Department of Applied Geology

The Role of Biological and Non-biological Factors in the Formation of Gold Anomalies in Calcrete.

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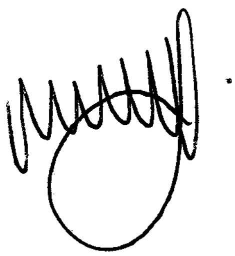
Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made. This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.



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Date……8th December 2011…………………………………………….

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I express gratitude to my co-authors of my submitted papers for their expertise in areas for which I have limited knowledge

Finally I would like to thank my CSIRO colleagues and others, too numerous to mention, who have helped me along the way with their support and expertise.

I would like to dedicate this thesis to my children in the hope that they pursue their thirst for knowledge to make the world a better place - no matter how old they may be.

ABSTRACT

Calcrete has been shown to contain significant Au, derived from nearby mineralisation, and this has led to its current use as an exploration sampling medium. Calcretes are secondary carbonates, principally consisting of calcite and dolomite that may precipitate in regolith in a semi-arid climate. They overprint existing regolith material and commonly contain this material (e.g. soil, colluvium, laterite, saprolite and rock) on, and within, which they form. Vadose (pedogenic) and phreatic (formed by groundwater) are the two principal types of calcrete. Pedogenic calcretes are those that form in unsaturated soil horizons and are widely distributed in southern Australia and in all continents of the world. They may dissolve and re-precipitate within soil horizons, giving rise to several generations of carbonates, depending on changing climate conditions. This thesis will be restricted to pedogenic calcretes.

Despite the common use of pedogenic calcrete as a sampling medium there is a paucity of published research on how Au anomalies actually form in this material. Thus fundamental research is required to be undertaken on the nature of the Au-in-calcrete association, which will promote better understanding of how, when and where calcrete sampling is applicable for the exploration industry. In order to investigate the relationship between Au and calcrete several Au prospects from South Australia were selected for field and laboratory study, including Challenger, Barns, and Edoldeh Tank. Additional samples were investigated from the Bounty Deposit (Western Australia) where Au concentrations in calcrete are an order of magnitude higher than the South Australian counterparts.

At Challenger, the origin of the calcrete that is associated with Au was investigated. Pre-Cambrian rocks, such as the Archaean at Challenger, have very high 87Sr/86Sr ratios compared to rocks that have only recently been formed such as those derived from marine sources. Strontium isotopes were determined at Challenger and demonstrated to be derived from a marine source rather than the bedrock, despite the association of Sr (and, by inference, Ca) with Au. It was concluded that pedogenic processes (e.g. capillarity, bioturbation, evapotranspiration) caused exotic alkaline earth metals to become associated with residual Au. At Challenger, more than 95% of the Sr (Ca) was derived from marine sources (dust, rainfall and/or aerosol). The relationship between marine-

derived calcrete and Au has never been established for auriferous calcrete before and is significant since it suggests that the origin of the alkaline earth metals (Sr and Ca) is not important for its association with Au; Au is clearly originally derived from the regolith underlying the calcrete. Furthermore, a strong correlation with distance from the coast showed that the nearer to the ocean then the greater the contribution of marine Sr (low 87Sr/86Sr ratio) occurs. In a companion study, stable C isotopes were examined from the same auriferous calcrete samples and it was demonstrated, for the first time, that both C3 and C4 plants (trees and grasses) were equally dominant contributors to the inorganic C in the calcrete. Thus, the calcite in the soil (Ca and carbonate ion) is derived principally from marine and plant sources.

At Barns, disseminated Au mineralisation has created a contiguous Au-in-calcrete anomaly developed immediately above and within the saprolite. However, linear (seif) sand dunes have buried the anomaly in places. A biogeochemical survey was undertaken along and across the sand dunes over mineralisation at Barns to examine the role of vegetation in creating the Au-in-calcrete anomaly. A clear biogeochemical anomaly was identified in plant foliage, bark and litter demonstrating that Au was being taken up by roots that were tapping into buried calcrete, or mineralisation beneath it, in some cases, at least 8 m below the surface, and then depositing the Au at the surface on top of the dune. Having demonstrated the uptake of Au by plants, a dune was excavated and powdery calcrete developed in a rhizosphere within the dune was investigated. Significantly, the calcrete was shown to be highly anomalous in Au (five times above background) and thus, for the first time, it was shown that plants have had a key role in the development of a Au-in-calcrete anomaly, and, importantly, in transported regolith. Furthermore, thermoluminescence of quartz grains was commissioned and shown that the emplacement of sand above the calcrete was about 26 000 years old, indicating that the anomaly was younger than this. Mass balance calculations were performed and showed that the Au in the sand dune may have accumulated in less than 10 000 years; calcrete around the root has developed during the life of the tree. Clearly, Au-in-calcrete anomalies can form relatively rapidly compared with the age of sediments themselves.

As Au concentrations were generally low (<20 ppb) at Barns, the nature of the Au-in-calcrete was investigated in samples from Bounty where concentrations reach 1 ppm. Having established a causal relationship between Au-in-calcrete and vegetation at Barns, direct evidence of the role of plants at the micron scale was sought. Samples were chosen from a soil profile that showed a strong positive correlation between Au and Ca and thus a minimal effect of detrital Au. Using LA-ICP-MS, SXRF (synchrotron X-ray fluorescence) and XANES (micro-X-ray absorption near-edge structure), it was shown for the first time that (i) the distribution of Au-in-calcrete at the micron scale was variable and (ii) Au occurs in both particulate and ionic form. Furthermore, ionic Au associated with Br was found in a root tubule. These observations are evidence of an evapotranspiration model for the formation of the strong, down-profile relationship between Au and calcrete i.e. Au has been mobilised then precipitated with the carbonate as vadose water has been removed from the soil by vegetation. Bromine is a typical element (with chloride and sulphate) found in evaporates. There is no chemical affinity between Au and Ca in the soil profile since further detailed analyses on sub-samples using wet chemical, LA-ICP-MS (laser ablation inductively coupled mass spectrometry) and SXRF techniques show that a Au-Ca relationship is not apparent at the sub-millimetre scale. Gold and Ca are behaving similarly but independently and they do not (at the µm scale) form a chemical bond with carbonate minerals.

At Edoldeh Tank (ET) Au prospect the distribution of Au on a tenement-scale was investigated. It was shown that geomorphological factors influence the shape and tenor of Au-in-calcrete anomalies. By their very nature Au-in-calcrete anomalies are dispersed over a wide area (to make them an effective sample medium) and this study served to document the factors involved. The ET prospect (Gawler Craton, South Australia) hosts one of the largest Au-in-calcrete anomalies in Australia and is typical of many such prospects identified in the region. For *in situ* regolith, Au is concentrated in surficial calcrete and above an upper saprolite zone depleted in Au. The Au anomaly extends downslope from a ridge of calcrete and silcrete covered saprolite into adjacent and transported regolith dominated by thin (~5 m) aeolian sand cover. The anomaly is locally broadened by downslope hydromorphic dispersion and cemented within laminated calcrete in the transported regolith. The laminated calcrete was examined in detail and the nature of the Au was found to be similar to that found at Bounty i.e. the Au in the calcrete occurs in nano-scale particulate and possibly ionic forms. In field experimental studies indicate that Au and also Ag are actively dispersing in the soil. The Ag content may be a means of distinguishing transported anomalies from those developed *in situ* and the calcrete is much older (120 000 years) than that found at Barns.

The combined individual site studies at Challenger, Barns, ET and samples from Bounty advance our understanding of the formation of Au-in-calcrete anomalies. The work has shown that an association between Au and calcrete can form at the sub-micron (ionic) to profile scale from both abiotic (geomorphology, climate, mineralisation style) and biotic (vegetation) factors; abiotic factors can shape the overall form, tenor and evolution of the Au-in-calcrete anomaly. No direct evidence was found of the role that micro-organisms play in the formation of Au-in-calcrete anomalies although experimental results from elsewhere suggest that this may be plausible, at least, in the laboratory. Further work on the role of bacteria on the formation of Au-in-calcrete anomalies in the natural environment should be encouraged. The size and shape of Au-in-calcrete anomalies may be influenced by mineralisation style, hydrology and topography and while these were briefly investigated further work is needed.

TABLE OF CONTENTS

CHAPTER 1

INTRODUCTION

1 Preamble

An association of Au with calcrete or soil carbonate has been known about for over a half of century but has only been documented in detail and exploited by industry since the late 1980's. The initial discovery and documentation of the strong Au-in-calcrete relationship was from the Bounty Gold Deposit (Western Australia) in 1987 (Lintern, 1989). Calcrete is an easily identifiable and common soil material found in arid to semi-arid parts of the world, including southern Australia (Goudie, 1972). Gold accumulates in calcrete and particularly in areas closer to mineralisation (Lintern and Butt, 1993a). Thus, the association is of great economic importance since its use as a geochemical sample medium will assist exploring for buried Au deposits. Many Au prospects have been discovered over the last two decades using calcrete (e.g. Drown, 2003) with some being developed into mines (Edgecombe, 1997) and this success continues. Despite the discovery of the Au-calcrete association, and clear financial incentive, detailed knowledge on the process and factors involved has remained limited. A better understanding of biotic and non-biotic factors that influence the way Au anomalies form in calcrete may improve our understanding of the process, improve mineral exploration techniques and reduce exploration costs. In order to study Au-in-calcrete anomalies an appreciation of calcrete itself is required; this includes its nomenclature, classification, distribution and origins.

2 Nomenclature of calcrete

There are a number of terms that describe the carbonate-rich material that occurs in the regolith and include calcrete, pedogenic carbonate, regolith carbonate accumulations, soil carbonate, soil lime, and soil inorganic carbon. Common alternative terms for calcrete include caliche (N. America), kunkar (India), croute (costra, carapace,) calcaire (France); other terms are akkyrshi, bhata, chamara gota, cornstone, calcin, canto (tosca) blanco, chebi-chebi, dhandla, deckkalk, gitti, harsua, kafkalla, kalk kruste, mbuga limestone, nari, paree, rimrock, reh, sabath, torba beda, tafezza, trab, trfkert, tepetate and vlei limestone (Blake, 1902; Goudie, 1972; Lamplugh, 1902; Roy, 2009). The multitude of local names for calcrete reflects its importance to local communities where it has found important use principally as a building and road making material.

"Calcrete" is essentially a field term that commonly occurs in the literature. The term "calcrete" has been used by mineral exploration companies and others since its brevity and historical use gives it advantages over terms such as "pedogenic carbonate", "regolith carbonate accumulations" and "soil carbonate"; for similar reasons the term "caliche" is used in North America. One of the disadvantages of using the term "calcrete" is that it has connotations of being indurated as with the term "concrete" and this has led to some confusion as to its identification in the field.

The term calcrete was first suggested by Lamplugh, (1902) for a conglomerate (near Dublin, Ireland) consisting of surficial sand and gravel cemented into a hard mass by calcium carbonate precipitated from solution and redeposited through the agency of infiltrating waters, or deposited by the escape of carbon dioxide from vadose water. "Caliche" was introduced into the literature about the same time and refers to a calcareous pedogenic horizon(s) (Blake, 1902). A modern definition of calcrete describes "regolith carbonate accumulations, forming more or less well cemented aggregates composed largely of calcium carbonate, but not excluding dolomitic or magnesitic material" (Eggleton, 2001). It includes massive, pisolitic, pebbly, laminar (slabby) or powdery forms that respond positively to the 0.1M HCl test by producing CO_2 gas. This modified definition is more appropriate for this thesis and thus will be used to describe these accumulations of calcite, dolomite or other carbonates in soil.

Groundwater (valley or phreatic) calcrete or those formed on marine limestone rocks have formed in a different way and will not be discussed in this thesis. Groundwater calcretes are precipitated from groundwater and typically form in the axis of dry river valleys. They can be many tens of kilometres in length and are important for U mineralisation (Carlisle, 1980; Deutscher et al., 1980). Gold occurrences have been reported in groundwater calcretes from Western Australia (Ypma, 1991). Calcrete is also distinct from limestone rock which is a sedimentary unit derived from marine deposition and commonly contains marine shells. However, calcrete may develop on the surface of limestone and/or be derived from it. Thus any distinction between limestone rock and calcrete which has been pedogenically derived from it at the surface is imprecise. Much of South Australia is covered in calcrete which has some constituents that were probably originally derived from aeolian products of weathering limestone rocks of the Nullarbor Plain (Crocker, 1946). Even inland calcrete may contain identifiable casts of marine organisms of apparent aeolian origin (e.g. foraminifera tests, Sheard, 2007).

3 Calcrete classification

Many attempts have been made to classify calcrete types (e.g. Goudie, 1983; Netterberg, 1980; Carlisle, 1980; Van Zuidam, 1976). The classification systems are based on colour, texture, carbonate crystallinity, gross morphology, hardness, hydraulic setting, degree of maturity, mineralogy, geochemical composition, biogenic features, genesis or other systems. The most common and practical systems are based on morphology; these facilitate field descriptions and avoids the problem of genesis (Chen, 2002). It has been proposed that different calcrete forms dominate different landscapes within Australia (Anand et al; 1997; Chen et al., 2002). In this thesis, it was convenient to lend terms from the classification system of Netterberg (1980) including powdery, nodular, pisolitic, tubular, hardpan (including laminated calcrete), and boulders or cobbles (massive calcrete).

4 Carbonate distribution

Calcretes are found throughout the world and in particular western USA, southern South America, southern and northern Africa, the Middle East , southern and eastern Europe, central Asia and Australia (Figure 1).

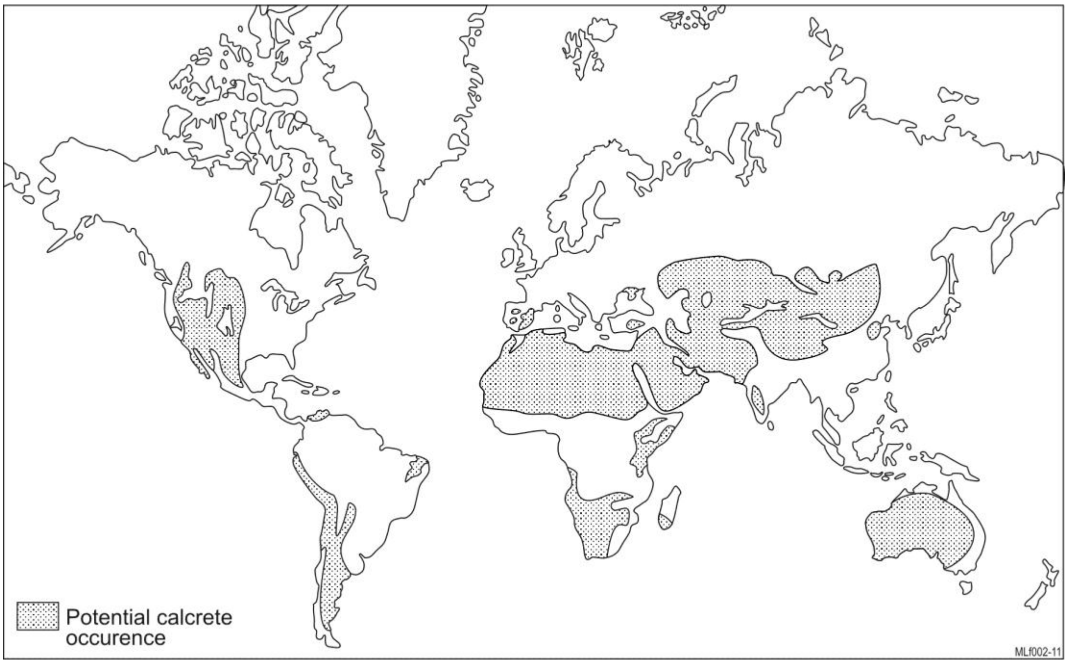


Figure 1: Distribution of probable calcrete occurrence. Derived from soil inorganic C (>8 kg m^{-2} to 1 m depth) map (modified from Lintern, 2002; data from FAO-UNESCO, 2000).

In Australia, the distribution of calcretes has been variably documented (e.g. Northcote et al., 1975; reviewed by Chen et al., 2002). In Western Australia, the Menzies Line is an important environmental and geological diffuse boundary relating to the distribution of calcrete and hence exploration techniques in the Yilgarn Craton. It is a broad (up to 100 km wide) 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; Mahizhnan, 2004). The changes are possibly a response to climatic factors, although the sharpness with which the changes occur is more abrupt than any climatic gradient (Butt et al., 1977; Carlisle et al., 1978). 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. 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 the axes of major drainages. Groundwaters are neutral to alkaline and less saline than in the south. 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.

5 The origin of calcrete

Calcretes have been described from around the world but few specifically from near or over Au deposits. Calcrete forms, and is retained, in soils that have specific environmental conditions (e.g., Lintern, 1997; Anand and Paine, 2002; Figure 2). The formation process is highly complex and involves interaction of a number of site-specific factors at a variety of scales. For example, calcrete type in a particular soil profile may be dependant on substrate (soil type; Northcote et al., 1975), rainfall (frequency, timing and volume; Jenny, 1941), evapotranspiration rates, proximity to Ca source (marine or local bedrock; Anand et al., 1997), geomorphology (Semmel, 1982) and aspect. Progressively, calcrete will replace (Nahon et al., 1977, Wang et al., 1994) and displace host materials (Watts, 1978) until the original regolith host or even bedrock becomes barely unrecognisable. Calcretes may form as a result of biological activity (e.g. Semeniuk and Searle, 1985; Philips et al., 1987; Wright et al., 1988; Alonso-Zarza, 1999; Goudie, 1996; Anand et al., 1997; Loisy et al., 1999; Zhou and Chafetz, 2009). Calcretes may be dismantled by erosion, bioturbidity and local hydrological processes (Arakel, 1991).

Gold bearing calcrete needs to be characterised with the same rigour as that applied to calcrete that is not associated with Au. In addition, other factors may need to be investigated including mineralisation-style (Au particle size, Au chemistry, lithology), regolith (degree of weathering, presence of secondary cementation, landforms) and biota (vegetation, micro-organisms, bioturbation).

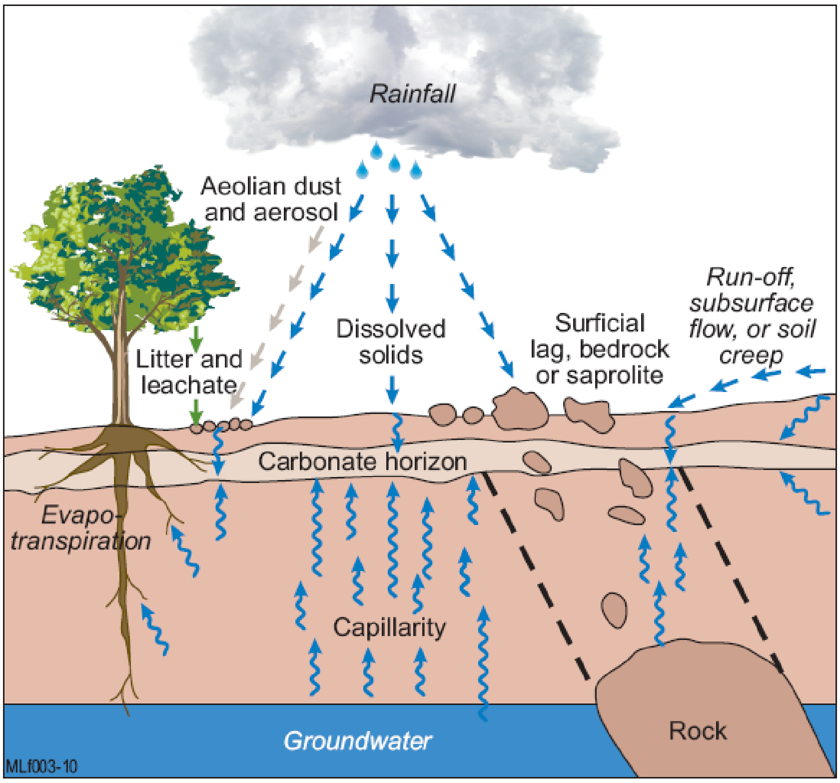


Figure 2: Schematic diagram showing possible sources of calcium in pedogenic carbonate (calcrete) horizon (Lintern, 1997).

