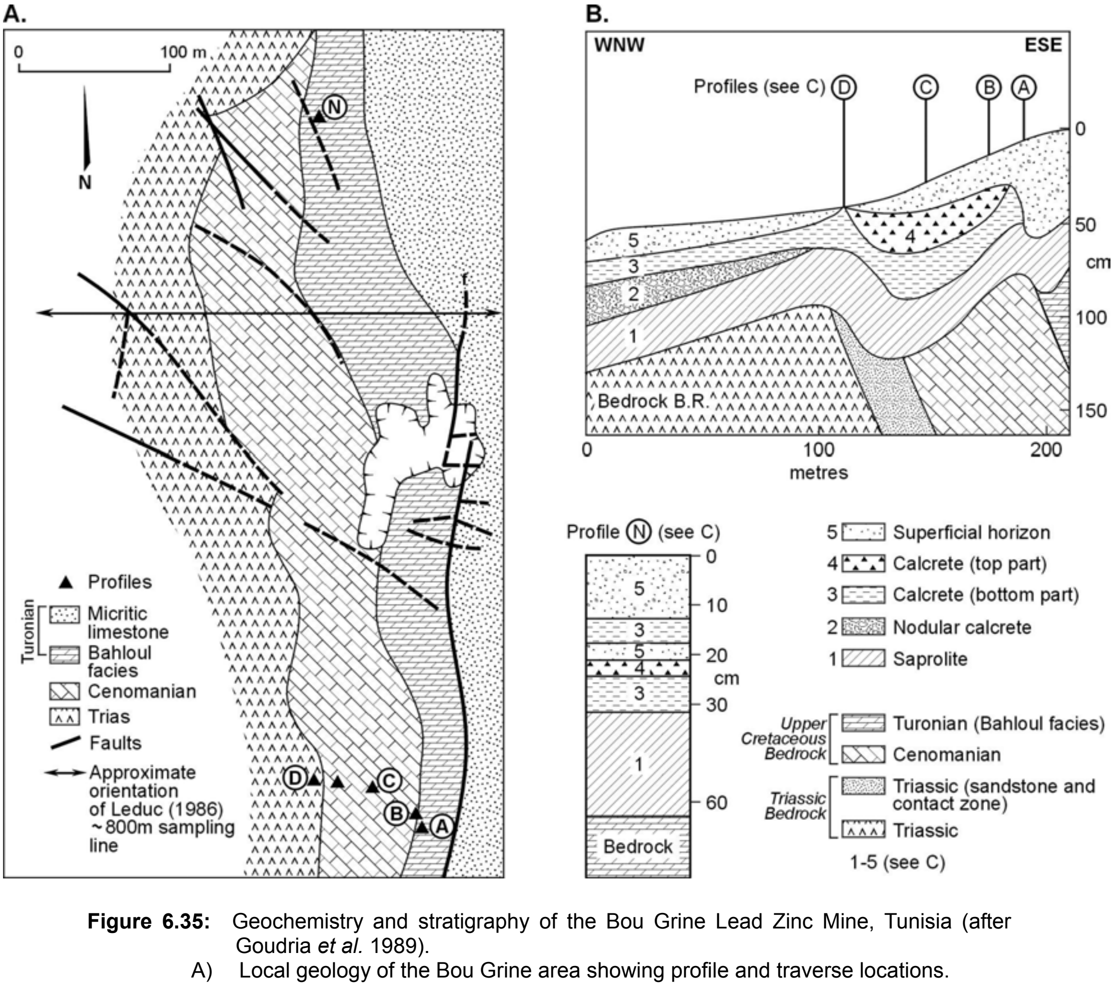


Figure 6.35: Geochemistry and stratigraphy of the Bou Grine Lead Zinc Mine, Tunisia (after Goudria *et al.* 1989).
A) Local geology of the Bou Grine area showing profile and traverse locations.
B) Regolith detail and profile locations.

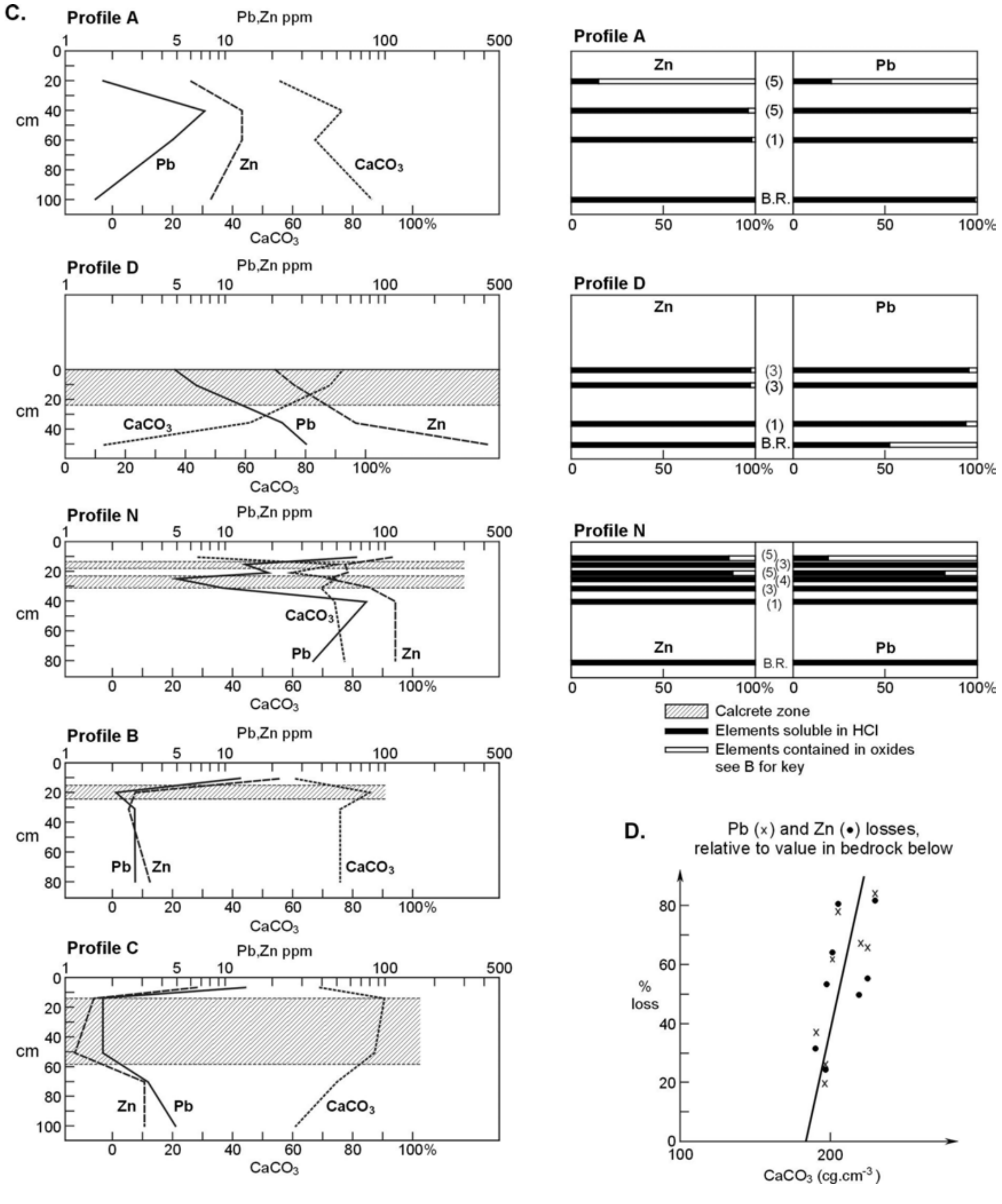


Figure 6.35 (continued): Geochemistry and stratigraphy of the Bou Grine Lead Zinc Mine, Tunisia (after Goudria *et al.* 1989).

C) Geochemical profiles and selective extraction studies.

D) Pb and Zn losses relative to bedrock as a function of carbonate content.

A petrological study indicated a progressive replacement and in-filling of cracks of the original parent rock material by micrite (fine-grained carbonate). The replacement conserves structural and geometrical features and volume, even though its constituents disappear. The geochemical and petrological data suggest that during hard calcrete layer formation, assumed to have been derived from re-working of the parent rock, absolute concentrations of metals such as Pb and Zn have decreased compared with the parent rock (Figure 6.35D). Of the Pb and Zn in the calcrete, >95% is soluble in dilute HCl. In samples that have lower carbonate contents, most Pb and Zn are not soluble but are associated with Fe oxides (Figure 6.35C).

In conclusion, Guedria and colleagues suggest that hard calcretes are not an ideal sample medium to use in base metal exploration but recommend that material beneath the calcrete is probably better even though this may still be partly calcareous. They suggest that anomaly contrasts decrease with increasing age of the calcrete and repetition of periods of calcrete formation.

Leduc (1986) performed an orientation study over the Bou Grine Lead Zinc deposit comparing "humic" soil with calcrete. In contrast to Guedria *et al.* (1989), Leduc found that there was little difference between Pb and Zn contents of the soil compared with the calcrete, although metal contents in the calcrete were slightly lower (Figure 6.36). Both sample media appeared to be capable of locating mineralisation. A subsequent geochemical survey carried out on a 25x50 m grid established anomalies that were later successfully drilled.

The different conclusions from the two studies are not easily explained from the given data. The study of Leduc (1986) suggests that it is not necessary to avoid calcrete during sampling, whereas the more detailed study by Guedria *et al.* (1989) clearly indicates that metal concentrations have been reduced by absolute amounts during the process of calcrete formation presumably by a leaching process.

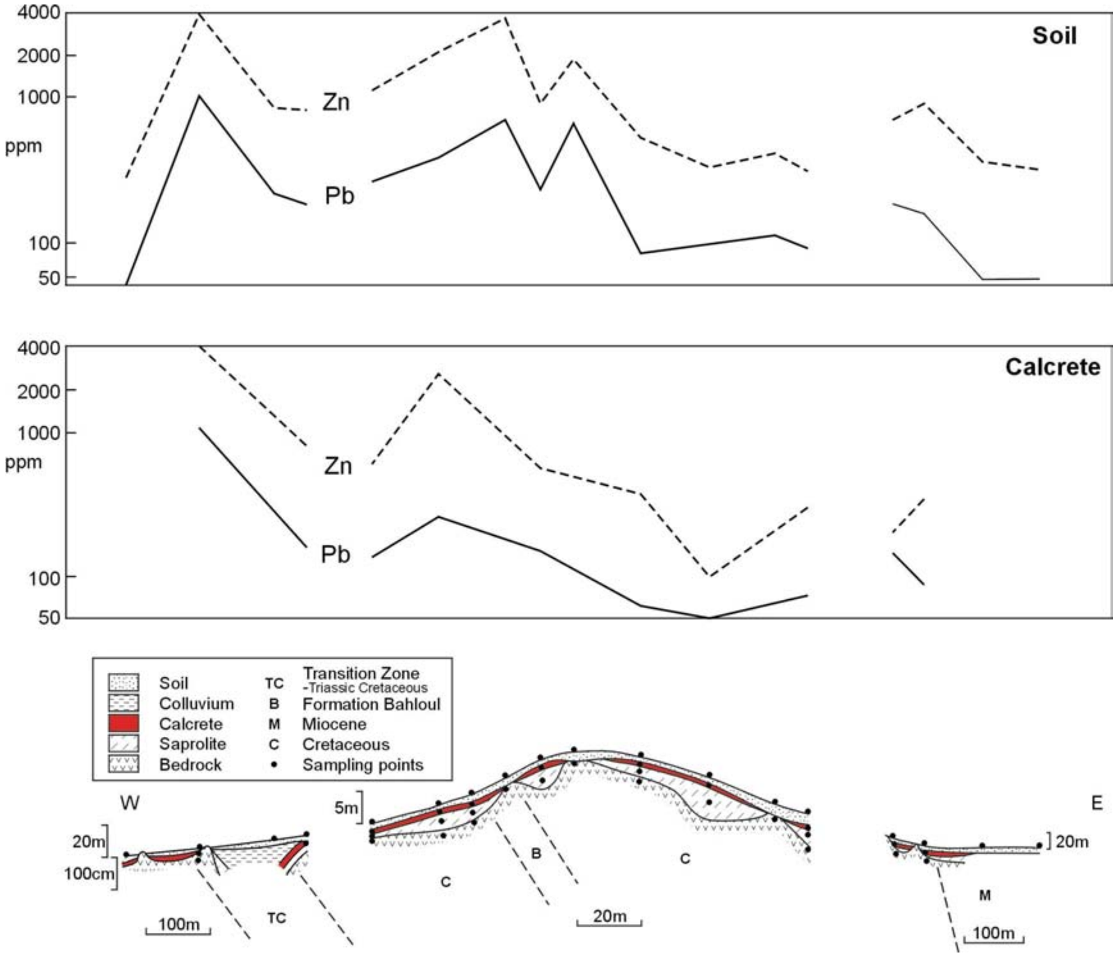


Figure 6.36: Geochemistry and stratigraphy over the Bou Grine Pb-Zn Mine (after Leduc 1986).

6.2.4.2 Transported overburden host (Type T)

(34) Kadina, Yorke Peninsula, SA. (Mazzucchelli *et al.* 1980, Butt 1992)

Proterozoic sulphide mineralisation (2% Cu) at Kadina, SA, is obscured by up to 70 m of Cainozoic transported and residual overburden (Mazzucchelli *et al.* 1980). Nodular, powdery and massive calcretes (0.6-2.0 m thick) developed within shallow clay loam soils overlie up to 40 m of transported clays deposited on saprolite. A study of Cu distribution was conducted over an area with relatively shallow overburden (5-10 m). The calcretes are alkaline (up to pH 9.5), whereas underlying units are acid (pH 4.5-6.0). Copper is distributed in narrow zones (to 15 m wide) in saprolite with >1000 ppm Cu surrounded by ~90 m wide dispersion haloes defined by the 250 ppm contour (Figure 6.37). Analysis for cold-extractable (acid ammonium acetate) Cu gave a 'mushroom-shaped' anomaly, with the strongest part immediately beneath the calcrete-clay interface. Low-order anomalies extended through the calcrete and were evident in the topmost samples at 1.5 m depth. The extractable-Cu response at the calcrete-clay contact was similar in location and dimensions to that obtained by saprolite sampling, but was more evenly distributed. Accordingly, shallower, more widely-spaced drilling could have been used in the initial stages of exploration without appreciable risk of missing significant anomalies. The extractable Cu pattern is considered to be due to continuing upward migration of Cu in highly saline acidic groundwaters, with some lateral dispersion occurring prior to fixation in the zone of high pH, represented by the calcrete.

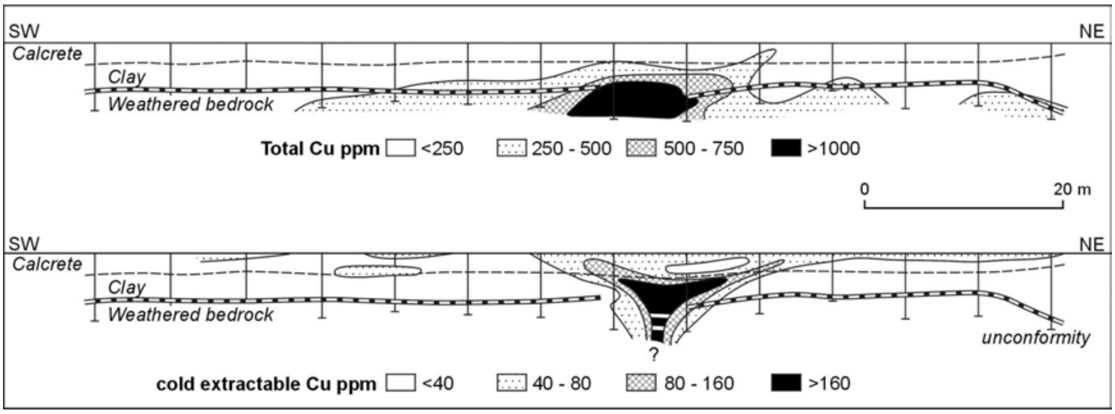


Figure 6.37: Regolith stratigraphy and Cu distribution at Kadina (after Mazzucchelli *et al.* 1980).

The distribution of Cu and Au was also examined in regolith profiles from the Poona pit at Moonta and similar results were found. A peak of total Cu (up to 200 ppm) occurring at the base of a 2-3 m thick calcrete horizon was found to be coincident with the occurrence of alunite in 6-10 m of transported overburden (Hartley 2000); Au concentrations were commonly higher (>4 ppb), however, in the calcrete horizon.

(35) Rocky Range Copper Deposit, Utah, USA. (Erickson and Marranzino 1960, Butt 1992)
A similar hydromorphic mechanism to that at Kadina is considered to have formed an epigenetic Cu anomaly in calcrete coatings on pebbles in alluvium downslope from mineralisation at Rocky Range Copper Deposit, Utah, (USA), although the dispersion is governed principally by gravity rather than upwards migration of groundwater. A chalcopyrite-bearing skarn is overlain by 6-70 m of alluvium, on a gently sloping (7o) pediment footslope in the Rocky Range mountains (Erickson and Marranzino 1960). The Cu distribution and anomalies (>300 ppm), shown by the <180µm fraction of the alluvial soil, probably indicate detrital Cu minerals derived from old workings upslope, although a few isolated high values were present above the buried mineralisation (Figure 6.38). In contrast, the Cu contents of calcareous crusts scraped from pebbles were highest (200->400 ppm) close to mineralisation, and the ratio Cu in calcrete/alluvium exceeded 1.5 at sites overlying or downslope from it. Thus, Cu appears to have been liberated from the sulphide mineralisation under acid conditions and precipitated preferentially in the neutral to alkaline environment of the calcrete. Dispersion is presumably further augmented due to mechanical dispersion downslope.

(36) Mt Gunson, Stuart Shelf, SA. (Lintern *et al.* 1998)
The Mt Gunson Copper deposits occur in the Neoproterozoic Stuart Shelf, overlying the eastern edge of the Gawler Craton (Figure 6.39A). They lie 60 km W of the Torrens Hinge Zone, which separates the Shelf from the Adelaide Geosyncline and coincide with a NNW-trending transcontinental gravity lineament (the G2 corridor), which continues through the Olympic Dam Deposit (O'Driscoll 1986, Preiss 1993). Mineralisation occurs in several units of the Adelaidian and pre-Adelaidian sequence, but principally in the Pandurra Formation, Cattle Grid Breccia, Tapley Hill Formation and Whyalla Sandstone. Two major styles of mineralisation are recognised at Mt Gunson and exemplified by the two areas studied by Lintern *et al.* (1998) (Figure 6.39B). Firstly, in the Cattle Grid open cut mine, mineralisation generally occurs at the interface between the Pandurra Formation and the Whyalla Sandstone. According to Van Herk *et al.* (1975), the ore is flat-lying, stratiform and epigenetic, lying beneath 15 to 35 m of Whyalla Sandstone and up to 10 m of Quaternary sand. The mineralised unit (termed Cattle Grid Breccia) consists of a blanket of brecciated, silicified, red-bed Pandurra Formation

sandstone, averaging 4.5 m in thickness (Williams and Tonkin 1985, Preiss 1987). Secondly, at the Windabout Prospect, Cu mineralisation is much deeper and is largely confined to black calcareous shales of the Tapley Hill Formation, which, in the area studied, occurs at depths between 65 m and 97 m depth, with a general thickness of 15 to 25 m. It is separated from the Quaternary units by Tregolana Shale and Whyalla Sandstone. The richest Cu grades (average 1-3 % Cu) occur at the base of the Tapley Hill Formation at about 70 m depth, and the indicated mineral resource is 18.7 Mt of Cu at 1% and Co at 0.05%. No Cu data are available for the lower regolith above the Tapley Hill Formation, although Cu concentrations in the Whyalla Sandstone immediately above the Tapley Hill Formation are generally of 10 to 100 ppm (data derived from Pacminex Pty Ltd).

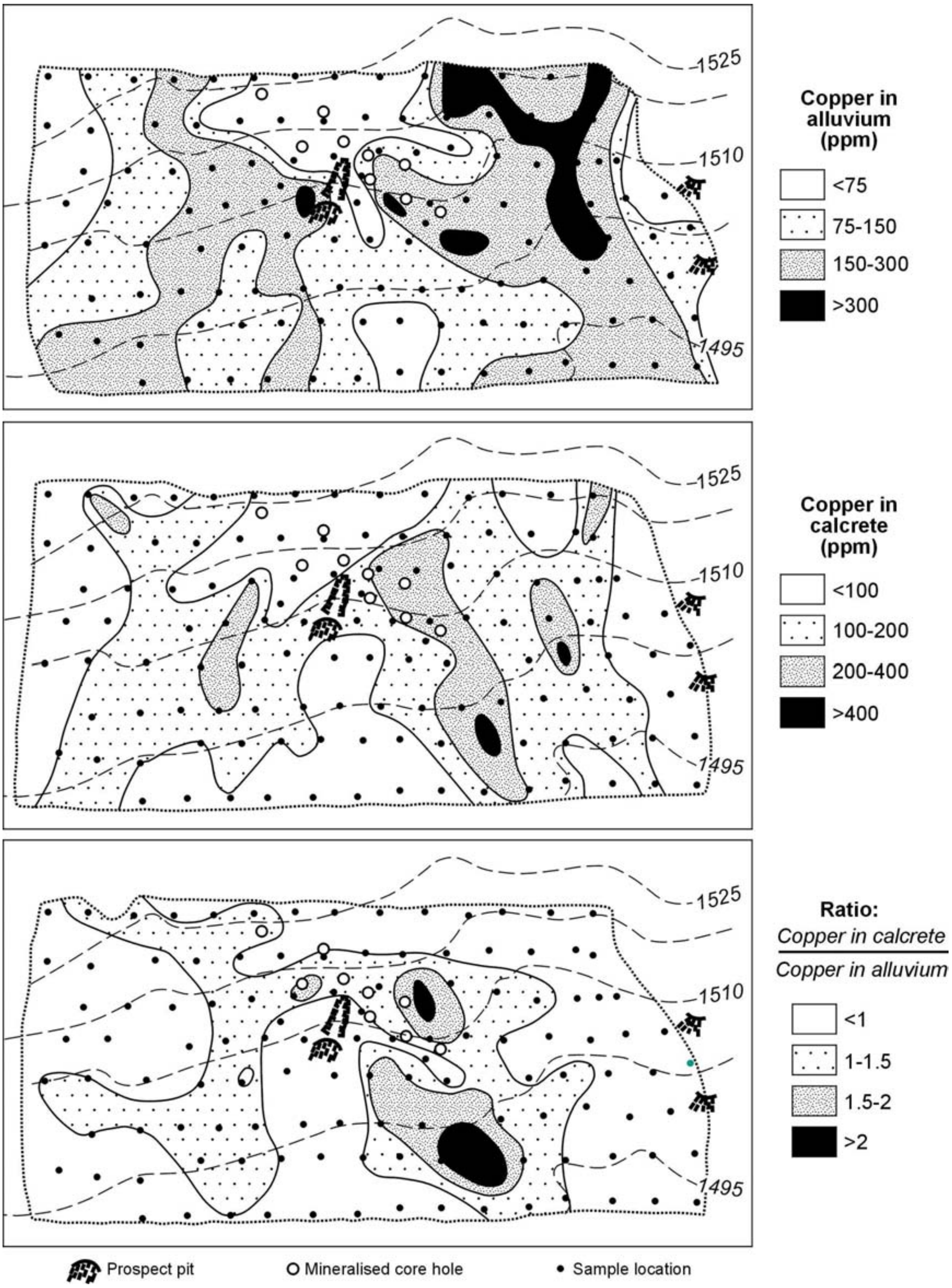


Figure 6.38: Copper distribution at Rocky Range (after Erickson and Marranzino 1960).

The area surrounding the local high point of Mt Gunson (259 m AHD, about 100 m above the surrounding terrain) has relatively low topographic relief and is dominated by low rises related to Proterozoic outcrop (Figure 6.39A). The Cu deposits are located just W of Pernatty Lagoon, which is one of a number of large, rectilinear, and approximately N-S oriented dry salinas in this region. Cainozoic sediments, in particular the Quaternary orange sand dunes and related sand spreads, mantle the pre-Cainozoic land surface and impose a local and regional topographic pattern (about EW). Aeolian dust as clay, silt, carbonate and gypsum, has been incorporated by illuviation and solution into the otherwise sandy (also aeolian) Cainozoic sedimentary landforms.

The available mine pits provide an excellent window into the regolith, which is otherwise poorly exposed in this area. Tertiary and Quaternary weathering and concomitant cementing processes have modified the regolith. Crystalline gypsum veining is common within the Quaternary sand spreads and appears to pre-date the calcrete influx and normally underlies it. Large (cm scale) individual euhedral gypsum crystals are also found in the red-mottled gley clays that overlie the Stuart Shelf sediments at Windabout. These gley clays are probably either mid to late Tertiary or early to mid-Quaternary in age and may represent slow deposition under water-logged conditions. Carbonate occurs as silt, sand, earthy coatings and segregations, or as more indurated forms of calcrete-grain cement/coatings, pisoliths and nodules. Calcrete is generally present throughout the Quaternary sands in the Cattle Grid area but, at Windabout, it is restricted to near the surface and to the base of the sands (16-17 m

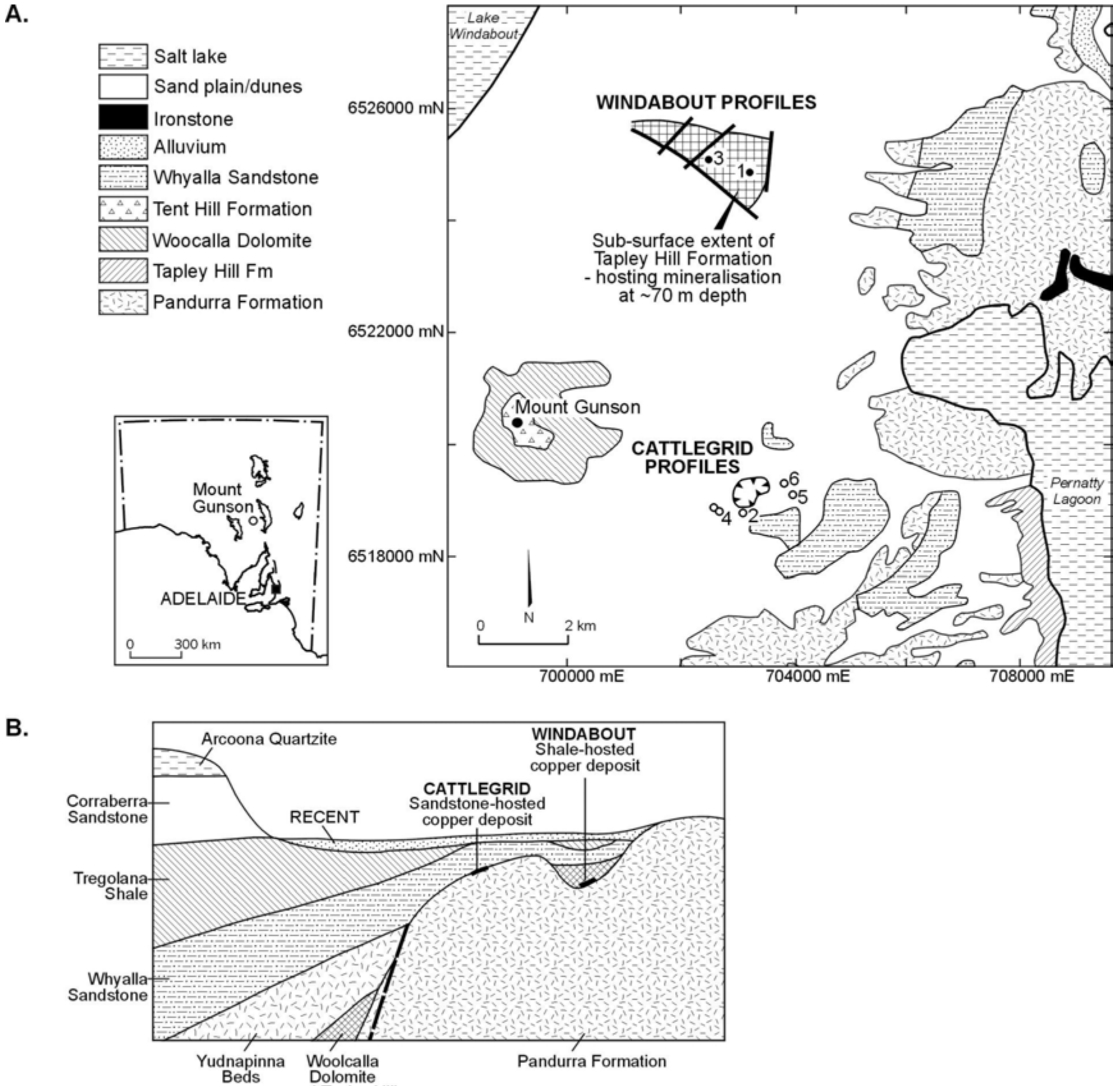


Figure 6.39: Element distribution and regolith at the Mt Gunson Copper Deposits. A) Local geology showing location of regolith profiles. B) Cartoon of geological section showing two styles of mineralisation.

