REGOLITH CARBONATE ACCUMULATIONS IN WESTERN AND CENTRAL NSW: CHARACTERISTICS AND POTENTIAL AS AN EXPLORATION SAMPLING MEDIUM

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ABSTRACT

Regolith carbonate accumulations (including calcretes and dolocretes) have become popular sampling media for gold exploration programs in parts of Western Australia and South Australia. In the Broken Hill and Cobar regions of eastern Australia regolith carbonates are also suitable sampling media for gold exploration providing the environmental conditions for their genesis are accounted for. Regolith carbonate chemistry, mineralogy, morphology and landscape setting are important features to consider as they reflect genetic environmental conditions associated with physical and chemical dispersion pathways. Regolith carbonate accumulations with morphologies reflecting a pedogenic origin (such as nodular facies) and featuring high Ca/Mg ratios (and correspondingly more calcite than dolomite) appear to have the strongest association with gold. This also corresponds with regolith carbonate accumulations that show the greatest amount of evidence for biological activity (such as calcified fungal hyphae, algal filaments and rhizomorphs), suggesting that biological processes sensitive to the more saline groundwaters encountered lower in the regolith are important in facilitating this relationship. The regolith carbonate accumulations also show well developed catenary differentiation indicating that landscape setting and lateral dispersion are major controls on the features of these materials. A major regional geographical division between a dominance of pedogenic regolith carbonate accumulations to the south and groundwater regolith carbonate accumulations to the north extends across central and western NSW. This division is similar to differences in flora, fauna, climate and other regolith features, observed along the Menzies Line in southern Western Australia. Rainfall seasonality and source have a profound influence on rainfall chemistry, and along with other commonly described chemical sources for regolith carbonate accumulations, appears to be an important contributor to the development and distribution of regolith carbonate accumulations. Regolith carbonate accumulations are perhaps best considered as representing a balance where the rate of supply of the required chemical constituents is greater than the rate of leaching and erosion. This means that considerable variability and complexity of regolith carbonate accumulation development may exist within a mosaic of variable environmental conditions, rather than simply reflectling single genetic controls such as climatic aridity.

Key words: Calcrete, Dolocrete, Calcite, Dolomite, Mineral Exploration, Gold, Regolith, Broken Hill, Cobar,

INTRODUCTION

Recent research on regolith carbonate accumulations in Australia has revealed their significance as a geochemical sampling medium for mineral exploration and provided the impetus for a sampling "feeding frenzy" (Lintern & Butt 1993; 1997). However many fundamental questions about these materials still remain. Furthermore, although regolith carbonates are abundant in many parts of eastern Australia there has been little consideration of the applicability of this research beyond Western Australia and South Australia. The recognition of suitable and comparable sampling media and the subsequent interpretations of their geochemistry depend upon an appreciation of the factors controlling physical and chemical dispersion pathways. As many of these dispersion pathways are controlled by the local environmental conditions, the environmental (including the palaeoenvironmental) significance of these materials needs to be accounted for. Some uncertainties or inconsistencies exist in the understanding of the environmental relationships associated with regolith carbonates. For example:

- previous studies mostly suggest that regolith carbonate accumulations, such as calcretes, reflect climatic aridity (e.g. Goudie 1983; Milnes 1992). In Australia however, regolith carbonates occur across southern Australia in both temperate and arid areas, but are more limited in distribution in many parts of central Australia that have experienced aridity throughout much of the Neogene and Quaternary;
- a wide range of genetic models and sources for the chemical constituents of regolith carbonate accumulations have been proposed, each with different chemical and physical dispersion pathways;
- at a basic level, the mineralogy of regolith carbonates reflects chemical and other environmental conditions related to physical and chemical dispersion characteristics. Understanding carbonate mineralogy is therefore of fundamental importance to assessing mineral exploration applications of these materials. There are few accounts relating regolith carbonate mineralogy to morphology and physical and chemical dispersion settings related to mineral exploration applications (e.g. Hill et al., 1998);
- there are many reports of so-called "false anomalies" where anomolous carbonate chemistry cannot be related to an underlying mineralisation source. Furthermore some regolith carbonate accumulations located above mineralisation may not feature anomalous geochemistry. Rather than being "red herrings", some of these "false anomalies" could represent cases where the chemical and physical dispersion pathways are not well constrained or understood; and,
- a fundamental influence on the environmental controls on regolith dispersion patterns is the regolith-landform setting. There appears to be some uncertainty regarding the importance of landscape setting for determining features of regolith carbonate accumulations (e.g. Milnes 1992, p.340) and in many studies landform setting is at best dealt with briefly.