6 Mineral exploration case histories

A historically-based literature review of the use of calcrete in mineral exploration (with an emphasis on Au) was undertaken; this comprised a chapter in a book (Lintern, 2002). In addition, literature reviews were conducted for each of the five published papers for this thesis. A brief summary of the book review follows. Calcrete sampling has had a relatively recent history as far as mineral exploration is concerned. According to McGillis (1967), the use of calcrete as a geochemical guide to metal deposits began in Russia during the late 1950s, although this did not include Au deposits. Its potential may have been recognised earlier by Cuyler (1930) who suggested Ca-rich waters, rising under hydrostatic pressure, deposit calcrete in faulted areas, which are commonly associated with mineral deposits. Outside of Russia, the value of calcrete as a specific geochemical sampling medium was not fully recognised until the early 1970s, although early reference to a possible HCl soluble Au component in calcrete was made by Sokoloff (1949). One of the first records of calcrete as a geochemical sampling medium appears to have been in the Yilgarn Craton, 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 (Western Australia). Other mainly base metal studies in South Africa and Australia followed during the next decade (e.g. Mazzucchelli et al., 1980; Frick, 1985; Leduc, 1986; Guedria et al., 1989; Tordiffe et al., 1989; Harrison, 1990). The general Au-calcrete association has been recorded in several anecdotal accounts (e.g., Kriewaldt, 1969; K. Schulz, pers. comm. to C.R.M. Butt, 1985) and in the scientific literature (e.g., Smith and Keele, 1984; Mann, 1984a, b; Smith, 1987; Lawrance, 1988a; Glasson et al., 1988); however, it appears that some of these accounts may be referring to fortuitous detrital Au particles encapsulation in calcrete directly, or associated, for example, with ferruginous pisoliths (laterite), rather than a true correlation. Despite these studies, exploration companies have never systematically used calcrete as the sample medium of choice during these early years and it was never considered for Au exploration.

Calcrete became a specific sample medium during Au exploration in Australia from the late 1980s until the present as a result of CSIRO (Commonwealth Scientific and Industrial Research Organisation) and later CRC LEME research (Cooperative Research Centre for Landscape Evolution and Mineral Exploration). 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 and geochemical 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 south of Southern Cross, Western Australia) with spectacular results (Lintern, 1989; Lintern et al., 1992; Lintern and Butt, 1993a). For the first time a precious (apparently inert) metal was demonstrated to be highly correlated (not merely associated) with Ca (calcrete), a mobile element in the soil; this was strong evidence for the soluble and mobile nature of Au in the soil. The results also 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 (Lintern and Butt, 1993a). The correlation was widespread at the Bounty Deposit in soils typical of those found throughout the auriferous greenstones of the Eastern Goldfields of Western Australia. Thus, there was a great potential for the widespread use of calcareous soil (calcrete) for exploration purposes. Further research confirmed the relationship to be robust throughout the southern Yilgarn Craton and indicated that calcrete was a geochemical sample medium that could be used with confidence, pending certain important provisos (Lintern et al., 1996, 1997).

Calcrete sampling reached a significant milestone as an exploration technique when its use was publicly acknowledged to have located 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 in the Gawler Craton, calcrete was highlighted and recommended by many as the principal sampling technique to be used (e.g. Bonwick, 1997; Edgecombe, 1997). The success of calcrete sampling in SA subsequently spread into NSW (Smith et al., 1996; Hill et al., 1998; McQueen, 2006) and Victoria (Anon, 1998).

By the end of the 1990s, calcrete was being acclaimed as the sampling medium of choice back in the Yilgarn Craton by a much wider audience of exploration companies than the early 1990s, many of whom were not familiar with the earlier Western Australian research, but had been swayed by the successes in SA (e.g. Rubicon, Hornet and Pegasus discoveries, Boyer and Grivas, 1999; Golden Cities discovery, Kehal et al., 1999; Ghost Crab discovery, Miller et al., 1999). Clearly the technique has taken several years to filter through to the junior explorers, despite the new discoveries being located in the Yilgarn where it was first recognised. As with many other geochemical sampling media, such as soil, lateritic residuum, 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 is used in many other parts of the world for mineral exploration including the Americas (S. Gatehouse, pers. comm; L. Bettenay, pers. comm.; Anon, 1998), southern and northern Africa, (Frick, 1985; Leduc, 1986; Guedria et al., 1989; Tordiffe et al., 1989), and parts of the former USSR. Recently, calcretes were used in the exploration for kimberlites (Roy, 2009).

7 Objectives of research

The principal research question to be answered here is *what are the factors involved in Au-in-calcrete anomaly formation*? This may involve a number of subsidiary questions including some that may be beyond the scope of this thesis:

- Where is the Au located in the calcrete?
- Are there any mineralogical associations of Au-in-calcrete?
- Under what conditions will Au be precipitated in/on and mobilised from calcrete?
- Do biologically-generated ligands mobilise Au in calcareous soils or is it a purely inorganic process?
- How long does it take to form Au-in-calcrete soil anomalies?
- What is the principal mechanism by which Au-in-calcrete anomalies form?
- Do the mechanisms of Au-in-calcrete formation differ depending on site conditions?

Thus, the principal objective of this research is to better understand the formation of Au-in-calcrete anomalies in the regolith and, based on this, develop more effective procedures for their use in mineral deposit detection. Specific objectives to answer some of the research questions include:

- Determining the geochronology of selected Au-in-calcrete anomalies.
- Determining the origin of Au-bearing calcrete.
- Establishing the nature of Au contained within the calcrete.
- Characterising calcareous soil profiles that contain Au.
- Determining controls on the formation and evolution of Au-in-calcrete anomalies.

Research on Au-in-calcrete to date has largely been involved with documentation of the phenomenon and determining its spatial extent for exploration purposes. The main problem is that few process studies have been undertaken and so little is known about the detailed nature of Au-in-calcrete and how the Au actually resides in the calcrete.

8 Research Design

The research design for this thesis followed the plan as set out in the candidacy. The plan was to review gold in calcrete occurrences, then investigate the fundamental question of whether calcretes associated with gold deposits e.g. at Challenger were essentially any different from other calcretes. This completed the plan was then to examine broad scale influences on the distribution of gold in calcrete e.g. at ET before investigating specifically the compelling control that vegetation has on gold in calcrete at the soil profile level. Following this, detailed examination of samples to look at possible biological influences was undertaken. The research flow did not necessarily occur in that precise order as avenues of research opened at specific sites as the study evolved.

The research was conducted at four principal sites in Australia (Figure 3), three in South Australia and one in Western Australia. All sites contained calcrete but varied in other site characteristics such as style and extent of mineralisation, regolith thickness and type, vegetation, climate and groundwater (Table 1).

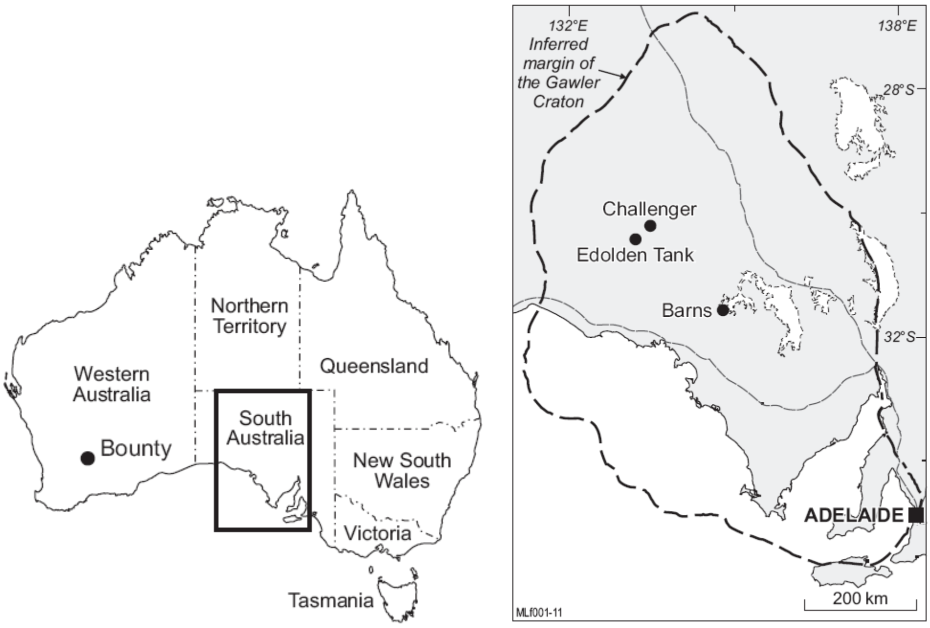


Figure 3: Diagram showing locations of main study sites where research was conducted for this thesis.

Table 1: Characteristics of the principal sites accessed in this study.

Characteristics	Challenger/ Gawler Craton	Edoldeh Tank	Barns	Bounty
Thickness of regolith	> 50 m	> 50 m	> 50 m	> 50 m
Thickness of transported cover	1 m	5 m	8 m	2 m
Depth to mineralisation	3 m	30 m	30 m	5 m
Vegetation	Bluebush Senna	Acacia Eucalyptus Casuarina	Eucalyptus	Eucalyptus

Soil type	Red-brown hardpan	Sandy clay	Sand	Heavy clay
Rainfall				
Groundwater depth	Not found	50 m	35 m	Not found

The investigations were multi-disciplinary and required specialist assistance from some other researchers e.g. synchrotron analyses. Gold anomalies were selected and mapped according to site characteristics. Calcrete anomalies were studied with possible mitigating factors including calcrete type, environmental factors and the mineralisation-style they are derived from. Soil profiles and soil samples were studied in detail to identify their chemical, mineralogical and biological characteristics using the following techniques: laser ablation inductively coupled mass spectroscopy (LA-ICPMS), ICPMS, ICP optical emission spectroscopy (ICPOES), X-ray diffraction (XRD), synchrotron X-ray fluorescence (SXRF) and ion microprobe. Samples were collected to conduct laboratory tests on solubility and nature of Au complexes in soil. The role of biota in Au anomaly formation was critically examined. The age of Au-in-calcrete anomalies was also determined to get a better understanding on how quickly they may form. The work conducted at each principal site is summarised in Table 2.

Table 2: Studies conducted at the four principal research sites.

Study conducted	Challenger/ Gawler Craton	Edoldeh Tank	Barns	Bounty
Regolith characterisation	yes	yes	yes	yes
SEM	yes	yes	no	yes
Synchrotron	no	yes	no	yes
Laser ablation ICPMS	no	yes	yes	yes
Isotopes (Sr and C)	yes	yes	yes	no
Thermoluminescence dating	no	yes	yes	no
Biogeochemistry	yes	yes	yes	yes
Microbiology	no	yes	no	yes

This research contributes towards answering some of the many questions that remain for understanding this important phenomenon and will ultimately assist Au exploration companies in their quest for the discovery of new ore deposits.

9 Organisation of thesis

This thesis is comprised of eight chapters. Chapter 1 (this chapter) is an introduction and includes an explanatory overview of the work, significant findings of the thesis, describes how the research papers are linked, identifies the limitations of the research and highlights future directions. A brief literature survey is described which is an extract from the full literature survey which was published as a book chapter and is reproduced in Appendix 1 (Lintern 2002). Chapter 2 to 6 are Microsoft Word™ versions of papers that have been published as pdf documents in international journals (Table 3).

Chapter 2 describes the source of the carbonate and alkaline earth metals contained within pedogenic carbonate containing Au athe Challenger Gold Deposit. It also demonsrates the strong marine influence on pedogenic carbonates in an east-west transect to the east of the Nullarbor Plain.

Chapter 3 details the preliminary study at Edoldeh Tank gold anomaly in the Western Gawler Craton. The influence of geomorphology in shaping geochemical anomalies is shown.

Chapter 4 is concerned with experimental work at part of the Edoldeh Tank gold anomaly and shows that Au is being mobilised as an ionic species in the soil.

Chapter 5 clearly shows that vegetation is playinga strong role in the formation of gold in calcrete anomalies at Barns gold prospect.

Chapter 6 details laboratory analyses of calcrete and shows a the micron scale how biota are playing a role in anomaly formation in the rhizosphere and that Au occurs partly in an iolnic form and realted to evaporation.

Chapter 7 discusses the findings from the thesis and shows how the studies from the different sites are linked and show that both biotic and abiotic factors are involved in Au-in-calcrete formation.

Chapter 8 concludes the thesis.

Table 3: The published and accepted papers written for this thesis.

Title of paper or book chapter	**Authorship**	**Publication details**	**Journal reviewers**	**Chapter in thesis**
Calcrete sampling for mineral exploration	M.J. Lintern	In Calcrete: characteristics, distribution and use in mineral exploration (eds. X.Y. Chen, M.J. Lintern and I.C. Roach). CRC LEME, Perth, Australia, 31-109. (2002)	M. Skwarnecki. M. Cornelius C. Butt R. Anand	Summary in 1
The source of pedogenic carbonate associated with Au-calcrete anomalies in the western Gawler Craton, South Australia	M.J. Lintern M.J. Sheard A.R. Chivas	Chemical Geology 235 (2006): 299–324	D. Rickard Anonymous reviewers	2
The gold-in-calcrete anomaly at the ET gold prospect, Gawler Craton, South Australia	M.J. Lintern M.J. Sheard N.B. Buller	Applied Geochemistry 26 (2011): 2027-2043	D. Arne M. Arundell Anonymous reviewers	3
Experimental studies on the gold-in-calcrete anomaly at Edoldeh Tank gold prospect, Gawler Craton, South Australia	M.J. Lintern R.M. Hough C.G. Ryan	Journal of Geochemical Exploration 112 (2012) 189–205	R. Koole A. Schmidt-Mumm B. Smee Anonymous reviewers	4
Vegetation controls on the formation of Au anomalies in calcrete and other materials at the Barns Gold Prospect, Eyre Peninsula, South Australia	M.J. Lintern	Geochemistry: Exploration, Environment, Analysis, 7 (2007): 249–266	G.E.M. Hall C.E. Dunn Cliff Stanley	5
Ionic Au-in-calcrete revealed by LA-ICP-MS, SXRF and XANES	M.J. Lintern R.M. Hough C.G. Ryan J. Watling M. Verrall	Geochimica et Cosmochimica Acta 73 (2009): 1666-1683	J. Chorover Anonymous reviewers	6

10 Co-authorship of papers

The paper entitled “The source of pedogenic carbonate associated with Au-calcrete anomalies in the western Gawler Craton, South Australia” included the work of two co-authors whose contributions are outlined below.

Melvyn Lintern

Responsible for the collection of samples. Overall writing and compilation of the manuscript, including both scientific and grammatical editing. Responsible for the overall generation and interpretation of scientific data including that from Challenger, the east west transect and other areas from the western Gawler Craton. Responsible for the generation of Figures 1-3, 5-15.

Malcolm Sheard

Assistance with choice of sample collection sites. Largely responsible for descriptions under “Calcrete” in “Study locations” and for descriptions in Table 1. Scientific and grammatical editing. Responsible for the generation of Figure 4.

Allan Chivas

Scientific and grammatical editing. Responsible for most of the isotopic analyses.

Signed:

Melvyn Lintern

Malcolm Sheard

Allan Chivas

The paper entitled "Ionic Au-in-calcrete revealed by LA-ICP-MS and synchrotron radiation" included the work of four co-authors whose contributions are outlined below.

<u>Melvyn Lintern</u>
Responsible for the initiation of ideas for experiment and collection of samples. Responsible for the overall conducting of scientific experiments. Overall writing and compilation of the manuscript, interpretation of processed data, and scientific and grammatical editing. Responsible for the overall generation of scientific data.

<u>Rob Hough</u>
Assisted with operation of synchrotron experiments and production of XANES spectra from the synchrotron. Writing of some of the synchrotron methods section Some grammatical editing.

<u>Chris Ryan</u>
Responsible for the operation of the synchrotron, processing of raw data and generation of GeoPIXE geochemical maps. Writing of some of the synchrotron methods section. Some scientific editing.

<u>John Watling</u>
Assisted with initial discussions of LA-ICP-MS experimental design. Some grammatical editing.

<u>Michael Verral</u>
Assisted with operation of SEM, elemental analyses using EDAX and production of SEM images. Some grammatical editing.

Signed:

Melvyn Lintern

Rob Hough

Chris Ryan

John Watling

Michael Verrall

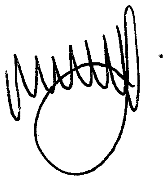
The paper entitled "The gold-in-calcrete anomaly at the ET gold prospect, Gawler Craton, South Australia." included the work of two co-authors whose contributions are outlined below.

Melvyn Lintern
Responsible for the initiation of the work. Responsible for the collection of samples. Overall writing and compilation of the manuscript, including both scientific and grammatical editing. Responsible for the overall generation and interpretation of scientific data. Responsible for the generation of all figures.

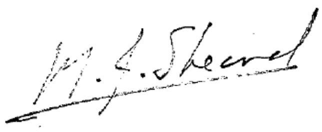
Malcolm Sheard
Largely responsible for descriptions under "Calcrete" in "Study locations" and for descriptions in Table 1. Minor scientific and grammatical editing.

Nicola Buller
Assisted with microbiological methodology. Minor scientific editing.

Signed:



Melvyn Lintern



Malcolm Sheard

Nicola Buller

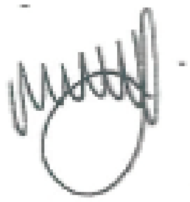
The paper entitled "Experimental studies on the gold-in-calcrete anomaly at Edoldeh Tank gold prospect, Gawler Craton, South Australia" included the work of two co-authors whose contributions are outlined below.

<u>Melvyn Lintern</u>
Responsible for the initiation of the work. Responsible for the collection of samples. Overall writing and compilation of the manuscript, including both scientific and grammatical editing. Responsible for the overall generation and interpretation of scientific data. Responsible for the generation of all figures.

<u>Rob Hough</u>
Assisted with operation of synchrotron experiments. Generation of distribution images of using GeoPixe for Figure 16 (Lintern et al., in press).

<u>Chris Ryan</u>
Responsible for the operation of the synchrotron and collection of raw data. Minor editing in Synchrotron methods section.

Signed:



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CHAPTER 2

THE SOURCE OF PEDOGENIC CARBONATE ASSOCIATED WITH GOLD-CALCRETE ANOMALIES IN THE WESTERN GAWLER CRATON, SOUTH AUSTRALIA

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ABSTRACT

Elevated Au concentrations above bedrock mineralisation are commonly closely associated with calcrete in arid residual and semi-residual soils in Australia. The origin of Australian calcrete has been argued for many years but there have been very few published studies. Calcrete from Au deposits and prospects and elsewhere in the Gawler Craton (South Australia) were studied for their geochemical composition, and Sr and C isotope ratios. By comparing carbonate $^{87}Sr/^{86}Sr$ ratios with underlying weathered rock and bedrock, it is demonstrated that many samples have overwhelmingly atmospheric Sr (>94%) and, by inference, Ca (>98%) rather than a local bedrock or soil mineral origin. The isotopic composition of calcretes at the Challenger Gold Deposit lie on a mixing trend of decreasingly marine Sr from the Nullarbor Plain to Tarcoola, 300 km to the east. The $\delta^{13}C_{PDB}$ values (−7.5‰ to +0.1‰) suggest that the carbonate C in calcrete has a mixed origin derived from C3 and C4 plants. A model is presented to explain how the Au–Ca association may form in calcrete at Challenger based on these new Sr and C isotope data and in which the role of plants and atmospherically deposited Sr and Ca combine with pre-existing Au in the soil. The implication for mineral exploration is that, since most of the Ca is derived from marine sources, it is not a pre-requisite that autochthonous soil minerals (derived from underlying weathered bedrock) supply Ca for calcrete to form and for the Au–Ca association to occur. Thus, the independence of the Ca

with respect to underlying lithology reaffirms the usefulness of calcrete as a sampling medium for Au exploration

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CHAPTER 3

THE GOLD-IN-CALCRETE ANOMALY AT THE ET GOLD PROSPECT, GAWLER CRATON, SOUTH AUSTRALIA

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ABSTRACT

Much of Australia has an extensive regolith cover that conceals basement rocks and hinders mineral exploration and this situation is particularly acute in the western Gawler Craton (South Australia), where, in addition to fluvial, marine and colluvial sediments, the land surface is extensively cloaked by sand dunes. This study documents the Au distribution at the ET Au prospect (Great Victoria Desert) in the western Gawler Craton (South Australia). Although no economic Au mineralisation has yet been found at ET, the prospect hosts one of the larger Au-in-calcrete anomalies in Australia and is typical of many such prospects identified in the region. In addition to calcrete, the distribution of Au in regolith and biotic sample media was also examined.