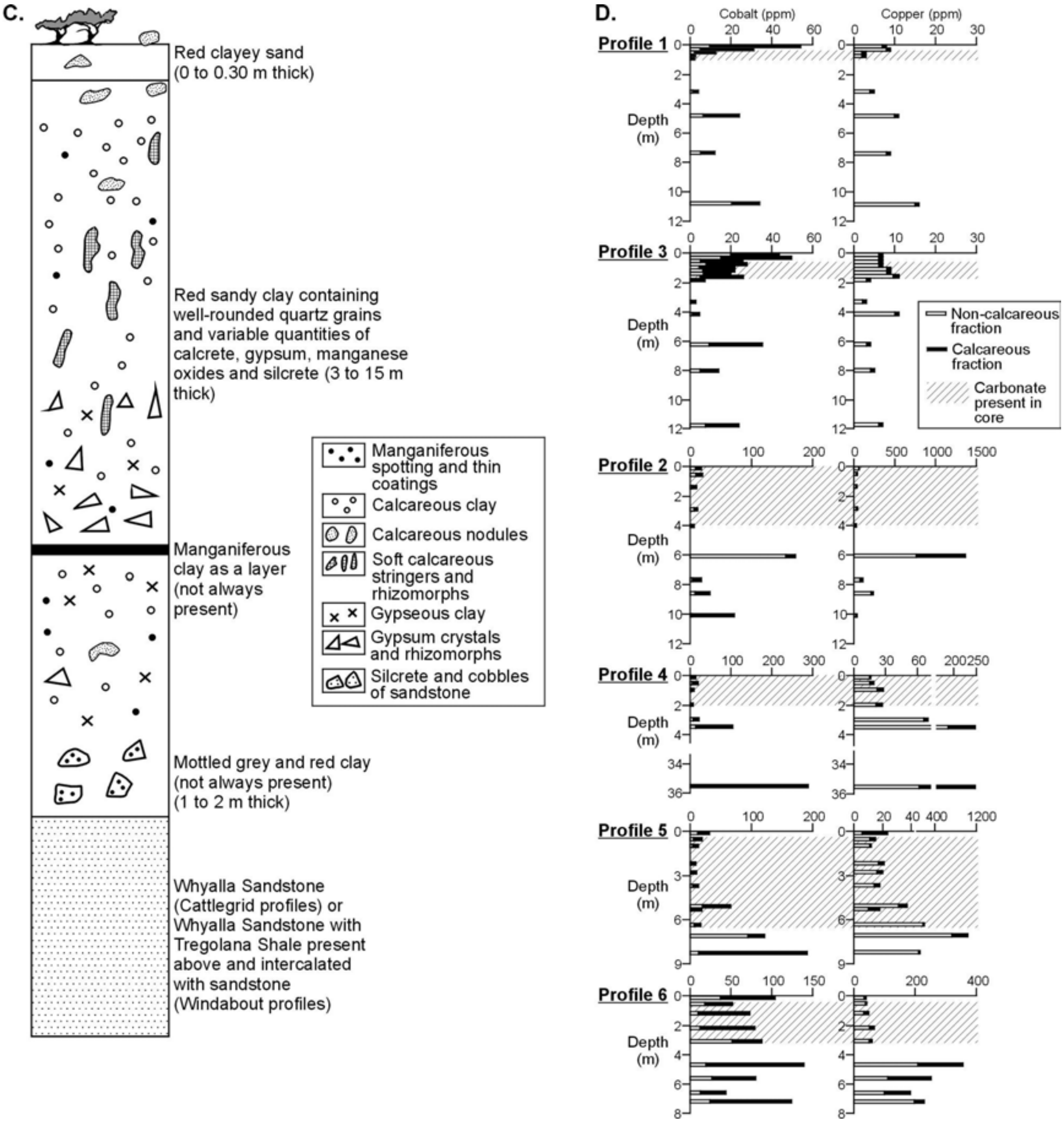


Figure 6.39 (continued): Element distribution and regolith at the Mt Gunson Copper Deposits.
C) Cartoon of regolith profile. D) Distribution of Co and Cu in regolith profiles.

depth), just 2 m above the gley clays. Manganese-rich materials are present as cutans, gypcrete coatings or inclusions, and occur low in the Cainozoic sand profile (>6 m). A distinct narrow zone of dark Mn-rich material was observed in two profiles at Cattle Grid (Figure 6.39C).

Three reagents were sequentially used on an aliquot of pulverised sample to examine the solubility of selected metals (Ca, Mg, Fe, Ag, As, Au, Bi, Co, Cr, Cu, Ni, Pb, Th, U and Zn) in three different phases in the regolith (Chao, 1984): (i) pH 5 acetate solution (for the carbonate and surface adsorbed metals phase), (ii) 0.1 M hydroxylamine (Mn oxides-oxyhydroxides phase) and (iii) 0.25 M hydroxylamine (amorphous Fe oxides phase). A separate aliquot of sample was dissolved using a triple acid digest to enable calculation of a fourth "insoluble" phase.

At Cattle Grid, anomalous total concentrations of Co, Cu, Ni and Zn were found sporadically, but not consistently, in the soils (Figure 6.39D). Manganese oxide staining is common throughout the soils, but only in three profiles (2, 5 and 6) is Mn sufficiently concentrated to be clearly visible on the pit face. Here, it was found that highly anomalous concentrations of Cu (and other metals) were associated with Mn oxides, which occur as grains, flakes, fragments and coatings on sand grains and larger sandstone clasts.

The Windabout profiles showed generally poorer surface soil responses for most base metals and chalcophiles (Cu, Ni, Pb and Zn) compared to Cattle Grid, perhaps reflecting the greater depth of sediment (70 m compared with 30 m) or the different style of mineralisation. In contrast, Co appears to be anomalous at Windabout in the top 20 cm and appears to be associated with Mn in theacetate-extractable (calcareous) fraction. The gypseous horizon immediately beneath has generally lower concentrations of Co and Cu.

The reagents dissolved only minor proportions of the total Fe, with the greatest dissolution for 0.25 M hydroxylamine. In general, extractable Mn is 50% or more of the total Mn, with most dissolved Mn in the pH 5 acetate solution, possibly representing trace Mn substitution in the calcrete either in calcite or, as the separate phase, rhodochrosite. At Windabout, the limited data suggests that for Cu, Zn and Pb, at least, no significant concentrations can be found in the upper regolith, even though these elements are associated with the Tapley Hill-style of mineralisation (Johns 1974, Rattigan *et al.* 1977). However, there are clear enrichments of these and other elements with Mn-rich materials, although additional sampling is required to test the exploration utility of such materials. The situation for Co is less clear, with significantly high concentrations found in surficial materials and apparent associations of Co with higher Mn in the calcareous horizon.

6.2.5 Platinum case studies

(37) Plat Reef, Bushveld Complex, South Africa (Frick 1985)
A study of the regolith in the Plat Reef area of the central Transvaal indicated that in most areas a thick colluvium is present. The colluvium is derived from material that has been moved considerable distances. As a result, a study of volatile elements such as Hg, As and S as geochemical indicators of underlying mineralisation was undertaken. The behaviour of these elements was compared with elements such as Ni, Co, Cu and Fe that were considered to be non-volatile and have moved laterally with the soil. Ferruginous material is common in the area, whereas calcrete is present in only limited amounts.

The Plat Reef consists of a stratified horizon in the Bushveld Complex with appreciable amounts of sulphides, copper sulphides and PGEs (Figure 6.40A). Four traverses crossing mineralisation were investigated and results suggested to Frick (1985) that, where colluvium is thin (1-2 m), all the elements used could locate mineralisation (Figure 6.40B). Where colluvium is thicker (>4 m), only Hg yields anomalies (directly above mineralisation), whereas other elements gave erratic results. Mercury concentrations also appeared to be higher above faults that intersect the ore body and were related to the depth of the ore body. Arsenic gave erratic results probably because it can become adsorbed on other components in the soil such as Fe oxides. Frick (1985) considers this to be the result of the reaction between arsenious acid and calcite to form minerals of the weilite group ($CaH(AsO_4).nH_2O$) (Figure 6.40C). It also appears that As and Hg may be flushed from the soil by rain; subsequent replenishment seems to confirm the active nature of the dispersion.

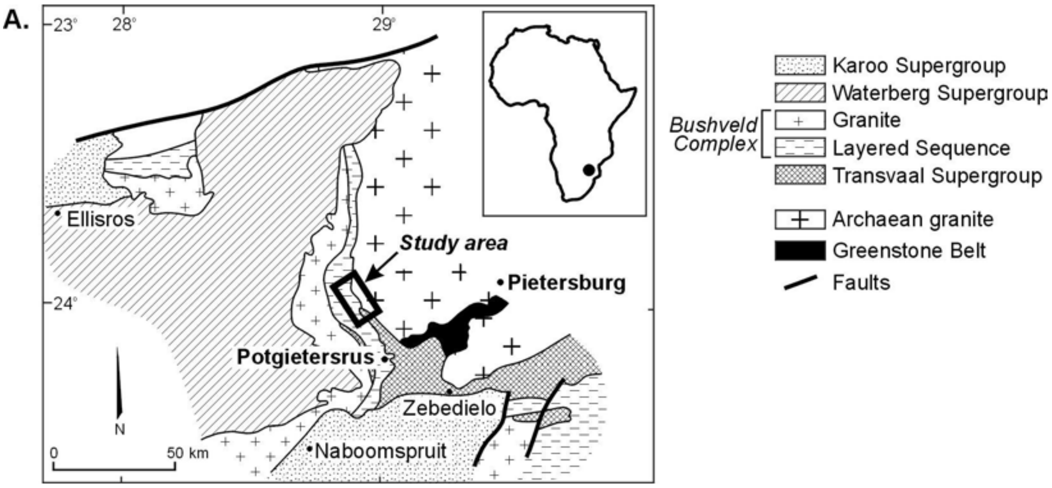


Figure 6.40: Arsenic distribution at Plat Reef (after Frick 1985). A) Regional geology.

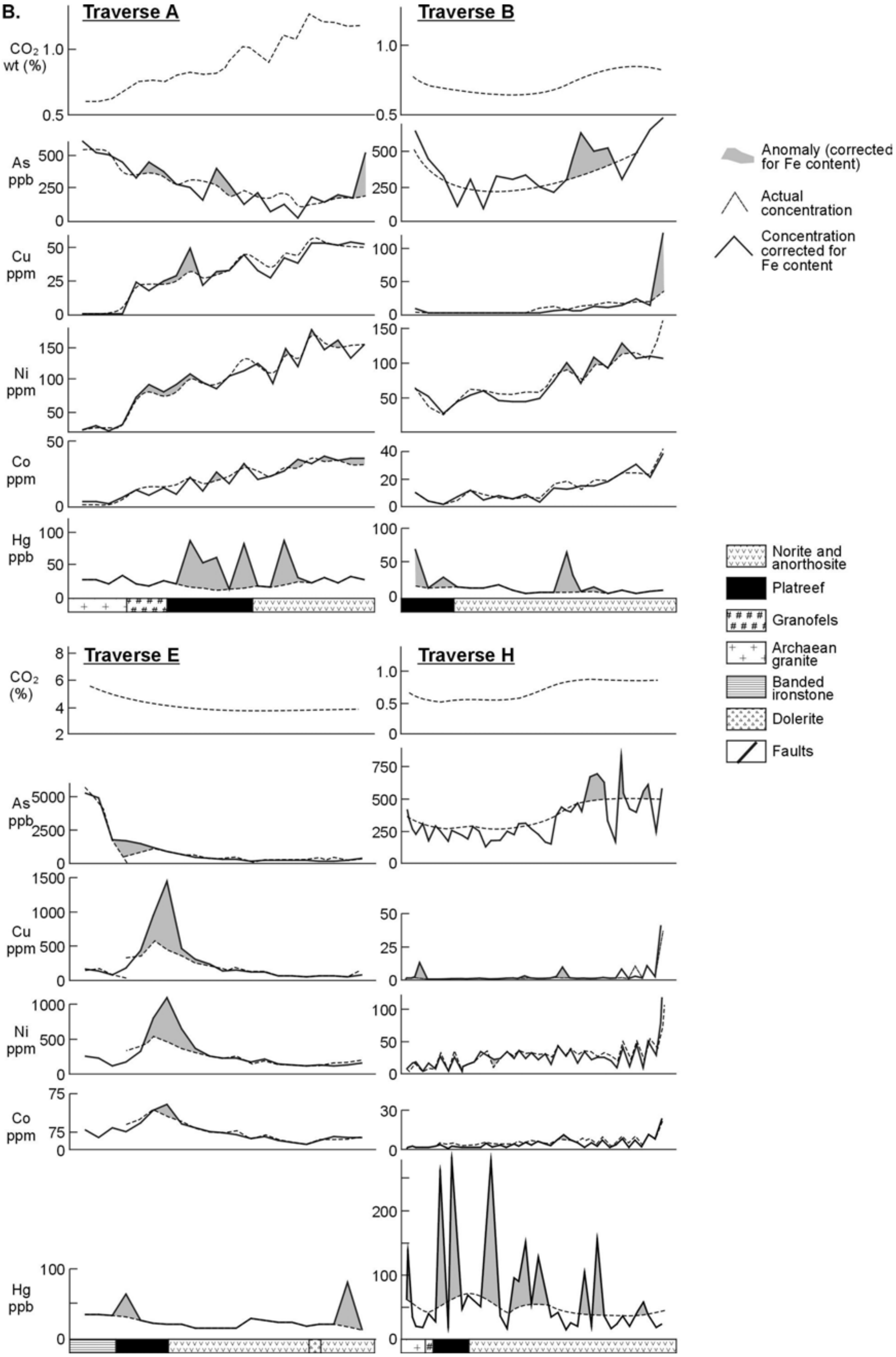


Figure 6.40 (continued): Arsenic distribution at Plat Reef (after Frick 1985). B) Geochemical traverses A, B, E and H.

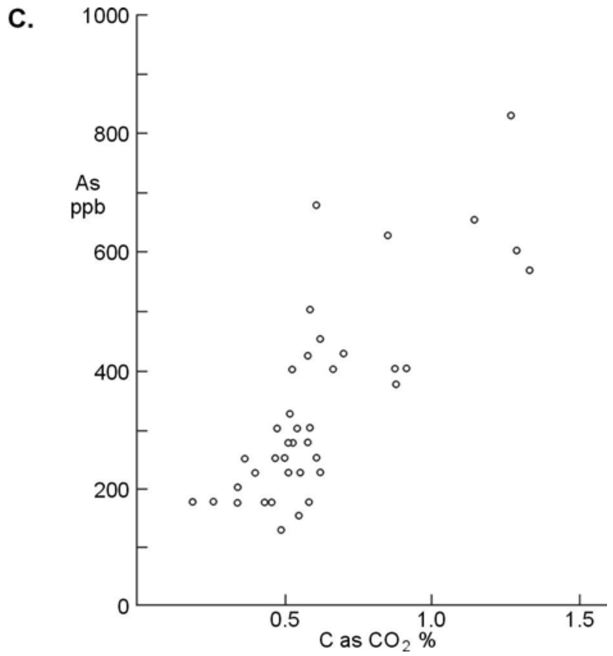


Figure 6.40 (continued): Arsenic distribution at Plat Reef (after Frick 1985).
C) Arsenic versus CO_2 (calcrete) for traverse H samples.

(38) Windimurra Complex, WA. (Harrison 1990, Butt 1992)
The Windimurra Complex is a weakly layered mafic-ultramafic complex located about 400 km NE of Perth, WA. Mineralisation containing >2 ppm PGE is associated with narrow (0.8-2.0 m) bands of disseminated and massive chromite, about 50 m apart. The mineralised sequence is covered by shallow residual lithosols containing coarse fragments coated by calcrete (R.J. Perring, verb. comm. to C.R.M. Butt 1990). The <180µm fractions of these soils, collected at 5-30 cm depth at 10 m intervals across strike, were analysed by fire assay fusion followed by ICP-MS. On the traverse illustrated by Harrison (1990), mineralisation was indicated by an anomaly 130 m wide (maxima 43 ppb Pt, 37 ppb Pd), defined by a threshold of 8 ppb compared to a background of 2 ppb, for both Pt and Pd. In comparison, Cu and Ni gave apical anomalies of 230 ppm and 300 ppm respectively. Inspection of the data suggested that soil anomaly was accurately reflecting mineralisation and a zone with high-background PGE contents; the extent of the anomaly is such that a wider sample spacing (e.g. 20m) may have been adequate. The specific role, if any, of the soil carbonates in PGE dispersion was not assessed. Mineralisation was also detectable in stream sediment samples (<180µm fraction), using the same threshold values.

6.2.6 Uranium case studies (summarised from Butt 1992)

6.2.6.1 Introduction

Epigenetic U enrichment in groundwater calcretes, carbonate-cemented sediments and overburden during the late Cainozoic has resulted in potentially economic surficial deposits. Such deposits are known in arid terrains in Africa, the Americas and Australia (IAEA 1984). They have formed by the solution and transport of U from a dispersed source (usually weathering granitic rocks) followed by concentration and precipitation in a relatively confined site, commonly as carnotite ($K_2(UO_2)_2V_2O_8.3H_2O$). The deposits are classified as follows (Toens and Hambleton-Jones 1984):

1) Fluviatile: in palaeovalleys and drainages containing sediments with aeolian, colluvial, alluvial, lacustrine or evaporitic components.
2) Lacustrine/playa: in dry or ephemeral lakes with evaporitic and fine-grained clastic sediments.
3) Pedogenic: in residual or transported regolith, associated with calcrete, dolocrete or gypcrete.

The only known deposits with economic significance are of the fluviatile type, with the carnotite associated with non-pedogenic, groundwater calcretes (Australia and Somalia), and calcareous and/or gypsiferous sands and gravels (Namibia and South Africa). Exploration for these deposits has depended upon radiometric surveys of favourable geological and geomorphological environments, followed by reconnaissance drilling of the anomalies, which themselves constitute the deposits. Soil or regolith sampling to search for a dispersion halo has been unnecessary. Future exploration may focus on concealed deposits that have formed as precipitates within undisturbed sediments, and those that have no radiometric expression because either they are very recent (and have not reached radiometric equilibrium) or differences in mobility have separated the daughter products from the parent U. Conversely, strong anomalies may be due to the concentration and deposition of Ra either distant from the U deposit, or where no U deposition has occurred at all. Consequently, understanding the genesis of these deposits, which involves weathering and dispersion in the regolith, is important for the interpretation of hydrogeochemical data in the exploration for buried and radiometrically blind deposits.

6.2.6.2 Fluviatile, lacustrine and pedogenic deposits of uranium

A number of factors may be involved in the genesis of fluviatile and lacustrine deposits (Mann and Deutscher 1978) but the most important, especially for those in Australia, are the evaporative concentration of U, V and K in groundwaters and the redox control of V mobility; a lesser role is ascribed to changes in pH and in CO_2 partial pressures that cause dissociation of uranyl carbonate complexes. The cations (U, V, K) are all derived from weathered granitoids and transported in groundwaters to the valley axis (Figure 6.41). Uranium is soluble as uranyl carbonate complexes and V as a tetravalent cation. Precipitation of carnotite occurs where concentrations of U and K have been elevated by evaporation and where V is oxidised to the pentavalent state. This may be where V has diffused upwards from depth under a redox gradient or where a subsurface bar has caused upwelling of groundwaters to relatively oxidising conditions, accompanying effects being mounding and spread of calcrete. However, calcrete is not the only host to mineralisation and in many deposits carnotite is precipitated in other sediments.

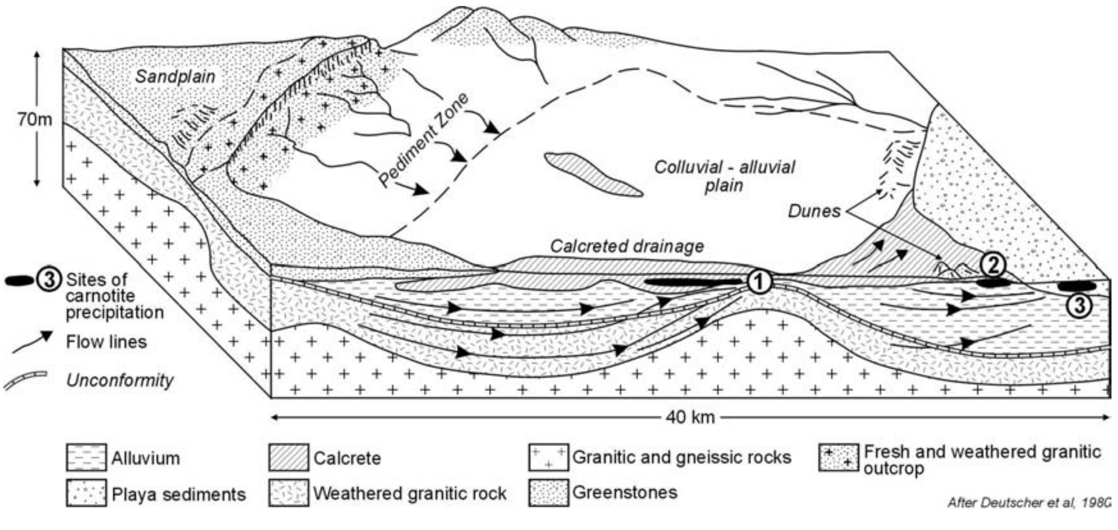


Figure 6.41: Cartoon of U mineralisation in fluviatile and lacustrine carbonate deposits (after Deutscher *et al.* 1980).

Enrichment of U may occur in pedogenic calcrete and underlying carbonated weathered bedrock in the upper 1 to 5 m of the profile. Such enrichment tends to overlie specific source rocks or occur a short distance downslope from them. It is formed by the capillary rise or evaporative pumping of groundwater above the water-table, so that activities of K+, V5+ and U6+ exceed the solubility product of carnotite. Total U contents exceeding 1000 ppm have been recorded (e.g. Minindi Creek, Butt 1988) but, because the volume ratios of source to enrichment site are small, mineable tonnages are low and the deposits are unlikely to be economic. Pedogenic concentration over source rocks having high abundances (>5-10 ppm) of labile U may constitute false anomalies in exploration for concealed primary deposits, the surface expression of which may arise by analogous processes. However, anomalies derived from primary mineralisation would be expected to contain trace element signatures in addition to K and V.

6.3 Discussion

The case studies (summarised in Table 6.4) illustrate the importance of regolith classification in determining the effectiveness of calcrete sampling when exploring for Au and other metals. For Type A and Type B regolith regimes, the beneficial use of calcrete, as an exploration medium, is clear.

Target elements appear to be present in other materials at the surface, e.g. lateritic residuum, mottles, saprolite and quartz, prior to the accumulation of calcrete. Initially, the interaction of pre-existing material with the gradual introduction of calcrete is one of dilution. Later, the carbonate serves to displace, disrupt and replace pre-existing materials during the process of calcrete formation. Clasts of the original host from the micro- to the macro-scale can become incorporated in the calcrete and these may or may not contain target elements. Thus, the metal contents of calcrete may contain spuriously high values (particularly Au), which are due to clastic materials incorporated within the material. In situations where there have been recent additions to the soil profile of calcrete or other aeolian material, metal concentrations may be diluted; aeolian sand can be removed from calcrete by sieving. One method by which "nugget effects" and diluents (e.g., aeolian material) may be averaged for calcareous soils to give less erratic data, is to take a composite sample of soil using an auger, as is commonly done in the Eastern Goldfields, WA. This, of course, adds to the costs of sampling, but will provide more reliable data than soil sampling alone in many circumstances. If aeolian material is particularly prevalent, e.g. sand then selection of sieved coarse calcrete material should be considered, as has been successfully used in parts of the Gawler Craton, SA.

Gold occurs in two different forms in the calcrete and, as a result, the selection of calcrete as a "consistent" sample medium requires some caution:

1) Au may occur in clasts and become physically incorporated into the calcrete, either as a discrete grain or incorporated within a host, e.g. ferruginous granule.
2) Au appears to have undergone a chemical transformation to a chemical species that allows it to become concentrated within, rather than diluted by, the calcrete.

This is most clearly shown in profiles where only powdery, newly-formed, calcrete occurs (e.g. Bounty and Panglo case studies) but it has undoubtedly occurred elsewhere where there is now great thicknesses of older calcrete and the strong correlations have been lost by other pedogenic processes. A theoretical physico-chemical process has been proposed for the manner in which Au and Ca become closely associated in calcrete, but clearly more chemical speciation studies need to be undertaken (Lintern 1989). Briefly, the process requires Au and Ca to be in the soil environment, i.e. particulate, colloidal or chemical Au dispersed from host material such as laterite or saprolite and Ca as wind-blown carbonate. It is proposed that Au is complexed with organic ligands produced by soil flora and fauna, e.g. fungi, bacteria, algae, plant root exudates. After rain and soil moisture build-up, the Au and Ca become relatively mobile and are re-distributed independently, albeit over distances of a few microns, within the soil profile. Some Au and Ca will be adsorbed by plants and re-cycled to the surface. As the soil moisture dries due to evaporation and transpiration processes, the solubility limits of the Ca and Au complexes are reached and they are precipitated. Their close correlation in the soil implies that the solubilities appear to be very similar. The cycle is repeated the next rainfall event, and so on. Numerous (possibly hundreds or thousands) rainfall events will gradually cause some of the Ca and Au to become normally (Gaussian) distributed (with respect to distance from the land surface) in the soil. The distribution is likely to develop a skew to the surface if soil is eroded, or skewed deeper if rainfall increases over a period of time and/or new material becomes deposited e.g. sand.

Evidence in support of the process includes:

1) the strong association between Au and calcrete as shown by soil profiles in the case studies;
2) the strong relationship between Au and soil moisture in soil profiles from Argo and Zuleika (Lintern and Gray 1995b, Lintern and Butt 1992);
3) the soluble nature of Au in laboratory studies (Gray *et al.* 1990);
4) the hypothetical presence of Au complexes in the near-surface environment (Gray 1998); and
5) the presence of Au in plants (e.g. Lintern 1989).

One of the factors that may influence calcrete as a sample medium is the depth at which it is found. The depth at which it appears to be accumulating does not appear to be wholly related to, or predictable from, the annual rainfall, as suggested by Jenny (1941) or Yaalon (1983). For example, the rainfall at

Table 6.4: Case study summary. Locations are in WA unless stated. Mineralisation abbreviated to “min” and maybe secondary in some cases.

No.	Location	Type	Target	Depth to mineralisation	Transported overburden thickness	Other information
1	Kalgoorlie	A	Au	Not known		As (pathfinder) is diluted in calcrete
2	Mulline	A	Au	<5	<1	Gold in both laterite and calcrete
3	Callion	A	Au	<2	<1	Highest Au in calcrete
4	Mararoa	B	Au	20	<1	Arsenic normalised from Fe oxides, Au over min.
5	Bounty	B, T	Au	<5->10	<1-10	Strong evidence for hydromorphic Au
6	Runway	B	Au	50 m	<1	Anomalous Au in calcrete
7	Lights of Israel	B	Au	<2	<1	Gold in calcrete developed in mottled zone
8	Challenger	B, T	Au	<2-20	<1-20	Au in calcrete – calcrete cementing quartz veins
9	Mt Pleasant	T	Au	<5	<1-5	Probable anomalous Au in calcrete. Particulate Au
10	Granny Smith	T	Au	5-20	1-3	Mostly background Au in calcrete. Calcrete not in surface material
11	Wombola	T	Au	40	3-7	Anomalous Au in calcrete. Inconclusive.
12	Apollo	T	Au	15	7	Background Au in calcrete
13	Argo	T	Au	20-30	7-60	Background Au in calcrete
14	Safari	T	Au	8	5-10	Anomalous Au in calcrete
15	Kanowna Belle	T	Au	50	5-10	Anomalous Au in calcrete, Fe granules
16	Matt Dam	T	Au	35	1-16	Anomalous Au in calcrete, Fe granules
17	Golden Delicious	T	Au	20	9-16	Background Au in calcrete
18	Deep South	T	Au	15	10-15	Anomalous Au in calcareous hardpan.
19	Panglo	T, B	Au	30	10	Anomalous Au in calcrete and in adjacent saprolite. Inconclusive study
20	Zuleika	T, B	Au	20	20	Anomalous Au in calcrete possibly unrelated to min.
21	Ghost Crab	T	Au	40	1-25	Anomalous Au in calcrete
22	Marigold, USA	T	Au	30-100	20-100	?Mobile metals above sulphides due to migration of acid (as H^+ or CO_2 gas)
23	Steinway	T	Au	35	30	Anomalous Au in calcrete, Fe granules
24	Kanowna QED	T	Au	30	30	Anomalous Au in calcrete. Inconclusive study
25	Mulgarrie	T, B	Au	35	35	Inconclusive study
26	Wollubar-Enigma	T	Au	55	55	Background Au in calcrete
27	Higginsville	T, B	Au	<1-50	<1-50	Anomalous Au in calcrete, Fe granules
28	Kurnalpi	T	Au	60	60	Background Au in calcrete
29	Nevada, USA	T	Au/Ag	Not known	Not known	Ag in calcrete used as regional tool for Au deposits
30	Pioneer	B	Ni-Cu	<2	<2	Metals occur attached to Mn oxides within the calcrete.
31	Jacomynspan, SA	B	Cu-Ni	<3	<3	Metals occur attached to Fe oxides within the calcrete.
32	Putsberg SA	B	Cu	2-15	2-15	Anomalous Cu in ferruginous granules within the calcrete.
33	Bou Grine, Tun.	B	Pb-Zn	2	<2	Lead and Zn associated with carbonate in the calcrete and not Fe oxides.
34	Kadina	T	Cu	Up to 70	Up to 40	Copper precipitated on calcrete by upward migration of groundwater
35	Rocky R., USA	T	Cu	6-70	6-70	Copper precipitated on calcrete coatings by downslope water percolation
36	Mt Gunson	T	Cu	70	70 m	Copper and Co associated with Mn oxides in/about calcrete horizons
37	Plat Reef, SA	A B T	PGE	Not known	1->4	Arsenic anomalous in calcrete
38	Windimurra	B	PGE	Not known	<2	Inconclusive study (insufficient detail)
39	U Case Studies	T	U	1->10	1-10 m	Valley calcretes anomalous in U to form deposits in their own right

Laverton (about 220 mm) is slightly less than at Kalgoorlie (about 280 mm), yet the zone of carbonate accumulation is variable occurring below 3 m and at least to 9 m. Clearly, other factors are important for the depth at which carbonate (but not Au) accumulates, and may include the following inter-related characteristics of the region:

1) Type (frequency and duration) of rainfall; rainfall is mostly cyclonic and commonly occurs in large quantities over a short period during summer months. The high evaporation rates imply that soils dry more rapidly than in the winter-rainfall areas. This, in turn, results in a shorter growing season.
2) Hydrology; most rainfall does not percolate down through the soil profile but probably either flows over the surface, or channels preferentially through macropores that occur in the hardpan; the clay-rich calcareous soils that occur S of the Menzies Line, on the other hand, allow more general permeation of water through micropores.
3) Type of vegetation; *Acacia* dominate the landscape rather than *Eucalyptus* which predominantly occur S of the Menzies Line.
4) Low organic content and, presumably, biological activity in soils N of the Menzies Line.
5) Soils are acid becoming alkaline with depth, whereas in the southern Yilgarn, many soil types are alkaline becoming acid with depth.