This paper looks at some of the fundamental features of regolith carbonates in western and central NSW, particularly near the mining centres of Broken Hill and Cobar (Figure 1). Some of the relationships between regolith carbonates and environmental features and the significance of these to mineral exploration programs are then discussed.

TERMINOLOGY AND CLASSIFICATION

A wide range of terminologies and approaches to the classification of regolith carbonate materials have been used (see Goudie 1983 and Wright & Tucker 1991 for overviews, and more recent discussions in Anand et al. 1998; Hill et al. 1998). In this study the term "regolith carbonate accumulation" is used when referring to a mass of secondary carbonate minerals within the regolith. This is less misleading than the use of a word involving the suffix "crete" when applied in the general sense, embracing the wide range of carbonate compositions commonly encountered in the regolith. It also does not have the connotation of being associated with a fully indurated and surficial "crust", as many parts of the regolith enriched in carbonate minerals are soft and friable. The term "calcrete" is considered appropriate specifically for indurated regolith carbonate accumulations dominated by calcium carbonate (as intended in most definitions, e.g. Goudie 1983; Netterberg 1980). Similarly " dolocrete" and "magcrete" may be used for indurated regolith carbonate accumulations dominated by dolomite and magnesium respectively.

Genetic classification terms, such as "pedogenic" and "groundwater" carbonates are avoided when initially describing these materials, however they may be used when interpretations of genesis and hydrological setting are clear. For initial descriptions this study uses the morphological classification of Netterberg (1967; 1980) with some further aspects from the review by Wright & Tucker (1991) as the basis for field description of regolith carbonates. Although Netterberg interpreted these morphological forms as representing morphological stages of development, their initial use here is simply in a descriptive sense, followed by interpretations of genesis.

SOME FUNDAMENTAL FEATURES OF REGOLITH CARBONATE ACCUMULATIONS FROM WESTERN AND CENTRAL NEW SOUTH WALES

MORPHOLOGICAL CARBONATE FACIES

The description of the fundamental morphological facies of regolith carbonate accumulations are outlined from four profiles in the Broken Hill region (shown in Figure 1), and selected hand specimen descriptions from the Broken Hill and Cobar regions. The chemistry and mineralogy of these facies is also discussed and represented in Figure 2.