The study at ET shows that:

(i) For *in situ* regolith, Au is concentrated in surficial calcrete and above an upper saprolite zone depleted in Au.

(ii) The Au anomaly extends from a ridge of weathered Archaean basement into adjacent and transported regolith dominated by thin (~5 m) aeolian sand cover. The anomaly appears to be locally broadened by lateral dispersion in the transported

overburden, or, possibly, Au additions to the surface from underlying buried mineralisation.

(iii) Calcrete appears to be the most consistent sample medium for Au providing coherent anomalies compared with soil, vegetation, near surface drill cuttings and *Bacillus cereus*.

(iv) Gold appears to be the best target element in upper regolith or calcrete, although As may provide supplementary information on the location of prospective mineralisation.

Calcrete sampling has been a successful exploration technique to reveal cohesive Au anomalies within *in situ* regolith. Where transported regolith dominates and landforms are favourable e.g. sloping, calcrete (containing Au) will disperse (in solution and/or mechanically eroding) and thus provide a spatially larger target area for mineral exploration purposes. However, in these settings, the actual source of mineralisation may be difficult to locate due to various factors related to the dispersion processes and weathering history. At ET, other sampling media such as bacteria (*Bacillus cereus)* and vegetation have a greater uncertainty associated with them and their anomalies are not as cohesive.

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CHAPTER 4

EXPERIMENTAL STUDIES ON THE GOLD-IN-CALCRETE ANOMALY AT EDOLDEH TANK GOLD PROSPECT, GAWLER CRATON, SOUTH AUSTRALIA.

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ABSTRACT

Calcrete sampling is the near-surface exploration method of choice for Au in many drier parts of the world, particularly southern Australia. Edoldeh Tank is a weakly mineralised Au prospect in calcrete terrain that lies at the eastern edge of the Great Victoria Desert dunefield (South Australia). At Edoldeh Tank a variety of calcretes occur but the dominant form is a laminated calcrete horizon (LCH). The mineralogy of the near-surface soil is relatively simple and consists of calcite, dolomite, quartz, kaolinite and minor smectite; quartz dominates the unconsolidated overlying sandy soil, and carbonate minerals dominate the LCH. We determine the distribution and nature of the Au at a small scale using a variety of techniques, including SEM, LAICPMS and SXRF and dated sediments to understand calcrete genesis. In a series of thirty excavated soil pits, Ca and Au concentrations increased with depth, markedly so at the LCH. We provide multiple lines of evidence to show there is a general association of Au with calcrete but not a strong correlation as seen with soil profiles elsewhere that have younger, recently formed powdery calcrete. Experiments suggest Au and Ag are currently mobile in this environment despite the low rainfall and that Au occurs in two forms: Au (possibly ionic) occurs throughout the sample with some regions having higher concentrations than others; particulate Au occurs randomly but is more common where the general level of Au is higher. The laminated nature of the calcrete suggests it has formed episodically.

An association of Ag with Au in calcrete suggests a means to distinguish anomalies that have developed in residual regolith from those that have dispersed into adjacent sediments. Laminated calcrete is just as effective an exploration sample medium as powdery calcrete. Mobilised Ca, Au and Ag in calcrete can extend the lateral extent and distance from the source of the geochemical anomaly thus providing an effective vector to target for sampling. A landscape dispersion model of Au in calcrete is presented, which requires further testing, to assist the mineral explorer in covered terrains.

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CHAPTER 5

VEGETATION CONTROLS ON THE FORMATION OF GOLD ANOMALIES IN CALCRETE AND OTHER MATERIALS AT THE BARNS GOLD PROSPECT, EYRE PENINSULA, SOUTH AUSTRALIA

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ABSTRACT

A biogeochemical study was undertaken at Barns Gold Prospect, a Au-in-calcrete discovery in the northern Eyre Peninsula (South Australia). The prospect is located in highly weathered Proterozoic rocks and is overlain by more than a 1 m of aeolian quartz sand but, significantly, the cover thickens to 8 m over part of the mineralization due to a longitudinal sand dune. The dune is well-vegetated, with *Melaleuca* shrubs and *Eucalyptus* trees up to 5 m high.

Results indicate that anomalous Au occurred over mineralization in plant organs, litter, soils and sand. The highest Au concentrations (9 ppb) occurred in calcareous rhizomorphs high up in the dune. Luminescence dating determined that the dune took no longer than 27000 years to form and mass balance calculations indicate that the Au anomaly in the dune could have taken less than 10000 a to form. Mechanisms for the Au accumulation in the sand are postulated but it appears that a biological process, principally involving vegetation, is the most viable.

A 200 m sample spacing of vegetation appears to be adequate for exploration of this type of deposit. Below the sand, calcrete provides a robust sampling medium. At present, due to limited knowledge of exploration methods in this type of environment, the mineral explorer must either expend significant finacial resourses augering through areas of sand cover to collect the buried calcrete samples, or have lower confidence that vegetation and surficial soil samples will detect mineralization.

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CHAPTER 6

IONIC GOLD IN CALCRETE REVEALED BY LA-ICP-MS, SXRF AND XANES

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ABSTRACT

Highly anomalous Au concentrations in calcrete were discovered in 1987 at the Bounty Gold Deposit, Western Australia. A strong correlation was noted between the Ca, Mg, Sr and Au in soil profiles which has not only attracted the interest of mineral explorers but also chemists, soil scientists, metallurgists and climatologists. Gold has been considered an inert element and so its strong association with the alkaline earth group of relatively mobile elements is both remarkable and intriguing. Despite widespread interest, there have been few published papers on the Au-calcrete phenomenon. Here, we present work conducted on calcareous soil samples from above the Bounty mineralisation in Western Australia, prior to mining.

Using SXRF (synchrotron X-ray fluorescence) and XANES (micro-X-ray absorption near-edge structure), we have shown for the first time the distribution of Au-in-calcrete and that it occurs in both particulate and ionic form. Much of the ionic Au associated with Br is found in a root tubule. The observations are consistent with an evapotranspiration model for the formation of Au in the calcrete; Au has been mobilised then precipitated as vadose water has been removed from the soil by trees and shrubs. While the association between Au and Ca is very strong in bulk sample analyses down the soil profile, other detailed analyses on sub-samples using wet chemical, LA-ICP-MS

(laser ablation inductively coupled mass spectrometry) and SXRF techniques show that it is not apparent at the sub-millimetre scale. This suggests that the Au and Ca are behaving similarly but independently and they do not (at the µm scale) co-precipitate with carbonate minerals.

These results corroborate other studies that suggest biotic influences can affect the mobilisation and distribution of Au in surficial materials. Water-extractable Au-in-calcrete has been reported previously and the ionic Au described in this study likely represents that soluble component. The presence of easily solubilised Au in soils has been widely discussed and exploited for mineral exploration.

CHAPTER 7

GENERAL DISCUSSION

The origin of Australian calcrete has been argued for many years but there have been very few published studies. Since Au is associated with calcrete in arid soils in Australia, it is important to determine whether the Ca, Sr and inorganic C, contained within the carbonate, is derived locally from the surrounding rocks and whether this is an important factor in the formation of Au-in-calcrete anomalies. For example, do anomalies only occur if Ca and Sr are derived from local rocks? Calcrete from Au deposits and prospects and elsewhere in the Gawler Craton (South Australia) were studied for their geochemical composition, and Sr and C isotope ratios (Chapter 2). By comparing carbonate $^{87}Sr/^{86}Sr$ ratios with underlying weathered rock and bedrock, it was demonstrated that most samples are dominated by overwhelmingly atmospheric Sr and, by inference, Ca rather than a local bedrock or soil mineral origin. Furthermore, it was shown that the isotopic composition of calcretes at the Challenger Gold Deposit lie on a mixing trend of decreasingly marine Sr from the Nullarbor Plain to Tarcoola, 300 km to the east. This implies that all calcrete in the Gawler Craton has a substantial input from marine sources. The $\delta 13C_{PDB}$ values (−7.5‰ to +0.1‰) suggest that the soil inorganic carbon in calcrete has a mixed origin derived from C3 and C4 plants. A model is presented to explain how the Au–Ca anomaly may form in calcrete at Challenger based on these new Sr and C isotope data and in which the role of plants (biotic factor) and atmospherically deposited Sr and Ca (abiotic factor) combine with pre-existing Au in the soil (Chapter 2); similar origins for the carbonate were found at Barns (Chapter 5). The implication for mineral exploration is that, since most of the Ca is derived from marine sources, it is not a pre-requisite that autochthonous soil minerals (derived from underlying weathered bedrock) supply Ca for calcrete to form and for the Au–Ca association to occur. Thus, the independence of the Ca with respect to underlying lithology reaffirms the efficacy of calcrete as a sampling medium for Au exploration

A typical Au-in-calcrete anomaly and the Au distribution in other regolith materials and plants at the Edoldeh Tank (ET) prospect in the western Gawler Craton (South Australia) are described in Chapter 3. The ET prospect hosts one of the largest Au-in-calcrete anomalies in Australia and is typical of many such prospects identified in the region, most of which have not been described in the literature. To date, economic mineralisation at

ET has not been found. The distribution of Au in regolith and biotic sample media was also examined to examine their relationship with calcrete.

For the geochemical survey at ET, the principal results indicate that:

(v) For *in situ* regolith, Au is concentrated in surficial calcrete and above an upper saprolite zone depleted in Au.

(vi) The Au anomaly extends from a ridge of weathered Archaean basement into adjacent and transported regolith dominated by thin (~5 m) aeolian sand cover. The anomaly appears to be locally broadened by lateral dispersion in the transported regolith, or, possibly, Au additions to the surface from underlying buried mineralisation.

(vii) Calcrete appears to be the best consistent sample medium for Au providing coherent anomalies compared with soil, vegetation, near surface drill cuttings and *Bacillus cereus*.

(viii) Gold appears to be the best target element, although As may provide supplementary information on the location of prospective mineralisation.

In general, calcrete sampling for Au exploration is a technique that works particularly well at Edoldeh Tank and provides coherent anomalies for in situ regolith. Where transported regolith dominates and landforms are favourable, calcrete (containing Au) will disperse (chemically and mechanically) and thus provide a spatially larger target area for mineral exploration purposes. However, in these settings, the actual source of mineralisation may be difficult to locate due to various factors related to the dispersion processes and weathering history. At ET, other sampling media such as *Bacillus cereus* and vegetation have a greater uncertainty associated with them and their anomalies are not as coherent. There is not a clear relationshipe between Au-in-calcrete and biota anomalies at ET.

The detailed and experimental study at ET (Chapter 3) indicates that a variety of calcretes occur but the dominant form here is a laminated calcrete horizon (LCH). This calcrete form is common throughout the world and is in contrast to the powdery calcrete found at Bounty (Chapter 6) and in the upper part of the sand profile at Barns (Chapter 5). The mineralogy of the soil is relatively simple and consists of calcite, dolomite, quartz, kaolinite and smectite; quartz dominates the unconsolidated overlying sandy soil, and carbonate minerals dominate the LCH.

The distribution and nature of the Au was determined at a large scale at ET using a variety of techniques, including SEM, LAICPMS and SXRF (c.f. Chapter 6) and the dating of sediments, that apprised us with the antiquity of calcrete (c.f. Chapter 5) in this area, was undertaken. In a series of thirty excavated soil pits, Ca and Au concentrations increased with depth, markedly so at the LCH (Chapter 3). There appears to be a general association of Au with calcrete but not a strong correlation as seen with soil profiles elsewhere that have younger, recently formed powdery calcrete. Experiments suggest Au and Ag are currently mobile in this environment despite the low rainfall and that Au occurs in two forms: Au (possibly ionic) occurs throughout the sample with some regions have higher concentrations than others; particulate Au occurs randomly but is more common where the general level of Au is higher. The laminated nature of the calcrete (the LCH) suggests it has formed episodically. The association of Ag with Au-in-calcrete suggests a means to distinguish anomalies that have developed in residual regolith from those that have dispersed into adjacent sediments.

It was concluded that the laminated calcrete at ET is just as effective an exploration sample medium as compared with powdery calcretes found elsewhere (Chapter 6). Mobilised Ca, Au and Ag in calcrete can extend the lateral extent and distance from source of the geochemical anomaly thus providing an effective vector to target for sampling. The Au distribution at this scale is related to geomorphology rather than biological controls (Chapter 5 and 6). A dispersion model of Au-in-calcrete is presented.

Biotic factors that may influence the formation of Au-in-calcrete anomalies (Chapter 5: c.f Chapter 6). Initially, a biogeochemical study was undertaken at the Barns Gold Prospect, a Au-in-calcrete discovery in the Northern Eyre Peninsula (South Australia). The prospect is located in highly weathered Proterozoic rocks and is overlain by at least 1 m of aeolian quartz sand that thickens to 8 m as a longitudinal sand dune over part of the mineralisation. The dune is well-vegetated, with *Melaleuca* shrubs and *Eucalyptus* trees up to 5 m high. The study showed that over mineralisation anomalous Au concentrations occur in plant organs, litter, soils and sand. The highest Au concentrations (9 ppb) in the dune occur in calcareous rhizomorphic calcrete high up within the dune. Luminescence dating shows that the dune took no longer than 27 000 years to form (compared with 120 000 years at ET; Chapter 4) and mass balance calculations indicate that the Au anomaly in the dune has formed in less than 10 000 years. Mechanisms for the Au accumulation in the sand are postulated and it is clear that a biotic process, principally involving vegetation, is the most viable mechanism by which the Au-in-calcrete anomalies form in the dune. The carbonate has its origins in plants and marine factors as (c.f Challenger; Chapter 2). Gold concentrations were too low to investigate the distribution of Au at the micron scale as at ET (Chapter 4) and Bounty (Chapter 6).

Below the sand, more indurated calcrete provides a robust sampling medium. At present, due to limited knowledge of exploration methods in this type of environment, the mineral explorer must either expend additional financial resources augering through areas of sand cover to collect buried calcrete samples, or have lower confidence that vegetation and surface soil samples will detect mineralisation. This study is comparable to that undertaken at ET (Chapters 3 and 4) and provides the link between Au-bearing calcrete created by vegetation and the larger scale Au-in-calcrete anomalies created by geomorphological influences.

The nature of the Au found within calcrete was studied from samples from Bounty Gold Deposit (Chapter 6). Highly anomalous Au concentrations in calcrete were first discovered in 1987 at the Bounty Gold Deposit, Western Australia. A strong correlation was noted between the Ca, Mg, Sr and Au (in soil profiles) which has not only attracted the interest of mineral explorers but also chemists, soil scientists, metallurgists and climatologists. Gold has been considered an inert element and so its strong association with the alkaline earth group of relatively mobile elements is both remarkable and intriguing. Using LA-ICP-MS, SXRF (synchrotron X-ray fluorescence) and XANES (micro-X-ray absorption near-edge structure), the distribution of Au-in-calcrete was shown for the first time and that Au occurs in both particulate and ionic form (c.f. Chapter 4). Much of the ionic Au associated with Br was found in a root tubule clearly showing an association between Au-in-calcrete and biotic factors. The presence of Br (as an element commonly found in evaporite minerals) is further evidence of water being removed from this microenvironment causing precipitation. All these observations are consistent with an evapotranspiration model for the formation of Au in the calcrete; Au has been mobilised then precipitated as vadose water has been removed from the soil by trees and shrubs (Chapter 5). While the association between Au and Ca is very strong in bulk sample analyses down the soil profile, other detailed analyses on sub-samples using wet chemical, LA-ICP-MS (laser ablation inductively coupled mass spectrometry) and SXRF techniques show that it is not apparent at the sub-millimetre scale. This suggests that the Au and Ca mobilities are similar but independent of one another and that Au does not (at the µm scale) co-precipitate with carbonate minerals.

The thesis attempted to answer a series of questions and while an attempt on these was undertaken a number of other lines of research and questions were posed that were beyond the scope of this research. Some of these are included below:

1) Microorganisms have been suggested to play a role in mobilising and precipitating Au in the natural environment. Recently, experimental studies have suggested that there may be a role of bacteria in the formation of Au-in-calcrete anomalies (Reith and Schmidt Mumm, 2007; Reith et al., 2009). While these studies show the theoretical involvement of bacteria there is a paucity of data describing if, how and when bacteria are involved in Au-in-calcrete anomaly formation in the natural environment. Further work in this area of research should be encouraged.
2) Calcium and Mg isotopes could be used to investigate the source of these elements in calcrete. Currently, Sr is used as a substitute for Ca but better detection and precision is now available to make the use of Ca and Mg more productive. Dolomite often occurs in gold-in-calcrete profiles and the mode of formation of this mineral in soils is enigmatic.
3) Further work on the form of gold in calcrete needs to be undertaken. The implication of this thesis was that an evaporite was playing a role e.g. Br but it is hard to believe that an organic complex is not at least playing a partial role in the formation of these anomalies given the proximity of plant roots.
4) All the soil profile work has been done in Australia. By sampling down a profile, particularly in early stage (Stage 1 of Gile et al., 1966) it can be clearly seen that Au and Ca are strongly related. Sampling outside Australia is suggested since we cannot discount a specific role played by Australian flora e.g. *Eucalyptus* or *Acacia* in the formation of the anomalies.

CHAPTER 8

CONCLUSION

This thesis makes several original contributions to knowledge in applied geology and specifically mineral exploration for buried Au deposits. The principal findings of this thesis and published in a series of papers are:

1) Gold anomalies in calcrete can form in the rooting zone of vegetation by causing the precipitation of elements due to evapotranspiration.
2) Gold can occur as both ionic and particulate Au in calcrete.
3) Gold deposition was found in the root tubules in calcareous soil.
4) Some Au was associated with Br in calcrete.
5) Gold may associate with calcrete during the life of a tree. Sand dunes containing powdery calcrete and anomalous Au can form in <26 000 years. Laminated calcrete containing Au formed in <120 000 years.
6) Gold-in-calcrete anomalies (with Ag) may be extended laterally due to geomorphological characteristics and create larger anomalies that may be difficult to reconcile with the original source.

Collectively these papers have shown that there are both biotic and abiotic factors involved in the formation of Au-in-calcrete anomalies which may form quickly i.e. during the age of a tree. The balance between Au-in-calcrete anomaly formation and its dilution and dispersal is in a dynamic equilibrium moderated principally by environmental factors such as climate, soil factors and geomorphology. Biotic and abiotic factors are important for mineral exploration purposes since they may serve to both generate and disperse Au anomalies in the near surface environment. While several questions concerning gold-in-calcrete have been answered, or at least addressed, several more have been posed.

In conclusion, through publication of papers, this thesis has had an impact on the scientific community and the exploration industry through greater understanding of how the process of gold in calcrete has formed and details of the parameters that affect the formation of the anomalies. Calcrete is a major exploration sampling medium in Australia and elsewhere and is regularly reported in company briefs, quarterly reports, annual reports IPOs. Companies learn about this knowledge commonly through workshops, seminars and conferences rather than the written word contained within scientific papers and theses. The impact of knowledge gained by exploration personnel is, in my opinion, far greater from the spoken word and in-field demonstrations rather than reading the scientific literature.

REFERENCES

Adams, A.E., 1980. Calcrete profiles in the Eyam Limestone (Carboniferous) of Derbyshire: petrology and regional significance. Sedimentology 27, 651-660.

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, 144 pp.

Alonso-Zarza, A.M., 1999. Initial stages of laminar calcrete formation by roots: examples from the Neogene of central Spain. Sedimentary Geology, 126, 177–191.