The depth of transported overburden is the most important factor in determining whether sampling surficial calcrete is likely to be effective or not. For Au, there are no comprehensive case studies demonstrating that calcrete sampling would convincingly lead to the discovery of buried mineralisation where the depth of transported overburden exceeds 10 m. At some sites e.g. Wombola and Matt Dam, Au appears to be unusually highly concentrated in the calcrete when compared with other sites e.g. Zuleika, to be explained by simple upward movement of Au from a buried source. Even where the depth of transported overburden is less than 10 m, there are many cases where calcrete sampling does not locate mineralisation and/or where calcrete does not occur in significant quantities e.g Granny Smith (N of the Menzies Line). Although a fairly detailed study was undertaken, Safari requires further investigation to prove conclusively that calcrete sampling can be effective through overburden thicknesses as great as 5-10 m. Here, a mechanism(s) for the accumulation has not been established but progressive bioturbation, capillarity, soil gas, and vegetation may be involved. The reason for the accumulation of Au in calcrete at Safari and not in other areas, such as Argo and Apollo where the depth of transported material is less, is not easily explained but may be due to the possible differences in age or type of sediments. Superficially, there are sites where anomalous Au in calcrete overlies deeply buried mineralisation. However, there is strong evidence for the derivation of Au being from upslope rather than vertically from underlying mineralisation, particularly when detailed studies have been undertaken e.g., Higginsville and Steinway; these last two sites contrast with Zuleika where shallowly buried mineralisation barely produces an anomaly at all. In cases where calcrete has been acclaimed as a sample medium capable of discovering deeply buried mineralisation, unusually high concentrations of Au in the calcrete e.g. greater than 100 ppb, should arouse suspicion and suggest other causes. Although many studies may provide good examples of the use of calcrete in transported overburden, they are often coupled with a paucity of data (e.g. regolith-landform maps, topography, stratigraphy, detailed soil analysis) for a rigorous scientific appraisal to be made. Unfortunately, many studies have helped to promote an overly optimistic outlook for the use of calcrete in transported regolith: this may not be justified.

For Cu and other metals, case studies have been insufficiently detailed or numerous to demonstrate convincingly that the calcrete horizon, or material just beneath it, are effective sample media in areas of transported overburden. Only where the overburden is relatively shallow (<10 m), does there appear to be evidence of concentration of metal in calcrete as with Au, e.g. Kadina and Moonta, but whether this is due to upwards movement of metal-enriched groundwater or down gradient groundwater flows e.g. Rocky Range is not clear.

6.4 Recommendations for exploration

(1) The case studies indicate the importance of regolith characterisation before deciding on an exploration programme for a particular area. At present, this can only be achieved with drilling and regolith-landform mapping, but recent remote sensing techniques such as airborne EM,

Landsat TM and radar altimetry may give some hope in being able to map large areas with relative ease. Ideally, the regolith should be classified in terms of Type A, B or T. In terms of using calcrete for exploration, regolith Types A and B (regolith developed within variably weathered bedrock) appear to present fewer problems than Type T (regolith developed in transported material over Types A or B). The deeper the transported overburden, the less effective is calcrete as an exploration sample medium. The case studies suggest that where Type T regolith has transported material exceeding 10 m in thickness, it is unlikely that any response in the calcrete can be directly attributable to underlying mineralisation.

(2) Calcrete appears to both replace and displace host material, whether it be laterite, saprolite or sediment, and has a variable effect on the subsequent distribution of elements of interest within the original material. Calcrete commonly acts as a diluent in soils for base metal exploration, whereas Au appears to accumulate, or at least reside preferentially, within the calcareous horizons. The presence of parent material containing high concentrations of metal within the calcrete, e.g., in ferruginous granules, which may be a by-product of lateritic duricrust disintegration, may tend to distort the apparent effectiveness of the calcrete itself.

(3) The sampling procedure for calcrete depends on the type, depth and presence of other material. Nodular or laminar calcretes can be beneficiated by sieving away the fine fraction (particularly aeolian sand). These may be found at depth and can be sampled by digging small pits and breaking indurated surface with, for example, a crowbar or a robust auger. Powdery calcretes are best sampled by taking soil composites (e.g. 0-1 m) with an auger. This is particularly important on a prospect scale where large variations in the metal content of the calcrete may be expected due to inclusions. Loose nodular calcretes found on the surface should be avoided since (i) their origin is unknown, and (ii) they may have been preferentially leached of metals of interest. A sample size of 1 kg is sufficient for most samples.

(4) The identification of calcrete is most important. Calcrete samples may artificially enhance (for gold) or dilute (for base metals) the expected geochemical response and so it is important to be able to compare (in a sampling batch) similar materials or at least be aware of potential complications. The nature of the calcrete has already been mentioned in (2) above and so “calcrete” samples could include anything from, for example, a pure calcite deposit consisting of 40% Ca to fresh rock coated with a carbonate skin with a Ca concentration of less than 1%; both extremes will effervesce when acid is applied. Analysing the sample for, at least, Ca, Fe and ore-associated elements is recommended for an exploration programme. The analysis of Ca and field observation of effervescence will assist in estimating the amount of carbonate, although the presence of gypsum and other Ca-bearing minerals can give falsely high Ca concentrations. Iron concentrations will provide information on elements known to be scavenged, including pathfinders for Au, such as As and base metals.

(5) The use of partial or selective leaching techniques appears to be useful in some cases but the cost of such a procedure may be prohibitive in routine exploration. Leaching is used to enhance a geochemical response either by (i) removal of a perceived dilution effect caused by the carbonate, or (ii) specifically analysing for the mobile phase of the metal occurring in the carbonate itself.

(6) Sample spacing depends on many factors. As a guide, sample spacing that should be similar to a normal soil sampling programme recommended for that area. Obviously, sample spacing may be quite broadly spaced for initial regional work (1.6 km grid) but may be narrowly spaced for defining drilling targets (10 m).

(7) Sample preparation and analysis, data handling and interpretation rules apply to calcrete sampling as they would for any other geochemical programme. Appropriate standards must be included in submissions to analytical companies and preferably be of calcrete or similar material. Acid digests of calcretes must be of sufficient strength to digest the carbonate and take up the analyte of interest. Cyanide digests are recommended for Au dissolution when carbonate is present. Appropriate detection limits must be used; as a guide, if there is a detection limit of 0.1 ppb (recommended) then the minimum contoured gridded value should be not lower than 1 ppb, i.e 10 times the detection limit. Do not expect high correlations between Ca and Au from soil samples (e.g. 0-0.1 m, 0-1 m) collected during a routine sampling programme; high correlations are only observed in samples collected vertically down a soil profile.

(8) The results indicate that whilst pedogenic calcrete is important for mineral exploration, the role of groundwater calcretes has not been determined. Uranium is the exception since it may form mineral deposits within groundwater calcretes in its own right. At Granny Smith, north of the Menzies Line, calcretes possibly representing an intermediate form were investigated and shown to be of little value when compared with other regolith materials.

Chapter 7

Distribution in Australia: calcrete landscapes

X.Y. Chen, N.J. McKenzie and I.C. Roach

7.1 Data and interpretation of regolith carbonate distribution

The maps describing the distribution of Australian calcretes and regolith carbonates include data drawn from a number of sources (Figure 7.1.1, page 159). A small portion of the continent is covered by relatively high quality maps that are the result of various research projects (Figure 7.1.1, page 159). However, for most of Australia the information on regolith carbonate distribution is of relatively low quality and data for some areas are simply absent for a variety of reasons. In order to present the data objectively and informatively, several maps are presented here, separating raw data and interpretation.

Figure 7.1.2 (back cover page and the CD with full-sized figure) shows the data extracted from the following sources:
The 1:250,000 geological maps.
The 1:250,000 geological map series covers the whole of the Australian continent; therefore these maps have been used as the basis for compiling maps of calcrete and regolith carbonates. Where possible, polygons containing descriptions of calcrete or other regolith carbonates have been extracted from the digital 1:250,000 geological map sheets produced by each State or Territory. However, much of the 1:250,000 geological map information is compiled from sketches of the paper maps. Data describing the occurrence of calcrete or regolith carbonate have very different accuracy and precision between adjoining map sheets. Maps have been produced by many different geologists with different backgrounds, using different standards and over a long period from the early 1950's to the late 1990's. The major limits of reliability of the 1:250,000 geological map series recognised during this compilation include:

- Inconsistency between map sheets. Calcretes and regolith carbonates are mapped in some sheets but have been ignored in others. This has resulted in mapped calcretes and/or regolith carbonates on one sheet stopping at the sheet boundary because they are not mapped at all on the adjacent sheets.
- In some sheets calcretes and/or regolith carbonates are simply put, together with other units which do not contain any regolith carbonates, into a group of *surficial burden* or *Late Quaternary deposits* because they were recognised as surficial or young deposits. The distribution of calcretes and regolith carbonates is exaggerated if the whole group is regarded as containing regolith carbonate.
- Different terms such as *kankar*, *kunkar*, *travertine*, *nodular carbonates* and *nodular limestone* have been used when referring to calcretes and regolith carbonates. Great caution is needed to differentiate carbonates deposited in lake and marine environments from regolith carbonates, particularly when the term *limestone* is used.

The 1:2,000,000 Atlas of Australian Soil (Northcote et al. 1975)
This soil map was based on existing soil information by the compiling time (prior 1975) and 1:250,000 Geological Series. The map shows the major soil groups throughout Australia including some major and minor calcareous soils. McKenzie *et al.* (2000) provide interpretations of the presence or absence of regolith carbonates mapped as this dataset. Their interpretations underestimate the distribution of regolith carbonates because the presence of carbonate was not always used as a criterion within the dataset.

In the soil map, each mapping unit includes several soil types, of which major or minor types may be calcareous. These two situations are differentiated in Figure 7.1.2 (back cover page and the CD with full-sized figure). The calcareous soils may principally include calcretes or regolith carbonates that occur within soil profiles, in most cases within 1 or 2 m of the surface. The map excluded most of the deep-lying hardpan calcretes in ancient drainage lines in Western Australia, although this type is very widely distributed (e.g., Butt *et al.* 1977). Information from this map, obtained in digital form from the Bureau of Resource Science WWW site (as the Digital Atlas of Australian Soils), is incorporated into this compilation only in areas where no other information exists.

It is important to recognise that this dataset has its own severe limitations. Where no soil information existed the 1:250,000 Geological Series was used to provide information. In many cases, these maps also contained inconsistent or incorrect data.

South Australia 1:50,000 agricultural land and soil maps
Some data are derived from detailed (1:50,000 scale) mapping of soil carbonates in the agricultural lands of South Australia (PIRSA 2001). These are detailed maps providing very accurate descriptions of the distribution of calcrete and calcareous soils. Reports attached to these soil maps (e.g., McCord 1995), have great detail regarding the occurrence and morphology of calcretes and regolith carbonates. However, these only cover a small portion of the higher rainfall areas that are more important to agriculture. Similarly, calcretes occurring beneath soil cover over 2-3 m depth tend to be ignored by soil scientists.

The 1:250,000 Land Systems of NSW and Victoria
These are used for the western NSW and western Victoria.

The compiled data map (Figure 7.1.2, back cover page) follows the following rules:

1. All of the mapping units that contain any type of regolith carbonates are extracted and shown on the compiled map,
2. The extracted data are shown as they are in the geology and soils maps, including the discrepancies existing between adjacent map sheets,
3. Various types of regolith carbonates are not differentiated.

<u>BRS point soil database</u>
Figure 7.1.3 (page 160 and the CD with full-sized figure) shows the presence or absence of regolith carbonates in soil profiles which were recorded in the Australian Soil Resource Information System prepared for the National Land and Water Resources Audit (NLWRA 2001). The supporting soil profile database contains records for 166,171 sites. These data were collected during land resource surveys by States, Territory and Commonwealth agencies in recent decades. Most sites are located in the arable regions of Australia. The soil profile data have to be interpreted with care because observations are generally restricted to the upper two metres and there is no absolute guarantee that the presence of carbonate has always been recorded. Carbonate is considered present when one or more of the following criteria appears in the profile record:

- presence of calcrete either as a pan or substrate (i.e. type of pan = K or substrate mass genetic type = KC according to McDonald *et al.* 1990)
- presence of soil horizons with a *k* subscript denoting carbonate (e.g. B2*k* horizon)
- presence of carbonate nodules or segregations
- presence of carbonate in the fine earth (effervescence).

Sites where the presence of carbonate has not been recorded are also presented. A small minority of these sites may contain carbonate. These point data distinguish some areas with and without calcareous soils, e.g. in southeastern and southwestern corners of the continent (Figure 7.1.3, page 160). However, these cannot be readily converted to distribution areas of regolith carbonates, because: i) the points are not evenly distributed and are concentrated in agricultural areas of the continent marginal zones, ii) there are rarely any areas with calcareous soil profiles exclusively and calcareous soils are closely mixed with non-calcareous ones, iii) the nature of data as points instead of mapped areas.

There are other sources of data. For example, regolith maps produced by AGSO cover a small portion of the continent and provide some information on regolith carbonate distribution.

Because all of the constraints mentioned above, the raw data maps (Figures 7.1.2 back cover page and 7.1.3, page 160) have some problems, including:

1. many straight lines (Figure 7.1.2 back cover page and the CD), indicating the discrepancies between data sourced from maps of different generation and type. In some areas, regolith carbonates are totally ignored;
2. significant exaggeration of regolith carbonate distribution, in the case where a mapping unit (a polygon) in the source map contains several members which are not all calcareous;
3. underestimation of deeply buried regolith carbonate existence, particularly in soil maps and soil data which rarely include the information beneath the soil depth or depth of auger refusal.

An interpretive map of regolith carbonate distribution is produced (Figure 7.1.4), intending to deal with the above problems. It shows regolith carbonate distribution in four categories:

1) areas with regolith carbonates almost everywhere (>90% of the polygon), e.g. in Nullarbor Plain and in valley calcrete areas of northern Yilgarn Plateau,
2) areas mostly with regolith carbonates (50-90% of the polygon), e.g. parts of the Mallee region and the southern Yilgarn Plateau,
3) areas with patchy distribution of regolith carbonate (5-50% of the polygon), e.g. the Simpson Desert dunefields, and
4) areas with rare and isolated sites of regolith carbonates (<5%, mostly less than 1% of the polygon).

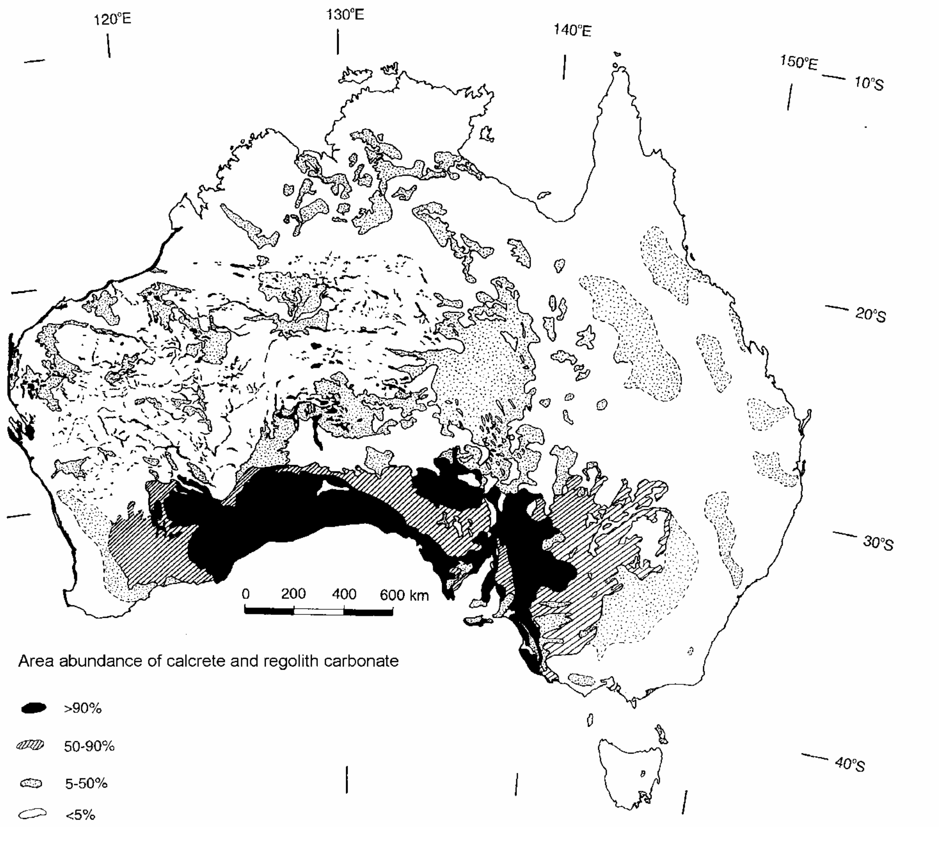


Figure 7.1.4. Interpretive map of Australian calcrete and regolith carbonates, based on the data presented in Figures 7.1.2 and 7.1.3, and on many published and unpublished papers and reports. The distribution areas of regolith carbonates are in four categories: from >90% to <5% (mostly <1%) of the area with regolith carbonates. More detailed distribution patterns are presented in Section 7.2.

In addition to the data compiled in Figures 7.1.2 back cover page and 7.1.3, page 160, the interpretations are also based on various published and unpublished papers and reports describing the occurrence of regolith carbonates, landforms, geology and soils in different areas. This interpretive map should be treated with caution. It shows regional abundance and the general distribution patterns of regolith carbonates across the continent. It may not be precise enough to be used in the field to locate calcrete areas.

Further interpretations on distribution patterns of regolith carbonates across Australia are presented later (Section 7.2), as summaries of the relationships between regolith carbonates and landforms, geology, regolith materials, soils and climate.

7.2. Calcrete landscapes

7.2.1. Introduction

In the following sections, various calcretes and regolith carbonates across the continent are described, based on various published and unpublished papers, reports and maps. It was convenient to group them into geographic regions, as the calcretes have shown significant differences from one region to another. Calcretes across Australia are formed under different conditions of climate, geology, topography and landform histories. This has resulted in a wide range of associations of calcrete (regolith carbonate) and landforms and host regoliths.

The concept of calcrete landscape is proposed here to use as a guideline to summarise Australian calcretes. A calcrete landscape is '*an area with wide to patchy distribution of calcretes and regolith carbonates that exhibit regular associations with landform, bedrock and regolith. One calcrete landscape differs from another by characteristics of calcrete (regolith carbonates) and/or the particular associations with landforms and regoliths.'* For a calcrete landscape, all regolith carbonates are included, e.g., a few carbonate nodules scattered within soils which may not be termed 'calcrete'.

Figure 7.2.1 shows the divisions of the ten calcrete landscapes which have been identified across the Australian continent. Detailed descriptions are presented below.

7.2.2. Valley calcrete along ancient drainage lines

The data

This calcrete landscape has been well studied in Australia because of the associated uranium deposits. The term 'valley calcrete' is based on the association between the calcrete and the 'valley-fill sediments that occur in both broad fossil valleys and existing trunk drainage systems' (Sofoulis 1963, Butt *et al*. 1977). The calcrete is dominantly a hardpan type with great thickness and lateral extension. Because of its distinctive occurrence and potential economic value of uranium and groundwater source, the calcrete was defined as a distinct mapping unit in most of the relevant 1:250,000 Geological Series maps.

Location and distribution

This calcrete landscape has a wide distribution in the western and central parts of the continent (Figure 7.2.1), including the northern Yilgarn Plateau, the Pilbara Region, the Sandland Region, the Central Australian Ranges Region and the southern Lander-Barkly Plains (for geographical regions see Jennings and Mabbutt 1986). It can be further divided into western, central and eastern divisions. The western division is separated from the central division by the 'Meckering Line', a boundary which marks the extent of major river channel incision (Mulcahy 1967). The boundary between the central and the eastern divisions cannot be clearly located with the available data.

The southern boundary is marked by the ‘Menzies Line’ (Section 6.2.2), a relatively narrow geographical boundary extending east-west with remarkably different vegetation, soil, and groundwater chemistry on either side (Butt *et al.* 1977, Carlisle 1978). However, the change of calcrete morphology, from very thick hardpan calcrete in the north to much thinner nodular calcrete in soils in the south, is more gradual than the changes in some other features.

Climate

The climate is arid with hot summers and moderate winters. The annual rainfall ranges between 170 and 250 mm, mostly as erratic late summer storms, and the annual potential evaporation varies between 3,300 and 4,200 mm.

Geological and physiographical settings

The basement of the western and central divisions consists of Archaean granitoids and greenstones, Proterozoic granites and gneisses, and Proterozoic sedimentary rocks of the Precambrian Western Shield. The eastern division extends to the Amadeus Basin with a sequence of Proterozoic and Palaeozoic sedimentary rocks above the Archaean basement.

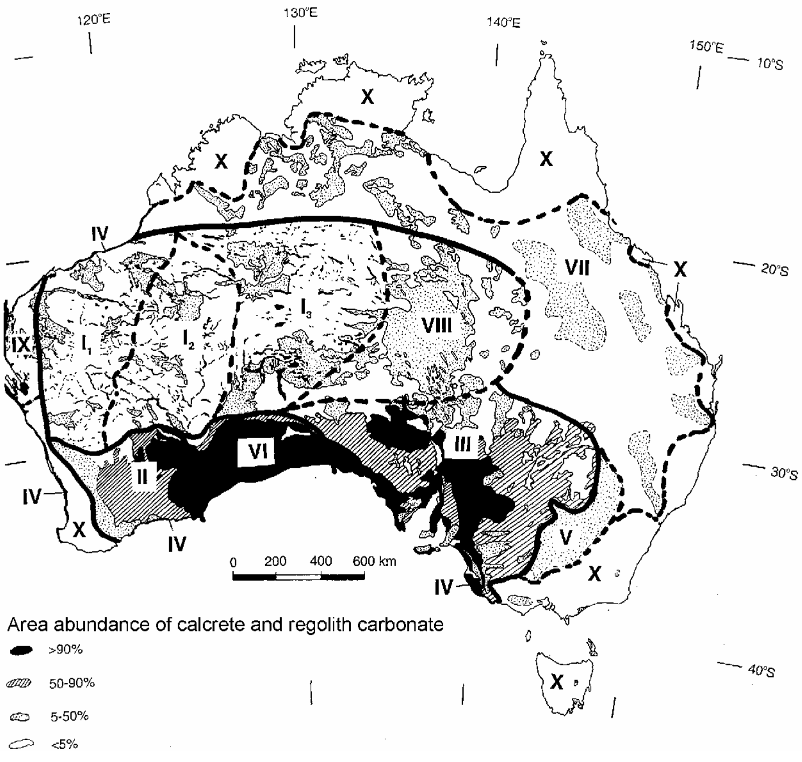


Figure 7.2.1. Divisions of ten calcrete landscapes in Australia: $I_{(1-3)}$ - hard pan calcrete along ancient drainage valleys- western, central and eastern sub-divisions; II - nodular calcretes of the southern Yilgarn Plateau; III - calcretes of Mallee soil zones; IV - tubular and hardpan calcretes of coastal dunes; V - nodular regolith carbonates in aeolian dust deposits; VI - boulder/nodular/pisolitic calcretes of Nullarbor Plain; VII - regolith carbonate nodules in clayey soils on Ca-rich parent materials in semi-arid to semi-humid zones; VIII - nodular regolith carbonate in aeolian sands of central Australia; IX - crustal calcrete overlying limestone of the Western coastal plain; X – humid regions with very rare regolith carbonates. For the percentage values in the key see also the caption of Figure 7.1.4. More descriptions are in the text.

The western and central division are mostly within a very extensive ancient plateau. The relief is very low, with most of the terrain lying between 150 and 500 m ASL, rarely exceeding 650 m. The major landform types include low hills and rises with extensive debris fans, alluvial plains, plateaux, iron-indurated breakaways, sand plains, dune fields and salt lakes along broad valleys.

The broad valleys, where the calcretes occur, are believed to have been occupied by palaeorivers of Early Tertiary age or even older (Ollier 1986, Wyrwoll 1988). These valleys are very broad, as wide as tens of kilometres or more, and shallow with very low gradients. Elongated playa lakes occur along the central axes of these valleys and some can be traced for tens to hundreds of kilometres, forming disconnected chains.

Within the eastern division, there are low ranges rising several hundred metres above valley plains, sandy plains and basins. There are also some ancient drainage systems indicated by chains of playa lakes.

Occurrence

Central Division

The valley calcretes occur along the major ancient drainage lines or very extensive and shallow valleys. They occur as elongated sheets occupying the central tracts of trunk valleys (Figures 7.2.2, 7.2.3, page156 7.2.4, page 156), varying in width from a few hundred metres to 50 km or more and may be over 100 km in length (e.g., Butt *et al.* 1977).

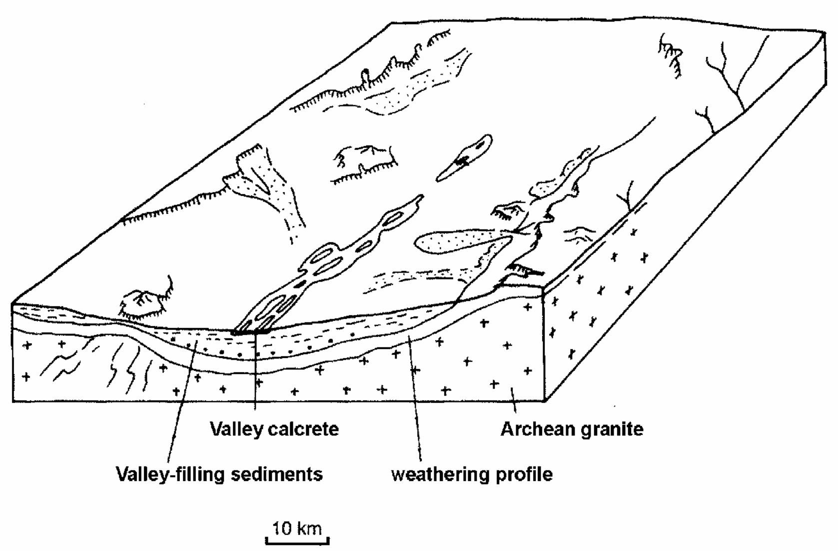


Figure 7.2.2. Schematic diagram showing the occurrence of valley calcrete along the central tracts of extensive shallow valleys (ancient drainage lines) in the northern Yilgarn Plateau (adapted from Carlisle 1978)(see also Figure 6.41).

Their thickness is usually 5 to 10 m but often exceeds 30 m along the axis. Longitudinal gradients are commonly less than 1:1000. They commonly lead to playas where they broaden out to deltaic platforms around the shores of the playas. The calcretes frequently form positive relief features in the valleys, being raised and mounded to 3 m or more above the flanking alluvial plains. The structures of mound (MO) and diapir (DP) developed in the calcrete is shown by Figure 7.2.5 (page 157)(Robertson *et al.* 1996).

Western Division

West of the 'Meckering Line', where the rejuvenation of valley incision has occurred, the calcretes form terraces and mesa caps, from several metres up to 30-35 m above the river bed (Figure 7.2.6, page 157)(e.g., Butt *et al.* 1977). The calcretes are over 10 m on higher terraces and relatively thin (1-3 m) in the lower terraces.

Eastern Division

The calcrete occurs mostly along the central tracts of broad valley plains, although some occurs along the edges of alluvial fans. Within the plains, calcretes are commonly exposed, cropping out slightly higher than the surrounding sandplain surfaces (Figure 7.2.7, page 157). Some playa lakes occur as closed basins within the valley plains and have incised into the plain surfaces, leaving scarps of calcrete more than 10 m high (Arakel 1991).

A surveyed transect (Figure 7.2.8) shows a 4-6 m thick calcrete occurring at a higher elevation than the playa lakes. The thickness of the calcrete in this division is commonly about 10 m or less.

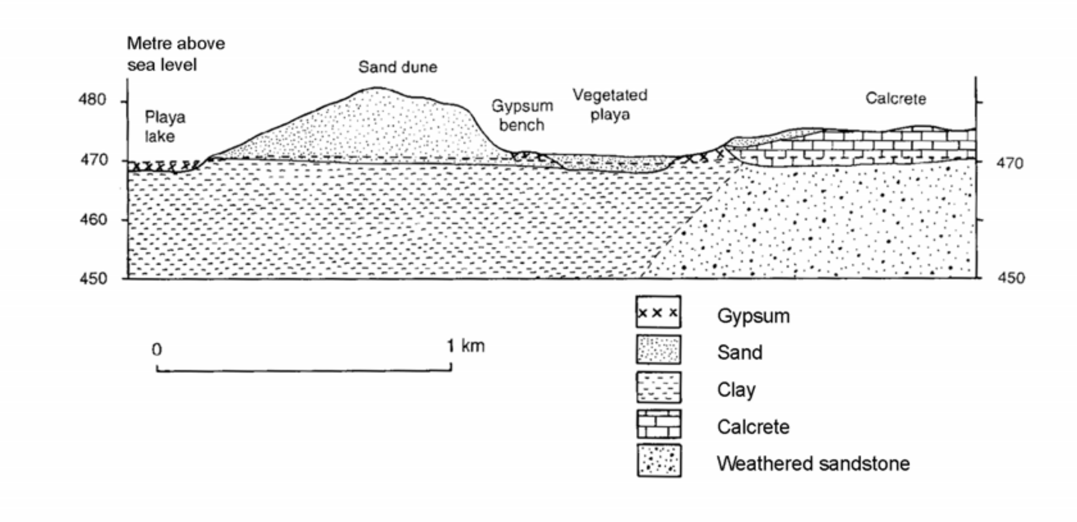


Figure 7.2.8. A transect showing the topographic relationships between calcrete and playa lakes in the central part of an ancient drainage line, near Curtin Springs, central Australia (from Jacobson *et al.* 1988).

There are some nodular regolith carbonate and calcareous soils in this division and they are distributed more widely than the hardpan calcrete in the central part of the ancient valleys (Figure 7.1.4).