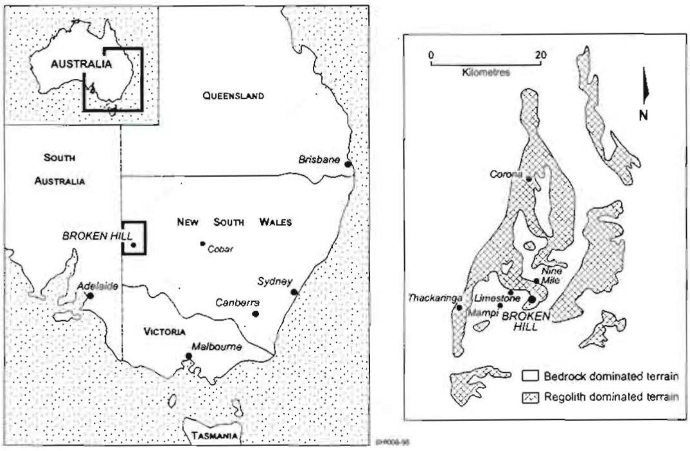

Figure 1: *Location of study sites in western New South Wales*

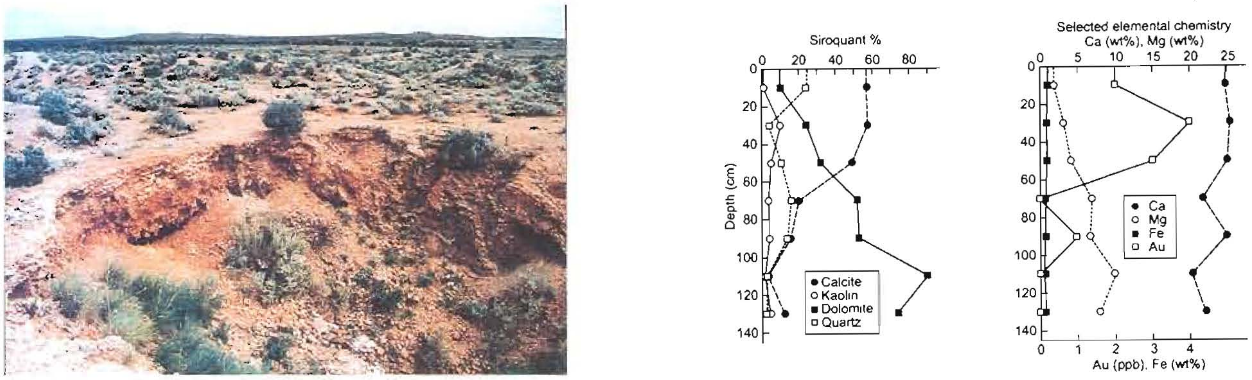

Figure 2(a): *Aspects of the chemistry, mineralogy and morphology of four regolith carbonate profiles from the Broken Hill region. a) Limestone Station Profile;*

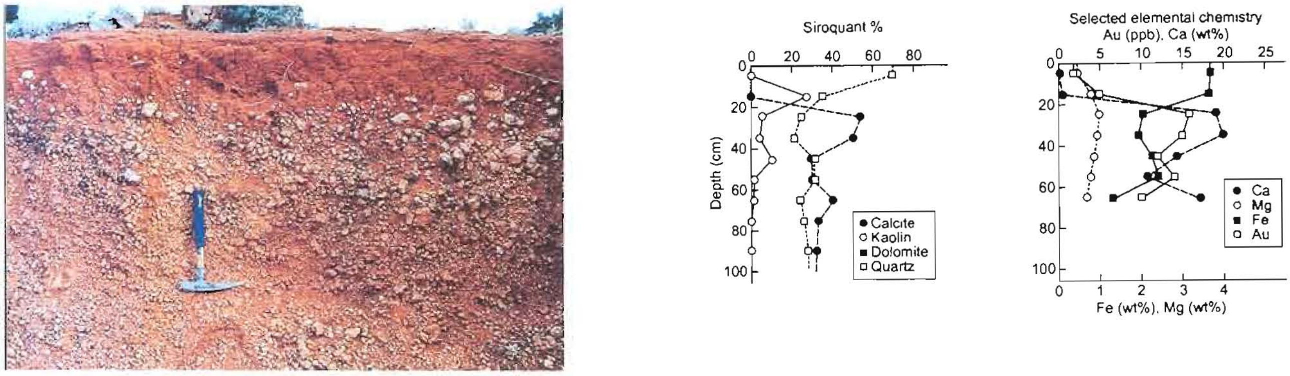

Figure 2(b): *Aspects of the chemistry, mineralogy and morphology of four regolith carbonate profiles from the Broken Hill region. b) Marnpi Profile*