Anand, R.R., 2001. Evolution, classification and use of ferruginous regolith materials in gold exploration, Yilgarn Craton, Western Australia. Geochemistry: Exploration, Environment and Analysis 1, 221-236.

Anand, R.R. and Paine, M., 2002. Regolith geology of the Yilgarn Craton, Western Australia: implications for exploration. Australian Journal of Earth Sciences 49, 3-162.

Anand R.R., Smith, R.E., Innes, J. and Churchward, H.M., 1989. Exploration geochemistry about the Mt Gibson Au deposits, Western Australia. CRC LEME Report 20R. 93p. (Reissued as Open File Report 35, CRC LEME, Perth, 2001).

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., Smith R.E., Phang C., Wildman J.E., Robertson I.D.M. and Munday T.J., 1998. Geochemical exploration in complex lateritic environments of the Yilgarn Craton, Western Australia. P240A Final Report 50. (Originally published as CSIRO. Division of Exploration Geoscience. Report; 442R, 1993). CRC LEME Open File Report 50, Perth, Australia. 3 volumes.

Anand, R.R., Cornelius, M. and Phang, C., 2005. Use of biota in mineral exploration in areas of transported cover. In: 22nd IGES, Perth, Australia. Abstracts Volume. Promaco Conventions Pty Ltd.

Anderson, M., 2010. First gold pour at White Dam. Exco Resources Ltd. http://www.excoresources.com.au/. (Last accessed 19th August 2010)

AngloGold Ashanti, 2007. (www.anglogoldashanti.co.za). Last accessed on 25th August 2008

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

Anon, 1998. Wedderburn Venture-Victoria and Sonoran Gold Exploration-Mexico. Gawler Gold NL Annual Report, p12-16.

Anon, 2009. Tenement activity, ELs 2761 and 3460 (Env. 11 774; third partial relinquishment report). Equinox Resources Ltd, Minotaur Operations Pty Ltd and Toro Energy Energy Ltd. Mines and Energy Quarterly Journal, 53:52.

Anon, 2010b. Helix Resources Limited. Tunkillia Project, South Australia. http://www.helix.net.au/tunkillia.24.html. Last accessed 19th August 2010).

Anon, 2010b. Southern Gold Limited. Challenger Area Project. http://www.southerngold.com.au/project.php?id=21. Last accessed 19th August 2010).

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

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., 1995. Quaternary vadose calcretes revisited. Journal of Australian Geology and Geophysics. 16: 223-230.

Aspandiar, M.F., Anand, R.R., Gray, D. and Cucuzza, J., 2004. Mechanisms of metal transfer through transported overburden within the Australian regolith. Explore – Newsletter for the Association of Applied Geochemists 125, 9–12.

Australian Bureau of Meteorology, 2004. World Wide Web address: http://www.bom.gov.au/. Australian Bureau of Meteorology 2007. http://www.bom.gov.au/ climate/averages/tables/cw_018044.shtml. (last accessed 18th May 2007).

Bailey, S.W., Hornbeck, J.W., Driscoll, C.T. and Gaudette, H.E., 1996. Calcium inputs and transport in a base-poor forest ecosystem as interpreted by Sr isotopes. Water Resources Research 32, 707–719.

Bain, D.C. and Bacon, J.R., 1994. Strontium isotopes as indicators of mineral weathering in catchments. Catena 22, 201–214.

Bakker, A.W. and Schippers, B., 1987. Microbial cyanide production in the rhizosphere in relation to potato yield reduction and *Pseudomonas* spp.-mediated plant growth reduction. Soil Biology and Biochemistry 19, 452–458.

Baranova N.N. and Ryzhenko B.N., 1981. Computer simulation of the Au-Cl-S-Na-H2O system in relation to the transport and deposition of Au in hydrothermal processes. Geochemistry International 18, 46-60.

Barats A., Pecheyran, C., Amouroux, D., Dubascoux, S., Chauvard, L. and Donard, O.F.X., 2007. Matrix-matched quantitative analysis of trace-elements in calcium carbonate shells by laser-ablation ICP-MS: Application to the determination of daily scale profiles in scallop shell (*Pecten maximus*). Analytical and Bioanalytical Chemistry 387, 1131-1140.

Baskar, S., Baskar, R., Mauclaire, L. and McKenzie, J.A., 2006. Microbially induced calcite precipitation in culture experiments: possible origin for stalactites in Sahastradhara caves, Deradun, India. Current Science 90, 58–64.

Beard, J.S., 1990. Plant Life of Western Australia. Kangaroo Press Pty Ltd, NSW, Australia. 319 pp.

Benbow, M.C., Crooks, A.F., Rankin, L.R., Martin, A.R. and Fairclough, M.C., 1995. BARTON map sheet. South Australia. Geological Survey. Geological Atlas 1:250,000 Series, sheet SH/53-9.

Benbow, M.C., Lindsay, J.M. and Alley, N.F., 1995. Eucla Basin and paleodrainage: Nullarbor Limestone. In: Drexel, J.F., Preiss, W.V. (Eds.), The Geology of South Australia: Vol. 2. The Phanerozoic. South Australia Geological Survey. Bulletin, vol. 54, pp. 178–186.

Bern, C.R., Townsend, A.R. and Lang Farmer, G. 2005. Unexpected dominance of parent-material strontium in a tropical forest on highly weathered soils. Ecology, 86, 626–632.

Blake, W.P., 1902. The caliche of southern Arizona: An example of deposition by the vadose circulation. Genesis of Ore Deposits. Am. Inst. Min. Met. Eng. Trans. 31, 220–226.

Bonwick, C.M., 1997. Discovery of the Challenger Gold Deposit: implications for future exploration on the Gawler Craton. New Generation Gold Mines '97. Case Histories of Discovery. Conference Proceedings, AMF, Adelaide, Australia, AMF, pp ch7-1 to ch7-15.

Bowler, J.M. and Polach, H.A., 1971. Radiocarbon analysis of soil carbonates: an evaluation from paleosols in southeastern Australia. In: Yaalon, D. (Ed.), Paleopedology-Origin, Nature, and Dating of Paleosols. Israel University Press, Jerusalem, pp. 97–108.

Bowler, J.M., 1976. Aridity in Australia: age, origins and expression in aeolian landforms and sediments. Earth-Science Reviews 12, 279–310.

Boyer, D. and Grivas, R., 1999. The East Kundana Gold Deposits— persistence pays. New Generation Gold Mines '99. Case Histories of Discovery. Conference Proceedings, Australian Mineral Foundation, Adelaide, Australia (unpaginated).

Boyle, R.W., 1979. The geochemistry of gold and its deposits. Geological Survey of Canada Bulletin 280, 583 pp.

Boyle R.W., Alexander W.M. and Aslin G.E.M., 1975. Some observations on the solubility of Au. Geological Survey of Canada Paper 75-24, 6p.

Boyle, R.W. and Dass, A.S., 1967. Geochemical prospecting – use of the A horizon in soil surveys. Economic Geology 62, 274–276.

Braissant O., Cailleau, G., Aragno, M. and Verrechia, E.P., 2004. Biologically induced mineralisation in the tree Milicia excelsa (Moraceae): its causes and consequences to the environment. Geobiology 2, 59-66.

Bristow, A.P.J., Gray, D.J. and Butt, C.R.M., 1996a. Geochemical and spatial characteristics of regolith and groundwater around the Golden Delicious Prospect, Western Australia. CSIRO Australia. Division of Exploration and Mining, Perth. Restricted Report 280R. CRC LEME, Perth. Restricted Report 15R. CRC LEME/AMIRA Project 409: Yilgarn Transported Overburden.181 pp.

Bristow, A.P.J., Lintern, M.J., and Butt, C.R.M., 1996b. Geochemical expression of concealed Au mineralisation, Safari Prospect, Mt Celia, Western Australia. CRC LEME Report 13R/Exploration and Mining Report 281R. 58p. (Reissued as Open File Report 104, CRC LEME, Perth, 2001).

Brooks, R.R., 1995. Insects and mineralisation. In: Brooks, R.R., Dunn, C.E. and Hall, G.E.M. (eds) Biological Systems in Mineral Exploration and Processing. Ellis Horwood Limited, Hemel Hempstead, England, 147–158.

Brown, A.D. and Hill, S., 2003. Litter Dams: A new method of mapping surface dispersion vectors at the White Dam Prospect, Curnamona Craton, SA in: I.C. Roach (Ed), Advances in Regolith, CRC LEME, Perth. pp. 24-28.

Brugger, J., Pring, A., Reith, F., Ryan, C., Etschmann, B., Liu, W., O'Neill, B., and Ngothai, Y., 2010. Probing ore deposits formation: New insights and challenges from synchrotron and neutron studies. Radiation Physics and Chemistry 79, 151-161.

Burford E.P., Hillier S., and Gadd G.M., 2006. Biomineralisation of fungal hyphae with calcite ($CaCO_3$) and calcium oxalate mono- and dihydrate in carboniferous limestone microcosms. Geomicrobiology Journal 23, 599-611.

Butler, B.E., 1956. Parna-an aeolian clay. Australian Journal of Science 18, 145–151. Butt, C.R.M., 1992a. Exploration in calcrete terrain. In: Butt, C.R.M., Zeegers, H. (Eds.), Regolith Exploration Geochemistry in Tropical and Subtropical Terrains. Handbook of Exploration Geochemistry, vol. 4. Elsevier, Amsterdam, pp. 295–298.

Butt, C.R.M., 1988. Major uranium provinces: Yilgarn Block and Gascoyne Province. In: Recognition of Uranium Provinces. International Atomic Energy Agency, Vienna, pp 273-304.

Butt, C.R.M., 1989. Genesis of supergene gold deposits in the lateritic regolith of the Yilgarn Block, Western Australia in: R.R. Keays, W.R.H. Ramsay and D.I. Groves (Eds.). The geology of Gold Deposits: The Perspective in 1988. Economic Geology Monograph 6. Economic Geology, New Haven, pp 460-470.

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, pp 295-391.

Butt, C.R.M., 1998. Supergene gold deposits. AGSO Journal of Australian Geology and Geophysics 17, 89-96.

Butt, C.R.M., 2005. Geochemical dispersion, process and exploration models in: Butt, C.R.M, Roberston, I.D.M, Scott, K.M., and Cornelius, M. (Eds.) Regolith expression of Australian ore systems. CRC LEME Bentley, Western Australia., pp 81-106.

Butt, C.R.M. and Zeegers, H., (editors), 1992. Regolith Exploration Geochemistry in Tropical and Subtropical Terrains. Elsevier, Amsterdam, 607 pp.

Butt, C.R.M., Horwitz, R.C.H. and Mann, A.W., 1977. Uranium occurrences in calcretes and associated sediments in Western Australia, Report FP16. CSIRO Australia, Division of Mineralogy, Perth, pp. 67.

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: Final Report. CSIRO Exploration and Mining Restricted Report 333R. 163p. (Reissued as Open File Report 86, CRC LEME, Perth, 2001).

Butt, C.R.M., Lintern, M.J. and Anand, R.R., 2000. Evolution of regoliths and landscapes in deeply weathered terrain - implications for geochemical exploration. Ore Geology Reviews 16, 167-183.

Butt, C.R.M., Lintern, M.J. and Bristow, A.P.J., 2005a. Safari Bore Gold Deposit, Western Australia. IN: Butt, C. R. M.; Robertson, I. D. M.; Cornelius, M., and Scott, K. M., editors. Regolith expression of Australian ore systems. Perth: CRC LEME. pp.328-329. (also published on CRC LEME website in 2003 http://www.crcleme.org.au/Pubs/Monographs/RegExpOre.html). (Last accessed 19th August 2010).

Butt, C. R. M.; Robertson, I. D. M.; Cornelius, M., and Scott, K. M. (editors), 2005b. Regolith expression of Australian ore systems. Perth: CRC LEME. 423 p.

Cabri, L.J., Newville, M., Gordon, R.A., Crozier, E.D., Sutton, S.R., McMahon, G. and Jiang, D., 2000. Chemical speciation of Au in arsenopyrite. Canadian Mineralogist 38, 1265-1281.

Cailleau, G., Braissant, O., Dupraz, C., Aragno, M. and Verrecchia, E. P., 2005. Biologically induced accumulations of CaCO3 in orthox soils of Biga, Ivory Coast. Catena 59, 1-17.

Cailleau, G., Verrecchia, E. P., Braissant, O., and Emmanuel, L., 2009. The biogenic origin of needle fibre calcite. Sedimentology 56, 1858-1875.

Callen, R.A. and Benbow, M.C., 1995. Chapter 11, Quaternary. The Deserts – Playas, Dunefields and Watercourses in: Drexel, J.F. and Preiss, W.V. (Eds). The Geology of South Australia. Volume 2. The Phanerozoic. South Australia. Geological Survey. Bulletin 54, 244-251.

Cameron, E.M., Hamilton, S.M., Leybourne, M.I., Hall, G.E.M., and McClenaghan, M.B., 2003. Finding deeply buried deposits using geochemistry. Geochemistry: Exploration, Environment, Analysis 4, 7-32.

Capo, R.C. and Chadwick, O.A., 1993. Application of strontium isotopes to the mass balance of calcium in desert soils: eolian inputs versus in situ weathering. Fall Meeting Am. Geophys. Union. Geol. Soc. Am. Abst. Programs, vol. 25, p. 394.

Capo, R.C. and Chadwick, O.A., 1999. Sources of strontium and calcium in desert soil and calcrete. Earth and Planetary Science Letters 170, 61–72.

Capo, R.C., Stewart, B.W. and Chadwick, O.A., 1998. Strontium isotopes as tracers of ecosystem processes: theory and methods. Geoderma 82, 197–225.

Capo, R.C., Whipkey, C.E.B., Blachère, J.R. and Chadwick, O.A. 1995. Pedogenic origin of dolomite in a basaltic weathering profile, Kohala peninsula, Hawaii. Geology, 28, 271–274.

Carlisle, D., 1980. Possible variations on the calcrete-gypcrete uranium model. Open-file Report, U.S. Department of Energy, GJBX-53(80), 38 pp.

Carlisle, D., Merifield, P., Orme, A. and Kolker, O., 1978. The distribution of calcretes and gypcretes in southwestern United States and their uranium favourability, based on a study of deposits in western Australia and Southwest Africa (Namibia). US Dept. Energy Open File Report GJBX 29(78). 274 pp.

Cerling, T.E., 1984. The stable isotopic composition of modern soil CO_3 and its relationship to climate. Earth and Planetary Science Letters 71, 229–240.

Chandran, S.P., Pasricha, R., Bhatta, U.M., Satyam, P.V., and Sastry, M., 2007. Synthesis of gold nanorods in organic media. Journal of Nanoscience and Nanotechnology 7, 2808-2817.

Chao, T.T., 1984. Use of partial dissolution techniques in geochemical exploration. Journal of Geochemical Exploration 20: 101-35.

Chaudhri M.A., Watling J. and Khan F.A., 2007. Spatial distribution of major and trace elements in bladder and kidney stones. Journal of Radioanalytical and Nuclear Chemistry 271, 713-720.

Chen, X.Y., 2002. Morphology and occurrence. In: Chen, X.Y., Lintern, M.J., Roach, I.C. (Eds.), Calcrete: Characteristics, Distribution and Use in Mineral Exploration. CRC LEME Perth, Australia, pp. 5-7.

Chen, X.Y., McKenzie, N.J. and Roach, I.C., 2002. Distribution in Australia: calcrete landscapes. In: Chen, X.Y., Lintern, M.J., Roach, I.C. (Eds.), Calcrete: Characteristics, Distribution and Use in Mineral Exploration. CRC LEME Perth, Australia, pp. 110-138.

Chin R. J., Hickman A.H., and Thorn R., 1982. Hyden, Western Australia. Geological Survey of Western Australia 1:250000 Geological Series Explanatory Notes.

Chiquet, A., Michard, A., Nahon, D. and Hamelin, B., 1999. Atmospheric input vs. in situ weathering in the genesis of calcretes: an Sr isotope study at Gálvez (central Spain). Geochimica et Cosmochimica Acta 63, 311–323.

Chivas, A.R., De Deckker, P., Wang, S.X. and Cali, J.A., 2002. Oxygen isotope systematics of the nektic ostracod Australocypris robusta. In: Holmes, J.A., Chivas, A.R. (Eds.), The Ostracoda—Applications in Quaternary Research. Am. Geophys. Union, Geophysical Monograph, vol. 131, pp. 301–313.

Cohen, D. R., Kelley, D. L., Anand, R. and Coker, W. B., 2010. Major advances in exploration geochemistry, 1998-2007. Geochemistry: Exploration, Environment, Analysis 10, 3-16.

Cornelius, M., Morris, P.A. and Cornelius, A.J, 2006. Laterite geochemical database for the Southwest Yilgarn Craton, Western Australia. CSIRO Report P2006/75. CSIRO Australia. ISBN 1 921 039 418. 27 p.

Cornelius, M., Robertson, I.D.M., Cornelius, A.J., and Morris, P.A., 2007. Laterite geochemical database for the western Yilgarn Craton, Western Australia: Western Australia Geological Survey, Record 2007/9. 44 pp.

Couto, J.A., Fernandez, J.A., Aboal, J.R. and Carballeira, A., 2003. Annual variability in heavy-metal bioconcentration in moss: sampling protocol optimization. Atmospheric Environment, 37, 3517–3527.

Cowley, W.M., and Freeman, P.J. (compilers), 1993. Geological Map South Australia. Geological Survey of South Australia, Department of Mines and Energy. Adelaide, Australia.

Cox, M.W. and Hollister, V.F. 1955. The Chollet project, Stevens County, Washington. Mining Engineering 7, 937–940.

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, pp. 437-460.

Craig, H., 1953. The geochemistry of stable carbon isotopes. Geochimica et Cosmochimica Acta 3, 53–92.

Crocker, R.L., 1946. Post-Miocene climatic and geologic history and its significance in relation to the genesis of the major soil types of South Australia. CSIRO Bull. No. 39. 56 pp.

Cuyler, R.H., 1930. Caliche as a fault indicator. Abstract. Bulletin of the Geological Society of America, 41: 109.

Daly, S.J. and Fanning, C.M., 1993. Chapter 3, Archaean. In: Drexel, J.F., Preiss, W.V. and Parker, A.J. (Editors). The Geology of South Australia. Volume 1. The Precambrian. South Australia. Geological Survey. Bulletin 54, 33-48.

Daly, S.J., Webb, A.W. and Whitehead, S.G., 1978. Archaean to early Proterozoic banded Fe formations in the Tarcoola Region, South Australia. Royal Society of South Australia. Transactions, 102, 141-149.

Daly, S.J., Fanning, C.M. and Fairclough, M.C., 1998. Tectonic evolution and exploration potential of the Gawler Craton. AGSO Journal of Australian Geology and Geophysics 17, 145–148.

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).

Dart, R.C., Barovich, K.M. and Chittleborough, D., 2005. Pedogenic carbonates, strontium isotopes and their relationship with Australian dust processes. In: Roach, I.C. (Ed.), Regolith 2005. Conference Abstracts. Canberra, Cooperative Research Centre for Landscape Environments and Mineral Exploration (CRC LEME), pp. 64–66.

Dell, M.R., 1992. Regolith-landform relationships and geochemical dispersion about the Kanowna-Belle Au Deposit, W.A. Honours Thesis. University of Tasmania. 89 pp 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 (Editors), Conceptual Models in Exploration Geochemistry – Australia. Journal of Geochemical Exploration 12, 158-161.

Deutz, P.,Montanez, I.P. and Monger, H.C., 2002. Morphology and stable and radiogenic isotope composition of pedogenic carbonates in late Quaternary relict soils, New Mexico, USA: an integrated record of pedogenic overprinting. Journal of Sedimentary Research 72, 809–822.

Dick, J., De Windt, W.,De Graef, B., Saveyn, H., Van Der Meeren, P., De Belie, N. and Verstraete, W., 2006. Bio-deposition of a calcium carbonate layer on degraded limestone by Bacillus species. Biodegradation 17, 357-367.