Morphological features

Valley calcretes are dominantly hardpan type. However, they vary considerably in texture and structure, from dense, massive, hard and porcellanous to soft, porous, perhaps chalky, with nodules, and botryoidal or cellular forms. Varying amounts of clay and quartz sand may be present and relic sedimentary bands are common. The calcrete body can be structureless or weakly bedded, with a variety of heave, mound, cave and/or collapse structures. Authigenic silica commonly occurs within calcretes and most commonly near the top and lower part of calcrete profiles. The silica is in opaline form and occurs as irregular lenses, blotches, siliceous nodules and intraclasts within the calcrete masses, and fillings in solution pipes and fracture lines in the calcretes. In some cases this silica is so concentrated and laterally continuous that it forms silcrete.

The upper most part of the calcrete tends to have cracks and to be brecciated, even forming carbonate boulders and gravels (Figure 7.2.9, page 157). Dissolution, re-cementation and karst features are also common. Some fragments of calcrete may be transported for a short distance and rounded by dissolution, forming carbonate nodules within soil profiles.

Type profiles

Many calcrete profiles in this calcrete landscape have been described by Butt *et al.* (1977), Arakel *et al.* (1989) and Jacobson *et al.* (1988).

A summarised calcrete profile (Carlisle *et al.* 1978) consists of four major zones, from the top downwards:

1) overburden, up to several metres, including sandy to clayey soils, silica-cemented hardpan, mixtures of nodular (up to cobble-sized) carbonate, sand and clay;
2) calcrete, from metres to tens of metres thick, hardpan type with complex internal fabrics and structures, commonly silicified. The upper boundary is sharp, but the lower boundary is transitional, with less cementation and admixtures of clay;
3) clays and sands, from metres to tens of metres thick, various sediments from clay to sands, calcareous in upper zones; and
4) basement, commonly being weathered granitic rocks.

It is noted that the overburden at the top of the above type profile consists of various soil/regolith materials and nodular carbonate (or nodular calcrete). Some other morphological types of calcretes may also occur. For example, a profile in the northern part of Yilgarn Plateau consists of powdery, nodular and laminated calcretes within a depth of 1.5 m of the surface (A. Mahizhnan, per. comm.). Landscape evolution The formation of valley calcrete involves four general stages: drainage (broad valley) development; initial carbonate precipitation; consolidation; and maturation, during which mounds form by upward pressure, due to precipitation of carbonate at groundwater level (Mann and Horwitz 1979, Figure 7.2.10).

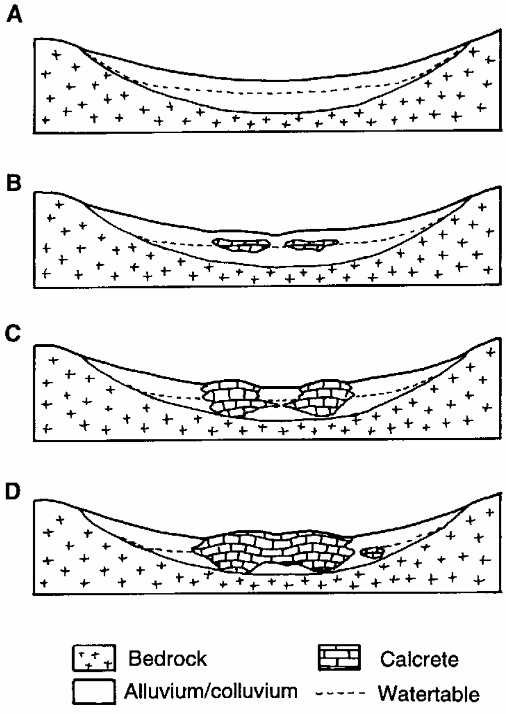


Figure 7.2.10. An illustration of the stages in the development of valley calcrete in western and central Australia.

A). Shallow groundwater system in a broad drainage channel.

B). Initial carbonate precipitation.

C). Growth of pods and domes.

D). Maturation of calcrete and surface reworking (from Mann and Horwitz 1979).

The drainage lines or broad valleys are remnants of ancient drainage systems formed during the Tertiary or even earlier (Ollier 1986, Van De Graaff *et al* 1977). These broad drainage channels are filled with alluvial sediments and shallow groundwater provides a suitable environment for calcrete to form.

Calcium and carbonate ions are transported toward the valley axis in the groundwater system, resulting in the precipitation of authigenic carbonate near the watertable (within the capillary zone and below the watertable, Figure 7.2.11, Mann 1974, Carlisle 1978).

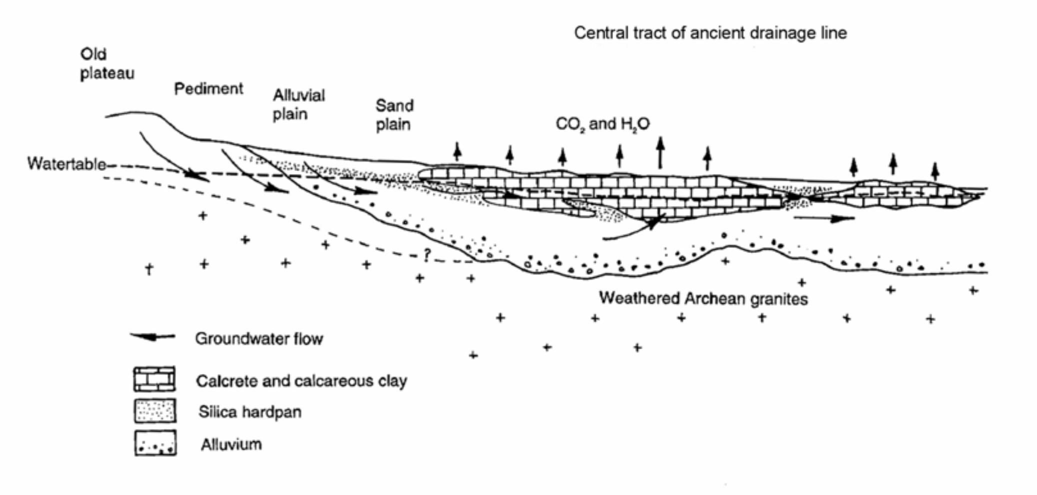


Figure 7.2.11. Illustration of carbonate precipitation in the central tracts of ancient drainage lines in Western and central Australia. Flowing towards the central part of the drainage line, the groundwater becomes saturated due to degassing of CO_2 and evaporation (adapted from Mann 1974, Carlisle *et al.* 1978).

As carbonate precipitation proceeds in the phreatic zone forming pods and domes, surface mounds may form as carbonate is pushed upwards, displacing the overlying alluvium and colluvium (Figures 7.2.3, page 156 and 7.2.5, page 157). As carbonate is pushed above the watertable, it is affected by percolating rainwater, erosion and deposition, which may result in the features of dissolution (e.g., karst), recrystallization, mechanical break down, transportation and re-deposition.

7.2.3 Nodular calcretes of the southern Yilgarn Plateau

Locations

This calcrete landscape is located in the southern part of the Yilgarn Plateau of Western Australia, from the Menzies Line southward to the area near the coast (Figure 7.2.1). The eastern boundary is along the margins of Nullarbor Plain; however, the western boundary is unclear.

Climate

The climate is semi-arid to arid with warm to hot summers and mild to cool winters. The annual rainfall, mainly as winter rains, ranges from less than 200 mm inland to about 500 mm in the southwest. The annual potential evaporation ranges from about 3,000 mm to about 2,000 mm, decreasing towards southwest.

Geological and physiographical settings

The basement of the Yilgarn Plateau is the Western Shield consisting of Archaean granitoids and greenstones, Proterozoic granites and gneisses, and Proterozoic sedimentary rocks. This calcrete landscape occurs mostly within a very extensive ancient plateau. The relief is low, with most of the terrain lying between 150 and 500 m (ASL), rarely exceeding 650 m. The major landform types include low hills and rises with extensive debris fans, alluvial plains, plateaux, iron-indurated breakaways, sand plains, dune fields and salt lakes along broad valleys. The broad valleys are geomorphically similar to those of the northern Yilgarn Plateau as described above (Section 7.2.2). However, the groundwater beneath the playa lakes within the broad valleys shows some differences, tending to have higher salinity and lower pH than that north of the Menzies Line (e.g., Butt *et al.* 1977).

Distribution and occurrence

In this calcrete landscape, calcretes are widely distributed (Figure 7.2.12) and are more abundant in the eastern part, e.g., in the Kalgoorlie region, decreasing towards the west (Figure 7.1.4).

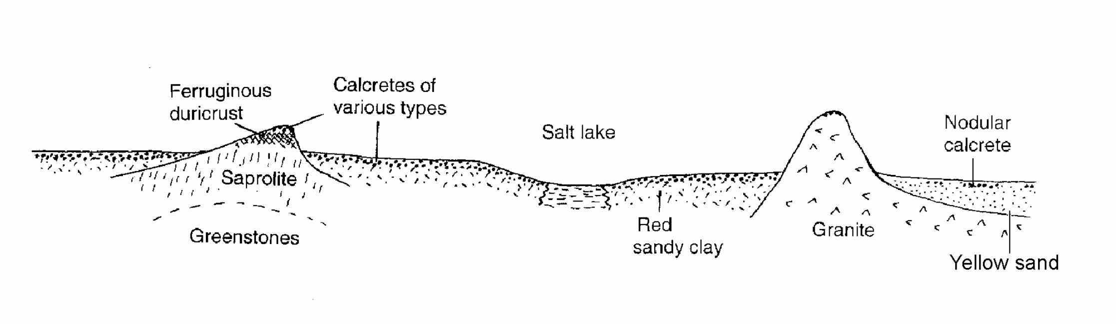


Figure 7.2.12. Illustration of wide distribution of calcretes in the calcrete landscape 'Nodular calcrete of the southern Yilgarn Plateau'. Except for salt lakes and steep hillslopes, calcretes occur in soils covering various landforms and bedrocks.

Various calcretes occur on different landforms, e.g., as a mantle covering low ridges and filling shallow depressions. Calcretes are associated with various sediments and overlie different types of bedrock.

The relationships between calcrete, bedrock and landform vary across this calcrete landscape (Anand *et al.* 1997). In the Mt. Gibson area, near the northwestern corner of this calcrete landscape, calcrete occurs mostly in areas of mafic rocks (greenstones) and is abundant in erosional regimes, patchy to absent in relict and depositional regimes (Anand *et al.* 1997). In the granitic terrain, calcrete is only present in minor amounts in depositional regimes, and is absent from sand-plains in relict and erosional regimes. In the Kalgoorlie area, however, calcrete is distributed more widely, in all the relict, erosional and depositional regimes (Figure 7.2.13), and occurs also commonly on the granitic terrain but more abundant on greenstones.

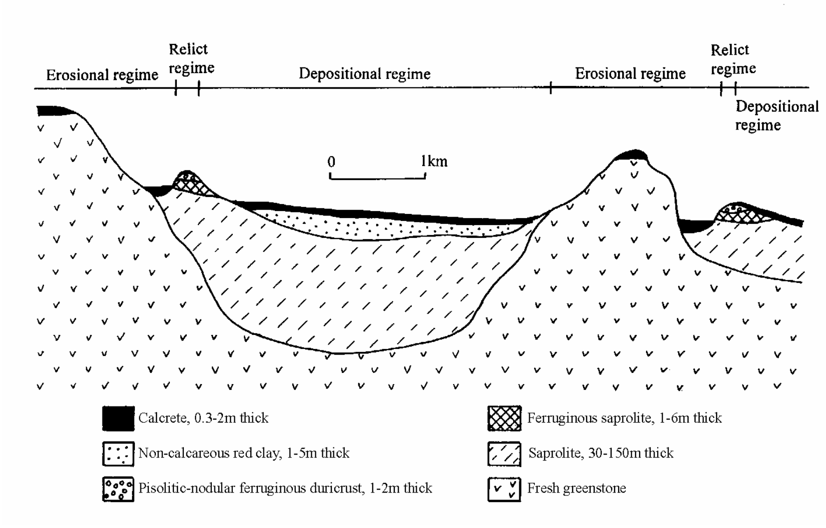


Figure 7.2.13. Schematic cross-section of the Kalgoorlie region showing the relationships between regolith, landscapes and calcrete (from Anand *et al.* 1997).

Thick and extensive sheets of hardpan calcrete are basically absent from the broad drainage lines (in contrast with the northern Yilgarn Plateau), although they exist at one or two sites, e.g., at Grants Patch, 40 km north-west of Kalgoorlie (Kern and Commander 1993), and along the western margin of a small playa 50 km west of Kalgoorlie (N30°56', E120°12', Figure 7.2.9, page 157).

In this calcrete landscape, calcrete layers occur in soil profiles at depth from surface down to 1 or 2 metres, and in some cases up to 4 metres deep (Anand *et al*. 1997). On the 1:250,000 geological maps, calcrete is commonly described as being associated with reddish loams of alluvium and colluvium (e.g., Figure 2.1.3, page 154). Less commonly, nodular calcrete (or carbonate nodules) occurs in yellow sands overlying weathered granite (e.g., Figure 3.5.5, page 156).

Morphological features

The calcretes in this region are described on most 1:250,000 geological maps as sheet and nodular kankar and orange-brown nodules within reddish sandy loam and clay loam.

Although nodular calcretes are dominent, other morphological types are also common, including powdery, pisolitic and hardpan types (Anand *et al.* 1997). The hardpan calcrete of this calcrete landscape is much thinner than the valley calcrete of the northern Yilgarn Plateau, being mostly several tens of centimetres thick.

In a compiled regolith map of Kalgoorlie region (Chan *et al*. 1992), which overlaps part of this calcrete landscape, variable calcrete morphological types are described, including nodular, sheet (hardpan), pisolitic, rubbly and massive, but nodular and sheet types are most common.

Figures 2.1.3 (page 154), 2.1.10 (page 155) and 3.5.5 (page 156) show some examples of calcrete in this calcrete landscape.

Genesis

The sources of calcium may be partly from the weathering of bedrock, as indicated by the coincident occurrence of more abundant calcrete on Ca-rich greenstones (Anand *et al*. 1997). However, based on mass-balance calculations, Anand *et al.* (1997) found that all the four selected soils overlying various bedrocks show a gain in Ca, irrespective of the parent rock. This indicates external derivation of Ca, probably through aeolian deposition, laterally-moving soil water and erosion and deposition of calcrete fragments (Anand *et al*. 1997).

Rainwater and aeolian dusts may be another source of Ca (e.g., Hingston and Gailitis 1976). Calcium may also come from the remnants of Cretaceous to Eocene marine limestones which are distributed almost as far north as Kalgoorlie (e.g., Carlisle *et al*. 1978). Erosion, deflation, dissolution and groundwater transport within these limestones may provide calcium to the adjacent areas.

The calcretes in this calcrete landscape are referred to in most references as pedogenic calcrete (e.g., Carlisle *et al*. 1978, Anand *et al*. 1997), although detailed genetic processes are not explained. The features supporting a pedogenic origin include that:

- the calcretes occur in soil profiles and is distributed across various landforms instead of along drainage lines;
- the dominant calcrete morphologies are nodular, pisolitic, powdery and thin hardpan, contrasting to the thick massive hardpan calcrete north of the Menzies Line (Section 7.2.2);
- silicification is rare.

The control of the Menzies Line

The Menzies Line divides the summer-rain dominant areas in the north from the winter-rain dominant areas in the south. It forms a boundary between two calcrete landscapes (I and II in Figure 7.2.1) which are strongly contrasted, with thick (up to tens of metres) hardpan groundwater calcrete in the north and nodular pedogenic calcrete in the south. Earlier and later, researchers (e.g., Butt *et al*. 1977, Carlisle *et al.* 1978) tried to explain such a remarkable contrast by different climatic and hydrologic conditions. In the north, the rainfall occurs mostly as summer storms but in the south the winter rains are relatively consistent. The higher temperature and higher potential evaporation in the north result in much drier soil moisture conditions. In contrast, soils may remain moist much longer during winter in the south.

Butt *et al.* (1977) suggested that the preferential occurrence of pedogenic calcretes in winter rainfall regions is probably due to the longer growing regime that, in consequence, results in greater root respiration and evolution of CO_2, and hence higher carbonates in soil moisture.

Carlisle *et al.* (1978) suggested that in the north, a fraction of summer storms may infiltrate quickly and deeply enough to be more or less safe from evaporation and loss of CO_2. A relatively small fraction of the storm rain remains in the soil moisture zone and is subject almost immediately to evapotranspiration. Thus there is very little opportunity for precipitation of carbonate in the soil moisture zone. South of the Menzies Line, moderate to large portions of the rainfall occur during winter and may remain for much longer in soil moisture zone. The evaporation of this soil water will build up salts (including carbonate) in soils. Moreover, Carlisle *et al.* (1978) suggested that more abundant calcareous dusts and salts in the rainfall may be part of the explanation of the abundant pedogenic calcrete in the south. The data collected by Hingston and Gailitis (1976) show that there are relatively more salts precipitated from rainfall and dusts in the south than in the north.

The remarkable differences between the calcrete on the two sides of the Menzies Line have not yet been well explained, as pointed out by Anand *et al* (1997) and by C. Butt (person. commun.). The hypothesis and suggested explanations (e.g., Carlisle *et al.* 1978) need to be tested, and more data and research are needed.

7.2.4 Calcretes of Mallee soil zones

The term

This calcrete landscape is characterised by many morphological calcrete types and various complex calcrete profiles. Most calcretes occur in soil profiles, within 1 or 2 m of the surface. The dominant soil type is the most common calcareous soil – solonized brown soils (Northcott Codes: Gc1.1, Gc1.2, Gc2.1, Gc2.2 and Gn1.13), also known as 'Mallee soils' (Milnes and Hutton 1983). These soils are now referred to as Calcarosols (Isbell 1996).

Locations

This calcrete landscape occurs in the southern part of the continent (Figure 7.2.1), including southern South Australia and the Mallee Region of southwestern NSW and northwestern Victoria. The western boundary of this calcrete landscape is along the eastern margin of the Nullarbor Plain. To the east, this calcrete landscape stops at Riverine Plain and West Victorian Plains and Uplands. However, the northern boundary is not very clear and possibly follows the broad climatic boundary between the northern summer rainfall and the southern winter rainfall provinces. To the south, this calcrete landscape has a boundary with another calcrete landscape: tubular and hardpan calcretes of dunes (IV, Figure 7.2.1) along the coastal zone.

Climate

The climate is arid to semi-arid with hot summers and mild to cool winters. The annual rainfall ranges from about 200 mm inland to about 600 mm towards the coast, mainly as winter rains. The annual potential evaporation is much higher, up to ten times that of the rainfall.

Geological and physiographical settings

Physiographically, this calcrete landscape consists of (Jennings and Mabbutt 1986):

- Eyre Peninsula, with low rounded hills, alluvial plains, stable dunes and salt lakes,
- southeastern part of Great Victoria Desert Dunefield,
- Gulf Ranges, including prominent ranges, low hills belt, dissected plateau, undulating lowland, alluvial plains and salt lakes, and
- Mallee dune fields and sandplains.

Geological components in this calcrete landscape include the Gawler Block, the western part of the Murray Basin, the Flinders Block and the St Vincent Basin. Various rock types occur, from gneissic and granitic rocks to metasedimentary and volcanic rocks.

Tertiary marine sequences, which mainly occur in Murray Basin, consist of sands, calcareous sands, mudstone and limestone. Dunefields and aeolian sand plains are widely distributed in this calcrete landscape, including the longitudinal dunes of the southern part of the Great Victoria Desert, the longitudinal dunefields and sandplains of the Mallee Region and scattered dunefields in Eyre Peninsula.

Aeolian dust deposits are common in many parts of inland South Australia, forming a blanket of calcareous materials which are described as calcareous sandy clay loam to light clay (Jeffery and Hughes 1995). These are interpreted (Crocker 1946) as loess winnowed from the calcarenite barrier sequences. In the Mallee Region, a clayey aeolian dust deposit is also widely distributed and was termed as parna (Butler 1956). Some dunes in both the Eyre Peninsula and Mallee regions contain red clay bands in the dune profiles (Jeffery and Hughes 1995, McCord 1995), which are likely trapped aeolian dust materials, similar to those found in the source bordering dunes along the Murrumbidgee River (e.g., Bowler 1978, Chen 1997a, 1998) and the Lachlan River (Hesse 1998).

Distribution and occurrence

In this calcrete landscape, calcretes are widely distributed and occupy more than 50-60% of the total area. Enclosed in this calcrete landscape are a few areas with less calcretes, such as the Flinders-Lofty Ranges, part of the Gawler-Cleve Ranges and in some playa lakes (Figure 7.2.14).

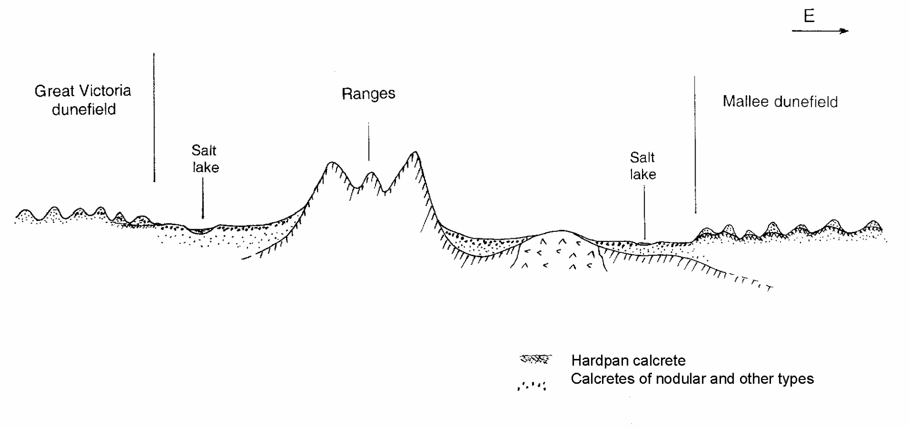


Figure 7.2.14. Illustration of wide distribution of various calcretes in the calcrete landscape ‘Calcretes of the Mallee soil zone’.

In the southern Mallee Region, calcretes are widely distributed across undulating plains, rises and flats (Figure 7.2.15, McCord 1995).

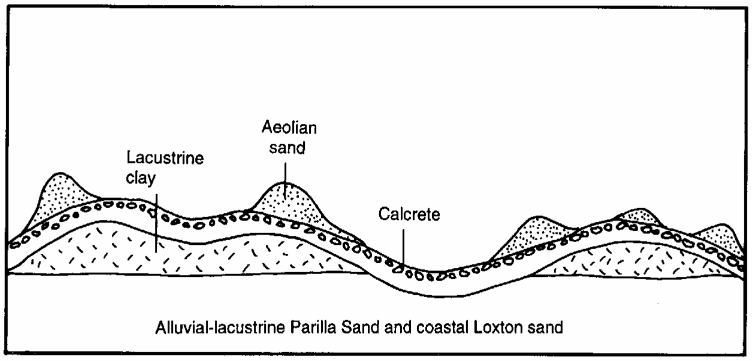


Figure 7.2.15. Schematic diagram showing the wide distribution of hardpan calcrete in a landscape system of the southern Mallee Region with undulating calcrete rises and sparse overlying dunes (adapted from McCord 1995).

In dunefields, calcretes occur commonly in the swales between dunes and are buried at greater depth in the dunes (McCord 1995). In the northern Mallee Region, calcretes occur more commonly in dunefields and sandplains (e.g., Wetherby and Oades 1975).

Calcretes occur widely throughout the Eyre Peninsula, except for some siliceous dunes and some relatively steep-sloped hills. Calcretes form an almost continuous layer in soils across the undulating plains and the swales between dunes (Jeffery and Hughes 1995).

In the southern Great Victoria Desert, calcretes also occur commonly. However, the dunes are more siliceous and less clayey, with calcretes within dunes at lower depths than those of the Mallee dunefields, and in the swales between dunes (Figures 7.2.16, page 157, 7.2.17, page 157).

Further north, carbonates occur in grey-brown and red calcareous desert soils, commonly as powders dispersed throughout the soil profiles (Jessup 1961).

In salt lakes and around their margins, various gypsum deposits occur and calcretes are much less common.

Morphological features

All the morphological types of calcrete described in Chapter 2 occur in this calcrete landscape (Crocker 1946, Crawford 1965, Wetherby and Oades 1975, Milnes and Hutton 1983, Jeffery and Hughes 1995, McCord 1995 and Hill *et al.* 1998). The calcretes occur dominantly within soil profiles (1-2 m from the surface), with following major characteristic features:

Hardpan calcrete occurs commonly, with a thickness varying from tens of centimetres up to more than one meter, but rarely over 2 m. The internal structure varies from massive and structureless to complex forms such as brecciated, re-cemented nodules, laminated and floating gravels. In contrast with the hardpan calcrete in valley calcrete (see Section 7.2.2), silicification is rare and the thickness is much less.

Nodular calcrete is the most common type and carbonate nodules vary greatly in size (from a few mm to tens of cm), in shape and in hardness (from soft to highly indurated).

Tubular (*rhizomorphic*) *calcrete* is much less common than in the coastal zones (see Section 7.2.5) and tends to occur with other morphological types of calcrete (e.g., Hills *et al.* 1998).

Powdery calcrete is reported from the southern Mallee Region (McCord 1995) as a soft layer containing greater than 50% calcium carbonate, over 1 m thick and with a thin (less than 20 cm) hardened upper zone. However, in many calcrete profiles, dispersed powdery carbonates occur, mixed with carbonate nodules.

Pisolitic calcrete has been reported from some areas, e.g., the Mallee Region (Gill 1973) and the York Peninsula (Crawford 1965).

Boulder calcrete is common, either overlying a hardpan calcrete or occurring as a single type in a soil profile.

Honeycomb and *laminar calcretes* occur as well, mostly associated with other morphological types.

Figures 2.1.2 (page 154), 2.1.4 (page 154), 2.1.7 (page 155), 2.1.8 (page 155), 2.1.11 (page 155), 2.1.12 (page 155) and 7.2.17 (page 157) show various morphological types of calcrete in this calcrete landscape.

The calcrete profiles vary greatly, from simple profiles which consist of mainly one morphological type of calcrete, to complex profiles with several types of calcrete either mixed or separated in a vertical sequence. An example is shown in Figure 7.2.18.

Genesis

Most authors (e.g., Crocker 1946, Crawford 1965, Milnes and Hutton 1983, Hills *et al.* 1998) believe that the calcretes in this calcrete landscape are mainly formed by soil forming processes, i.e., leaching of parent calcareous sediments and illuviation of carbonates in lower soil profiles. Reworking and re-cementation after initial carbonate precipitation are believed to be responsible for development of complex calcrete profiles (e.g., Crawford 1965). For relatively thick (>1-2 m) hardpan calcrete, additional contributions of calcium carbonate from laterally-moving groundwaters may be involved, particularly for those occurring in landform depressions (Crawford 1965, Milnes and Hutton 1983).

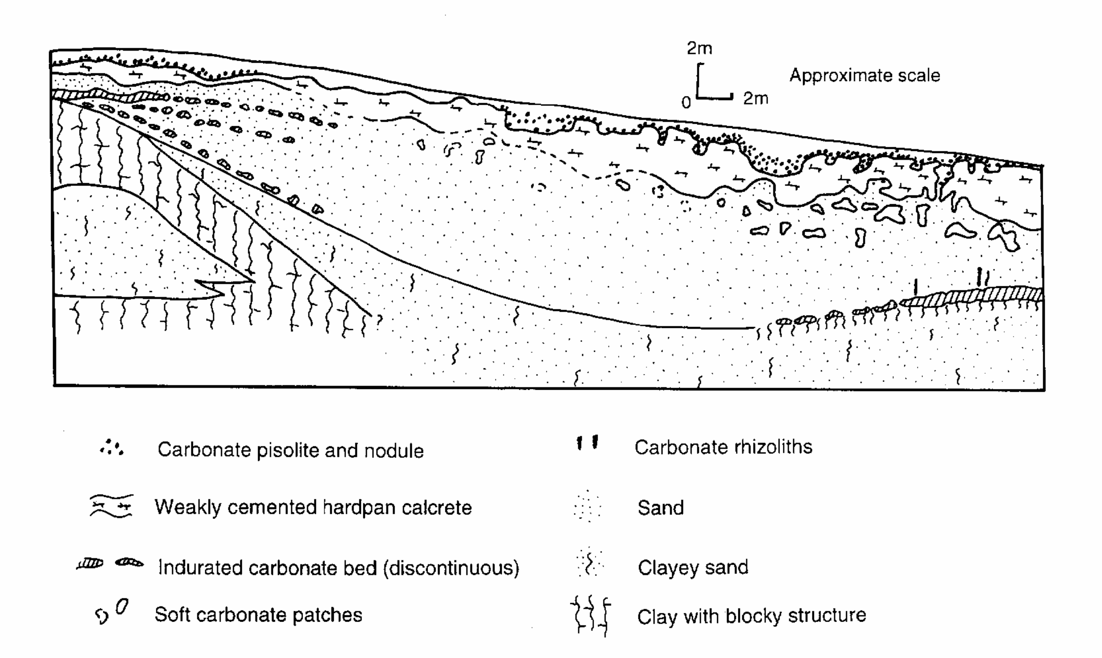


Figure 7.2.18. Diagrammatic sketch of a complex calcrete profile exposed in a railway cutting about 20 km south of Adelaide. There are various morphological types of calcrete (regolith carbonate). The thickness of calcrete increases towards the topographically lower areas and a few karstic dissolution features have developed (adapted from Phillips and Milnes 1988).

7.2.5. Tubular and hardpan calcretes of coastal dunes

Locations

Although there are dunes along most coastal zones around the Australian mainland, Tasmania and many islands, calcretes and regolith carbonates are distributed only along the drier coasts of western Victoria (including Bass Strait, e.g. Flinders Island (Dimmock 1957)), South Australia and southern Western Australia (Figure 7.2.19). In humid coastal zones, regolith carbonates are rare (Davies 1986).

Climate

The climate is semi-arid to semi-humid with hot to warm summers and mild to cool winters. The annual rainfall ranges widely from about 250 mm up to about 800 mm, mostly as winter rains. The annual potential evaporation ranges from about 1,000 mm to nearly 3,000 mm.