Dominion, 2010. http://www.dml.com.au/irm/content/home.html. (Last accessed 19th August 2010)

Dongarrá, G., Varrica, D. and Sabatino, G., 2003. Occurrence of platinum, palladium and Au in pine needles of Pinus pinea L. from the city of Palermo (Italy). Applied Geochemistry 18, 109–116.

Doyle, M.G., Kendall B.M., Gibbs D., 2007. Discovery and characteristics of the Tropicana gold district in: Bierlein FP, Knox-Robinson CM (Eds), Proceedings of Geoconferences (WA) Inc. Kalgoorlie 07 Conference. Geoscience Australia Record 2007/14, p186-190.

Dregne, H.E., 1983. Desertification of arid lands. Harwood Academic Publishers. 242 pp.

Drexel, J.F., Preiss, W.V., Parker, A.J. (editors.), 1993. The Geology of South Australia: 1. The Precambrian. Geological Survey of South Australia. Bulletin, vol. 54. Drouet, T., Herbauts, J., Gruber, W., Demaiffe, D., 2005. Strontium isotope composition as a tracer of calcium sources in two forest ecosystems in Belgium. Geoderma 126, 203–223.

Drouet, T., Herbauts, J., Gruber, W. and Demaiffe, D., 2005. Strontium isotope composition as a tracer of calcium sources in two forest ecosystems in Belgium. Geoderma 126, 203–223.

Drown, C.G., 2003. The Barns Gold Project: discovery in an emerging district. Primary Industries and Resources, South Australia. MESA Journal 28, 4–9.

Drown, C., 2005. Geochemically driven exploration in the Central Gawler Province. In: Mineral Exploration Through Cover - 2005. A. Schmidt Mumm, J. Keeling and K. Wills (editors). University of Adelaide, South Australia. Abstracts Volume p 27-28.

Dunn C.E., 1986. In: Summary of Investigations Saskathchewan Energy and Mines, Saskathchewan Geological Survey. Miscellaneous Report 86-4, pp. 129-134.

Dunn, C.E., 1986. Biogeochemistry as an aid to exploration for Au, platinum and palladium in the northern forests of Saskatchewan, Canada. Journal of Geochemical Exploration 25, 21–40.

Dunn, C.E., 1995. Biogeochemical prospecting for metals. In: BROOKS, R.R., Dunn,C.E. and Hall, G.E.M. (eds) Biological Systems in Mineral Exploration and Processing. Ellis Horwood, Hemel Hempstead, 371–425.

Dunn C.E. and Hoffman E., 1986. Multi-element study of vegetation from a zone of rare-earth rich allanite and apatite in northern Saskatchewan, Canada. Applied Geochemistry 1, 375-381.

Durand, N., Ahmad, S.M., Hamelin, B., Gunnell, Y. and Curmi, P., 2006. Origin of Ca in South Indian calcretes developed on metamorphic rocks. Journal of Geochemical Exploration 88, 275–278.

Eastham, J., Scott, P.R., Steckis, R.A. and Barton, A.F.M., 1993. Survival, growth and productivity of tree species under evaluation for agroforestry to control salinity in the Western Australian wheatbelt. Agroforestry Systems, 21, 223–237.

Edgecombe, D., 1997. Challenger Gold Deposit. Primary Industries and Resources, South Australia. MESA Journal 4, 8–11.

Eggleton, R.A., 2001. Regolith Glossary. CRC LEME. Perth Australia. ISBN 0-7315-3343-7. 144 p.

Ercole, C., Cacchio, P., Botta, A. L., Centi, V. and Lepidi, A., 2007. Bacterially induced mineralisation of calcium carbonate: the role of exopolysaccharides and capsular polysaccharides. Microscopy and Microanalysis 13, 42-50.

Erdman, J.A. and Olson, J.C., 1985. The use of plants in prospecting for Au: a brief overview with a selected bibliography and topic index. Journal of Geochemical Exploration 24, 281–304.

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. 26 pp.

Fairbrother, L., Shapter, J., Brugger, J., Southam, G., Pring, A., and Reith, F., 2009. Effect of the cyanide-producing bacterium *Chromobacterium violaceum* on ultraflat Au surfaces. Chemical Geology 265, 313-320.

FAO-UNESCO, 2000, Soil Map of the World, digitized by ESRI. Soil climate map, USDA-NRCS, Soil Survey Division, World Soil Resources, Washington D.C. http://soils.usda.gov/use/worldsoils/mapindex/sic.html (Last accessed 6th October 2010).

Ferris, G. Wilson, M., 2004. Tunkillia Project; Proterozoic shear-zone-hosted gold mineralisation within the Yarlbrinda shear zone. Mines and Energy Resources South Australia Quarterly Journal (MESA Journal) 35, 6-12.

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.

Furnare L.J., Vailionis A., and Strawn D.G., 2005. Molecular-level investigation into copper complexes on vermiculite: Effect of reduction of structural iron on copper complexation. Journal of Colloid and Interface Science 289, 1-13.

Garnett, D.L., Rea, W.J. and Fuge, R., 1982. Geochemical exploration techniques applicable to calcrete-covered areas. In: H.W. Glenn (Editor). Proceedings of the 12th Commonwealth Mining and Metallurgical Institute Congress, Geological Society of South Africa, Johannesburg, pp. 945-955.

Geological Survey, 1990. Geology and mineral resources of Western Australia. Memoir 3. Geological Survey of Western Australia, Perth, 827 pp.

Gibbons, L., 1997. Regolith study of the Old Well gold prospect, Tarcoola District, Gawler Craton. Univeristy of Adelaide. Honours thesis (unpublished). 37 p (+ appendices).

Gile. L.H., Peterson, F.F. and Grossman, R.H., 1966. Morphological and genetic sequences of carbonate accumulation in desert soils. Soil Science, 101, 347-360.

Gile, L.H. and Grossman, R.B., 1979. The Desert Project Monograph. US Dept. Agric., Soil Conservation Service. 984 pp.

Gilkes, R.J., 1998. Biology and the regolith: an overview in: Eggleton, R.A. (Ed) the State of the Regolith. Proceedings of the second Australian Conference on Landscape Evolution and Mineral Exploration, Brisbane, Queensland 1996. Geological Society of Australia. Special Publication 20, 110-125.

Gill, E.D., 1955. The Australian 'arid period'. Australian Journal of Science 17, 204–206.

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.

Goede, A., McCulloch, M., McDermott, F. and Hawkesworth, C., 1998. Aeolian contribution to Sr and Sr isotope variations in a Tasmanian speleothem. Chemical Geology 149, 37–50.

Goudie, A., 1972. The chemistry of world calcrete deposits. Journal of Geology 80, 449-463.

Goudie, A.S., 1983. Calcrete. In: Goudie, A.S., Pye, K. (Eds.), Chemical Sediments and Geomorphology. Academic Press, London, pp. 93–131.

Goudie, A.S., 1996. Organic agency in calcrete development. Journal of Arid Environments 32, 103-110.

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. 70 pp.

Gray D.J., 1998. The aqueous chemistry of Au in the weathering environment. CSIRO Exploration and Mining Report EG4R and CRC LEME Open File Report 38.

Gray, D.J. and Lintern, M.J., 1997. Mobility of gold in soils of the southern Yilgarn Craton. Kalgoorlie '97: An International Conference on Crustal Evolution, Metallogeny and Exploration of the Yilgarn Craton - An Update. AGSO Extended Abstracts Record 1997/41: pp 223–228.

Gray, D.J. and Lintern, M.J. 1998. Chemistry of Au in soils from the Yilgarn Craton, Western Australia. In: EGGLETON, R. A. (ed.) The State of the Regolith. Proceedings of the Second Australian Conference on Landscape Evolution and Mineral Exploration. Springwood, NSW. Geological Society of Australia Special Publication, 209–221.

Gray, D.J., Lintern, M.J. and Longman, G.D., 1990. Chemistry of Au in some Western Australian Soils. CSIRO Division of Exploration Geoscience, Perth, Restricted Report 126R, 62 pp. (Reissued as Open File Report 68, CRC LEME, Perth, 1999).

Gray, D.G., Butt, C.R.M. and Lawrance, L.M., 1992. The geochemistry of gold in lateritic terrains. In: C.R.M. Butt and H. Zeegers (Editors), Regolith Exploration Geochemistry in Tropical and Subtropical Terrains. Handbook of Exploration Geochemistry, 4. Elsevier, Amsterdam, pp 461–482.

Gray D.J., Lintern M.J., and Longman G.D., 1998. Readsorption of Au during selective extraction - observations and potential solutions. Journal of Geochemical Exploration 61, 21-37.

Green, G.P., Bestland, E.A. and Walker, G.S., 2004. Distinguishing sources of base cations in irrigated and natural soils: evidence from strontium isotopes. Biogeochemistry 68, 199–225.

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.

Guha, M. 1961. A study of the trace element uptake of deciduous trees. Thesis. University of Aberdeen.

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. pp 519-524

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.

Hamidi, E.M. 1996. Alteration et formation des encroutements carbonates sur basaltes: Exemple des basaltes triasiques du Moyen Atlas (Maroc). Thesis. University of Aix-Marseille III, France.

Hamidi, E.M., Colin, F., Michard, A., Boulange, B. and Nahon, D., 2001. Isotopic tracers of the origin of Ca in a carbonate crust from the Middle Atlas, Morocco. Chemical Geology 176, 93–104.

Harrison, N., Bailey, A., Shaw, J.D., Petersen, G.N. and Allen, C.A., 1990. Ora Banda Au 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. pp 389-394.

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, pp. 1-15.

Harrison, S.P. and Dodson, J., 1993. Climates of Australia and New Guinea since 18,000 yr B.P.. In: Global Climates Since the Last Glacial Maximum. University of Minnesota Press, USA, 265–293.

Hart, D.M., 1995. Litterfall and decomposition in the Pilliga State Forests, New South Wales, Australia. Australian Journal of Ecology 20, 266–272.

Hartley, K., 2000. Regolith studies of the Moonta Copper Mines Yorke Peninsula, South Australia. Thesis. University of Melbourne. 68 pp plus appendices.

Hathorne, E.C., Alard, O., James, R.H. and Rogers, N.W, 2003. Determination of intratest variability of trace elements in foraminifera by Laser Ablation Inductively Coupled Plasma-Mass Spectrometry. Geochemistry Geophysics Geosystems 4, 8408.

Hay, R.L. and Reeder, R.J., 1978. Calcretes of Olduvai Gorge and Ndolanya Beds of northern Tanzania. Sedimentology 25, 649-973.

Heald, S.M., Cross, J.O., Brewe, D.L. and Gordon, R.A., 2007. The PNC/XOR X-ray microprobe station at APS sector 20: Proceedings of the 14th National Conference on Synchrotron Radiation Research - SRI 2007. Nuclear Instruments and Methods in Physics Research Section A 582, 215-217.

Helix, 2010. http://www.helix.net.au/tunkillia.24.html. (Last accessed 19th August 2010)

Hellsten, K.J., Colville, R.G., Crase, N.J. and Bottomer, L.R., 1990. Davyhurst Au 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. pp 367-371.

Hendy, E., Lanzirotti, A., Rasbury, T. and Lough, J., 2006. Synchrotron µXRF mapping of elemental distributions across coral skeleton micro-architecture. Geochimica et Cosmochimica Acta 70 [18, Supplement 1], A246.

Hérail, G., Lagos, J., and Vivallo, W., 1999. Gold dispersion in Andean desert environments (Atacama, Chile). Journal of Geochemical Exploration 66, 427-439.

Hering J.G. and Morel, F.M.M., 1988. Humic acid complexation of calcium and copper. Environmental Science and Technology 22, 1234-1237.

Hesse, P.P., 1994. The record of continental dust from Australia in Tasman Sea sediments. Quaternary Science Reviews 13, 257–272.

Hildreth, R.A. and Henderson, W.T., 1971. Comparison of $^{87}Sr/^{86}Sr$ for sea water strontium and the Eimer and Amend SrCO3. Geochimica at Cosmochimica Acta 35, 235.

Hill, S. M., McQueen, K. G., and Foster, K. A., 1998. Regolith carbonate accumulations in western and central NSW: characteristics and potential as an exploration sampling medium. In: Taylor, G. and Pain, C. Eds.). New Approaches to an Old Continent. Proceedings, Regolith '98. 3rd Australian Regolith Conference. Cooperative Research Centre for Landscape Evolution and Mineral Exploration (CRC LEME), Kalgoorlie, Western Australia, pp 191-208.

Hingston, F.J. and Gailitis, V., 1976. The geographic variation of salt precipitated over Western Australia. Australian Journal of Soil Research 14, 319–335.

Holbrook, R. and Anderson, J.M., 1980. An improved selective and diagnostic medium for the isolation and enumeration of *Bacillus cereus* in foods. Canadian Journal of Microbiology 26, 753-759.

Hornbrook, E.H.W., 1971. Mercury in permafrost regions; occurrence and distribution in the Laminak Lake area, Northwest Territories. Geological Survey of Canada Paper, 71-43.

Hough, R.M., Butt, C.R.M., Reddy, S.M. and Verrall, M., 2007. Gold Nuggets: Supergene or Hypogene? Australian Journal of Earth Sciences 54, 959-964.

Hough, R.M., Noble, R.R.P., Hitchen, G.J., Hart, R., Reddy, S.M., Saunders, M., Clode, P., Vaughan, D., Lowe, J., Gray, D.J., Anand, R.R., Butt, C.R.M., and Verrall, M., 2008. Naturally occurring gold nanoparticles and nanoplates. Geology 36, 571-574.

Huenneke, L.F., Clason, D. and Muldavin, E. 2001. Spatial Heterogeneity in Chihuahuan Desert Vegetation: Implications for Sampling Methods in Semi-Arid Ecosystems. Journal of Arid Environments, 47, 257–270.

Hulme, K.A. and Hill, S.M., 2004. Seasonal element variations of Eucalyptus camaldulensis biogeochemistry and implications for mineral exploration: an example from Teilta, Curnamona Province, western NSW. In: Roach, I.C. (ed.) Regional Regolith Symposia. CRC LEME, Canberra, 151–156.

Huntley, D.J., Godfrey-Smith, D.I.and Thewalt, M.L.W., 1985. Optical dating of sediments. Nature, 313, 105–107.

Hutton, J.T. and Leslie, T.I., 1958. Accession of non-nitrogenous ions dissolved in rainwater to soils in Victoria. Australian Journal of Agricultural Research 9, 492–507.

Hutton, J.T., 1982. Calcium carbonate in rain. In: Wasson, R.J. (Ed.), Quaternary Dust Mantles of China, New Zealand and Australia. Conference Abstracts, pp. 139–140.

IAEA, 1984. Surficial Uranium Deposits. Report of the Working Group on Uranium Geology. International Atomic Energy Agency, Vienna, 252 pp.

Jacquier D.W., McKenzie N.J., Brown K.L., Isbell R.F. and Paine T.A., 2001. Interactive Key to the Australian Soil Classification. Interactive CD ROM. CSIRO Publishing, Melbourne, Australia.

Jenny, H., 1941. Factors of Soil Formation. McGraw-Hill, New York, N.Y., 281p.

Johns, R.K., 1974. Base metal mineralisation in the Pernatty Lagoon region. South Australia. Geological Survey. Report of Investigations, 42.

Johnson, B.J., Miller, G.H., Magee, J.W., Gagan, M.K., Fogel, M.L. and Quay, P.D., 2005. Carbon isotope evidence for an abrupt reduction in grasses coincident with European settlement of Lake Eyre, South Australia. Holocene 15, 888–896.

Johnstone J.H., Lowry D.C. and Quilty P.G., 1973. The geology of southwestern Australia - a review. Journal of the Royal Society of Western Australia 56, 5-22.

Joyce, A.S., 1984. Geochemical exploration. Australian Mineral Foundation (Inc.). 183 pp.

Karlsson T., Persson P., and Skyllberg U. Extended X-ray Absorption Fine Structure Spectroscopy evidence for the complexation of cadmium by reduced sulfur groups in natural organic matter. Environmental Science and Technology 39, 3048-3055.

Keeling, J. 2004. Metal dispersion through transported cover at Moonta, South Australia. In: Roach, I.C. (ed.) Regional Regolith Symposia. CRC LEME, Canberra, 166–170.

Kehal, H., Anderson, A., Shrimpton, K., Harris, S. and Osborn, M., 1999. Golden cities: the discovery of Au deposits in Archaean granite. New Generation Gold Mines '99. Case Histories of Discovery. Conference Proceedings, Australian Mineral Foundation, Adelaide, Australia.

Kelly, E.F., Amundson, R.G., Marino, B.D. and DeNiro, M.J., 1991. Stable C isotopic composition of CO_3 in Holocene grassland soils. Soil Science Society of America Journal 55, 1651–1658.

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.

Khalifa, M.A., Kumon, F., and Yoshida, K., 2009. Calcareous duricrust, Al Quasim Province, Saudi Arabia: Occurrence and origin. Quaternary International 209, 163-174.

Kirkham, R., Dunn, P.A., Kucziewski, A., Siddons, D.P., Dodanwela, R., Moorhead, G., Ryan, C.G., De Geronimo, G., Beuttenmuller, R., Pinelli, D., Pfeffer, M., Davey, P., Jensen, M., Paterson, D., De Jonge, M.D., Kusel M. and McKinlay, J., 2010. The Maia Spectroscopy Detector System: Engineering for integrated pulse capture, low-latency scanning and real-time processing. Australian Institute of Physics Congress Conference Proceedings, 1234, 240.

Klappa C.F., 1980. Rhizoliths in terrestrial carbonates: classification, recognition, genesis and significance. Sedimentology 27, 613-629.

Knauth, L.P., Brilli, M. and Klonowski, S., 2003. Isotope geochemistry of caliche developed on basalt. Geochimica et Cosmochimica Acta 67, 185–195.

Korobushkina, E.D., Chernyak, A.S.. and Mineev, G.G., 1974. Dissolution of Au by microorganisms and products of their metabolism. Microbiology, 43, 37–41.

Korobushkina, E.D., Karavaiko, G.I. and Korobushkin, I.M., 1983. Biochemistry of Au. In: Hallberg, R. (Ed.), Environmental Biogeochemistry. Ecol. Bull, vol. 35. Publishing House of the Swedish Research Councils, Stockholm, pp. 325–333.

Kremer, R.J. and Souissi, T., 2001. Cyanide production by rhizobacteria and potential for suppression of weed seedling growth. Current Microbiology, 43, 0182–0186.

Kriewaldt, M.J.B. (compiler), 1969. Kalgoorlie 1:250 000 Geological Series Explanatory Notes. Geological Survey of Western Australia, 18 p.

Kuimova N.G. and Zhilin O.V., 2002. Biogenic crystallization of ionic Au by microcytes. Transactions (Doklady) of the Russian Academy of Science/ Earth Science Section 387, 936.

Lacelle, D., 2010. Discussion: "The biogenic origin of needle fibre calcite" by G. Cailleau et al. (2009), Sedimentology 56: 1858-1875. Sedimentology 57, 1147-1149.

Lakin H.W., Curtin G.C. and Hubert A.E., 1974. Geochemistry of Gold in the Weathering Cycle. United States Geological Survey. Bulletin 1330. 80 pp.

Lamplugh, G.W., 1902. Calcrete. Geological Magazine, 39: 575.

Lattman, L.H., 1973. Calcium carbonate cementation of alluvial fans in southern Nevada, Bulletin of the Geological Society of America 84, 3013-3028.

Lawrance, L.M., 1988. Geochemical dispersion anomalies in transported overburden around the quartz vein system at the Mount Pleasant Au mine, Western Australia. In: Second International Conference on Prospecting in Arid Terrain. Perth, Western Australia (Abstract Volume). Australasian Institute of Mining and Metallurgy, Melbourne, pp. 87-93. (Abstract).

Lawrance, L.M., 1991. Distribution of Au and ore-associated elements within lateritic weathering profiles of the Yilgarn Block, Western Australia. University of Western Australia. PhD Thesis. 191 pp.

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, pp 365-367.

Le Gleuher, M., Anand, R.R., Eggleton, R.A. and Radford, N., 2008. Mineral hosts for Au and trace metals in regolith at Boddington Au deposit and Scuddles massive copper-zinc sulphide deposit, Western Australia: an LA-ICP-MS study. Geochemistry: Exploration, Environment, Analysis 8, 157-172.

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.

Lee, J. H., Kamada, K., Enomoto, N., and Hojo, J., 2007. Morphology-selective synthesis of polyhedral gold nanoparticles: What factors control the size and morphology of gold nanoparticles in a wet-chemical process. Journal of Colloid Interface Science 316, 887-892.

Lengke, M F., Ravel, B., Fleet, M.E., Wanger, G., Gordon, R.A. and Southam, G., 2007. Precipitation of Au by the reaction of aqueous Au(iii) chloride with cyanobacteria at 25-80^{o}C - studied by X-Ray Absorption Spectroscopy. Canadian Journal of Chemistry 85, 651-659.

Li, W., Pan, G., Zhang, M.Y., Zhao, D.Y., Yang, Y.H., Chen, H. and He, G.Z., 2008. EXAFS studies on adsorption irreversibility of Zn(Ii) on TiO2: Temperature Dependence. Journal of Colloid and Interface Science 319, 385-391.

Lian, B., Hu, Q., Chen, J., Ji, J. and Teng, H.H., 2006. Carbonate biomineralisation induced by soil bacterium *Bacillus megaterium*. Geochimica et Cosmochimica Acta 70, 5522-5535.

Lintern, M.J., 1989. Study of the distribution of Au in soils at Mt Hope, Western Australia. CSIRO Division of Exploration Geoscience, Perth, Restricted Report 24R, 40 pp. (Reissued as Open File Report 65, CRC LEME, Perth, 1999)

Lintern, M.J., 1996a. Geochemical studies of the soil at the Runway Au prospect, Kalgoorlie, Western Australia. CRC LEME 26R/Exploration and Mining Report 250R. 22 pp.

Lintern, M.J., 1996b. Further geochemical studies of the soil at the Panglo Au deposit, Kalgoorlie, Western Australia. CRC LEME 10R/Exploration and Mining Report 251R. 80 pp.

Lintern M.J., 1997. Calcrete sampling for Au exploration. Mines and Energy Resources South Australia Quarterly Journal 5, 5-8.

Lintern, M.J., 2001. Exploration for gold using calcrete – lessons from the Yilgarn Craton, Western Australia. Geochemistry: Exploration, Environment and Analysis 1, 237-252.

Lintern M.J., 2002. Calcrete sampling for mineral exploration. In Calcrete: characteristics, distribution and use in mineral exploration (eds. X.Y. Chen, M.J. Lintern and I.C. Roach). CRC LEME, Perth, Australia, 31-109.

Lintern, M.J. (compiler), 2004. The South Australian Regolith Project final report-summary and synthesis. CRC LEME Perth, Australia, Open File Report 156. 41 p.

Lintern, M.J., 2005a. Birthday gold prospect, Gawler Craton, South Australia in: Butt, C.R.M.; Robertson, I.D.M.; Cornelius, M., and Scott, K.M., (Eds) Regolith expression of Australian ore systems. Perth: CRC LEME. pp.219-221 (also published on CRC LEME website in 2003 http://www.crcleme.org.au/Pubs/Monographs/RegExpOre.html). (Last accessed 19th August 2010).

Lintern, M.J., 2005b. Challenger gold prospect, Gawler Craton, South Australia in: Butt, C.R.M.; Robertson, I.D.M.; Cornelius, M., and Scott, K.M., (Eds) Regolith expression of Australian ore systems. Perth: CRC LEME. pp.236-238. (also published on CRC LEME website in 2004 http://www.crcleme.org.au/Pubs/Monographs/RegExpOre.html). (Last accessed 19th August 2010).

Lintern, M.J., 2005c. Steinway gold deposit, W.A. in Butt, C.R.M.; Robertson, I.D.M.; Cornelius, M., and Scott, K.M., (Eds) Regolith expression of Australian ore systems. Perth: CRC LEME. pp.330-332. (also published on CRC LEME website in 2004 http://www.crcleme.org.au/Pubs/Monographs/RegExpOre.html). (Last accessed 19th August 2010).

Lintern, M.J., 2007. Vegetation controls on the formation of gold anomalies in calcrete and other materials at the Barns Gold Prospect, Eyre Peninsula, South Australia. Geochemistry: Exploration, Environment and Analysis 7, 249-266.

Lintern, M.J. and Scott, K.M., 1990. The distribution of Au and other elements in soils and vegetation at Panglo, Western Australia. CSIRO Division of Exploration Geoscience, Perth, Restricted Report 129R, 100 pp. (Reissued as Open File Report 44, CRC LEME, Perth, 1998).

Lintern, M.J. and Butt, C.R.M., 1991. The distribution of Au and other elements in soils at Mulline, Western Australia. CSIRO Australia. Division of Exploration Geoscience, Perth. Restricted Report 159R. CSIRO/AMIRA Project P241. 62 pp.

Lintern, M.J. and Butt, C.R.M., 1992. The distribution of Au 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. 95 pp.

Lintern, M.J. and Butt, C.R.M., 1993a. Pedogenic carbonate - an important sampling medium for Au exploration in semi-arid areas. Exploration Research News Number 7. CSIRO Division of Exploration Geoscience. 16 pp.

Lintern, M.J. and Butt, C.R.M., 1993b. The distribution of Au 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. 78 pp.

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. 121 pp.

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. 153 pp.

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. 41 pp.

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. 36 pp.

Lintern, M.J. and Craig, M.A., 1996. Further geochemical studies of the soil at the Steinway Au prospect, Kalgoorlie, Western Australia. CRC LEME 27R/ Exploration and Mining Report 252R. 53 pp and map.

Lintern, M.J. and Sheard, M.J., 1998. Regolith studies related to the Challenger Gold Deposit, Gawler Craton, South Australia. Geochemistry and stratigraphy of the Challenger Gold Deposit. CRC LEME Restricted Report 78R, 2 Volumes. 95 pp and Appendices (un-paginated).

Lintern, M.J. and Sheard, M.J., 1999. Regolith geochemistry and stratigraphy of the Challenger gold deposit. Mines and Energy Resources South Australia Quarterly Journal (MESA Journal), 14, 9-14.

Lintern, M.J., Anand, R.R., 2007 (compliers). Field Guide for AMIRA Project P778 Eastern Goldfields (WA). CRC LEME Restricted Report 281R/E7M Report P2007/1001 (unpaginated).

Lintern, M.J., Churchward, H.M. and Butt, C.R.M., 1990. Multi-element soil survey of the Mount Hope Area, Western Australia. CSIRO Division of Exploration Geoscience, Perth, Restricted Report 109R, 84 pp. (Reissued as Open File Report 40, CRC LEME, Perth, 1998).

Lintern, M.J., Downes, P.M. and Butt, C.R.M., 1992. Bounty and Transvaal Au deposits, Western Australia. In: Butt, C.R.M., Zeegers, H. (Eds.), Regolith Exploration Geochemistry in Tropical and Subtropical Terrains. Handbook of Exploration Geochemistry, vol. 4. Elsevier, Amsterdam, pp. 351–355.

Lintern, M.J., Craig, M.A., Walsh, D.M. and Sheridan, N.C., 1996. . The distribution of Au and other elements in surficial materials from the Higginsville palaeochannel Au deposits, Norseman, Western Australia. CSIRO Australia, Division of Exploration and Mining, Perth. Restricted Report 28R. CRC LEME/AMIRA Project 409: Yilgarn Transported Overburden. (Reissued as Open File Report 102, CRC LEME, Perth, 2001)

Lintern, M.J., Butt, C.R.M. and Scott, K.M., 1997. Gold in vegetation and soil - three case studies from the goldfields of southern Western Australia. Journal of Geochemical Exploration 58, 1–14

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. 75 pp.

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. 71 pp

Lintern, M.J., Sheard, M.J. and Gouthas, G., 2002. Preliminary regolith studies at ET, Monsoon, Jumbuck, South Hilga and Golf Bore Prospects, Gawler Craton, South Australia. CSIRO Exploration and Mining. Report 864R, 2 Volumes. 43 pp + 262 pp Appendices.

Lintern, M.J., Tapley, I.J., Sheard, M.J.,Craig, M.A.,Gouthas, G., and Cornelius, A.J., 2003. Regolith studies at Edoldeh Tank Gold Prospect. CRC LEME Open File Report 150, 2 Volumes. 392 p.

Lintern, M.J., Sheard, M.J. and Chivas, A.R. 2006. The source of pedogenic carbonate associated with Au-calcrete anomalies in the western Gawler Craton, South Australia. Chemical Geology 235, 299–324.

Lintern, M.J., Hough, R.M., Ryan, C.G., Watling, J. and Verrall, M., 2009. Ionic gold in calcrete revealed by LA-ICP-MS, SXRF and XANES. Geochimica et Cosmochimica Acta 73, 1666-1683.

Lintern, M.J., Kepic, A.W., Josh, M., 2009a. Using Ground Penetrating Radar to delineate sub-surface calcrete in the Great Victoria Desert, South Australia: implications for gold exploration. 24th International Applied Geochemistry Symposium, 2009, Fredericton, New Brunswick, Canada. Abstracts volume: p987-989.

Lintern, M.J., Robert M. Hough, Chris G. Ryan, John Watling and Michael Verrall, 2009b. Ionic gold in calcrete revealed by LA-ICP-MS, SXRF and XANES. Geochimica et Cosmochimica Acta 73, 1666-1683.

Lintern, M.J., Hough, R.H. and Ryan, C.G., 2011a. Experimental studies on the gold-in-calcrete anomaly at Edoldeh Tank Gold Prospect, Gawler Craton, South Australia. Journal of Geochemical Exploration (in press). DOI: 10.1016/j.gexplo.2011.08.008

Lintern, M.J., Sheard, M.J., Buller, N., 2011b. The gold-in-calcrete anomaly at the ET gold prospect, Gawler Craton, South Australia. Applied Geochemistry (in press). DOI :10.1016/j-apgeochem.2011.06.032

Loisy, C., Verrecchia, E.P. and Dufour, P., 1999. Microbial origin for pedogenic micrite associated with a carbonate paleosol (Champagne, France). Sedimentary Geology 126, 193–204.

Lyalikova, N.N. and Mockeicheva, L.Y. 1969. The role of bacteria in Au migration in deposits. Microbiology, 38, 682–686.

Ma, Y. and Rate, A. W., 2009. Formation of trace element biogeochemical anomalies in surface soils: the role of biota. Geochemistry: Exploration Environment Analysis 9, 353-367.

Machette, M.N., 1985. Calcic soils of the south-western United States. Geol. Soc. Am. Spec. Pap. No, vol. 203, pp. 1–21.

Machukera, J. and Paterson, P., 2009. Year in review. Carrick Gold Limited, Annual Report, 2009. http://www.carrickgold.com/qareports. (Last accessed 19th August 2010)

Madden, J., 1996. Regolith evolution and geochemical dispersion into transported overburden, Deep South Deposit, Mount Gibson, Western Australia. Honours Thesis. University of Western Australia. 48 pp.

Mahizhnan, A., 2004. Red-brown hardpan. Distribution, origin and exploration implications for gold in the Yilgarn Craton of Western Australia. PhD Thesis. Curtin University. 233 pp.

Magaritz, M. and Amiel, A.J., 1980. CaCO3 in a calcareous soil from the Jordan Valley, Israel. Its origin as revealed by the stable carbon isotope method. Soil Science Society of America Journal 44, 1059.

Magaritz, M., Kaufman, A. and Yaalon, D.H., 1981. CaCO3 nodules in soils: 18O/16O and 13C/12C ratios and 14C contents. Geoderma 25, 157–172.

Manceau, A., Marcus, M.A., Tamura, N., Proux, O., Geoffroy, N. and Lanson, B., 2004. Natural speciation of Zn at the micrometer scale in a clayey soil using x-ray fluorescence, absorption, and diffraction. Geochimica et Cosmochimica Acta 68, 2467-2483.

Manceau, A., Schlegel, M.L., Musso, M., Sole, V.A., Gauthier, C., Petit, P.E., and Trolard, F., 2000. Crystal chemistry of trace elements in natural and synthetic goethite. Geochimica et Cosmochimica Acta 64, 3643-3661.

Mann, A.W., 1984. Redistribution of gold in the oxidized zone of some Western Australian deposits in: Gold-mining, Metallurgy and Geology. Proceedings of the Regional Conference on Mining and Metallurgy, Perth and Kalgoorlie, October 1984. Australasian Institute of Mining and Metallurgy, pp 1-12.

Mann, A.W. and Deutscher, R.L., 1978. Genesis principles for the precipitation of carnotite in calcrete drainages in Western Australia. Economic Geology 73: 1724-37.

Mann A.W., Mann A.T., and Staltari S., 1998. Gold solubility in neutral-alkaline solutions. Minerals and Energy Research Institute of Western Australia Project Final Report M311, Perth, 57p.

Mann, A.W., Birrell, R.D., Fedikow, M.A.F., and De Souza, H.A.F., 2005. Vertical ionic migration: Mechanisms, soil anomalies, and sampling depth for mineral exploration. Geochemistry-Exploration Environment Analysis 5, 201-210.

Marion, G.M., Schlesinger, W.H., Fonteyn, P.J., 1985. Caldep: a regional model for soil CaCO3 (caliche) deposition in south western deserts. Soil Science 139, 468–481.

Markert, B. and Weckert, V., 1989. Fluctuations of element concentration during the growing season of *Polytrichum formosum*. Water, Air and Soil Pollution 43, 177–189.

Martin, A.R., 1997. The discovery of Au mineralisation at Tunkillia in the Gawler Craton. New Generation Gold Mines '97. Case Histories of Discovery. Conference Proceedings, Australian Mineral Foundation, Adelaide, Australia (unpaginated).

Mauger, A., Huntington, J.F. and Keeling, J. 2004. Mineral mapping and spectral logging of the Gawler Craton. In: ROACH, I.C. (ed.) Regional Regolith Symposia. CRC LEME, Canberra, 234.

Maxey (editor), 1997. Australian Gold Annual, 1997. 256 pp.

Mazzucchelli, R.H. and James, C.H., 1966. Arsenic as a guide to Au mineralisation in laterite-covered areas of Western Australia. Trans. Inst. Min. Metall., Section B, Appl. Earth Sci., 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 - Australia. Journal of Geochemical Exploration 12: 203-7.

McEntegart, L.B. and Schmidt Mumm, A., 2004. Gold mobility within dune systems on the Barns Prospect, Wudinna, South Australia: a partial extraction approach. In: Roach, I.C. (ed.) Regional Regolith Symposia. CRC LEME, Canberra, 235–240.

McFadden, L.D. and Tinsley, J., 1985. Rate and depth of pedogenic carbonate accumulation in soils: formulation and testing of a compartment model. Geological Society of America Special Paper 203, 23–42.

McFarlane, C.R.M, 2006. Palaeoproetrozoic evolution of the Challenger Au Deposit, South Australia, from monazite geochronology. Journal of Metamorphic Geology 24, 75–87.

McFarlane, C.R.M., Mavrogenes, J.A. and Tomkins, A.G., 2007. Recognizing hydrothermal alteration through a granulite facies metamorphic overprint at the Challenger Au Deposit, South Australia. Chemical Geology 243, 64-89.

McGeough, M. and Anderson, J.A., 1998. Discovery of the White Dam. Au-Cu mineralisation. AGSO Record 1998/25: 69-71.

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. 30 pp.

McGowran, B. and Li, Q., 1988. Cainozoic climate change and its implications for studying the Australian regolith. The State of the Regolith. Geological Society of Australia, pp. 86–103.

McInnes, B.I.A., Dunn, C.E., Cameron, E.M. and Kameko, L., 1996. Biogeochemical exploration for Au in tropical rain forest regions of Papua New Guinea. Journal of Geochemical Exploration 57, 227–243.

McQueen, K.G., 2006. Calcrete geochemistry in the Cobar-Girilambone Region, New South Wales. CRC LEME Perth Australia. Open File Report 200. 27 pp.

McQueen, K.G., Hill, S.M. and Foster, K.M. 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.

Melchior, A, Cardenas, J, and Dejonghe, L., 1994. Geomicrobiology applied to mineral exploration in Mexico. Journal of Geochemical Exploration 51, 193-212.

Melchior, A., Dejonghe, L. and Hughes, G., 1996. A geomicrobiological study of soils collected from auriferous areas of Argentina. Journal of Geochemical Exploration 56, 219-227.

Mikhailova, E.A. and Post, C.J., 2006. Stable carbon and oxygen isotopes of soil carbonates at depth in the Russian chernozem under different land use. Soil Science 171, 334–340.

Milham, P.J., Payne, T.E., Lai, B., Trautman, R.L., Cai, Z., Holford, P., Haigh, A.M. and Conroy, J.P., 2007. Can Synchrotron Micro-X-Ray Fluorescence Spectroscopy be used to map the distribution of cadmium in soil particles? Australian Journal of Soil Research 45, 624-628.

Miller, M., McLeod, R., Devlin, S. and Vinar, J., 1999. Discovery of the Ghost Crab Deposit, Kalgoorlie, Western Australia. New Generation Gold Mines '99, Perth, Western Australia. Australian Mineral Foundation. Conference Proceedings, p 127-141.

Milnes, A.R. and Hutton, J.T., 1983. Calcretes in Australia. In Soils, an Australian Viewpoint. London, CSIRO, Melbourne and Academic Press. Pp 119–162.

Milnes, A.R. and Ludbrook, N.H., 1986. Provenance of microfossils in aeolian calcarenites and calcretes in southern South Australia. Australian Journal of Earth Sciences 33, 145–159.

Monger, H.C., Cole, D.R., Gish, J.W. and Giordano, T.H., 1998. Stable carbon and oxygen isotopes in Quaternary soil carbonates as indicators of ecogeomorphic changes in the northern Chihuahuan Desert, USA. Geoderma 82, 137–172.

Monger, H.C., Daugherty, L.A., Lindemann, W.C. and Liddell, C.M., 1991. Microbial precipitation of pedogenic carbonate. Geology 19, 997–1000.

Morris. B.J. and Flintoft, M.W., 1999. Calcrete sampling of the Hawks Nest Prospect. Mines and Energy Resources South Australia Quarterly Journal (MESA Journal) 15, 5-7.

Mulec J., Kosi G., and Vrhovsek D., 2007. Algae promote growth of stalagmites and stalactites in karst caves (Skocjanske Jame, Slovenia). Carbonates and Evaporites 22, 6-9.

Munsell, 2000. Munsell® soil color charts. GretagMacbeth, New York. Unpaginated.

Murray, A.S. and Wintle, A.G., 2000. Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol. Radiation Measurements 32, 57–73.

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.

Nahon, D., Millot, G., Paquet, H., Ruellan, A. and Tardy, Y., 1977. Geochimie de la surface et formes du relief VII. Digestion et effacement des cuirasses ferrugineuses par les encroutements calcaires en pays aride, Sahara de Mauritanie. Scie. Geol. Bull., 30, 289-296.

Naiman, Z., Quade, J. and Patchett, P.J., 2000. Isotopic evidence for eolian recycling of pedogenic carbonate and variations in carbonate dust sources throughout the southwest United States. Geochimica et Cosmochimica Acta 64, 3099–3109.

Nakano, T., Jeon, S.R., Shindo, J., Fumoto, T., Okada, N. and Shimada, J., 2001. Sr isotopic signature in plant-derived Ca in rain. Water, Air and Soil Pollution 130, 769–774.

Netterberg, F., 1980. Geology of southern African calcretes: I. Terminology, description, macrofeatures and classification. Transactions of the Geological Society of South Africa 83, 255–283.

Neybergh, H., Moureau, Z., Gerard, P., Verraes, G. and Sulten, E., 1991. Utilisation des concentrations de *Bacillus cereus* dans les sols comme technique de prospection des gites auriferes. Chronique de la Recherche Miniere 502, 37-46.

Northcote, K.H., Hubble, G.D., Isbell, R.F., Thompson, C.H. and Bettenay, E., 1975. A description of Australian soils. CSIRO, Melbourne, Australia. 170 pp.