Geological and physiographical settings

In general, coastal plains are composed of Quaternary sediments deposited in marine, coastal-aeolian, lacustrine, estuarine, and fluviatile environments. Calcretes and regolith carbonates mostly occur within coastal dunes (fore-dunes or/and beach sand ridges). These dunes formed during the Holocene to early Pleistocene, as parallel ridges which grow progressively older inland. In South Australia and western Victoria, some Pleistocene dunes, termed as stranded beach ridges (e.g., Blackburn *et al.* 1965), are distributed up to more than 100 km inland from the present coast line. Capped mostly by hardpan calcrete (e.g., McCord 1995), these dunes are up to 50 m above the adjacent plains, and gently sloping (e.g., Cook *et al.* 1977). The dune sands are calcareous and mostly unconsolidated. In contrast, some Pleistocene dune sequences in the Shark Bay area of Western Australia are over 100 m thick and cemented. These are commonly termed as aeolianite (e.g., Read 1974).

Based on palaeomagnetic evidence, Cook *et al.* (1977) believe that the stranded Pleistocene beach ridges in South Australia and Victoria were formed in the last 700 ka.

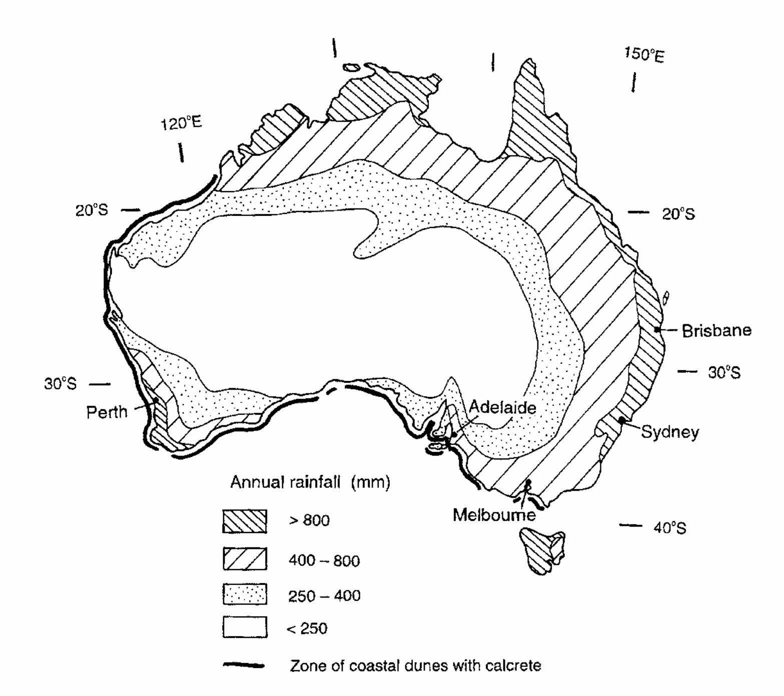


Figure 7.2.19. Distribution of calcretes and regolith carbonates in coastal dunes along the western and southern continental margins.

<u>Occurrence</u>
The occurrence of calcretes varies in coastal dunes of different ages (Figure 7.2.20).

Within the Holocene coastal dunes along southern Western Australia (e.g., Semeniuk and Meagher 1981, Semeniuk and Searle 1985), hardpan calcretes occur near the average water table within the upper part of the capillary fringe. They are sheet-like, from several centimetres to about 50 cm thick, and extend horizontally within dunes, up to several kilometres in direction across the coastline. In contrast, tubular calcrete (or rhizoconcretionary carbonates) occur at any level within the dunes and beach sands but mostly above the watertable. These carbonate rhizomorphs may be scattered within the dunes or concentrated at one or more horizons.

Many layers of hardpan calcrete, up to 1-2 m thick each, may occur within the Pleistocene dune sequences, separated by layers of aeolian sands. These sequences, termed as aeolianite, may reach great thickness (>100 m) (Figures 7.2.21, page 158 and 7.2.22, page 158). There are commonly carbonate rhizomorphs within the interbedded sand layers (e.g., Milnes and Hutton 1983). Complex calcrete stratigraphy, e.g., lateral coalescence and splitting, erosion faces and oblique unconformity, are common in the Pleistocene coastal dune sequences (e.g., Read 1974).

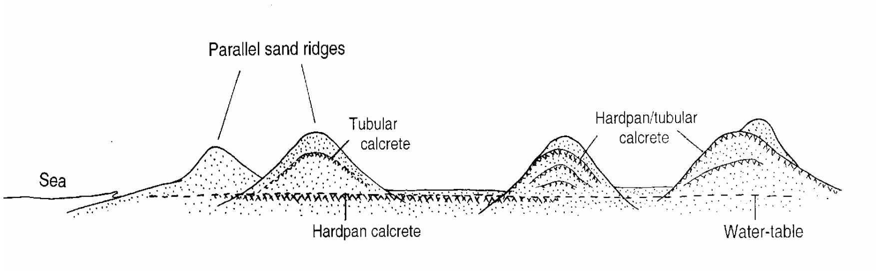


Figure 7.2.20. Illustration of calcrete occurrence in coastal sand ridges, with a hardpan calcrete near water table and tubular/hardpan calcretes in dunes. There are more layers of calcrete in the older dunes located further inland.

Morphological features

The hardpan calcretes vary significantly in their internal structures, from massive and structureless (Figure 2.1.1) to complex with re-cemented nodules, pisoliths and breccias. Some have abundant root moulds and casts at microscopic level. In a fully developed calcrete profile (Read 1974) or typical multiple profile (Arakel 1982) in the Pleistocene dunes of Western Australia, several morphological types occur in a regular sequence: pisolitic; laminar; breccia; hardpan; and mottled calcretes (Figure 7.2.23).

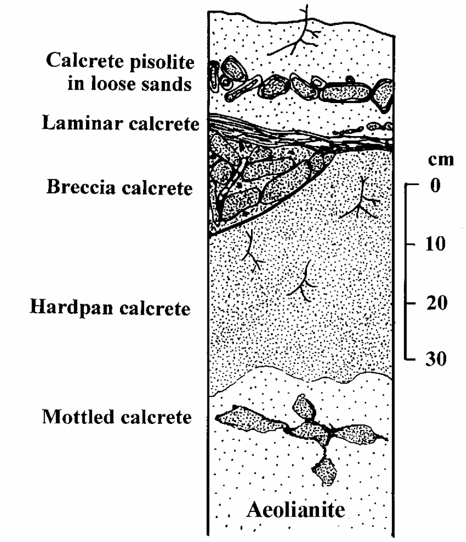


Figure 7.2.23. A typical multiple (mature) profile of calcrete in Pleistocene coastal dunes (from Arakel 1982).

In hardpan calcretes, dissolution and karst features are common, e.g., dissolution pipes in calcretes in the stranded Pleistocene beach ridges (e.g., Blackburn *et al.* 1965).

Figure 7.2.24 shows a typical profile of overlying red soil, hardpan calcrete and underlying sands in the stranded beach ridges of South Australia.

The tubular calcretes in the coastal dunes are carbonate rhizomorphs which can be best described as carbonate root casts and moulds, forming tubular and rod structures. Each discrete tubule ranges from less than 1 mm to several centimetres in diameter and over 1 m long. Some are hollow but most are solid, filled by sands or/and softer and powdery carbonates. These rhizomorphs may form a calcrete sheet (hardpan calcrete), as a connected net-like framework with spaces in-filled by sands (e.g., Figures 2.1.5, page 154, and 2.1.6, page 154), or may be sparsely scattered within the host sands.

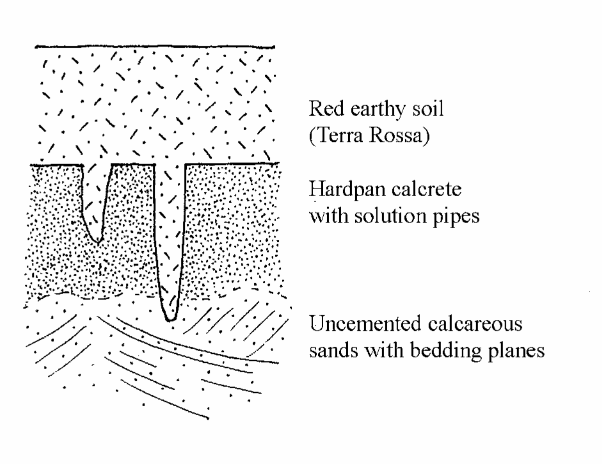


Figure 7.2.24. A schematic diagram showing Terra Rossa soil, calcrete and underlying calcareous sands on stranded beach ridges in southeast South Australia (adapted from Blackburn *et al.* 1965).

Vegetation

Most dunes with calcrete development are, or were once, colonised by vegetation, from woodland/forest to heath scrub. The thickness and morphological features of the calcretes are closely related to the vegetation type. Thicker and better developed calcrete (with all the features of massive, laminar, mottled, and rhizoconcretionary structures) occurs more commonly under woodland and forest vegetation (Semeniuk and Meagher 1981).

Genesis

Several models have been used to explain calcrete formation processes in the coastal zones (e.g., Read 1974, Semeniuk and Meagher 1980, Warren 1983). The Ca^{2+} and CO_3^{2-} come from two major sources: sea water, and the dune sands containing abundant biogenic calcareous grains, mainly as fragments of shells. Authigenic carbonates precipitate as:

- meteoric water leaches the calcareous dune sands and bring the dissolved carbonate to depth, and
- evaporative concentration occurs in the capillary zone above the water table.

In both processes of authigenic carbonate precipitation, vegetation is commonly involved. As roots and rootlets utilise the water, carbonate precipitates around them, forming rhizomorphs of micrite. Holes left by decayed dead roots may be filled later by carbonate or/and sands, forming a carbonate mould.

The model of Semeniuk and Meagher (1981) shows various processes of authigenic carbonate precipitation and calcrete formation (Figure 7.2.25).

The processes include:

1) meteoric waters dissolve surface $CaCO_3$ and carry it down the profile;
2) some water remains in the vadose zone to evaporate, leaving patches of $CaCO_3$ as calcrete mottles;
3) plant roots utilise pellicular water and $CaCO_3$ is precipitated around the roots as rhizoconcretions;
4) evaporation in the capillary zone causes $CaCO_3$ precipitation in the sands, forming $CaCO_3$ patches (calcrete mottles);
5) $CaCO_3$ precipitates around plant roots that utilise phreatic water in the same manner as 3) above;
6) development of a sheet of calcrete mottles overlying watertable;
7) water flows laterally or is locally ponded, leading to the development of more massive calcrete at the expense of the calcrete mottles;
8) laminar structure develops as water perches on the massive calcrete, forming thin crusts of $CaCO_3$;
9) $CaCO_3$ continues to precipitate under massive calcrete; and
10) calcrete may form above the main sheet in a perched moisture zone.

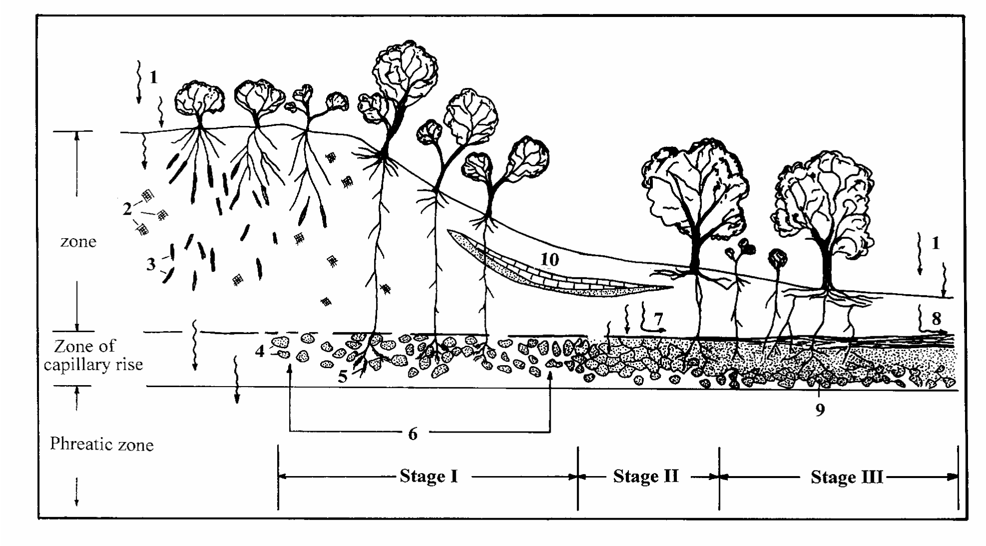


Figure 7.2.25. Illustration of the processes of authigenic carbonate precipitation and calcrete development in coastal dunes (from Semeniuk and Meagher 1981). Detailed descriptions of the numbered processes are given in the text.

In the model (Figure 7.2.25), both the dune and watertable are assumed to be stable and erosion and re-deposition are not involved. This model is probably more applicable to the Holocene coastal dunes (Semeniuk and Meagher 1981).

Read (1974) explained complex calcrete stratigraphy and morphology in the Pleistocene dune sequences (aeolianite) by erosion, brecciation, re-deposition, dissolution, and re-cementation. Arakel (1982) explained the mature multiple calcrete profile by an eight-stage model, beginning with the precipitation of authigenic carbonates and ending with the various diagenetic processes in the vadose zone. Warren (1983) has considered the influence of dune build-up and deflation on calcrete development (Warren 1983) and pointed out that a mature calcrete containing cemented intraclasts (or the breccias of Arakel 1982) may be formed as deflation lags that are buried and re-cemented.

Possible further division

This calcrete landscape may be further divided into 3 subdivisions:

1. Holocene dunes. They are distributed along present shorelines, extending up to a few kilometres inland. Calcretes in the dunes are relatively thin and simple in stratigraphy and morphology.
2. Pleistocene dunes of the western coasts. They are more cemented, reaching greater height (up to more than 100 m high) with many calcrete layers, and the sequences are more sandy with very low clay contents (e.g., Read 1974).
3. Pleistocene dunes (stranded beach ridges) of South Australia and Victoria. They are less cemented, lower (up to tens of meters) and more clayey (e.g., Milne and Hutton 1983). A red terra rossa soil has developed, overlying a hardpan calcrete (e.g., Blackburn *et al.* 1965).

In general, the Pleistocene coastal dunes are much higher and much more widely distributed, over 100 km inland from present shorelines. The calcretes within these dunes are much greater in quantity, forming many layers, and are more complex in stratigraphy and morphology.

7.2.6 Carbonate nodules in aeolian dust deposits (parna)

Locations

Aeolian dust deposits exist in many areas across the continent but are more concentrated and reach the greatest thickness, up to 3-4 m thick (Butler 1982), in southeastern Australia, including the Riverine Plain, part of the Mallee Region, the southern Western-Slopes and part of the Southern Tablelands including alpine areas. The distribution area is not well defined, because the dust deposits gradually thin away from their central areas of deposition and are incorporated into soil profiles. Even within the central areas of deposition, aeolian dust deposits and regolith carbonates are absent in some landforms, such as relatively steep hills, young alluvial/flood plains and colluvial fans.

Although there are significant aeolian dust deposits in part of the Mallee Region, the much more abundant calcretes that occur there differentiate the Mallee Region from this calcrete landscape.

Climate

The climate is arid to semi-arid with warm to hot summers and mild to cool winters. The annual rainfall ranges from about 250 mm in the west to about 600 mm in the Southern Tablelands in the east, mainly as winter rains. The annual potential evaporation ranges from about 2,500 mm to about 1,500 mm.

Geological and physiographical settings

Various types of Palaeozoic bedrock occur in the area, from metasedimentary to granitic and volcanic rocks. The carbonate nodules mainly occur within aeolian dust deposits which are clayey sediments covering different geological and topographical entities and forming a relatively uniform mantle. These aeolian clayey sediments, previously termed as 'parna' (Butler 1956, Butler and Hutton 1956), are believed to have been deposited mainly during several drier periods in the Pleistocene when wind transported large quantities of dust from the more arid inland to the east (Butler 1956, Bowler 1986, McTainsh 1989).

Several distinctive units within aeolian dust deposits have been identified. For example, in the Wagga Wagga region, three parna units have been identified (Beattie 1972), from older to younger:

1) Willis Parna, strongly structured brown and grey clay (up to 2 m thick),
2) Brucedale Parna, well structured yellowish clay (1-2 m), and
3) Yarrabie Parna, massive red clay (up to 1 m).

They cover most gently sloped landforms such as lower and foot slopes, undulating plains and gentle rises but commonly absent on relatively steep hills and on Holocene alluvial (flood) plains.

Three parna units have also been identified in some areas of the Riverine Plain (van Dijk 1958, 1961, Churchward 1962).

Occurrence

Carbonate nodules occur commonly in the aeolian dust deposits at various localities including Swan Hill (Churchward 1962), Cobar (Walker 1982), the Riverine Plain (Butler and Hutton 1956, van Dijk 1961) and Wagga Wagga (Beattie 1970, 1972). In general, the total carbonate content of the aeolian dust layers is less than 10%, e.g., at the Riverine Plain (van Dijk 1961, Hutton 1982, Pietsch 1998) and at Wagga Wagga (Beattie 1970, 1972, Chen 1997a).

Both the aeolian dust deposits and their carbonate content decrease from west to east (Figure 7.2.26).

In the more humid Southern Tablelands, aeolian dusts are thinner and patchy, rarely forming a continuous mantle. Instead, aeolian dusts are commonly incorporated into locally derived soil materials during pedogenic processes and erosion/re-deposition (e.g., Walker *et al*. 1988, Chartres *et al*. 1988). Carbonate nodules only occur locally in low-lying landforms, e.g., foot-slopes and drainage depressions, but are mostly absent in aeolian dust deposits in well-drained locations (e.g., Scott *et al*. 1998).

In vertical sequences, carbonate nodules occur more commonly in older aeolian dust deposits on the undulating rises and high plains, e.g., in the Willis Parna of Wagga Wagga region (Beattie 1972, Chen 1997a) (Figure 7.2.27A).

However, in the Riverine Plain, carbonate nodules occur commonly in the youngest aeolian clay layer but are rare or absent from the older aeolian clays (e.g., Churchward 1962, Butler 1967, Bowler 1978) (Figure 7.2.27B)

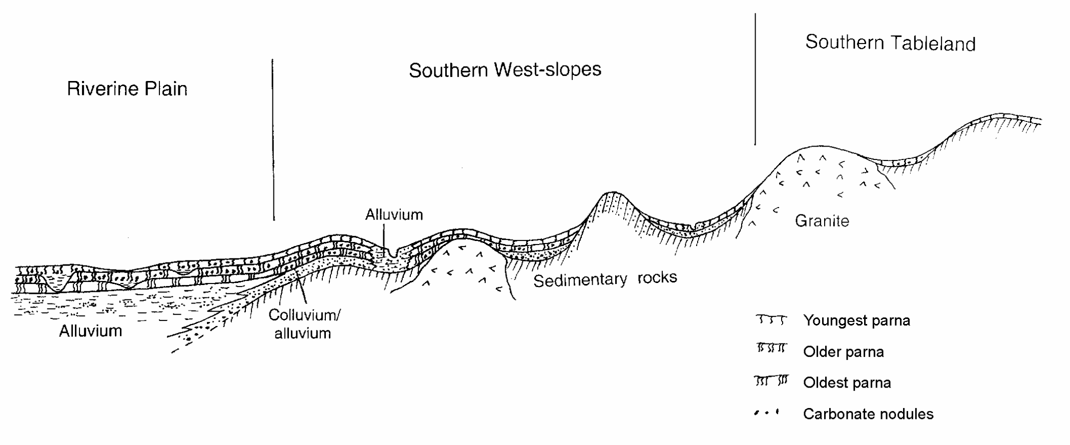


Figure 7.2.26. Illustration of the calcrete landscape 'carbonate nodules in aeolian dust deposits'. Both aeolian dust deposits and carbonate nodules become less common eastwards from the Riverine Plain to the Southern Tableland.

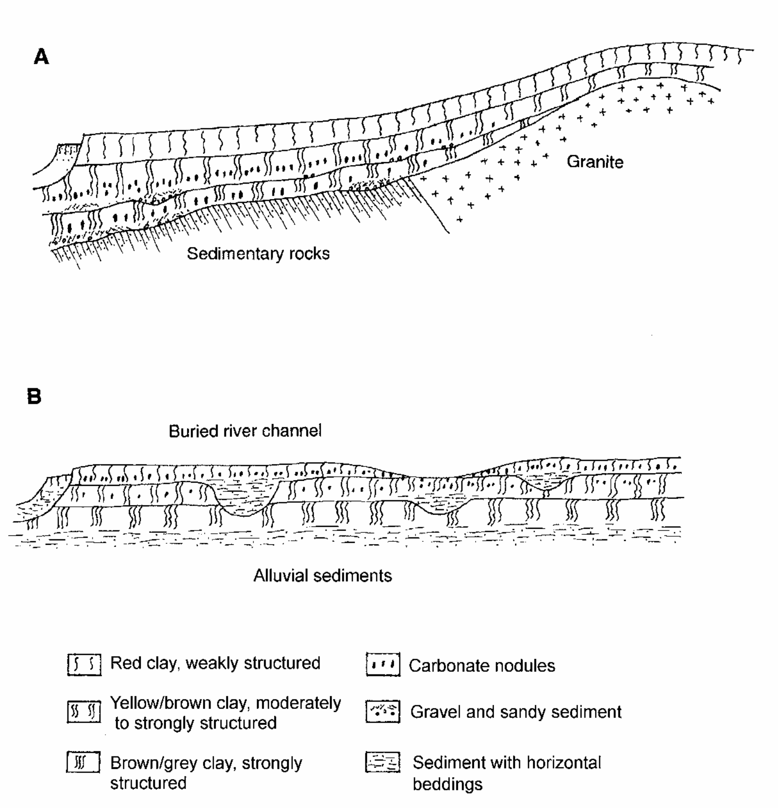


Figure 7.2.27. Schematic illustration of aeolian clay layers with carbonate nodules.

A In the Wagga Wagga region, carbonate nodules occur more commonly in older aeolian clay layers (adapted from Beattie 1972, Chen 1997a).

B In the Riverine Plain, carbonate nodules occur more commonly in the youngest aeolian clay layer (adapted from Churchward 1962, Butler 1967, Bowler 1978).

Morphological features

The carbonates in aeolian dusts may occur as dispersed tiny (<1 mm) aggregates and powders, which can only be detected by acid test (e.g., van Dijk, 1961). However, they occur more commonly as relatively large (>1 cm) nodules, which vary from soft to highly indurated.

The discrete nodules do not contact each other but dispersed throughout the clay. Some are elongated in one dimension and may be referred to as tubules. The size of nodules and/or tubules is small in younger parna, up to several centimetres, and larger in older parna, e.g., about 5-10 cm diameter and 25-100 cm long in the Willis Parna in Wagga Wagga region (Beattie 1970, 1972). The tubules are commonly rounded or ellipsoidal in cross-section, locally with concentric structures developed.

Genesis

The aeolian dusts are believed (e.g., Butler 1956, Beattie 1970, 1972) to be originally calcareous since they are derived from more arid inland areas. After deposition, the dispersed carbonates and other soluble salts were dissolved and leached by meteoric water. Carbonate nodules and tubules were formed within the lower part of the profiles as a result of eluviation/illuviation processes.

The absence of carbonate in the older aeolian clay layers in the Riverine Plain is explained by strong leaching due to alluvial activities before the youngest aeolian clay was deposited (e.g., Churchward 1962).

As rainfall increases eastward, relatively more intensive leaching limits the preservation of carbonates in the aeolian dust deposits.

7.2.7 Boulder/nodular/pisolitic calcretes of Nullarbor Plain

Locations

This calcrete landscape is located in the Nullarbor Plain in the central southern part of the continent (Figure 7.2.1). The boundaries to the west, north and east are well defined by the extension of Tertiary limestone of the Eucla Basin. The southern boundary is defined by the escarpment which separates this calcrete landscape from another - calcrete on the coastal dunes (Section 7.2.5).

Climate

The annual rainfall, mainly as winter rains, ranges from about 300 mm near the coast and decreases to less than 200 mm inland. The annual potential evaporation is from nearly 2000 mm at the coast, increasing to about 3,000 mm inland.

Geological and physiographical settings

The Nullarbor Plain can be divided (Jennings and Mabbutt 1986) into several parts: the Bunda Plateau - a covered karst plain; the Carlisle Plain in the north; and narrow coastal plains at the southern margin. Lowry (1971) made a slightly different and more detailed division. This calcrete landscape includes the Bunda Plateau and the Carlisle Plain. These slope gently to the south, from about 240 m (ASL) in the north to about 80 m near the coast in a distance of over 200 km. Across the Bunda Plateau, local relief is very low, rarely more than several metres, and it is commonly described as flat and featureless (Figure 7.2.28, page 158). However, Lowry (1971) described some landform features such as low rises with abundant limestone fragments, depressions occupied by clay flats, several degraded fault scarps, caves, and remnants of old river courses. The Carlisle Plain is characterised by enclosed depressions up to 30 m deep and 10 km across with centripetal drainage (Lowry 1971).

This calcrete landscape is located in the Eucla Basin, within which Tertiary limestones were deposited over Cretaceous and Permian sandstone and Pre-Cambrian basement rocks. Although the limestones can be further divided into the Upper-Eocene Toolinna Limestone, the Lower Miocene Abrakurrie Limestone, the Mullamullang Limestone member, and the Nullarbor Limestone (Lowry 1971), they are commonly referred to generally as the Nullarbor Limestones. They occur throughout the Bunda Plateau, reach a thickness of about 30 m, and are uniformly indurated. In the Carlisle Plain to the north, the limestone passes laterally into Colville Sandstone, a sequence of sandstone and claystone with minor limestone (Lowry 1971).

Distribution and occurrence

Although calcretes occur almost throughout this calcrete landscape, Lowry (1971) has recognised some significant variations. To the west and northwest, a layer (4-5 m thick) of clay and nodular to boulder calcrete, termed by Lowry (1971) as ‘rubbly kankar’, overlies Nullarbor Limestone. To the southwest, a layer (1-3 m thick) of clay and nodular/pisolitic calcretes covers most of the land surface and overlies Toolinna Limestone. To the north in the Carlisle Plain, a layer (0.5-1.5 m thick) of nodular/pisolitic calcrete in residual sand and clay overlies Nullarbor Limestone, Colville Sandstone and Precambrian rocks. Across the central part of the Nullarbor Plain, the upper part of the limestone is fractured and brecciated into slabs (Figure 7.2.29, page 158) which are separated by veins of clay and nodular/pisolitic carbonates (Lowry 1971). Many flats of colluvial clay in the central Nullarbor Plain have a superficial scattering of red nodular/pisolitic carbonates.

Morphological features

Various morphological types of calcrete occur in this calcrete landscape. Lowry (1971) described a few profiles of calcrete, consisting of cobble/boulder calcrete mixed with smaller carbonate nodules, of which some are concentrically laminated pisolites. These are the most common types of calcrete across Nullarbor Plain. There are other morphological types, including:

1) sheet or hardpan calcrete, formed by cementation of carbonate nodules and pisoliths;
2) white powdery calcrete more than 1m thick at lower part of a calcrete profile and grading down into underlying limestone; and
3) laminar calcrete, as veins following fractures in the limestone (Lowry 1971).

Genesis

The underlying limestone is believed to be the major and ultimate source of the calcium carbonate (Lowry 1971). However, the calcareous sands and clays overly various types of bedrock including non-calcareous Pre-Cambrian rocks on the Carlisle Plain, indicating that transportation of carbonate has occurred (Crocker, 1946). The local presence of the land snail *Bothriembryon* in the calcrete profiles indicates that there has been some reworking by wind or water (Lowry 1971). However, Lowry (1971) believes that the calcareous clay is mainly a residual material, because there is a good correspondence between the amount of quartz sand in the soil and that in the underlying beds. Rainwater may dissolve calcium carbonate and bring it downwards to the watertable, leaving insoluble components concentrated in the top part, such as quartz grains, iron oxide, and clay minerals (Lowry 1971). Some soil waters with high concentrations of Ca^{2+} and CO_3^{2-} may remain and evaporate in the soil, resulting in precipitation of a powder of microcrystalline calcite (Lowry 1971). This may further develop to nodular, pisolitic, hardpan and boulder/cobble calcretes.

Lowry (1971) also believed that the lower part of the calcrete, grading into weathered limestone, may replace the limestone, possibly by processes of dissolution and re-precipitation.

7.2.8 Carbonate nodules in clayey soils on Ca-rich parent materials in semi-arid to semi-humid zones

Location

This calcrete landscape occurs in semi-arid to semi-humid regions, including the northern parts of the Northern Territory and Western Australia, central and eastern Queensland and eastern New South Wales (Figure 7.2.1). The boundary between this and the valley calcrete landscape (Section 7.2.2) is well defined, but the boundary between this and the calcrete landscape of nodular regolith carbonate in aeolian sands of central Australia (Section 7.2.9) is not clear.

Climate

The climate is semi-arid to semi-humid, wet-dry tropics in northern part of the continent, summer-rain dominant in Queensland and northern part of NSW, and winter-rain dominant in southeastern NSW. The annual rainfall ranges mainly from 350 to 800 mm, but may reach about 1,000 mm in the eastern margins.

Summers (wet season in the north) are hot to very warm and winters (dry season in the north) are mild. The annual potential evaporation ranges from 2,000 mm to 3,600 mm, from two to ten times the amount of rainfall.

Geological and physiographical settings

This calcrete landscape extends through the continent from western to eastern edges and from northern to southern margins, and the underlying bedrocks are highly diverse, ranging from Archaean basement rocks, Early-Proterozoic metasedimentary rocks with dolerite and acid plutonic intrusives, to Lower and Middle Proterozoic sedimentary rocks and associated basic volcanic rocks (Plumb and Derrick 1975). Limestones of various ages, from Cambrian-Ordovician to Tertiary, commonly occur at various localities (e.g., Stewart *et al*. 1970, Smith 1972). In Queensland and NSW, there is a series of basalts along the eastern highlands extending from north Queensland to NSW (Johnson 1989)

Generally, the landforms are also diverse. In the Northern Territory and north West Australia, the relief of this calcrete landscape is subdued. Extensive and gently undulating plains are common. There are areas of rugged dissected plateaux and low ranges to the north-west and more sand plains to the south-east. There are widely distributed dark clayey soils on the alluvial plains of various rivers, commonly described as black soil plains on the 1:250,000 geological maps, though Stewart *et al.* (1970) used the term “nearly flat plains with grey cracking clays”. These black soil plains are broad to extensive, from flat to gently sloping, locally exhibiting linear or wavy, or less commonly, lattice, gilgai patterns.

In the part of Queensland and NSW, the landforms consists briefly of northeastern part of the Central Lowlands and a broad zone of highlands along the eastern continent margins, from north to south as Burdekin, Fitzroy, New England-Morton and Macquarie Uplands (Jennings and Mabbutt 1986). There are various landforms in the zone of highlands, including basaltic plateaux and tablelands, rugged ranges, hills and footslopes, dissected tablelands of various rocks, alluvial plains of major rivers, valley plains and sand plains. Dark clayey soils (Vertosols) are also common on various alluvial plains and undulating footslopes and valley plains.

Distribution and occurrence

Regolith carbonates in this calcrete landscape are mostly associated with dark clayey soils (Vertosols), although other soils are significant, e.g. red brown earths (Red or Brown Chromosols) (e.g. Downes and Sleeman 1955), and solonetzic soils (Sodosols) (e.g. Story *et al.* 1963, Perry 1964).

The dark clayey soils have been referred to by many names, including black and grey pedocalcic soils, heavy pedocalcic soils, dark cracking clays and dark grey clayey soils. Stewart *et al.* (1970) used Rendzina - a soil type in the Great Soil Groups, to refer to shallow dark clayey soils on limestone. However, these soils are often referred to as grey soils of heavy texture (Stewart 1956). Their major features include a colour ranging from dark grey to dark brownish grey, a uniform clay texture throughout the solum, always very plastic and invariably containing small carbonate concretions in small quantities (Stewart 1956). The thickness of these black soils is commonly about 2 m, and commonly no more than 6 m (Smith 1972).

These calcareous soils are commonly distributed in or close to areas with Ca-rich bedrocks, such as limestone (e.g., Perry 1964, Stewart *et al*. 1970, Jackson 1962, Smith 1972), basalts (e.g. Story *et al*. 1967, Galloway *et al*. 1974, Nicolls and Tucker 1956), calcareous sedimentary rocks with carbonate content up to 30% (e.g. Brewer and Butler 1953, Gunn *et al*. 1967). In eastern Australia, the calcareous soils occur commonly in areas with basalt, extending from north Queensland to Hunter Valley of NSW. The dark clayey soils overlying basalt extend further south to southern NSW and Victoria but are much less calcareous, which are not included in this calcrete landscapes.

These calcareous soils occur mainly in gently-sloped areas, including alluvial plains, valley plains, foot-slopes, alluvial cones and other undulating landforms.

It should be noted that the terms travertine and tufa are used for very different carbonate deposits in this calcrete landscape by different authors. In some cases, the terms have been wrongly used for regolith carbonate, e.g., reworked, re-cemented and re-precipitated carbonate deposits.

Real tufa, or carbonate precipitated from springs and river waters, has been reported from the Katherine area (Kruse *et al.* 1994). However, this is not calcrete or regolith carbonate because it is not an authigenic deposit (see Chapter 1).

The relationships between these regolith carbonates and soils and underlying bedrock are described in the 1:250,000 geological series notes, for example:
'massive travertine associated with black soil' (Plumb and Paine 1964); 'surficial deposits of travertine and tufa form platforms and low ridges which have developed on Devonian calcareous formations' (Griffin 1993); 'the grassy downs country is underlain by black and grey pedocalcic soils, moderately to weakly leached and with carbonate and gypsum horizons' (Randall 1966a, 1966b); 'a flat elongated plain, 30 miles long, …. has a surface of black gilgai soil and has well-defined margins; this soil appears to post-date the laterite and is possibly the weathering product of lacustrine limestone' (Paine 1963). 'extensive residual black soils have formed on Cambrian rocks (including limestones) on the Ord Plains' (Plumb 1968).

Moreover, Smith (1972) noted that exposures of limestone, which appears commonly as scattered carbonate blocks and boulders in black soils, are rare. Within the northern half of the Georgina Basin, pedocalcic grey soil is widespread on the Palaeozoic carbonate rocks (Smith 1972).
The travertine is more commonly distributed near lakes (e.g., Randall 1966a, 1966b) and alone drainage channels (e.g., Gemuts and Smith 1968). It is also commonly associated with black soils.

Morphological features

There are few detailed descriptions of the morphological features of the regolith carbonate in this calcrete landscape. In general, there are three types of carbonate in the soils and regolith:

1) small nodules;
2) carbonate fragments probably derived from underlying limestone; and
3) massive carbonate.

Commonly occurring in lower B and B/C horizons of these black soils, the quantity of carbonates is small, mostly from less than 1% to several percent, but occasionally up to about 30% of the calcareous horizons. Some analysed data were provided by Brewer and Butler (1953), Jessup (1965), Stewart (1956), Nicolls and Tucker (1956), and Smith *et al.* (1990). These carbonates are dominantly in forms of small (up to a few centimeters) nodules, and in very few cases as dispersed powders.

At some localities in limestone areas, limestone fragments are scattered on the land surface or within soil profiles, and range in size from gravel to boulder (e.g., Randall 1966b).

The travertine is typically listed on the 1:250,000 geological maps as a different deposit from limestone and carbonate in soils. It is commonly described as 'massive' (Plumb and Paine 1964) and morphologically equivalent to a hardpan calcrete. Randall (1966a, 1966b) indicated that the travertine occurs near some lakes as a layer of unknown thickness but exceeding 3 m, differing from lake or marine limestone by containing more detrital quartz and being less cohesive.

Origins

Although the term 'pedogenic' is used by some authors, the genesis of the regolith carbonate in this calcrete landscape has not been explained in any detail.

The close association between the dark clayey soils and regolith carbonates appears to be due to underlying Ca-rich bedrock which provides abundant calcium. Moreover, the high clay content and low permeabilities restrict leaching, and the carbonates derived from the underlying bedrock are therefore preserved, even in areas with an annual rainfall of about 1000 mm.

Some of the dark clay soils may be the residual weathering product of limestone (e.g. Paine 1963) or basalts (e.g. Brewer and Butler 1953, Galloway *et al*. 1974). However, most dark soils formed on transported sediments such as colluvium, alluvium, and deposits in swamps, which are derived from weathering product of basalts, limestone and other calcareous rocks (e.g. Randall 1966, Dunn 1963, Story *et al*. 1963, Gunn *et al*. 1967, Sweet 1972).

The regolith carbonates in this calcrete landscape may have formed in several ways: firstly, by reworking of limestone fragments mechanically, and secondly, by weathering of underlying Ca-rich rocks (e.g. limestone, basalt), groundwater transportation and carbonate re-precipitation within soils and near the watertable. Fragments derived from limestone become regolith carbonates, after being transported by alluvial/colluvial processes with dissolution and re-precipitation.

The origin of the massive carbonate is not clearly explained by any author. Randall (1966b) regarded the travertine as an aeolian loess, windblown material from the Tertiary lake limestone. Plumb and Paine (1964) suggested that the travertine may have been deposited in a Tertiary lake. However, its distribution near lakes, its massive texture and its great thickness may indicate that it is formed in the similar way as the valley calcrete or groundwater calcrete instead of a real travertine (see Section 7.2.2).

7.2.9 Carbonate nodules in aeolian sands of central Australia

Location

This calcrete landscape is located in central Australia (VIII in Figure 7.2.1), mainly in the western part of the Lake Eyre basin. The boundaries between this and other calcrete landscapes are not clearly defined and there are broad transitional zones.

Climate

This is the driest part of Australia, with annual rainfall of less than 200 mm. The annual potential evaporation is about 3000-4000 mm, up to twenty times the amount of rainfall. Summers are hot, winters are mild.

Geological and physiographical settings

This calcrete landscape is almost totally located within the Cainozoic Lake Eyre Basin, in the western part of the intracratonic Great Artesian Basin of Jurassic and Cretaceous age (Wopfner and Twidale 1967). Thus the area is underlain by varying thicknesses of Cretaceous shales and Jurassic sandstones which rest either on flat-lying Permian strata or on moderately to strongly folded Lower Palaeozoic or Proterozoic rocks.

The Cainozoic deposits are over 150 m thick in the Lake Eyre Basin. They consist of Eocene to Palaeocene lacustrine and fluvial sediments and Late Cainozoic (mostly Quaternary) fluvial channel and overbank deposits with some lacustrine intervals (Wasson 1983a). Miocene lacustrine cream dolomitic limestone, dolomitic clay, and sandy limestone, up to several tens of metres thick, are widely distributed in the central part of the Lake Eyre Basin (Wasson 1983a). The aeolian sands were deposited during the late Quaternary by reworking of fluvial sandy sediments, forming the dunefields of the Simpson-Strzelecki Deserts (Wasson 1983a, 1983b).

The major landforms of this calcrete landscape include dune fields with long linear dunes, Lake Eyre and many smaller playa lakes in the southern part. Source-bordering dunes were also formed along major rivers and around the margins of numerous playa lakes. To the north and north-east, there are weakly dissected limestone plains, stony plains with minor sand dunes, and flood plains.

Distribution and occurrence

There are mainly two types of regolith carbonate in this calcrete landscape: carbonate nodules associated with paleosols; and carbonate nodules originating from fragments of underlying limestone (Figure 7.2.30).

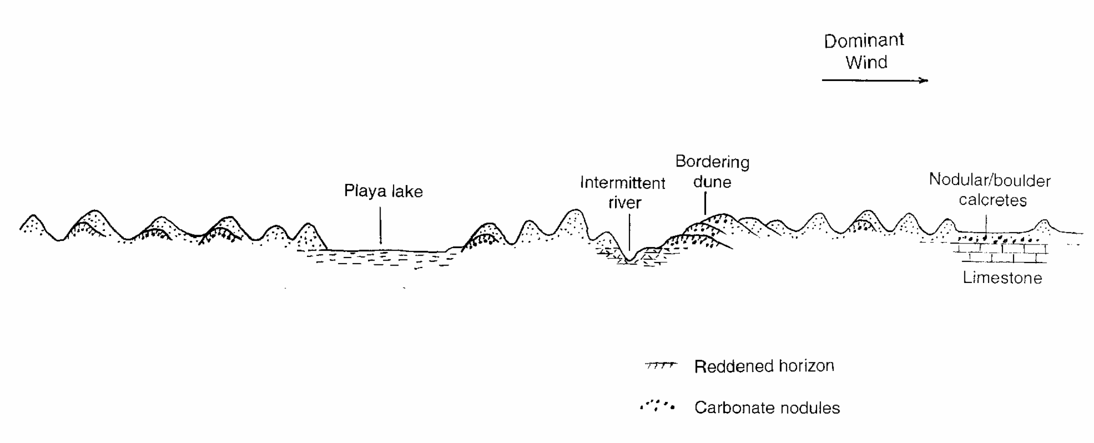


Figure 7.2.30. Illustration of the calcrete landscape 'Nodular regolith carbonate in aeolian sands of central Australia', showing the dunefield with buried calcareous paleosols and carbonate nodules in soils overlying limestone areas.

Calcareous paleosols are developed in many dunes and in alluvium. Most dunes have a thick upper part which was re-activated during Holocene time (e.g., Nanson *et al.* 1992, 1995). Carbonate is generally absent from this Holocene re-worked layer. Paleosols are common within older dunes underlying the Holocene sand mantles in the dune fields and in the source-bordering dunes near playa lakes and river channels. Most paleosols have a reddened horizon and a layer of carbonate nodules (Wasson 1983a, 1983b, Rogere 1984, Krieg 1985).

Figure 7.2.31 shows a sequence exposed along the margin of a playa lake, within which there are several layers of pedogenic carbonate nodules in both aeolian and alluvial sediments (Wasson 1983a). The ages of the paleosols are mostly Pleistocene, from 16 ka to older than 300 ka, although a minor calcareous paleosol about 7 ka had been found (Wasson 1983a, 1983b). In the dunefield, the distribution of calcareous paleosols is not very apparent because they are commonly overlain by the Holocene dunes.

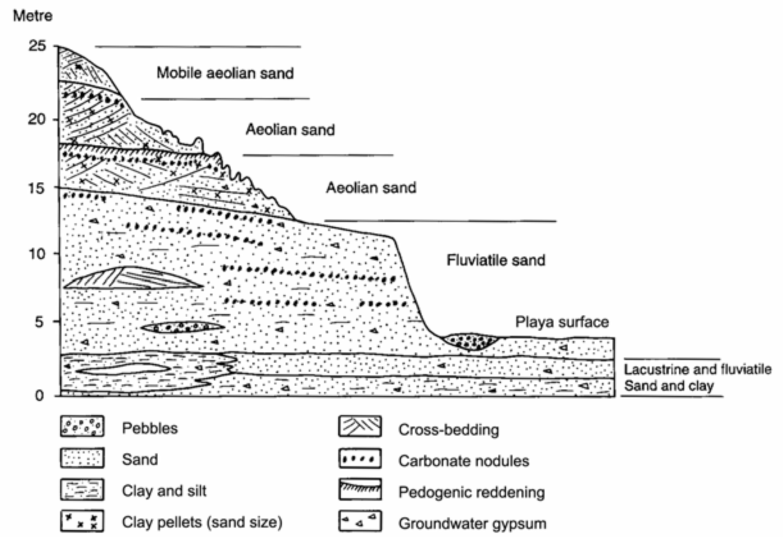


Figure 7.2.31. A composite stratigraphy along the margin of a playa lake in the Simpson Dunefield, showing carbonate nodules occurring in near-horizontal layers in a sequence of aeolian and fluviatile sands (adapted from Wasson 1983a).

In the limestone areas, fragments from the underlying limestone may be transported by alluvial/colluvial processes and incorporated into sediments and soils. During these processes, dissolution and re-precipitation may readily occur and these reworked fragments may be considered as regolith carbonates.

The mapped area (VIII in Figure 7.2.1) includes the distribution of both limestone and the Quaternary sediment units which contain calcareous paleosols. These may include some limestone areas without many fragments and some areas with deeply buried paleosols. Therefore, the area mapped as regolith carbonates in this calcrete landscape is probably exaggerated.

Morphological features

The regolith carbonates in this calcrete landscape have not been described in detail by any author. Wasson (1983a, 1983b) mentioned that carbonate occurred in zones that were commonly up to 1 m thick, consisting of nodules and root pseudomorphs (or rhizomorphs), and were approximately parallel to the surface. Krieg (1985) showed a photograph of a calcareous paleosol with carbonate nodules in a 20 cm thick zone about 1m below surface. The nodules are discrete and scattered and several centimetres in diameter.

Origin

Wasson (1983a, 1983b) interpreted the carbonate nodules as having formed by pedogenic leaching and re-precipitation near the ground surface in the zone of dense plant root growth. These calcareous soils may be subsequently covered by aeolian sands.

The source of the carbonate may have come from dusts produced by deflation of the numerous playa lakes, the weathered limestone surfaces and alluvium in floodplains, and in swales between linear dunes.

7.2.10 Hardpan calcrete overlying limestone of the western coastal plain

Location

This calcrete landscape occurs mainly in the Carnarvon province of the western coastal plains (IX in Figure 7.2.1). The eastern boundary with the Pilbara province and Yilgarn Plateau is well defined. To the west, there is also a clear boundary with the calcrete landscape of coastal dunes (Section 7.2.5).

Climate

The annual rainfall ranges from 200 to 300 mm. The annual potential evaporation is about 3,000 mm, more than ten times the annual rainfall. Summers are hot, winters are mild.

Geological and physiographical settings

This calcrete landscape is mainly composed of Cretaceous and Tertiary marine sedimentary rocks, including limestone, calcarenite, calcilutite, shale and sandstone. The Quaternary deposits on the coastal fringe, such as coastal dunes (aeolianites), are regarded as belonging to another calcrete landscape (see Section 7.2.5).

The topography is generally subdued except for the steep Cape Range to the west of Exmouth Gulf, where the altitude exceeds 300 m.

Distribution and occurrence

Data, particularly detailed descriptions of regolith carbonates in this calcrete landscape, are rare.

On the 1:250,000 geological maps (e.g., Hocking *et al.* 1985), some calcretes have been clearly differentiated from the calcrete of coastal dunes (Section 7.2.5) to the west and from the dissected valley calcrete (Section 7.2.2) to the east. They are described as authigenic calcareous duricrust overlying calcareous bedrock such as Toolonga Calcilutite (Kennedy Range sheet), and Korojon Calcarenite (Winning Pool-Minilya sheet). The calcrete in the Yaringa sheet is described as mature calcrete duricrust ubiquitously developed where Toolonga Calcilutite comes to the surface.

For soils, Bettenay (1983) mentioned that in the inland part of the Carnarvon Province, there are 'calcareous red earths and solonized brown soils' which have carbonates in the profiles. On the Cape Range, bare limestone with pockets of 'red calcareous soils' is dominant (Bettenay 1983).

Morphological features

For this calcrete landscape, there are no detailed descriptions of the calcrete or regolith carbonates.

On the 1:250,000 geological series maps, two major groups of calcrete have been mentioned. Firstly, there is calcareous duricrust overlying calcareous bedrock, described as brecciated, nodular, pisolitic, laminated, massive, and well-indurated. Secondly, there are friable, earthy and nodular carbonates within soil or sediments. This type occurs much less commonly than the calcareous duricrust type.

Origin

On the 1:250,000 geological series maps, calcrete (calcareous duricrust) has been interpreted as a diagenetic product of the underlying calcareous bedrock, although detailed explanations are not provided. Some examples of the interpretations are as follows:
'Calcrete is extensively developed as a duricrust on the Toolonga Calcilutite, and minor calcretization of consolidated alluvial/diluvial gravels has also occurred' (Wooramel sheet); '…in the west all calcareous units have undergone calcretization.' (Yanrey-Ningaloo sheet); 'calcrete is extensively developed both as a duricrust on the Toolonga Calcilutite and some other calcareous units, and as minor valley-fill calcrete in Precambrian areas. Minor calcretization of most superficial deposits has also occurred' (Kennedy Range sheet).

7.2.11 Provinces with very rare regolith carbonates

These provinces consist of more humid regions, including Tasmania, the eastern part of Australia, and small areas at south-western and northern locations of the continent (X in Figure 7.2.1). The annual rainfall ranges from 600 mm up to more than 1000 mm.

In these provinces, calcrete and regolith carbonate are generally absent but may occur at isolated sites, particularly at places with abundant supplies of calcium and magnesium, such as limestone, shelly coastal dunes, and around salty or brackish lakes.

References

Ahmat, T., Gole, M., Goleby, B., Morris, P., Swager, C. and Wyche, S., 1993. Greenstone terranes and the eastern goldfields seismic traverse. In: Williams, P.R. and Haldane, J.A., An international conference on crustal evolution, metallogeny and exploration of the Eastern Goldfields. Excursion Guidebook, Australian Geological Survey Record 1993/53, 144pp.

Anand, R.R., Smith, R.E., Innes, J. and Churchward, H.M., 1989. Exploration geochemistry about the Mt Gibson gold deposits, Western Australia. CSIRO Division of Exploration Geoscience Restricted Report 20R, 93pp.

Anand, R.R., Smith, R.E., Phang, C., Wildman, J.E., Robertson, I.D.M. and Munday, T.J., 1993. Geochemical exploration in complex lateritic environments of the Yilgarn Craton, Western Australia. CSIRO Australia. Division of Exploration and Mining, Perth. Restricted Report 442R. 297pp.

Anand, R.R., Phang, C., Wildman, J.E. and Lintern, M.J., 1997. Genesis of some calcretes in the southern Yilgarn Craton, Western Australia: implications for mineral exploration. Australian Journal of Earth Sciences, 44:87-103.

Anand, R.R., Phang, C., Wildman, J.E. and Lintern, M.J., 1998. Reply to the discussions on “Genesis of some calcretes in the southern Yilgarn Craton, Western Australia: implications for mineral exploration”. Australian Journal of Earth Sciences, 45:177-182.

Anon, 1997. Stuart Metals N.L. Annual Report. Principal office located at 9 Havelock Street, West Perth, Western Australia.

Arakel, A.V. 1980. Genesis and diagenesis of Holocene evaporitic sediments in Hutt Leeman Lagoons, western Australia. Journal of Sedimentary Petrology, 50:1305-1326.

Arakel, A.V., 1982. Genesis of calcrete in Quaternary soil profiles of the Hutt and Leeman Lagoons, Western Australia. Journal of Sedimentary Petrology, 52:109-125.

Arakel, A.V., 1986a. Vadose diagenesis and multiple calcrete soil profile development in Hutt Lagoon area, Western Australia. Revue de Geologie Dynamique et de Geographie Physique, 26:243-254.

Arakel, A.V., 1986b. Evolution of calcrete in palaeo-drainages of the Lake Napperby area, central Australia. Palaeogeogragpy, Palaeoclimatology, Palaeoecology, 54:283-303.

Arakel, A.V., 1991. Evolution of Quaternary duricrusts in Karinga Creek drainage system, central Australian groundwater discharge zone. Australian Journal of Earth Sciences, 38:333-347.

Arakel, A.V., 1996. Quaternary vadose calcretes revisited. In: Pain, C.F. and Craig, M. (Eds.). Proceedings of Australian Regolith Conference, Broken Hill, 14-17 November, 1994. AGSO Journal of Australian Geology and Geophysics. 16:223-230.

Arakel, A.V. & McConchie, D. 1982. Classification and genesis of calcrete and gypsite lithofacies in paleodrainage systems of inland Arstralia and their relationship to carnotite mineralization. Journal of Sedimentary Petrology, 52:1149-1170.

Arakel, A.V., Jacobson, G., Salehi, M. and Hill, C., 1989. Silicification of calcrete in palaeo-drainage basins of the Australian arid zone. Australian Journal of Earth Sciences, 36:73-89.

Aristarain, L.F. 1971. On the definition of caliche deposits. Zeitschrift fur Geomorphologie N.F. Bd. 15, Heft 3:275-289.

Arnaud, R.J.S. and Herbillon, A.J. 1973. Occurrence and genesis of secondary magnesium-bearing calcites in soils. Geoderma. 9:279-298.

Beattie, J.A., 1970. Peculiar features of soil development in Parna deposits in the eastern Riverina, N.S.W., Australian Journal of Soil Research, 8:145-156.

Beattie, J.A., 1972. Groundsurfaces of the Wagga Wagga region, New South Wales. Soil Publication No.28, CSIRO, 68pp.

Berner, R.A. 1971. Principles of chemical sedimentology. McGRAW-HILL Book Company. New York. 240pp.

Bettenay, E. 1983. Western region (II). In: Soils, an Australian viewpoint. CSIRO, Melbourne and Academic Press, London, pp179-187.

Blackburn, G., Bond, R.D. and Clarke, A.R.P., 1965. Soil development associated with stranded beach ridges in south-east South Australia. Soil Publication No. 22, CSIRO, Melbourne.

Blatt, H., Middleton, G. and Murray, R. 1980. Origin of sedimentary rocks. Prentice-Hall Inc. Englewood Cliffs, New Jersey. P782.

Boggs, S.J. 1987. Principles of sedimentology and stratigraphy. Merrill Publishing Company. Ohio, USA. 784pp.

Bowler, J.M. 1976. Aridity in Australia: age, origins and expression in aeolian landforms and sediments. Earth-Science Reviews, 12:279-310.

Bowler, J.M. 1978. Quaternary climate and tectonecs in the evolution of the Riverine Plain. In J.L. Davies and M.A.J. Williams (eds), Landform evolution in Australia, pp70-112. Australian National University Press, Canberra.

Bowler, J.M. and Polach, H.A., 1971. Radiocarbon analysis of soil carbonates: an evaluation from paleosols in southeastern Australia. In: Paleopedology - origin, nature, and dating of paleosols, D.Yaalon (ed.), pp97-108. Jerusalem: Israel University Press.

Bowler, J.M. 1986. Quaternary landform evolution. In: Jeans, D.N.(2nd ed.) Australia, A Geography. V.1, Sydney University Press. Australia.

Bradley, R.S. 1985. Quaternary paleoclimatology. Allen & Unwin Inc., Mass, USA.

Brewer, R. and Butler, B.E. 1953. Pedology of part of the upper Hunter Valley, New South Wales. CSIRO, Soil Publication No.2, Melbourne.

Bristow, A.P.J., Lintern, M.J. and Butt, C.R.M., 1996b. Geochemical expression of concealed gold mineralisation, Safari Prospect, Mt. Celia, Western Australia. CSIRO Australia. Division of Exploration and Mining, Perth. Restricted Report 281R. CRC LEME, Perth. Restricted Report 13R. CRC LEME/AMIRA Project 409: Yilgarn Transported Overburden.58pp.

Butler, B.E. 1956. Parna - An aeolian clay. Australian Journal of Science, 18:145-151.

Butler, B.E. 1958. Depositional systems of the Riverine Plain of southeastern Australia in relation to soils. Soil Publication 10, CSIRO, Australia. 35pp.

Butler, B.E. and Hutton, J.T. 1956. Parna in the Riverine Plain of south-eastern Australia and the Soils thereon. Australian Journal of Agricultural Research, 7:536-553.

Butler, B.E. 1967. Soil periodicity in relation to landform development in southeastern Australia. In: J.N. Jennings and J.A. Mubbert (Eds.): Landform studies from Australia and New Guinea. ANU Press, Canberra.

Butler, B.E. 1974. A contribution towards the better specification of parna and some other aeolian clays in Australia. Geomorphologie, 20:106-116.

Butler, B.E. 1982. The location of aeolian dust mantles in southeastern Australia. In: R.J. Wasson (Ed.), Quaternary dust mantles of China, New Zealand and Australia. Proceedings of a workshop, ANU, Canberra, pp141-144.

Butt, C.R.M. 1988. Major uranium provinces: Yilgarn Block and Gascoyne province, Western Australia. Proceedings of a Technical Committee Meeting on Recognition of Uranium Provinces, London, 18-20 September 1985. International Atomic Energy Agency, Vienna. pp273-304.

Butt, C.R.M. 1992. Semiarid and arid terrains. In Butt, C.R.M. and Zeegers, H. (Editors). Regolith Exploration Geochemistry in Tropical and Subtropical Terrains. Elsevier, Amsterdam, pp295-391.

Butt, C.R.M. and Zeegers, H. (Editors), 1992. Regolith Exploration Geochemistry in Tropical and Subtropical Terrains. Elsevier, Amsterdam, 607pp.

Butt, C.R.M., Horwitz, R.C. and Mann, A.W. 1977. Uranium occurrences in calcrete and associated sediments in Western Australia, CSIRO Mineral Research Laboratories, Div. of Mineralogy Report FP. 16. 67p.

Butt, C.R.M., Mann, A.W. and Horwitz, R.C. 1984. Regional setting, distribution and genesis of surficial uranium deposits in calcretes and associated sediments in Western Australia. In: Surficial Uranium Deposits. IAEA, Vienna. IAEA-TECDOC-322: 121-128.

Butt, C.R.M., Gray, D.J., Lintern, M.J., Robertson, I.D.M., Taylor, G.F. and Scott, K.M. 1991, Gold and associated elements in the regolith - dispersion processes and implications for exploration. Report 167R, CSIRO, Division of Exploration Geoscience, Perth.

Butt, C.R.M., Gray, D.J., Robertson, I.D.M., Lintern, M.J., Anand, R.R., Britt, A.F., Bristow, A.P.J., Munday, T.J., Phang, C., Smith, R.E. and Wildman, J.E., 1997. Geochemical exploration in areas of transported overburden, Yilgarn Craton and environs, Western Australia. CRC LEME 36R/Exploration and Mining Report 333R. 153pp.

Carlisle, D. 1980. Possible variations on the calcrete-gypcrete uranium model. Open-file Report, U.S. Department of Energy, GJBX-53(80), 38pp.

Carlisle, D. 1983. Concentration of uranium and vanadium in calcretes and gypcretes. In: Wilson, R.C.L. (Ed.), Residual deposits: surface related weathering processes and materials. The Geological Society of London. Blackwell Scientific Publications, Melbourne. pp185-195.

Carlisle, D., Merifield, P., Orme, A. and Kolker, O. 1978. The distribution of calcretes and gypcretes in southwestern United States and their uranium favorability, based on a study of deposits in Western Australia and Southwest Africa (Namibia). US Dept. Energy Open File Report GJBX 29(78). 274pp.

Chan, R.A., Craig, M.A., Hazell, M.S. and Ollier, C.D. 1992. Kalgoorlie regolith terrain map commentary, 1:1,000,000 Regolith Series. BMR, Australia.

Chao, T.T., 1984. Use of partial dissolution techniques in geochemical exploration. Journal of Geochemical Exploration 20: 101-35.

Chartres, C.J., Chivas, A.R. and Walker, P.H. 1988. The effect of aeolian accessions on soil development on granitic rocks in southeastern Australia. II. Oxygen isotope, mineralogical and geochemical evidence aeolian deposition, Australian Journal of soil research, 26:17-31.

Chen, X.Y. 1997a. Quaternary sedimentation, parna, landforms and soil landscapes of the Wagga Wagga 1:100,000 map sheet, southeastern Australia. Australian Journal of Soil Research. 35:643-648.

Chen, X.Y. 1997b. Pedogenic gypcrete formation in arid central Australia. Geoderma, 77:39-61.

Chen, X.Y. 1998. Aeolian dust deposits and soil landscapes: examples from Wagga Wagga, NSW. Symposium of Aeolian Dust: Implications for Australian Mineral Exploration & Mineral Environmental Management, Canberra, 25-26 November, 1998, Abstract, 20.

Chen, X.Y., 2001. The red clay mantle in the Wagga Wagga region, New South Wales: evaluation of an aeolian dust deposit (Yarabee Parna) using methods of soil landscape mapping. Australian Journal of Soil Research, 39:61-80.

Chen, X.Y., Spooner, N.A., Olley, J.M. and Qustiaux, D.G. (2002) Addition of Aeolian dusts to soils in southern Australia: red silty clay trapped in dunes bordering Murrumbidgee River in the Wagga Wagga region. Catena, 47:1-27.

Chen, Y. and Polach, H.A., 1986. Validity of C-14 ages of carbonates in sediments. Radiocarbon, 28(2A): 464-472.

Chen, Y., Jinfen, L., Head, J and Arakel, A.V., 1988. C-14 and ESR dating of calcrete and gypcrete cores from the Amadeus Basin, Northern Territory, Australia. Isotope Geochemistry, 9:80-85.