Noy-Meir, I., 1973. Desert ecosystems: environment and producers. Annual Review of Ecology and Systematics, 4, 25–51.

Nulsen, R.A., Bligh, K.J., Baxter, I.N., Solin, E.J. and Imrie, D.H., 1986. The fate of rainfall in a mallee and heath vegetated catchment in southern Western Australia. Australian Journal of Ecology, 11, 361–371.

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.

Oakes, B.W. and Hale, M., 1987. Dispersion patterns of carbonyl sulphide above mineral deposits. Journal of Geochemical Exploration, 28, 235–249.

Ong H.L. and Swanson V.E., 1969. Natural organic acids in the transportation, deposition and concentration of Au. Quarterly of the Colorado School of Mines 64, 395-425.

Parduhn, N. L. and Watterson, J. R.., 1984. Preliminary studies of *Bacillus cereus* distribution near a gold vein and a disseminated gold deposit. US Geological Survey. Open File Report 84-509. 8 pp.

Pares, Y. and Martinet, R., 1964. Intervention des bacteréries dans de cycle de l'or. Etude biologigue de phénomène. Bureau Recherches. Geologique Minieres (Fr.) Bull, vol. 3, pp. 1–29.

Pares, Y., Martinet, R., Cuper, J., Giraud, J., Loko, H., Gagnaire, L., Mauvieux, L., and Preira, M., 1965. Use of inexpensive culture media for gold solubilization by means of bacteria. Ann Inst Pasteur (Paris). 108, 674-681.

Parraga, J., Rivadeneyra, M.A., Martin-Garcia, J.M., Delgado, R., Delgado, G., 2004. Precipitation of carbonates by bacteria from a saline soil, in natural and artificial soil extracts. Geomicrobiology Journal 21, 55–66.

Paterson, D.J., Boldeman, J.W., Cohen D.D. and Ryan, C.G., 2007. Microspectroscopy beamline at the Australian Synchrotron. Australian Institute of Physics Congress Conference Proceedings 879, 864.

Pearce, N.J.G., Perkins, W.T., Westgate, J.A., Gorton, M.P., Jackson, S.E., Neal, C.R. and Chenery, S.P., 1997. A compilation of new and published major and trace element data for NIST SRM 610 and NIST SRM 612 glass reference materials. Geostandards Newsletter, 21, 115-144.

Pell, S.D., Chivas, A.R., and Williams, I.S., 1999. Great Victoria Desert: development and sand provenance. Australian Journal of Earth Sciences 46, 289-299.

Pendall, E., Amundson, R., 1990. The stable isotope chemistry of pedogenic carbonate in an alluvial soil from the Punjab, Pakistan. Soil Science 149, 199–211.

Phillips, S.E., Milnes, A.R., 1988. The Pleistocene terrestrial carbonate mantle on the southeastern margin of the St Vincents Basin, South Australia. Australian Journal of Earth Sciences 35, 463–481.

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.

Porto, C. G. and Hale, M., 1996. Mineralogy, morphology and chemistry of gold in the stone line lateritic profile of the Posse deposit, Central Brazil. Journal of Geochemical Exploration 57, 115-125.

Poszwa, A., Dambrine, E., Ferry, B., Pollier, B.and Loubet, M., 2002. Do deep tree roots provide nutrients to the tropical rainforest? Biogeochemistry 60, 97–118.

Potter, E.K., Stirling, C.H., Wiechert, U.H., Halliday, A.N. and Spotl, C., 2005. Uranium-series dating of corals in situ using Laser-Ablation MC-ICPMS. International Journal of Mass Spectrometry 240, 27-35.

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., (Editors). The geology of South Australia. Volume 1 The Precambrian. South Australia. Geological Survey. Bulletin. 54:171-197.

Quade, J., Chivas, A.R., McCulloch, M.T., 1995. Strontium and carbon isotope tracers and the origins of soil carbonate in South Australia and Victoria. Palaeogeography, Palaeoclimatology, Palaeoecology 113, 103–117.

Rainey, D. K. and Jones, B., 2009. Abiotic versus biotic controls on the development of the Fairmont Hot Springs carbonate deposit, British Columbia, Canada. Sedimentology 56, 1832-1857.

Rankin, L.R., Benbow, M.C., Fairclough, M.C. and Daly, S.J., 1996. BARTON, South Australia, sheet SH/53-9. South Australia. Geological Survey. 1:250,000 Series – Explanatory Notes. 44 pp.

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. Memoirs of the American Association of Petroleum Geologists 22, 250-282.

Rech, J.A., Quade, J., Hart,W.S., 2003. Isotopic evidence for the source of Ca and S in soil gypsum, anhydrite and calcite in the Atacama Desert, Chile. Geochimica et Cosmochimica Acta 67, 575–586.

Rehn, P. and Rehn, W., 1996. Mercury vapor anomalies at the Section 30 Deposit, Twin Creeks Mine, Nevada. In: Coyner, A.R. and Fahey, P.L. (eds) Geology and ore deposits of the Amercian Cordillera: Geological Society of Nevada Symposium Proceedings, Reno/Sparks, Nevada, April 1995, 30. Geological Society of Nevada, USA, 769–778.

Reith F., 2003. Evidence for a microbially mediated biogeochemical cycle of Au - a literature review. CRC LEME, Perth, Australia, Advances in Regolith 2003, 336-341.

Reith, F., and McPhail, D.C., 2006. Effect of resident microbiota on the solubilization of Au in soil from the Tomakin Park Gold Mine, New South Wales, Australia. Geochimica et Cosmochimica Acta 70, 1421–1438.

Reith, F. and Scmidt-Mumm, A., 2007. Microbially mediated formation of gold in calcrete anomalies in Australia. Goldschmidt Conference Abstracts, A831.

Reith, F., Mcphail, D.C. and Christy, A.G., 2005. *Bacillus cereus*, gold and associated elements in soil and other regolith samples from Tomakin Park Gold Mine in Southeastern New South Wales, Australia. Journal of Geochemical Exploration 85, 81-98.

Reith, F., Lengke, M.F., Falconer, D., Craw, D. and Southam, G., 2007. The geomicrobiology of Au. ISME Journal 1, 567-584.

Reith, F., Wakelin, S. A., Gregg, A. L., and Mumm, A. S., 2009. A microbial pathway for the formation of gold-anomalous calcrete. Chem. Geol. 258, 315-326.

Reuter J. H. and Perdue E.M., 1977. Importance of heavy metal-organic matter interactions in natural waters. Geochimica et Cosmochimica Acta 41, 325-334.

Rhodes, E., 2005. Project summary – ET Gold Prospect. Unpublished report. 19 p.

Rhodes, E., Fitzsimmons, K., Magee, J., Chappell, J., Miller, G., Spooner, N., 2004. The history of aridity in Australia: preliminary chronological data. In: Roach, I.C. (Ed.), Regolith 2004. Conference Abstracts. Canberra, Cooperative Research Centre for Landscape Environments and Mineral Exploration. CRC LEME, pp. 299–302.

Rhodes, E.J., 1988. Methodological considerations in the optical dating of quartz. Quaternary Science Reviews, 7, 395–400.

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. CSIRO Australia. Division of Exploration Geoscience, Perth. Restricted Report 232R. (Reissued as Open File Report 31, CRC LEME, Perth, 1998) 52p.

Robertson, I.D.M., King, J.D. and Anand, R.R., 2001. Regolith geology and geochemical exploration around the Stellar and Quasar gold deposits, Mt Magnet, Western Australia. Geochemistry: Exploration, Environment, Analysis 1, 353-364.

Rodgers P.B. and Knowles C.J., 1978. Cyanide production and degradation during growth of *Chromobacterium violaceum*. Journal of General Microbiology 108, 261-267.

Rose, A.W., Hawkes, H.E. and Webb, J.S., 1979. Geochemistry in Mineral Exploration. Academic Press, London. 657 p.

Rosylakov, N.A., Peshevitsky, B.I., Nepeya, L.A. and Tsimbalist, V.G., 1971. Geochemistry of Au in the processes of weathering crust formation. Int. Geochem. Congr., Moscow, Abstracts of reports II, 719-720.

Roy, A., 2009. Calcrete to kimberlite: A prospector's hunt for "kimberlite traits" in calcretes. Journal of the Geological Society of India 73, 320-324.

Ryan, C.G., 2000. Quantitative trace element imaging using PIXE and the nuclear microprobe. International Journal of Imaging Systems and Technology 11, 219-230.

Ryan, C.G. and Jamieson, D.N., 1993. Dynamic analysis: on-line quantitative PIXE microanalysis and its use in overlap-resolved elemental mapping. Nuclear Instruments and Methods in Physics Research Section B B77, 203-214.

Ryan, C.G., Etschmann, B.E., Vogt, S., Maser, J., Harland, C.L., Van Achterbergh, E. and Legnini, D., 2005. Nuclear Microprobe -Synchrotron synergy: towards integrated quantitative real-time elemental imaging using PIXE and SXRF. Nuclear Instruments and Methods in Physics Research Section B B231, 183-188.

Ryan, C.G., Siddons, D.P., Moorhead, G., Dunn, P., Kirkham, R., Dragone, A., De Geronimo, G., Hough, R. and Etschmann, B.E., 2006. The next generation of synchrotron fluorescence imaging for geological applications. Geochimica et Cosmochimica Acta 70, A550.

Ryan, C.G., Etschmann, B.E. and Cousens, D.R., 2007. GeoPIXE SXRF/PIXE quantitative analysis and imaging software. http://nmp.csiro.au/GeoPIXE.html. Last accessed 6th October 2010.

Ryan, C.G., Siddons, D.P., Kirkham, R., Dunn, P.A., Kuczewski, A., Moorhead, G., De Geronimo, G., Paterson, D.J., de Jonge, M.D., Hough, R.M., Lintern, M.J., Howard, D.L., Kappen P. and Cleverley, J., 2010. The New Maia Detector System: Methods for High Definition Trace Element Imaging of Natural Material, Australian Institute of Physics Congress Conference Proceedings, 1221, 9-17.

Sage, A., 2010. Corvette Prospect, Plumridge Project. Corvette Resources Limited. http://www.corvetteresources.com.au/. (Last accessed 19th August 2010)

Salehi, M.H., Khademi, H., Eghbal, M.K. and Mermut, A.R., 2004. Stable isotope geochemistry of carbonates and organic carbon in selected soils from Chaharmahal Bakhtiari Province, Iran. Communications in Soil Science and Plant Analysis 35, 1681–1697.

Salomons, W., Goudie, A. and Mook, W.G., 1978. Isotopic composition of calcrete deposits from Europe, Africa and India. Earth Surface Processes 3, 43–57.

Salomons, W. and Mook,W.G., 1986. Isotope geochemistry of carbonates in the weathered zone. In: P.Fritz, J., Fontes, Ch. (Eds.), Handbook of Environmental Isotope Geochemistry, vol 2. Elsevier, Amsterdam, pp. 239–269.

Salpeteur, I. and Sabir, H., 1989. Orientation studies for gold in the central pediplain of the Saudi Arabian shield. *Journal of Geochemical Exploration* **34**, 189-215.

Sato, M., 1960a. Oxidation of sulphide ore bodies: 1. Geochemical environments in terms of Eh and pH. Economic Geology 55, 928-961.

Sato, M., 1960b. Oxidation of sulphide ore bodies: 2. Oxidation mechanisms of sulphide minerals at 25oC. Economic Geology 55, 1202-1231.

Scagel, R., 1995. Applied geochemical prospecting: plants. In: Applied Biogeochemistry in Mineral Exploration and Environmental Studies. Notes to accompany course held on 13–14th May, 1995, in conjunction with the 17th International Geochemical Exploration Symposium, Townsville, Australia.

Schiller, P., Cook, G.B., Kitzinger-Skalova, A. and Wolf, E., 1973. The influence of seasonal variation for Au determination in plants by neutron activation analysis. Radiochemistry and Radioanalytical Letters, 13, 238–286.

Schmid, S., Worden, R.H., Fisher, Q.J., 2006. Variations of stable istopes with depth in regolith calcite cementa in the Broken Hill region, Australia: palaeoclimate evolution signal? Journal of Geochemical Exploration 89, 355–358.

Schmidt Mumm A. and Reith F., 2007. Biomediation of calcrete at the Au anomaly of the Barns prospect, Gawler Craton, South Australia. Journal of Geochemical Exploration 92, 13-33.

Schultz, J.L., Boles, J.R., Tilton, G.R., 1989. Tracking Ca in the San Joaquin Basin, California. A Sr isotopic study of carbonate cements at North Coles Levee. Geochimica et Cosmochimica Acta 53, 1991–1999.

Semeniuk, V and Meagher, T.D., 1981. Calcrete in Quaternary coastsal dunes in southwestern Australia: a capillary-rise phenomenon associated with plants. Journal of Sedimentary Petrology 51, 47-68.

Semeniuk, V. and Searle, D.J., 1985. Distribution of calcrete in Holocene coastal sands in relationship to climate, southwestern Australia. Journal of Sedimentary Petrology, 55, 86–95.

Semmel, W. D., 1982. Calcretes in Namibia and SE Spain; relations to substratum soil formation and geomorphic factors. Aridic Soils and Geomorphic Processes. Catena Supplement 2, 123-140.

Sergeev, N.B. and Gray D.J., 2001. Gold mass balance in the regolith, Mystery Zone, Mt Percy, Kalgoorlie, Western Australia. Geochemistry: Exploration, Environment, Analysis 1, 307-312.

Sheard, M.J., 2007. Regolith characterisation as an aid to mineral exploration in the Wudinna North Area, Central Gawler Province, South Australia, Volume 1. CRC LEME Open File Report 232. pp 53-54.

Sheard, M.J., Lintern, M.J., Prescott, J.R. and Huntley, D.J., 2006. Great Victoria Desert: new dates for South Australia's ?oldest desert dune system. Department of Primary Industries and Resources, South Australia. Mines and Energy South Australia Journal 42, 15-26.

Sibson, R.H. 2001. Seismographic framework for hydrothermal transport and ore deposition. In: Richards ,J.P. and Tosdal, R.M. (eds) Structural Controls on Ore Genesis. Reviews in Economic Geology, 14. Society of Economic Geologists, Boulder, Colorado, 25–50.

Singh, B., Sherman, D.M., Gilkes, R.J., Wells, M. and Mosselmans, J.F.W., 2000. Structural chemistry of Fe, Mn, and Ni in synthetic hematites as determined by Extended X-Ray Absorption Fine Structure Spectroscopy. Clays and Clay Minerals 48, 521-527.

Singh, B.P., Lee, Y., Pawar, J.S. and Charak, R. S., 2007. Biogenic features in calcretes developed on mudstone: examples from paleogene sequences of the Himalaya, India. Sedimentary Geology 201, 149-156.

Sipa Resources Ltd, 2007. Last accessed on 25th August http://members.iinet.net.au/~sipa/woodline.php

Smee B.W., 1998 A new theory to explain the formation of soil geochemical responses over deeply covered Au mineralisation in arid environments. Journal of Geochemical Exploration 61, 149-172.

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. Pp 4-7.

Smith A.D. and Hunt R.J., 1985. Solubilisation of Au by *Chromobacterium violaceum*. Journal of Chemical Technology and Biotechnology 35B, 110-116.

Smith B.A., Eggleton R.A., and Lintern M.J., 1996. Trace element geochemistry of calcretes: a guide for geochemical exploration. Regolith '96. The state of the regolith. Second Australian Conference on Landscape Evolution and Mineral Exploration. CRC LEME, Perth, Australia, Abstracts p46.

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, B.H. and Keele, R.A., 1984. Some observations on the geochemistry of Au mineralisation in the weathered zone at Norseman, Western Australia. Journal of Geochemical Exploration 22: 1-20.

Smith, B.W., Aitken, M.J., Rhodes, E.J., Robinson, P.D. and Geldard, D.M., 1986. Optical dating: methodological aspects. Radiation Protection Dosimetry 17, 229–233.

Smith, B.W., Rhodes, E.J., Stokes, S., Spooner, N.A. and Aitken, M.J., 1990. Optical dating of sediments: initial results from Oxford. Archaeometry 32, 19–31.

Smith, R.E., Anand, R.R., Churchward, H.M., Robertson, I.D.M., Grunsky, E.C., Gray, D.J., Wildman, J.E. and Perdrix, J.L., 1992. Laterite geochemistry for detecting concealed mineral deposits, Yilgarn Craton, Western Australia. CSIRO Division of Exploration Geoscience, Restricted Report 236R (Reissued as Open File Report 50, CRC LEME, Perth, 1998).

Smith, S.C., Kretschmer, E.L., 1992. Gold patterns in big sagebrush over the CX and Mag deposits, Pinson Mine, Humboldt County, Nevada. Journal of Geochemical Exploration 46, 147–161.

Sneath, P.H.A., 1972. Identification methods applied to *Chromobacterium*. In: Identification methods for microbiologists (eds. F.A. Skinner and D.W. Lovelock). London, Academic Press. p15-20.

Sneath, P.H.A., 1986. Endospore-forming Gram-positive rods and cocci in: Sneath, P. H. A., Mair, N. S., Sharpe, M. E., and Holt, J. G. (eds.) Bergey's Manual of Systematic Bacteriology vol 2, Williams and Wilkins, Baltimore. p1105-1139.

Sokoloff, V. P., 1949. Geochemical studies in Western Australia - Bullfinch and Kalgoorlie. Second Progress Report. Western Mining Company. Report No. K799. 30 p. Unpublished.

Specht, R.L., 1966. The growth and distribution of mallee–broombush (*Eucalyptus incrassata–Melaleuca uncinata* association) and heath vegetation near Dark Island Soak, Ninety-Mile Plain, South Australia. Australian Journal of Botany, 14, 361–371.

Stanley, C.R. and Noble, R.R.P., 2007. Optimizing geochemical threshold selection while evaluating exploration techniques using a minimum hypergeometric probability method. Geochemistry: Exploration, Environment, Analysis 7, 341-351.

Stanley, C.R., 2003. Statistical evaluation of anomaly recognition performance. Geochemistry: Exploration, Environment, Analysis 3, 3–12.

Stednick, J.D. and Riese, W.C., 1987. Temporal variation of metal concentrations in biogeochemical samples over the Royal Tiger Mine, Colorado, part II. Between-year variation. Journal of Geochemical Exploration 27, 53–62.

Stednick, J.D., Klem, R.B. and Riese, W.C., 1987. Temporal variation of metal concentrations in biogeochemical samples over the Royal Tiger Mine, Colorado, part I: Within year variation. Journal of Geochemical Exploration 29, 75–88.

Stevenson, B.A., Kelly, E.F., McDonald, E.V. and Busacca, A.J., 2005. The stable carbon isotope composition of soil organic carbon and pedogenic carbonates along a bioclimatic gradient in the Palouse Region, Washington State, USA. Geoderma 124, 37–47.

Stokes, S., Thomas, D.S.G. and Washington, R.W., 1997. Multiple episodes of aridity in southern Africa since the last interglacial period. Nature 388, 154–159.

Teasdale, J., 1997. Method for understanding poorly exposed terranes: the interpretative geology and tectonothermal evolution of the western Gawler Craton. Thesis. University of Adelaide, Adelaide (unpublished).

Teasdale, J., 1997. Methods for understanding poorly exposed terranes: the interpretive geology and tectonothermal evolution of the Western Gawler Craton. PhD Thesis. Geology and Geophysics, University of Adelaide, Adelaide, unpublished.

Thiede, D.S., Windle, S.J., Hall, G.E.M., McClenaghan, M.B. and Hamilton, S., 2005. SDP soil-gas geochemistry at Cross Lake, Ontario. In: 22nd IGES, Perth, Australia. Abstracts volume. Promaco Conventions Pty Ltd.

Thompson, C.H., 1981. Podzol chronosequences on coastal dunes of eastern Australia. Nature 291, 59–61.

Thompson, C.H., 1983. Development and weathering of large parabolic dune systems along the subtropical coast of eastern Australia. Zeitschrift für Geomorphologie N.F. Supplement, 45, 205–225.

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. 144 pp.