Chin, R.J., Hickman, A.H. and Thom, R. 1982. Hyden, Western Australia. Geological Survey of Western Australia 1:250,000 Geological Series Explanatory Notes. Geol. Surv. West. Aust.

Churchward, H.M. 1962. Soil studies at Swan Hill, Victoria. Australian Journal of Soil Research, 1:242-255.

Clarke, J.D.A. 1994. Evolution of the Lefroy and Cowan palaeodrainage channels, Western Australia. Australian Journal of Earth Sciences, 41:55-68.

Cloud, P.E. 1962. Behaviour of calcium carbonate in sea water. Geochim. Et Cosmochim. Acta 26:867-884.

Cook, P.J., Colwell, J.B., Firman, J.B., Lindsay, J.M., Schwebel, D.A. and von der Borch, C.C. 1977. The late Cainozoic sequence of southeast South Australia and Pleistocene sea-level changes. BMR Journal of Australian Geology and Geophysics. 2:81-88.

Cox, R., 1975. Geochemical soil surveys in exploration for nickel copper sulphides at Pioneer, near Norseman, Western Australia. In: I.L. Elliott and W.K. Fletcher (Editors). Geochemical Exploration 1974, Elsevier, Amsterdam, pp437-460.

Crawford, A.R. 1965. The geology of Yorke Peninsula. Geological Survey of South Australia. Bulletin No. 39. 96pp.

Crocker, R.L. 1946. Post-Miocene climatic and geologic history and its significantce in relation to the genesis of the major soil types of South Australia. CSIRO Bull. No. 39.

Cuyler, R.H., 1930. Caliche as a fault indicator. Abstract. Bulletin of the Geological Society of America, 41: 109.

Danchin, R. 1972. In: Aspects of the geochemistry of calcretes and soils from various localities in the North-west Cape. Anglo-American Research Laboratory, Johannesburg (unpublished report).

Davies, J.L. 1986. The coast. In: Jeans, D.N. (Ed.): The natural environment. Sydney University Press. pp203-222.

Degens, E.T. 1965. Geochemistry of sediments, a brief survey. Prentice-Hall, Inc. Englewood Cliffs, New Jersey. 342pp.

Dell, M.R., 1992. Regolith-landform relationships and geochemical dispersion about the Kanowna-Belle Au Deposit, W.A. Honours Thesis. University of Tasmania. 89pp plus appendices.

Deutscher, R.L., Mann, A.W., and Butt, C.R.M., 1980. Model for calcrete uranium mineralisation. In: C.R.M. Butt and R.E. Smith (Eds.), Conceptual Models in Exploration Geochemistry – Australia. Journal of Geochemical Exploration 12: 158-161.

Dimmock, G.M. 1957. The soils of Flinders Island, Tasmania. CSIRO, Soils and Land Use Series No. 23, Melbourne. 68pp.

Dixon, J.C. 1994. Duricrusts. In: Geomorphology of Desert Environments. edtors: A.D. Abrahams and A.J.Parsons, Chapman & Hall, London. pp82-105.

Downes, R.G. and Sleeman, J.R. 1955. The soils of the Macquarie region, New South Wales. CSIRO Soil Publication No.4, Melbourne.

Dregne, H.E., 1983. Desertification of arid lands. Harwood Academic Publishers. 242pp.

Dunn, P.R. 1963. Hodgson Downs – 1:250,000 Geological series. BMR, SD55-14.

Erickson, R.L. and Marranzino, A.P., 1960. Geochemical prospecting for copper in the Rocky Range, Beaver County, Utah. United States Geological Survey. Professional Paper 400-B., 98-101.

Erickson, R.L., Marranzino, A.P., Oda, U. and Janes, W.W., 1964. Geochemical exploration near the Getchell Mine, Humboldt County, Nevada. U.S. Government Printing Office, Washington. Geological Survey Bulletin 1198-A. 26pp.

Frick, C., 1985. A study of the soil geochemistry of the Platreef in the Bushveld complex, South Africa. Journal of Geochemical Exploration, 32:51-80.

Galloway, R.W., Gunn, R.H., Pedley, L. Cocks, K.D. and Kalma, J.D. 1974. Lands of the Balonne-Maranoa area, Queensland. Land Research Series No.34, Melbourne, 242pp.

Garnett, D.L., Rea, W.J. and Fuge, R., 1982. Geochemical exploration techniques applicable to calcrete-covered areas. In: H.W. Glenn (Ed.). Proceedings of the 12th Commonwealth Mining and Metallurgical Institute Congress, Geological Society of South Africa, Johannesburg, pp945-955.

Geological Survey, 1990. Geology and mineral resources of Western Australia. Memoir 3. Geological Survey of Western Australia, Perth, 827pp.

Gile, L.H., Peterson, F.F. and Grossman, R.B. 1966. Morphological and genetic sequences of carbonate accumulation in desert soils. Soil Science, 101:347-360.

Gill, E.D. 1973. Palaeopedology of the Murray River region between Mildura and Renmark, Australia. Memoirs of the National Museum of Victoria, 34:241-252.

Gill, E.D. 1975. Calcrete hardpans and rhizomorphs in western Victoria, Australia. Pacific Geology, 9:1-16.

Glasson, M.J., Lehne, R.W. and Wellmer, F.W. 1988. Gold exploration in the Callion area, Eastern Goldfields, Western Australia. Journal of Geochemical Exploration 31: 1-19.

Goudie, A.S. 1972a. On the definition of calcrete deposits. Z. Geomorphologie, 16:464-468.

Goudie, A.S. 1972b. The chemistry of world calcrete deposits. Journal of Geology. 80:449-463.

Goudie, A.S. 1973. Duricrusts in tropical and subtropical landscapes. Clarendon Press, Oxford.

Goudie, A.S. 1983. Calcrete. In: A.S. Goudie and K. Pye (Eds.), Chemical Sediment and Geomorphology. London, Academic Press. pp93-131.

Gray, D.J. 1992. Geochemical and hydrogeochemical investigations of alluvium at Mulgarrie, Western Australia. CSIRO Australia. Division of Exploration Geoscience, Perth. Restricted Report 339R. CSIRO/AMIRA Project P241A ; Newcrest Pty Ltd. 70pp.

Griffin, T.J. 1993. Lennard River – 1:250,000 Geological series (3rd ed.). Geological Survey of Western Australia. SE51-8.

Guedria, A., Trichet, J. and Wilhelm, E. 1989. Behaviour of lead and zinc in calcrete-bearing soils around Bou Grine, Tunisia - its application to geochemical exploration. Journal of Geochemical Exploration 32:117-32.

Gunn, R.H., Galloway, R.W., Pedley, L. and Fitzpatrick, E.A. 1967. CSIRO, Land Research Series No.18, Melbourne, 190pp.

Hall, G.C. and Holyland, P.W., 1990. Granny Smith Gold Deposit. In F.E. Hughes (Ed.). Geology of the mineral deposits of Australia and Papua New Guinea. The Australasian Institute of Mining and Metallurgy Monograph No 14. pp519-524.

Hallberg, J.A., 1983. Geology and mineral deposits of the Leonora-Laverton area, northeastern Yilgarn Block, Western Australia. A report and series of 1:50000 scale geological maps. Geological Survey of Western Australia Record 1983/8.

Harrison, N., Bailey, A., Shaw, J.D., Petersen, G.N. and Allen, C.A., 1990. Ora Banda gold deposits. In F.E. Hughes (ed). Geology of the mineral deposits of Australia and Papua New Guinea. The Australasian Institute of Mining and Metallurgy Monograph No 14. pp389-394.

Harrison, P.H., 1990. Platinum group elements. Review of exploration techniques and targets. Mineral exploration, geology and geophysics: Quo vadis? Australian Mineral Industries Research Association, Melbourne, pp1-15.

Hartley, K., 2000. Regolith studies of the Moonta Copper Mines Yorke Peninsula, South Australia. Honours Thesis, University of Melbourne. 68pp plus appendices.

Hay, R.L. and Wiggins, B. 1980. Pellets, ooids, sepiolite and silica in three calcretes of the south-western United States. Sedimentology, 27:559-576.

Hellsten, K.J., Colville, R.G., Crase, N.J. and Bottomer, L.R., 1990. Davyhurst gold deposits. In F.E. Hughes (Ed.). Geology of the mineral deposits of Australia and Papua New Guinea. The Australasian Institute of Mining and Metallurgy Monograph No 14. pp367-371.

Hesse, P.P. 1998. Quaternary dust flux and dust size records from Tasman Sea sediment records. Symposium of Aeolian Dust: Implications for Australian Mineral Exploration & Mineral Environmental Management, Canberra, 25-26 November, 1998, Abstract.

Hill, S.M., Taylor, G. and McQueen, K.G. 1998. Discussions on “Genesis of some calcretes in the southern Yilgarn Craton, Western Australia: implications for mineral exploration”. Australian Journal of Earth Sciences, 45:177-178.

Hill, S.M., McQueen, K.G. and Foster, K.A. 1999. Regolith carbonate accumulations in western and central NSW: characteristics and potential as an exploration sampling medium. In: Taylor, G.M. and Pain, C.F. (Eds.), State of the regolith. Proceedings of Regolith 98 Conference, pp191-208.

Hinston, F.J. and Gailitis, V. 1976. The geographic variation of salt precipitated over western Australia. Australian Journal of Soil Research, 14:319-335.

Hocking, R.M., Williams, S.J., Moore, P.S., Denman, P.D., Lavaring, I.H. and Von De Graaf, W.S.E. 1985. Kennedy Range – 1:250,000 Geological series. Geological Survey of Western Australia, SG50-1.

Hutton, J.T. 1982a. Calcium carbonate in rain. In: R.J. Wasson (Ed.), Quaternary dust mantles of China, New Zealand and Australia. Proceedings of a workshop, ANU, Canberra, pp139-140.

Hutton, J.T. 1982b. Chemical analysis of samples of parna from the Riverine Plain of southeastern Australia. In: R.J. Wasson (Ed.), Quaternary dust mantles of China, New Zealand and Australia. Proceedings of a workshop, ANU, Canberra, pp149-152.

Hutton, J.T. and Dixon, J.C. 1981. The chemistry and mineralogy of some South Australian calcretes and associated soft carbonates and their dolomitization. Journal of Geological Society of Australia, 28:71-91.

Hutton, J.T. and Leslie, T.I. 1958. Accession of non-nitrogenous ions dissoled in rainwater to soils in Victoria. Australian Journal of Agricultural Research, 9:492-507.

IAEA, 1984. Surficial Uranium Deposits. Report of the Working Group on Uranium Geology. International Atomic Energy Agency, Vienna, 252pp.

Isbell, R.F. 1962. Soils and vegetation of the Brigalow Lands, Eastern Australia. CSIRO, Soils and Land Use Series No.43, Melbourne, 59pp.

Isbell, R.F. 1996. The Australian soil classification. CSIRO Publishing, Collingwood, Victoria. 143pp.

Jackson, E.A. 1962. Soil studies in central Australia: Alice Springs-Hermannsburg-Rodinga area. CSIRO, Soil Publication No.19, Melbourne, 81pp.

Jacobson, G. and Arakel, A.V., 1986. Calcrete aquifers in the Australian Arid zone. In: Proceedings of international conference on groundwater systems under stress, Brisbane. Australian Water Resources Concil, pp55-63.

Jacobson, G., Arakel, A.V. & Chen,Y.J. 1988. The central Australian groundwater discharge zone: evolution of associated calcrete and gypcrete deposits. Australian Journal of Earth Science, 35:549-565.

Jeffery, P. and Hughes, B. 1995. Land zones of Eyre Peninsula. Report for Primary Industries, South Australia. 144pp.

Jennings, J.N. and Mabbutt, J.A. 1986. Physiographic outlines and regions. In: Jeans, D.N. (Ed.) Australia, A Geography. Sydney University Press, Australia. pp80-96.

Jenny, H., 1941. Factors of Soil Formation. McGraw-Hill, New York, N.Y., 281pp.

Jessup, R.W. 1961. Evolution of the two youngest (Quaternary) soil layers in the south-eastern portion of the Australian arid zone. Journal of Soil Science, 12:64-72.

Jessup, R.W. 1965. The soils of the central Portion of the New England region, New South Wales. CSIRO Soil Publication No.21, Melbourne, 48pp.

Johns, R.K., 1974. Base metal mineralisation in the Pernatty Lagoon region. South Australia. Geological Survey. Report of Investigations, 42.

Johnson, R. W. 1989. Intraplate Volcanism in Eastern Australia and New Zealand. Cambridge University Press, Melbourne.

Joyce, A.S., 1984. Geochemical exploration. Australian Mineral Foundation (Inc.). 183pp.

Kasterner, M., Keene, J.B. and Gieskes, J.M. 1977, Diagenesis of siliceous oozes: I. Chemical controls on the rate of opal-A to opal-CT transformation – an experimental study. Geochimica et Cosmochimica Acta 41:1041-1059.

Kern, A.M. and Commander, D.P. 1993. Cainozoic stratigraphy in the Roe Palaeodrainage of the Kalgoorlie region, Western Australia. Geological Survey of Western Australia. Professional Paper 34.

Keywood, M.D., Chivas, A.R., Fifield, L.K., Cresswell, R.G. and Ayers, G.P. 1997. The accession of chloride to the western half of the Australian continent. Australian Journal of Soil Research, 35:1177-1189.

Klappa, C.F. 1980. Rhizoliths in terrestrial carbonates: classification, recognition, genesis and significance. Sedimentology, 27:613-629.

Krauskopf, K.B. 1967. Introduction to geochemistry. McGraw-Hill Book Company. New York. 721pp.

Krieg, G.W. 1985. Dalhousie – 1:250,000 Geological series, Geological Survey of South Australia, SG53-11.

Krumbein, W.E. and Giele, C. 1979. Calcification in a coccoid cyanobacterium associated with the formation of desert stromatolites. Sedimentology, 26:593-604.

Kruse, P.D., Sweet, I.P., Stuat-Suitu, P.G., Wygralak, A.S., Pieters, P.E. and Crick, I.H. 1994. Katherine (2nd Ed.) – 1:250,000 Geological series. NT Geological Survey/AGSO, SD53-9.

Lamplugh, G.W. 1902. Calcrete. Geological Magazine, 39:575.

Lawrance, L.M., 1991. Distribution of gold and ore-associated elements within lateritic weathering profiles of the Yilgarn Block, Western Australia. University of Western Australia. PhD Thesis. 191pp.

Lawrance, L.M. and Butt, C.R.M. 1992. Mount Pleasant Au deposit. In: Butt, C.R.M. and Zeegers, H. (Editors), Regolith Exploration Geochemistry in Tropical and Subtropical Terrains. Elsevier, Amsterdam, pp365-367.

Leduc, C., 1986. Prospection geochimique de mineralisations de converture en milieu carbonate sons climat semi-aride: resultats d'une etude d'orientation de Zn-Pb de Bou Grine (Atlas tunisien). Chronique Des Mines Et De La Recherche Miniere 482: 33-37.

Leeder, M.R. 1982. Sedimentology, processes and product. Geoge Allen & Unwin, Sydney.

Lintern, M.J. 1989. Study of the distribution of gold in soils at Mt. Hope, Western Australia. CSIRO Australia. Division of Exploration Geoscience, Perth. Restricted Report 24R. CSIRO/AMIRA Project P241. 40pp.

Lintern, M.J. 1996a. Geochemical studies of the soil at the Runway gold prospect, Kalgoorlie, Western Australia. CRC LEME 26R/Exploration and Mining Report 250R. 22pp.

Lintern, M.J. 1996b. Further geochemical studies of the soil at the Panglo gold deposit, Kalgoorlie, Western Australia. CRC LEME 10R/Exploration and Mining Report 251R. 8pp.

Lintern, M.J. and Scott, K.M. 1990. The distribution of gold and other elements in soils and vegetation at Panglo, Western Australia. CSIRO Australia. Division of Exploration Geoscience, Perth. Restricted Report 129R. CSIRO/AMIRA Project P241. 100pp.

Lintern, M.J. and Butt, C.R.M. 1991. The distribution of gold and other elements in soils at Mulline, Western Australia. CSIRO Australia. Division of Exploration Geoscience, Perth. Restricted

Report 159R. CSIRO/AMIRA Project P241. 62pp.

Lintern, M.J. and Butt, C.R.M. 1992. The distribution of gold and other elements in soils and vegetation at Zuleika, Western Australia. CSIRO Australia. Division of Exploration Geoscience, Perth. Restricted Report 328R. CSIRO/AMIRA Project P241A. 95pp.

Lintern, M.J. and Butt, C.R.M. 1993a. The distribution of gold and other elements in soils at the Granny Smith Gold Deposit, Western Australia. CSIRO Australia. Division of Exploration Geoscience, Perth. Restricted Report 385R. CSIRO/AMIRA Project P241. 78pp.

Lintern, M and Butt, C. 1993b. Pedogenic carbonate: an important sampling medium for gold exploration in semi-arid areas. Exploration Research News No.7, CSIRO, Perth.pp7-11.

Lintern, M.J., and Gray, D.J. 1995a. Progress statement for the Kalgoorlie Study Area - Steinway Prospect, Western Australia. CSIRO Australia, Division of Exploration and Mining Report No. 95R. 121pp.

Lintern, M.J., and Gray, D.J. 1995b. Progress statement for the Kalgoorlie Study Area - Argo Deposit, Western Australia. CSIRO Australia, Division of Exploration and Mining Report No. 96R. 153pp.

Lintern, M.J., and Gray, D.J. 1995c. Progress statement for the Kalgoorlie Study Area - Kurnalpi Prospect, Western Australia. CSIRO Australia, Division of Exploration and Mining Report No. 97R. 41pp.

Lintern, M.J., and Gray, D.J. 1995d. Progress statement for the Kalgoorlie Study Area - Enigma Prospect (Wollubar), Western Australia. CSIRO Australia, Division of Exploration and Mining Report No. 98R. 36pp.

Lintern, M.J., Churchward, H.M. and Butt, C.R.M. 1990. Multi-element soil survey of the Mount Hope area, Western Australia. CSIRO Australia, Division of Exploration Geoscience Report No. 109R. 76pp.

Lintern, M.J., Craig, M.A., Walsh, D.M. and Sheridan, N.C. 1996. The distribution of gold and other elements in surficial materials from the Higginsville palaeochannel gold deposits, Norseman, Western Australia. CSIRO Australia. Division of Exploration and Mining, Perth. Restricted Report 275R. CRC LEME, Perth. Restricted Report 28R. CRC LEME/AMIRA Project 409: Yilgarn Transported Overburden. 104pp.

Lintern, M.J., Craig, M.A. and Carver, R.N. 1997. Geochemical studies of the soil and vegetation at the Apollo Au deposit, Kambalda, WA. CSIRO Australia. Division of Exploration and Mining, Perth. Restricted Report 274R. CRC LEME, Perth. Restricted Report 30R. CRC LEME/AMIRA Project 409: Yilgarn Transported Overburden. 75pp.

Lintern, M.J., Sheard, M.J. and Gray, D.J. 1998. Geochemical studies of the regolith at the Mt Gunson Copper Deposits, Stuart Shelf, South Australia. CRC LEME Report 76. 71pp

Lowry, D.C. 1971. Geology of the western Australian part of the Eucla Basin. Ph.D. Thesis, University of Western Australia. 249pp.

Machette, M.N. 1985. Calcic soils of the south-western United States. Geol.Soc.Am.Spec.Pap. No.203, pp1-21.

Madden, J. 1996. Regolith evolution and geochemical dispersion into transported overburden, Deep South Deposit, Mount Gibson, Western Australia. Honours Thesis. University of Western Australia. 48pp.

Magee, J.W. 1991. Late Quaternary lacustrine, groundwater, aeolian and pedogenic gypsum in the Prungle Lakes, southeastern Australia. Palaeogeogragpy, Palaeoclimatology, Palaeoecology, 84:3-42.

Mann, A.W. 1974. Chemical ore genesis models for the precipitation of carnotite in calcrete. CSIRO Mineral Research labs, Division Mineral Report, FP7, 18pp.

Mann, A.W. and Deutscher, R.L. 1978. Genesis principles for the precipitation of carnotite in calcrete drainages in Western Australia. Economic Geology, 73:1724-1737.

Mann, A.W. and Horwitz, R.C. 1979. Groundwater calcrete deposits in Australia: some observations from Western Australia. Journal of Geological Society of Australia, 26:293-303.

Maxey, 1997 (Editor). Australian gold annual, 1997. 256pp.

Mayer, L, McFadden, L.D. and Harden, J.W., 1988. Distribution of calcium carbonate in desert soils: a model. Geology, 16:303-306.

Mazzucchelli, R.H. and James, C.H., 1966. Arsenic as a guide to gold mineralisation in laterite-covered areas of Western Australia. Trans. Inst. Min. Metall., Section B, Applied Earth Sciences, 75:286-294.

Mazzucchelli, R.H. 1972. Secondary geochemical dispersion patterns associated with nickel sulphide deposits at Kambalda, Western Australia. Journal of Geochemical Exploration, 1: 103-116.

Mazzucchelli, R.H., Chapple, B.E.E. and Lynch, J.E. 1980. Northern Yorke Peninsular Cu, Gawler Block, S.A. Conceptual Models in Exploration Geochemistry - Australian Journal of Geochemical Exploration, 12:203-7.

McCord, A.K. 1995. A description of land in the southern Mallee of South Australia. Report for Primary Industries, South Australia. 222pp.

McDonald, R.C., Isbell, R.F., Speight, J.G., Walker, J. and Hopkins, M.S. 1990. Australian soil and land survey handbook – field handbook (2nd edition). Inkata Press, Melbourne, 198pp.

McFadden, L.D. and Tinsley, J. 1985. Rate and depth of prdogenic-carbonate accumulation in soils: formulation and testing of a compartment model. Geological Society of America Special Paper 203:23-42.

McGillis J.L., 1967. The Silver Content of Caliche on Alluvial Fans as a Regional Guide to Areas of Silver and Gold Mineralisation in the Basin and Range Province. Part fulfilment of MSc. Thesis. University of Nevada, Reno, USA. 30pp.

McKenzie, N.J., Jacquier, D.W., Ashton, L.J. and Cresswell, H.P. 2000. Estimation of soil properties using the Atlas of Australian Soils. CSIRO Land & Water Technical Report 11/00, Canberra.

McQueen, K.G., Hill, S.M. and Foster, K.A. 1999. The nature and distribution of regolith carbonate accumulations in southeastern Australia and their potential as a sampling medium in geochemical exploration. Journal of Geochemical Exploration, 67:67-82.

McTainsh, G.H. 1989. Quaternary aeolian dust processes and sediments in the Australian region. Quaternary Science Reviews, 8:235-253.

Miller, M., McLeod, R., Devlin, S and Vinar, J. 1999. Discovery of the Ghost Crab Deposit, Kalgoorlie, Western Australia. New Generation Gold Mines '99. Conference Proceedings, pp127-141.

Milnes, A.R. 1992. Calcrete. In: Martini, I.D. and Chesworth, W. (Eds.): Developments in Earth surface processes, weathering , soils and palaeosols. Elsevier, Amsterdum. pp309-347.

Milnes, A.R. and Hutton, J.T. 1983. Calcretes in Australia. In: Soils, an Australian viewpoint. CSIRO, Melbourne and Academic Press, London, pp119-162.

Milnes, A.R., Kimber, R.W. and Phillips, S.E. 1987. Studies in eolian calcareous landscapes of southern Australia. In: Aspects of loess research, L. Tungsheng (Ed.), pp130-139, Beijing, China Ocean Press.

Nahon, D., Janot, C., Karpoff, A.M., Paquet, M. and Tardy, Y., 1977. Mineralogy, petrography and structure of iron crusts (ferricretes) developed on sandstones in the western part of Senegal. Geoderma, 19:263-277.

Nanson, G.C., Chen, X.Y. and Price, D.M. 1992. Lateral migration, thermoluminescence chronology and colour variation of longitudinal dunes near Birdsville in the Simpson Desert, central Australia. Earth Surface Processes and Landforms, 17:807-819.

Nanson, G.C., Chen, X.Y. and Price, D.M. 1995. Aeolian and fluvial evidence of changing climate and wind patterns during the past 100 ka in the western Simpson Desert, Australia. Palaeogeography, Palaeoclimatology, Palaeoecology, 113:87-102.

Netterberg, F. 1967. Some road making properties of South African calcretes. Proc. 4th Reg.Conf.African Soil Mech. Fndn. Engng., Cape Town, 1:77-81.

Netterberg, F. 1980. Geology of southern African calcretes, I. Terminology, description, macrofeatures and classification. Trans. Geol. Soc. S. Africa, 83:255-283.

Nicolls, K.D. and Tucker, B.M. 1956. Pedology and chemistry of the basaltic soils of the Lismore District, N.S.W. CSIRO Soil Publication No.7, Melbourne, 153pp.

NLWRA 2001. Australian agricultural assessment 2001. National Land and Water Resources Audit, Canberra.

Northcote, K.H. 1975. Atlas of Australian soils. CSIRO, Melbourne.

O'Driscoll, E.S.T. 1986. Observations of the lineament-ore relation. In: Reading, H.G., Watterson, J. and White, S.H., (Editors). Major crustal lineaments and their influence on the geological history of the continental lithosphere. Royal Society of London. Philosophical Transactions, 317:195-218.

Ollier, C.D. 1986. Early landform evolution. In: Jeans, D.N. (Ed.): The natural environment. Sydney University Press, Sydney. pp97-116.

Perry, R.A. 1964. General report on lands of the Leichhardt-Gilbert area, Queensland. CSIRO, Land Research Series No.11, Melbourne, 224pp.

Paine, A.G.L. 1963. Tanumbirini – 1:250,000 Geological series. BMR, SE53-2.

Phillips, S.E. and Milnes, A.R., 1988. The Pleistocene terrestrial carbonate on the southeastern margin of the St Vincent Basin, south Australia. Australian Journal of Earth Sciences, 35:463-481.

Phillips, S.E. and Self, P.G., 1987. Morphology, crystallography and origin of needle-bibre calcite in Quaternary pedogenic calcretes of South Australia. Australian Journal of Soil Research, 25:405-428.

Phillips, S.E., Milnes, A.R. and Foster, R.C. 1987. Calcified filaments: an example of biological influences in the formation of calcrete in south Australia. Australian Journal of Soil Research. 25:405-428.

PIRSA 2001. Soils of South Australia's agricultural lands [CD ROM]. Primary Industries and Resources South Australia, Adelaide.

Plumb, K.A. 1968. Lissadell – 1:250,000 Geological series. BMR, SE52-2.

Plumb, K.A. and Derrick, G.M. 1975. Geology of the Proterozoic rocks of the Kimberley to Mt. Isa region. In: C.J. Knight (ed.): Economic geology of Australia and Papua-New Guinea. A.I.M.M., Melbourne.

Plumb, K.A. and Paine, A.G.L. 1964. Mount Young – 1:250,000 Geological series. BMR, SD53-15.

Preiss, W.V. (Compiler) 1987. The Adelaide Geosyncline: Late Proterozoic stratigraphy, sedimentation, palaeontology and tectonics. South Australia. Geological Survey. Bulletin, 53: 384-389.

Preiss, W.V., 1993. Neoproterozoic. In: Drexel, J.F., Preiss, W.V. and Parker, A.J., (Eds.). The geology of South Australia. Volume 1 The Precambrian. South Australia. Geological Survey. Bulletin. 54:171-197.

Quade, J., Chivas, A.R. and McCulloch, M.T., 1995. Strontium and carbon isotope tracers and the origins of soil carbonate in South Australia and Victoria. Palaeogeogragpy, Palaeoclimatology, Palaeoecology, 113:103-117.

Randall, M.A. 1966a. Brunette Downs – 1:250,000 Geological series. BMR, SE53-11.

Randall, M.A. 1966b. Alroy – 1:250,000 Geological series. BMR, SE53-15.

Rattigan, J.H., Gersteling, R.W. and Tonkin, D.G. 1977. Exploration geochemistry of the Stuart Shelf, South Australia. Journal of Geochemical Exploration 8:203-17.

Read, J.F. 1974. Calcrete deposits and Quaternary sediments, Edel Province, Shark Bay, Western Australia. Mem. American Association of Petrologic Geology, 22:250-282.

Robertson, I.D.M. and Tenhaeff, M.F.J. 1992. Petrology, mineralogy and geochemistry of soil and lag overlying the Lights of Israel Gold Mine - Davyhurst, WA. Volume 1 & Volume 2. CSIRO Australia. Division of Exploration Geoscience, Perth. Restricted Report 232R. CSIRO/AMIRA Project P241A. 107pp.

Robertson, I.D.M. and Buut, C.R.M. 1997. Atlas of weathered rocks. CSIRO Division of Exploration Geoscience Report 390, Perth.

Robertson, I.D.M., Koning, A.E., Anand, R.R. and Butt C.R.M. 1996. Atlas of transported overburden. CSIRO Exploration and Mining Restricted Report 296R. 122p. (Reissued as Open File Report 87, CRC LEME, Perth, 2001).

Rogere, P.A. 1984. Abminga – 1:250,000 Geological series. Geological Survey of South Australia, SG53-10.

Rosler, H.J. and Lange, H. 1972. Geochemical tables. Elsevier Publishing Company, Amsterdam. 468pp.

Sanders, C.C. 1974. Calcrete in Western Australia. Western Australian Geological Survey Annual Report. (1973), pp12-14.

Scott, K, Chen, X.Y. and Gatehouse, R. 1998. Guide of field trip for Symposium of Aeolian Dust: Implications for Australian Mineral Exploration & Mineral Environmental Management, 25-26 November, 1998, Canberra.

Semeniuk, V. and Meagher, T.D. 1981. Calcrete in Quaternary coastal dunes in southwestern Australia: a cappillary-rise phenomenon associated with plants. Journal of sedimentary Petrology, 51:47-68.

Semeniuk, V. and Searl, D.J. 1985. Distribution of calcrete in Holocene coastal sands in relationship to climate, southwestern Australia. Journal of sedimentary Petrology, 55:86-95.

Smee, B.W. 1998. A new theory to explain the formation of soil geochemical responses over deeply covered gold mineralization in arid environments. Journal of Geochemical Exploration 61:149-72.