Tiller, K.G., Smith, L.H., Merry, R.H., 1987. Accessions of atmospheric dust east of Adelaide, South Australia, and the implications for paedogenesis. Australian Journal of Soil Research 25, 43–54.

Toens, P.D. and Hambleton-Jones, B.B., 1984. Definition and classification of surficial uranium deposits. Surficial Uranium Deposits. International Atomic Energy Agency, Vienna, pp. 9-14.

Tomkins, A.G., Dunlap, W.J., Mavrogenes, J.A., 2004. Geochronological constraints on the polymetamorphic evolution of the granulite-hosted Challenger Gold Deposit: implications for assembly of the northwest Gawler Craton. Australian Journal of Earth Sciences 51, 1–14.

Tomkins, A.G., Mavrogenes, J.A., 2002. Mobilization of Au as a polymetallic melt during pelite anatexis at the Challenger deposit, South Australia: a metamorphosed Archaean Au deposit. Economic Geology 97, 1249–1271.

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.

Tourney, J. and Ngwenya, B.T., 2009. Bacterial extracellular polymeric substances (EPS) mediate $CaCO_3$ morphology and polymorphism. Chemical Geology 262, 138-146.

Treble, P.C., Chappell, J., Gagan, M.K., McKeegan, K.D., Harrison, T.M., 2005. In situ measurement of seasonal $\delta^{18}O$ variations and analysis of isotopic trends in a modern speleotherm from southwest Australia. Earth and Planetary Science Letters 233, 17–32.

Van Der Hoven, S.J., Quade, J., 2002. Tracing spatial and temporal variations in the sources of calcium in pedogenic carbonates in a semiarid environment. Geoderma 108, 259–276.

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, pp 113-124.

Van Zuidam, R.A., 1976. Geomorphological development of the Zaragoza region, Spain. Thesis, State University of Utrecht.

Verboom W. H. and Pate J. S., 2006. Evidence of active biotic influences in pedogenetic processes: case studies from semiarid ecosystems of south-west Western Australia. Plant and Soil 289, 103-121.

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. 136 pp. (unpublished)

Walker, J., Thompson, C.H., Fergus, I.F. and Tunstall, B.R., 1981. Plant succession and soil development in coastal sand dunes of subtropical eastern Australia. In: Forest Succession. Spinger, New York, pp 107–131.

Walker, S.R., Jamieson, H.E., Lanzirotti, A., Andrade, C.F. and Hall, G.E.M., 2005. The speciation of arsenic in iron oxides in mine wastes from the Giant Gold Mine, N.W.T.: application of synchrotron micro-xrd and micro-XANES at the grain scale. Canadian Mineralogist 43, 1205-1224.

Wang, H.M., Yang, F.Q., S.C. Xie and Zhou, Q.W., 1999. Soil *Bacillus cereus* serving as an indicator of gold mineralization related to underlying gold deposits in northwestern Sichuan province, Earth Science Journal, China University. Geoscience 24, 78–82 (Suppl., in Chinese with English abstract).

Wang, Y., Nahon, D., and Merino, E., 1994. Dynamic model of the genesis of calcretes replacing silicate rocks in semi-arid regions. Geochimica Et Cosmochimica Acta 58, 5131-5145.

Wasson, R.J., Fitchett, K., Mackey, B., and Hyde, R., 1988. Large-scale patterns of dune type, spacing and orientation in the Australian continental dunefield. Australian Geographer 19, 89-104.

Watterson, J.R., 1985. A procedure for estimating *Bacillus cereus* spores in soil and stream-sediment samples - a potential exploration technique. Journal of Geochemical Exploration 23, 243-252.

Watts, N.L., 1978. Displacive calcite: Evidence from recent and ancient calcretes. Geology 6, 699-703.

Watts, N.L., 1980. Quaternary pedogenic calcretes from the Kalhari (southern Africa): mineralogy, genesis and diagenesis. Sedimentology 27, 661–686.

Whipkey, C.E., Capo, R.C., Hsieh, J.C.C., Chadwick, O.A., 2002. Development of magnesian carbonates in Quaternary soils on the island of Hawaii. Journal of Sedimentary Research 72, 163–170.

Whittaker, R.H., 1975. Communities and Ecosystems. Macmillan, Toronto.

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.

Wilson, I.G., 1973. Ergs. Sedimentary Geology 10, 77–106.

Woo, K.S. and Khim, B.K., 2006. Stable oxygen and carbon isotopes of carbonate concretions of the Miocene Yeonil Group in the Pohang Basin, Korea: types of concretions and formation condition. Sedimentary Geology 183, 15–30.

Woodhead, J.D., Hellstrom, J., Hergt, J.M., Greig, A. and Maas, R., 2007. Isotopic and elemental imaging of geological materials by LA-ICP-MS. Geostandards and Geoanalytical Research 31, 331-343.

Wright, V.P, Platt, N.H. and Wimbledon, W.A., 1988. Biogenic laminar calcretes: evidence of calcified root-mat horizons in paleosols. Sedimentology 35, 603-620.

Wright, V.P., Platt, N.H., Marriott, S.B. and Beck, V.H., 1995. A classification of rhizogenic (root-formed) calcretes, with examples from the Upper Jurassic–Lower Cretaceous of Spain and Upper Cretaceous of Southern France. Sedimentary Geology 100, 143–158.

Xiaoqing Z. and Zhonggang W., 2002. Gold occurrence and ore genesis, Yata micro-disseminated Au deposit, Guizhou, Southwest China. Chinese Journal of Geochemistry 21, 370-373.

Yaalon, D.H., 1983. Climate, Time, and Soil Development. In "Pedogenesis and Soil Taxonomy, I. Concepts and Interactions" (Editors L.P. Wilding, N.E. Smeck and G.F. Hall). Elsevier, Amsterdam - Oxford - New York, pp 233-251.

Yang, B.X., Rivers, M., Schildkamp, W. and Eng, P.J., 1995. GeoCARS microfocussing Kirkpatrick-Baez mirror bender development. Review of Scientific Instruments 66, 2278.

Yang, Y.H., Sun, J.F., Xie, L.W., Fan, H.R. and Wu, F.Y., 2008. In Situ Nd isotopic measurement of natural geological materials by LA-MC-ICPMS. Chinese Science Bulletin 53, 1062-1070.

Yong, C. and Tong, L., 1985. Application of mercury survey technique over the mausoleum of Emperor Qin Shi Huang. Journal of Geochemical Exploration 23, 61–69.

Ypma, P. J., 1991. The concentration of gold in calcrete and its significance for lower Proterozoic gold-uranium mineralization in: Pagel, M. and Leroy, J.L. (Eds.) 25th Anniversary Meeting of the Society for Geology Applied to Mineral Deposits: Source, transport and deposition of metals. A. A. Balkema, Nancy, France, pp 719-722.

Zechmeister, H.G., Hohenwallner, D., Riss, A. and Hanus-Illnar, A., 2003. Variations in heavy metal concentrations in the moss species *Abietinella abietina* (Hedw.) Fleisch. according to sampling time, within site variability and increase in biomass. The Science of The Total Environment, 301, 55–65.

Zhilin O.V., Egorova L.N., and Kuimova N.G., 2004. *Micromycetes* of Au ore and placer deposits in the Amur Area. Mikologiya I Fitopatologiya 38, 34-39.

Zhou, J. and Chafetz, H.S., 2009. Biogenic caliches in Texas: The role of organisms and effect of climate. Sedimentary Geology 222, 207-225.

Statement

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APPENDICES

1. Extended literature review published as a book chapter:

Lintern M.J., 2002. Calcrete sampling for mineral exploration. In Calcrete: characteristics, distribution and use in mineral exploration (eds. X.Y. Chen, M.J. Lintern and I.C. Roach). CRC LEME, Perth, Australia, 31-109.

2. List of papers and book chapters related to the thesis topic authored or co-authored by the author since candidacy

Butt, C.R.M., Lintern, M.J. and Bristow, A.P.J., 2005. Safari Bore Gold Deposit, Western Australia. IN: Butt, C. R. M.; Robertson, I. D. M.; Cornelius, M., and Scott, K. M., editors. Regolith expression of Australian ore systems. Perth: CRC LEME. pp.328-329. (also published on CRC LEME website in 2004 http://www.crcleme.org.au/Pubs/Monographs/RegExpOre.html).

Gray, D.J. and Lintern, M.J., 2005. Granny Smith gold deposits, Western Australia. IN: Butt, C. R. M.; Robertson, I. D. M.; Cornelius, M., and Scott, K. M., editors. Regolith expression of Australian ore systems. Perth: CRC LEME. pp.256-258. (also published on CRC LEME website in 2005 http://www.crcleme.org.au/Pubs/Monographs/RegExpOre.html)

Josh, M., Lintern, M.J., Kepic, A.W. and Verrall, M., 2011. Impact of grain-coating iron minerals on dielectric response of quartz sand and implications for ground-penetrating radar. Geophysics. Vol. 76: 1–8

Lintern, M.J. (compiler), 2004. The South Australian Regolith Project final report-summary and synthesis. CRC LEME Perth, Australia, Open File Report 156. 41 p.

Lintern, M.J., 2005a. Birthday gold prospect, Gawler Craton, South Australia in: Butt, C.R.M.; Robertson, I.D.M.; Cornelius, M., and Scott, K.M., (Eds) Regolith expression of Australian ore systems. Perth: CRC LEME. pp.219-221 (also published on CRC LEME website in 2003 http://www.crcleme.org.au/Pubs/Monographs/RegExpOre.html). (Last accessed 19th August 2010).

Lintern, M.J., 2005b. Bounty gold deposit, Forrestania Greenstone Belt, Western Australia. IN: Butt, C. R. M.; Robertson, I. D. M.; Cornelius, M., and Scott, K. M., editors. Regolith expression of Australian ore systems. Perth: CRC LEME. pp.225-227. (also published on CRC LEME website in 2004 http://www.crcleme.org.au/Pubs/Monographs/RegExpOre.html)

Lintern, M.J., 2005c. Challenger gold prospect, Gawler Craton, South Australia in: Butt, C.R.M.; Robertson, I.D.M.; Cornelius, M., and Scott, K.M., (Eds) Regolith expression of Australian ore systems. Perth: CRC LEME. pp.236-238. (also published on CRC LEME website in 2004 http://www.crcleme.org.au/Pubs/Monographs/RegExpOre.html). (Last accessed 19th August 2010).

Lintern, M.J., 2005d. Challenger gold deposit area, South Australia. IN : Anand, R. R. and de Broekert, P., editors. Regolith-Landscape evolution across Australia. Perth: CRC LEME. pp.208-213. (also published on CRC LEME website in 2003 http://www.crcleme.org.au/Pubs/Monographs/RegLandEvol.html)

Lintern, M.J., 2005e. Higginsville palaeochannel gold deposits, Kambalda, Western Autralia. IN: Butt, C. R. M.; Robertson, I. D. M.; Cornelius, M., and Scott, K. M., editors. Regolith expression of Australian ore systems. Perth: CRC LEME. pp.264-266. (also published on CRC LEME website in 2004 http://www.crcleme.org.au/Pubs/Monographs/RegExpOre.html)

Lintern, M.J., 2005f. Steinway gold deposit, W.A. in Butt, C.R.M.; Robertson, I.D.M.; Cornelius, M., and Scott, K.M., (Eds) Regolith expression of Australian ore systems. Perth: CRC LEME. pp.330-332. (also published on CRC LEME website in 2004 http://www.crcleme.org.au/Pubs/Monographs/RegExpOre.html). (Last accessed 19th August 2010).

Lintern, M.J., 2005g. Zuleika Sands gold deposit, Ora Banda, WA. IN: Butt, C. R. M.; Robertson, I. D. M.; Cornelius, M., and Scott, K. M., editors. Regolith expression of Australian ore systems. Perth: CRC LEME. pp.354-356. (also published on CRC LEME website in 2004 http://www.crcleme.org.au/Pubs/Monographs/RegExpOre.html)

Lintern, M.J., 2007. Vegetation controls on the formation of gold anomalies in calcrete and other materials at the Barns Gold Prospect, Eyre Peninsula, South Australia. Geochemistry: Exploration, Environment and Analysis 7, 249-266.

Lintern, M.J., Sheard, M.J. and Gouthas, G., 2002. Preliminary regolith studies at ET, Monsoon, Jumbuck, South Hilga and Golf Bore Prospects, Gawler Craton, South Australia. CSIRO Exploration and Mining. Report 864R, 2 Volumes. 43 pp + 262 pp Appendices.

Lintern, M.J., Tapley, I.J., Sheard, M.J.,Craig, M.A.,Gouthas, G., and Cornelius, A.J., 2003. Regolith studies at Edoldeh Tank Gold Prospect. CRC LEME Open File Report 150, 2 Volumes. 392 p.

Lintern, M.J., Sheard, M.J. and Chivas, A.R. 2006. The source of pedogenic carbonate associated with Au-calcrete anomalies in the western Gawler Craton, South Australia. Chemical Geology 235, 299–324.

Lintern, M.J., Hough, R.M., Ryan, C.G., Watling, J. and Verrall, M., 2009. Ionic gold in calcrete revealed by LA-ICP-MS, SXRF and XANES. Geochimica et Cosmochimica Acta 73, 1666-1683.

Lintern, M.J., Hough, R.H. and Ryan, C.G., 2011. Experimental studies on the gold-in-calcrete anomaly at Edoldeh Tank Gold Prospect, Gawler Craton, South Australia. Journal of Geochemical Exploration (in press). DOI: 10.1016/j.gexplo.2011.08.008

Lintern, M.J., Sheard, M.J., Buller, N., 2011. The gold-in-calcrete anomaly at the ET gold prospect, Gawler Craton, South Australia. Applied Geochemistry (in press). DOI :10.1016/j-apgeochem.2011.06.032

Scott, K. M. and Lintern, M. J., 2005. Panglo gold deposit, Western Australia. IN: Anand, R. R. and de Broekert, P., editor. Regolith-Landscape evolution across Australia. Perth: CRC LEME. pp.344-346. (also published on CRC LEME website in 2003 http://www.crcleme.org.au/Pubs/Monographs/RegLandEvol.html).

Sheard, M.J., Lintern, M.J., Prescott, J.R. and Huntley, D.J., 2006. Great Victoria Desert: new dates for South Australia's ?oldest desert dune system. Department of Primary Industries and Resources, South Australia. MESA Journal 42: 15-26.

Skwarnecki, M.S. and Lintern, M.J., 2005. Blue Rose Au-Cu Prospect, South Australia. IN: Butt, C. R. M.; Robertson, I. D. M.; Cornelius, M., and Scott, K. M., editors. Regolith expression of Australian ore systems. Perth: CRC LEME. pp.359-361. (also published on CRC LEME website in 2004 http://www.crcleme.org.au/Pubs/Monographs/RegExpOre.html).

3. List of conference papers, abstracts and presentations related to the thesis topic authored or co-authored by the author since candidacy

Hough, R.M., Noble, R.R.P., Butt, C.R.M., Ryan, C.G. and Lintern, M.J., 2009. Tracing gold from the deeps to the surface. Proceedings of the 10th Biennial SGA Meeting of the Society for Geology Applied to Mineral Deposits. Editor: P.J. Williams et al. Townsville Australia, p716.

Noble, R.R.P., Grenik, E.M., Hough, R.M., Lintern, M.J., Gray, D.J., Hart, R., Clode, P. & Murphy, J., 2009. Morphology of gold nanoparticles synthesized from gold chloride and gold cyanide under evaporative conditions. Proceedings of the 24th International Applied Geochemistry Symposium, p. 193-196.

Lintern, M.J. 2004. Recent advances in the gold calcrete problem. CRC LEME MINEX symposium, Perth. Abstract. CRC LEME Perth

Lintern, M.J. 2005. Progress on anomaly formation in calcrete. CRC LEME MINEX symposium, Kalgoorlie. Abstract. CRC LEME Perth.

Lintern, M.J., 2006. There's gold in them thar sand hills! In: R.W. Fitzpatrick and P. Shand eds. Regolith 2006 - Consolidation and Dispersion of Ideas, CRC LEME, Perth, Western Australia, pp 215-216.

Lintern, M.J., 2007. Gold in calcrete - 20 years on. 5th Sprigg Symposium Mineral Deposits and Environment. Geological Society of Australia. Abstracts No. 87: 45-49.

Lintern, M.J. and Sheard, M.J., 2002. Regolith geochemistry and geochemical dispersion at the Challenger Gold Deposit. In: Geoscience 2002: Expanding horizons, 16th Australian Geological Convention Abstracts. p 424.

Lintern, M.J. and Rhodes, E., 2005. The dual role of vegetation in anomaly formation at Barns Gold Prospect, Eyre Peninsula, South Australia. 22nd International Geochemical Exploration Symposium, Perth, Western Australia. ISBN 1 86308 119 4. Abstract Volume, p72.

Lintern, M.J., Sheard, M.J. and Gouthas, G., 2004. Key findings from the South Australia Regolith Project. CRC LEME Regolith symposium, Adelaide. Abstract. CRC LEME Perth.

Lintern, M.J., Ryan, C.G. and Hough, R.M., 2009a. Gold in calcrete revealed. 24th International Applied Geochemistry Symposium, 2009, Fredericton, New Brunswick, Canada. Plenary presentation and Abstracts volume, p71-73.

Lintern, M.J., Ryan, C.G. and Hough, R.M., 2009b. Soluble ionic gold in soils. 24th International Applied Geochemistry Symposium, 2009, Fredericton, New Brunswick, Canada. Plenary presentation and Abstracts volume, p67-70.

Lintern, M.J., Hough, R.M., and Ryan, C.G., 2009. Mobile gold in soils. Goldschmidt, 2009, Davos, Switzerland. Presentation and abstracts volume, A770.

Lintern, M.J., Kepic, A.W., Josh, M., 2009. Using Ground Penetrating Radar to delineate sub-surface calcrete in the Great Victoria Desert, South Australia: implications for gold exploration. 24th International Applied Geochemistry Symposium, 2009, Fredericton, New Brunswick, Canada. Abstracts volume, p987-989.

Ryan, C.G., Kirkham, R., Hough R.M., Paterson D., Moorhead G., Lintern M.J., Siddons, D.P., de Jonge M.D., De Geronimo G., Howard D.L., Kappen, P. and Cleverley, J., 2009. "High definition elemental imaging of geological and environmental materials at the Australian Synchrotron", poster, Int. Conf. on Synchrotron Radiation Instrumentation (SRI2009), Melbourne, September 2009

Ryan, C.G., Siddons, D.P., Kirkham, R., Dunn P.A., Kuczewski, A., Moorhead G., De Geronimo G., Paterson D., de Jonge M.D., Hough R.M., Lintern M.J., Howard D.L., Kappen, P. and Cleverley, J., 2009. "The New Maia Detector System: Methods For High Definition Trace Element Imaging Of Natural Material", invited, Int. Conf. X-ray Optics and Microanalysis, Karlsruhe, September 2009, AIP Conference series, in press

Ryan, C.G., Kirkham, R., Siddons, D.P., Dunn P.A., Kuczewski, A., Moorhead G., De Geronimo G., Paterson D., de Jonge M.D., Howard D.L., Etschmann, B.E., Borg, S., Hough R.M., Cleverley J., Lintern M.J, Barnes, S.J., Davey P., Jensen M., 2010. The Maia X-ray detector array at the Australian Synchrotron: High definition SXRF trace element imaging. XRM2010: 10th International Conference on X-Ray Microscopy, Aug. 15-20, 2010, Chicago, Illinois USA.

Ryan, C.G., Kirkham, R., Siddons, D.P., Dunn P.A., Kuczewski, A., Moorhead G., De Geronimo G., Paterson D., de Jonge M.D., Howard D.L., Hough R.M., Cleverley J., Lintern M.J., Myers D., Davey P., Jensen M. and Laird, J., 2010. High definition trace element imaging of natural material using the new Maia X-ray detector array and processor. ICNMTA'2010, Leipzig, Germany.

Sheard, M.J. and Lintern, M.J., 2002. Exploration through transported cover and deeply weathered regolith, ET Gold Prospect, Gawler Craton, S.A. In: Geoscience 2002: Expanding horizons, 16th Australian Geological Convention Abstracts. p 312.

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