Smee, B.W. 1999. The effect of soil composition on weak leach solution pH: a potential exploration tool in arid environments. Explore – newsletter for the Association of Exploration Geochemists, January 1999. pp4-7.

Smith, B.H. and Keele, R.A. 1984. Some observations on the geochemistry of gold mineralization in the weathered zone at Norseman, Western Australia. Journal of Geochemical Exploration 22:1-20.

Smith, B.H. 1987. Dispersion of Gold in Soils. In "Meaningful Sampling in Gold Exploration." Bulletin No.7. Publ. Australian Institute of Geoscientists, Suite 1001, 10 Martin Place, Sydney, N.S.W. 2000.

Smith, K.G. 1972. Stratigraphy of the Georgina Basin. BMR Bulletin 111, Canberra.

Smith, K.J., Beckmann, G.G. and Little, I.P. 1990. Soils of the southern Lockyer Valley, Queensland. CSIRO, Soils and Land Use Series No.62, Melbourne.

Speck, N.H., Wright, R.L., van de Graaff, R.H.M., Fitzpatrick, E.A., Mabbutt, J.A. and Stewart, G.A. 1965. General report on lands of the Tipperary area, Northern Territory. CSIRO, Soil Publication No.13, Melbourne.

Stewart, G.A. 1956. The soils of the Katherine-Darwin Region, Northern Territory. Soil Publication, No. 6, CSIRO, Melbourne.

Stewart, G.A., Perry, R.A., Paterson, S.J., Traves, D.M., Slatyer, R.O., Dunn, P.R. Jones, P.J. and Sleeman, J.R. 1970. Lands of the Ord-Victoria area, Western Australia and Northern Territory. CSIRO Land Research Series, No. 28.

Story, R., Galloway, R.W., van de Graaff, R.H.M. and Tweedie, A.D. 1963. General report on the lands of the Hunter Valley. Land Research Series No.8, Melbourne, 152pp.

Story, R., Galloway, R.W., Gunn, R.H. and Fitzpatrick, E.A. 1967. Lands of the Isaac-Comet area, Queensland. CSIRO, Land Research Series No.19, Melbourne, 151pp.

Sweet, I.P. 1972. Delamere – 1:250,000 Geological series. BMR, SD52-16.

Talma, A.S. and Netterberg, F. 1983. Stable isotope abundances in calcretes. In: Wilson, R.C.L. (Ed.), Residual deposits: surface related weathering processes and materials. Blackwell Scientific Publications, Oxford. pp221-234.

Thomson, R.M. and Peachey, T.R. 1993. The Kanowna Belle case study – the discovery of a concealed orebody. In Williams, P.R. and Haldane, J.A. (Eds). An international conference on crustal evolution, metallogeny and exploration of the Eastern Goldfields. Excursion Guidebook, Australian Geological Survey Record 1993/53. 144pp.

Toens, P.D. and Hambleton-Jones, B.B. 1984. Definition and classification of surficial uranium deposits. Surficial Uranium Deposits. International Atomic Energy Agency, Vienna, pp9-14.

Tordiffe, E.A.W., Vermaak, J.J., van der Westhuizen, W.A. and Beukes, G.J. 1989. The Jacomynspan copper-nickel prospect - a study of secondary dispersion in the calcretes of the Northern Cape Province, South Africa. Exploration Geochemistry in Southern Africa. Journal of Geochemical Exploration 34:31-45.

Tucker, M.E. and Wright, V.P. 1990. Carbonate Sedimentology. Blackwell Scientific Publications, Oxford, 424pp.

Van De Graaff, W.J.E., Crowe. R.W.A., Bunting, J.A. and Jackson, M.J. 1977. Relic early Cainozoic drainages in arid western Australia. Z. Geomorphologie, 21:379-400.

Van Dijk, D.C. 1958. Principles of soil distribution in the Griffith-Yenda District, New South Wales. Soil Publication No. 11, CSIRO, Melbourne.

Van Dijk, D.C. 1959. Soil features in relation to erosional history in the vicinity of Canberra. CSIRO, Soil Publication No. 13. Canberra.

Van Dijk, D.C. 1961. Soils of the southern portion of the Murrumbidgee irrigation area. CSIRO, Soils and Land use Series, No. 40. 44pp.

Van Herk, H., Houston, M.L and Dudgeon, R.N. 1975. Planning, development and extraction of the Cattle Grid ore deposit, Mt Gunson. Proceedings of the Australasian Institute of Mining and Metallurgy Conference, Adelaide, S.A., June, 1975, pp113-124.

Vermaak, J.J. 1984. Aspects of the secondary dispersion of ore-related elements in calcrete-environments of the northern Cape Province. M.Sc. thesis, University of Orange Free State, Bloemfontein. 136pp. (unpublished)

Walker, P.J. 1982. Aeolian landforms in the Cobar-Tilpa area, NSW. In: R.J. Wasson (Ed), Quaternary dust mantles of China, New Zealand and Australia. Proceedings of a workshop, ANU, Canberra, pp197-200.

Walker,P.H., Chartres,C.J. and Hutka, J. 1988. The effect of aeolian accessions on soil development on granitic rocks in south-eastern Australia. I. Soil morphology and particle-size distributions. Australian Journal of Soil Research, 26:1-16.

Warren, J.K. 1983. Pedogenic calcrete as it occurs in Quaternary calcareous dunes in coastal south Australia. Journal of Sedimentary Petrology, 53:787-796.

Wasson, R.J. 1983a. The Cainozoic history of the Strzelicki and Simpson dunefields (Australia) and the origin of desert dunes. Zeitschrift fur Geomorphologie, N.F. Supplement Rd., 45:85-115.

Wasson, R.J. 1983b. Dune sediment types, sand colour, sediment provenance and hydrology in the strzelecke - simpson dunefield, Australia. In: M.E. Brookfield and T.S. Ahlbrandt (Eds.), Eolian Sediments and Processes, pp165-195. Elsevier Science Publishers B.V., Amsterdam.

Watts, N.L. 1980. Quaternary pedogenic calcretes from the Kalahari (southern Africa): mineralogy, genesis and giagenesis. Sedimentology, 27:661-686.

Wedepohl, K.H. 1971. Geochemistry. Holt, Rinehart and Winston, Inc., New York. 231pp.

Wetherby, K.G. and Oades, J.M. 1975. Classification of carbonate layers in highland soils of the northern Murray Valley, South Australia and their use in stratigraphic and land-use studies. Australian Journal of Soil Research, 13:119-132.

Williams, G.E. and Polach, H.A. 1969. The evaluation of 14C ages for soil carbonate from the arid zone. Earth Planetary Science Letter, 7:240-242.

Williams, G.E. and Polach, H.A. 1971. Radiocarbon dating of arid zone calcareous paleosols. Geological Society of America Bull. 82:3069-3086.

Williams, G.E. and Tonkin, D.G. 1985. Periglacial structures and palaeoclimatic significance of a late Precambrian block field in the Cattle Grid copper mine, Mount Gunson, South Australia. Australian Journal of Earth Science, 32:287-300.

Wopfner, H. and Twidale, C.R. 1967. Geomorphological history of the Lake Eyre Basin. In Landform studies from Australia and New Guinea, J.N. Jennings and J.A. Mabbutt (eds), ANU

Press, Canberra. pp118-143.
Wright, V.P. 1989. Terrestrial stromatolites and laminar calcretes: a review. Sedimentary Geology, 65:1-13.

Wright, V.P. and Tucker, M.E. 1991. Calcretes. Blackwell Scientific Publications, Carlton, Australia. 352pp.

Wyrwoll, K.H. 1988. Time in the geomorphology of Western Australia. Progress in Physical Geography, 12:237-263.

Yaalon, D.H. 1981. Pedogenic carbonate in aridic soils - magnitude of the pool and annual fluxes. Abstract, International Conference on Aridic Soils, Jerusalem. pp94.

Yaalon, D.H. 1983. Climate, Time, and Soil Development. In: L.P. Wilding, N.E. Smeck and G.F. Hall (Eds.), Pedogenesis and Soil Taxonomy, I. Concepts and Interactions. Elsevier, Amsterdam - Oxford - New York, pp233-251.

Figure 2.1.1,
A calcrete profile developed in calcareous coastal dune, South Australia. The carbonate content is > 90 % at a depth of 10-35 cm, and decreases from 44 % at 35-70 cm to 41 % at 70-120 cm and to 38 % at 120-150 cm. The lower part of the profile (70-150 cm) is relatively soft and only slightly cemented and may be regarded as a transitional type between powdery and hardpan calcretes. The upper part of the profile (10-70 cm) appears to have a higher degree of cementation.
(Photograph: McCord 1995)

Figure 2.1.2.
A profile of nodular calcrete (nodular regolith carbonate) in an alluvial plain at the Pinnacles, west of Broken Hill. The top 20 cm is a layer of red clayey sand which is interpreted to be a post-settlement deposit. The size of the carbonate nodules decreases towards the base of the profile and there is more powdery carbonate in the matrix. In the upper part, there are some carbonate pisolites (relatively rounded and with concentric structures).
(Photograph: Steven Hill)

Figure 2.1.3.
A calcrete profile in a sand plain, about 8 km southwest of Kalgoorlie, WA. The calcrete profile consists of three sub-layers with different types of regolith carbonate: 0-20 cm red clayey sands; 20-35 cm carbonate pisolites; 35-55 cm carbonate nodules, moderately indurated; 55-120 +: soft and powdery carbonate aggregates in red sandy clay.
(Photograph: X.Y. Chen)

Figure 2.1.4.
Carbonate pisolites taken from the upper part of the calcrete profile at the Pinnacles (see Fig. 2.1.2). The pisolites have relatively rounded shape, more massive cores with concentric laminations towards their margins. Some contain quartz grains and voids.
(Photograph: Steven Hill)

Figure 2.1.5.
Tubular calcrete developed in a Pleistocene coastal dune near Portland, Victoria. This can also be termed as carbonate rhizoliths (e.g., Klappa, 1980). Because of its resistance to deflation, this calcrete is presently exposed to the dune surface.
(Photograph: Steven Hill)

Figure 2.1.6.
A closer view of the carbonate rhizoliths of the coastal dune near Portland (same site as Fig. 2.1.5). This shows the inter-connected carbonate rhizomorphs, similar to plant root systems.
(Photograph: Steven Hill)

Figure 2.1.7.
Tubular regolith carbonate (or tubular calcrete) at Thackaringa Loop, in an alluvial plain about 25 km west of Broken Hill. Compared with the tubular calcrete of the coastal dune, the carbonate tubules in this profile are shorter in length, do not form an interconnected framework and are mixed with carbonate nodules.
(Photograph: Steven Hill)

Figure 2.1.8.
A specimen showing a thin (1 cm) layer of laminar carbonate coating a hardpan regolith carbonate. Note the complex fabric of the hardpan carbonate, with enclosed (re-cemented) carbonate nodules, pisoliths, and quartz and rock fragments. This specimen was taken from a calcrete (or regolith carbonate) profile developed in alluvium at the Nine Mile site, about 10 km north of Broken Hill. The profile consists of, from the top downwards: loose carbonate nodules, the laminated carbonate layer and the hardpan carbonate (hardpan calcrete).
(Photograph: Steven Hill)

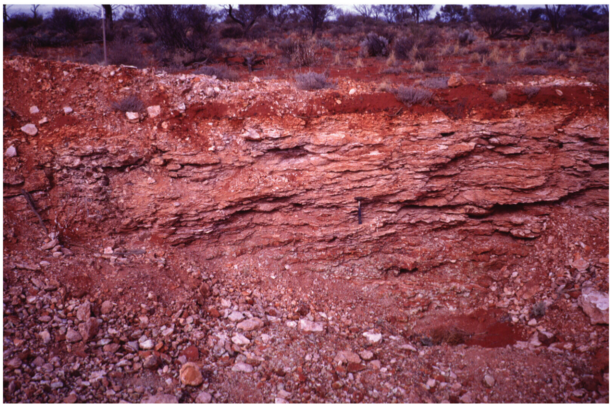


Figure 2.1.9.
An exposure at the Challenger Gold Deposit, 750 km NW of Adelaide (South Australia), showing weathered gneiss with well-developed near-horizontal joints, in which carbonate has precipitated and also partly replaced the weathered gneiss. Further precipitation of carbonates may result in a laminar calcrete.
(Photograph: Mel Lintern)

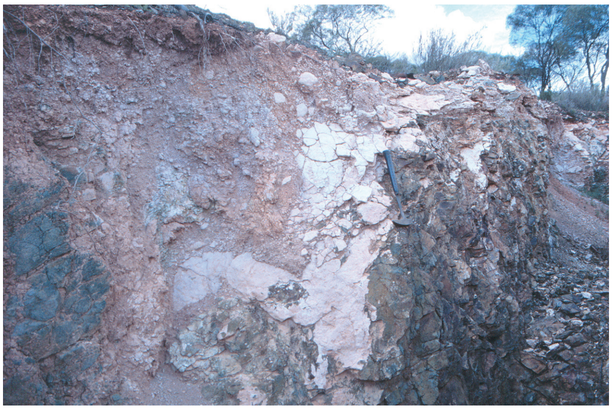


Figure 2.1.10.
Thin (up to 10 cm) layer of laminated carbonate occurring along joints in weathered rock. This site is located near Coolgardie, WA.
(Photograph: X.Y. Chen)

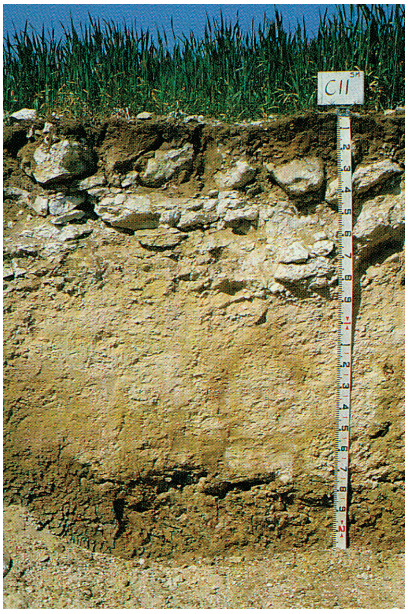


Figure 2.1.11.
A calcrete profile in the Mallee Region, SA. The profile comprises : 0-20 cm clayey sands; 20-80 cm carbonate boulders with a carbonate content > 50 % ; 80-170 cm powdery and nodular carbonates with a carbonate content 60-70 %; 170-210 +: clay.
(From McCord 1995)

Figure 2.1.12.
A hardpan calcrete profile in the undulating flats of the Mallee Region, SA. The profile consists of: 0-30 cm sandy clay loam with carbonate nodules and cobbles; 30-70 cm indurated carbonate (hardpan calcrete); 70-150 cm massive carbonate, less cemented than the layer above; 150-205 cm a layer with patches of carbonate and clay; 205-280 cm+: clay.
(From McCord 1995)

Figure 2.1.13.
A block of carbonate taken from hardpan calcrete in a sand plain near Laverton, WA. This shows the complex internal fabric and structures, such as re-cemented carbonate fragments, pisoliths, and laminar carbonate infilling cracks and cementing surrounding nodules.
(Photograph: X.Y. Chen)

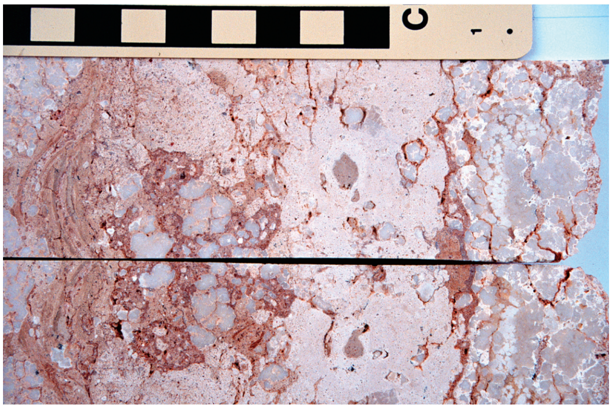


Figure 3.3.1.
A calcrete core taken from Titra, near the margin of Lake Lewis, central Australia. Both massive and irregular silica aggregates occur in the calcrete.
(Photograph: Pauline English)

Figure 3.5.5.
A profile from the southern Yilgarn Plateau (near Tammin, Western Australia) showing nodular regolith carbonate in soil/regolith overlying weathered granite. Note the previous land surface and more carbonate nodules occurring in the lower part of the previous topography.
(Photograph: X.Y. Chen)

Figure 4.1.1.
The upper most part of a calcrete profile at 'Limestone Station', in an alluvial plain about 10 km west of Broken Hill. The top 40 cm consists of: 0-20 cm nodular calcrete with highly indurated, weakly cemented carbonate nodules; 20-25 cm laminar calcrete, not well developed; and 25-40+ cm hardpan calcrete comprising a cemented carbonate layer with nodular structures.
This profile may be regarded as transitional between typical nodular and hardpan calcretes.
(Photograph: Steven Hill)

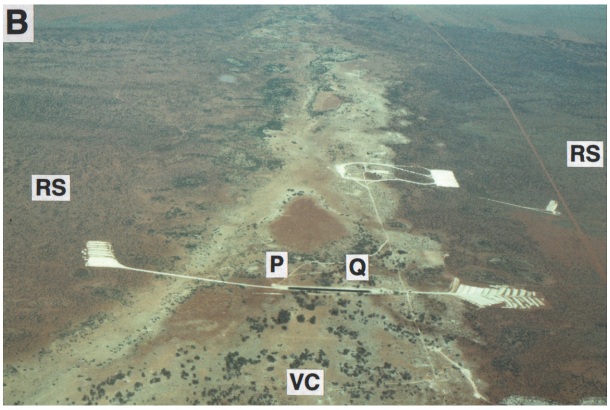


Figure 7.2.3.
Aerial view of the Yeelirrie palaeodrainage in northern Yilgarn Plateau, with valley calcrete (VC) surrounded by very gently sloping, red, sandy, alluvial plains (RS). The cross section PQ, as a cutting across the drainage, is shown in Figure 7.2.5.
(Photograph: Charles Butt)

Figure 7.2.4.
A pit dug into valley calcrete at a site near Sandstone, Western Australia. The exposed calcrete layer is at least 6 m thick.
(Photograph: X.Y. Chen)

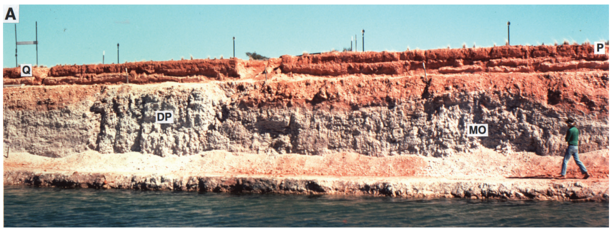


Figure 7.2.5.
Cross section (PQ) through valley calcrete and associated deposits. A diapir (DP) and a mound (MO) have developed in the calcrete by upward pressure, due to active precipitation of carbonate at groundwater level. Compare to Figure 7.2.3.
(Photograph: Charles Butt)

Figure 7.2.6.
A terrace 5-10m above the river bed of the Thomes River at Yinnetharra, West Australia. A layer of calcrete, 2-4 m thick, covers the terrace surface.
(Photograph: X.Y. Chen)

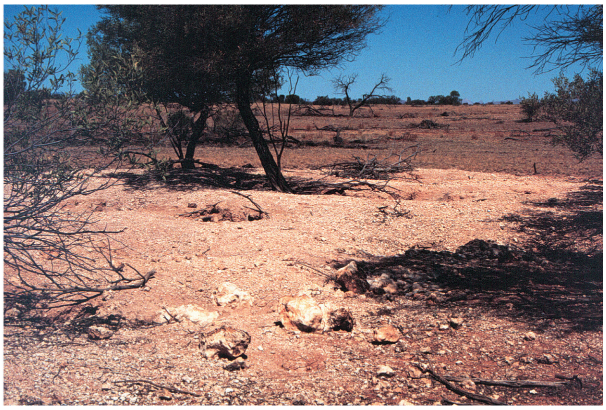


Figure 7.2.7.
Calcrete, near Lake Lewis, central Australia, forms slightly higher ground than the surrounding sand plain surface. Some dissolution holes have developed in the calcrete and have been used as a rabbit burrow.
(Photograph: Pauline English)

Figure 7.2.9.
A hardpan calcrete exposed on the western shore of a small playa lake, about 120 km west of Kalgoorlie. This shows the cracked and brecciated upper part of the calcrete forming carbonate boulders and gravels.
(Photograph: X.Y. Chen)

Figure 7.2.16.
Swale and a dune, near Immarna (eastern edge of Nullarbor Plain on Transcontinetal Line), Great Victoria Desert. Calcrete occurs commonly at a shallow depth in swales between dunes.
(Photograph: Mel Lintern)

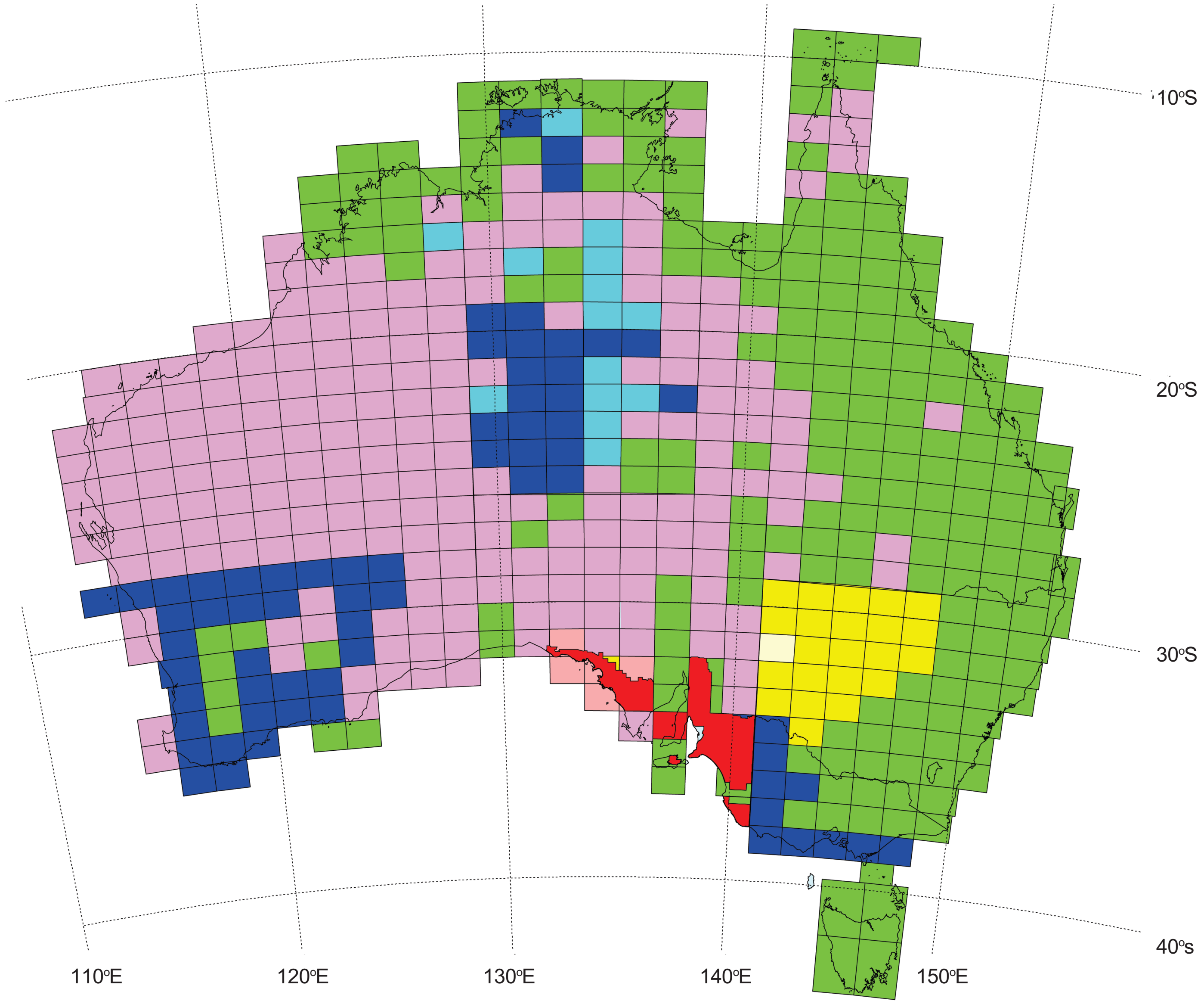
Figure 7.2.17.
An exposure of a low dune near Barton on the Transcontinetal Line (southern Great Victoria Desert), showing a calcrete overlain by non-calcareous aeolian sands.
(Photograph: Mel Lintern)

Figure 7.2.21.
An aeolianite sequence (Bridgewater Formation) exposed near the southern tip of the Eyre Peninsula, South Australia, showing many interbedded calcrete and aeolian sand layers. The whole exposed sequence is over 80 m high.
(Photograph: Mel Lintern)

Figure 7.2.22.
An aeolianite exposure at Moonta Bay, South Australia, showing 4-5 layers of nodular/massive calcrete interbedded with sandy clay, aeolian sediments.
(Photograph: Mel Lintern)

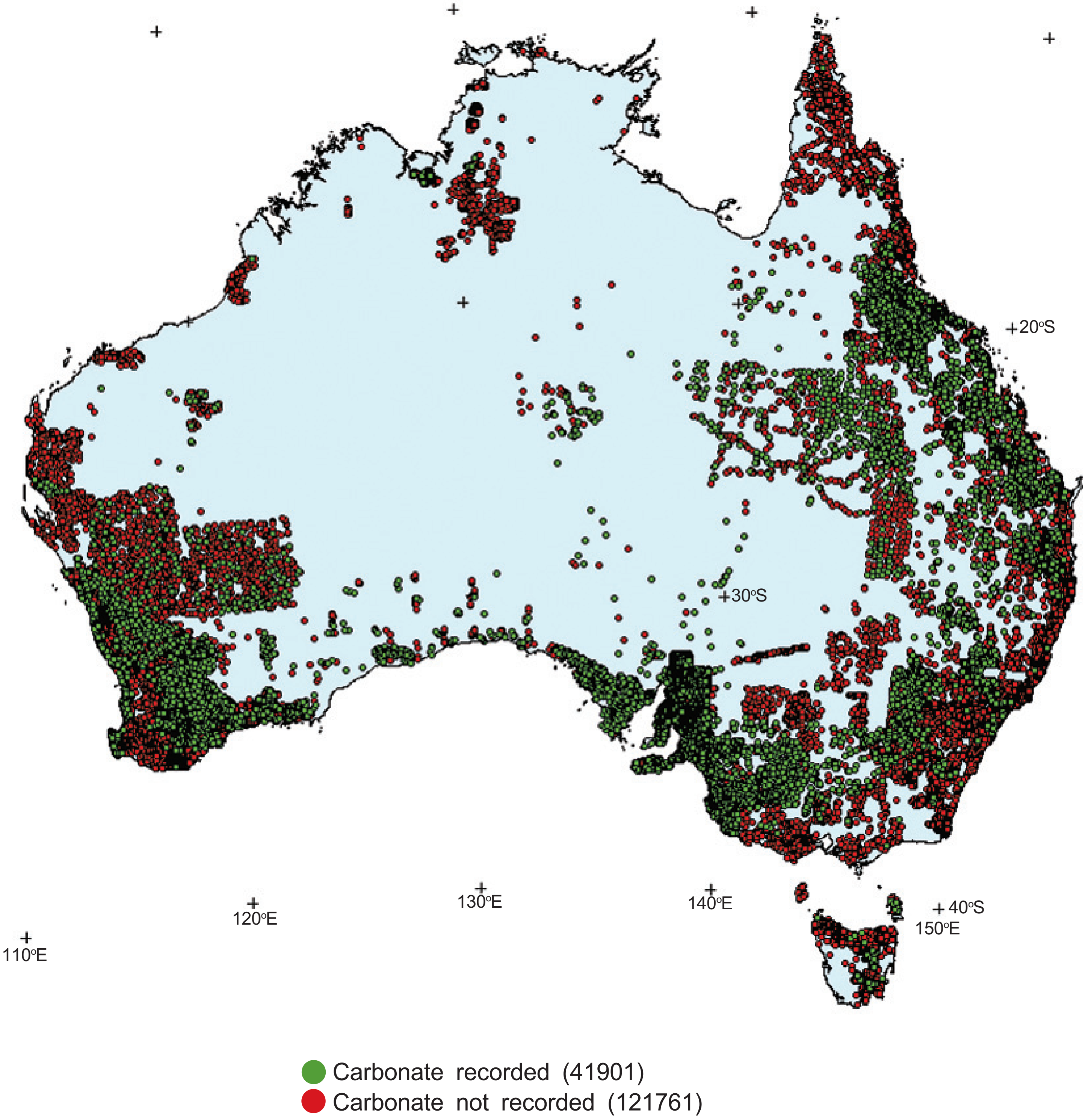
Figure 7.2.28.
A quarry exposure in the Nullarbor Plain, showing the flat surface, fractured Nullarbor Limestone covered by a thin soil layer.
(Photograph: Mel Lintern)

Figure 7.2.29.
Detailed view of the exposure shown by Figure 7.2.28, showing fractured limestone, and abundant limestone fragments in the thin soil layer. There are also regolith carbonate nodules within the soil.
(Photograph: Mel Lintern)



A	Recent digital mapping at scales greater than 1:250,000 (e.g. 1:100,000, 1:50,00, 1:25,000) by search organizations or state-based
A + D	Geological and soil surveys
B	Digital geological mapping at 1:250,000 scale by Commonwealth research organizations or state-based geological surveys
B + D	
C	Digital soil landscape and/or land systems mapping at 1:250,000 scale by state-based soil surveys
C + D	
D	Hand-drawn facsimiles of 1:250,000 scale mapping by research organizations or state-based geological surveys
E	Digital soil mapping at 1:2 million scale after Northcote et al. (1975)

Figure 7.1.1. Reliability diagram showing different types of data used for compiling the maps of Australian calcrete and regolith carbonates (Figures. 7.1.2, 7.1.4 and 7.2.1).



Simple Conic projection with standard parallels at 18°S and 36°S

Figure 7.1.3. Points (a total of 166,171) showing the presence or absence of regolith carbonates in soil profiles. The data come from the Australian Soil Resource Information System. For more explanation see the text.