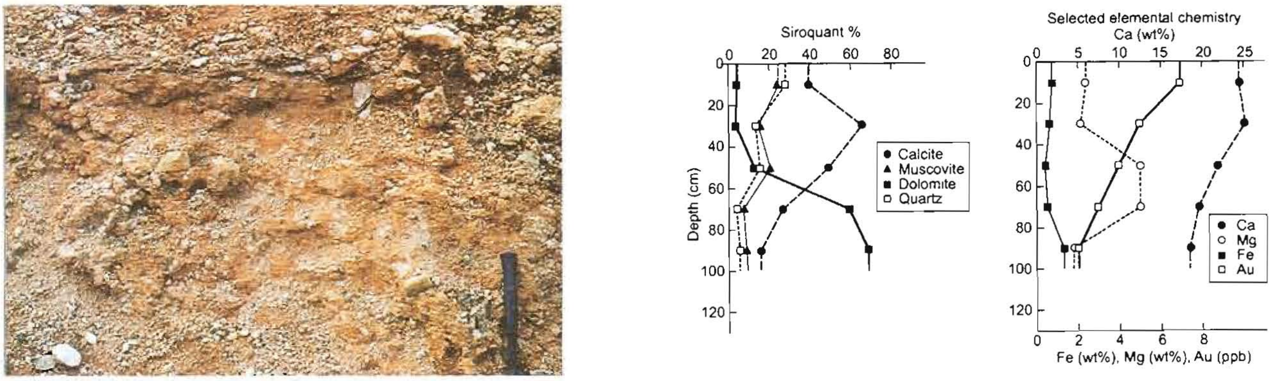

Figure 2(c): *Aspects of the chemistry, mineralogy and morphology of four regolith carbonate profiles from the Broken Hill region. c) Nine Mile Profile*

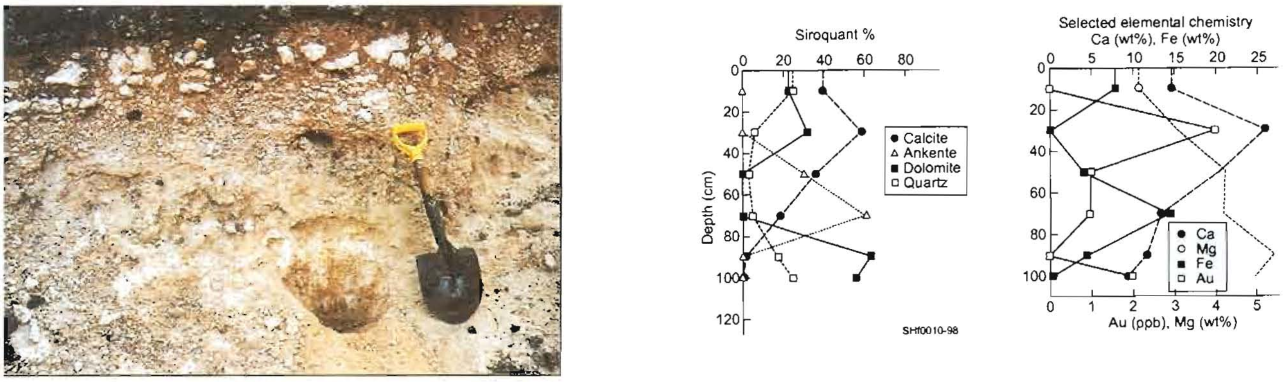

Figure 2(d): *Aspects of the chemistry, mineralogy and morphology of four regolith carbonate profiles from the Broken Hill region. d) Corona Profile*

NODULAR CARBONATE FACIES AND COATED GRAINS

These consist of weak to strongly indurated carbonate-rich bodies exceeding 2 mm in diameter. Nodules may occur within the upper parts of the carbonate silt facies, but are mostly above hardpans, such as within the Limestone Station profile. Some nodules are also typically cemented into the hardpans. Most nodules are buff to pink in colour, with calcite the major carbonate mineral. Some nodules may be dolomitic, particularly towards the lower parts of this facies.

The centre of nodules mostly consist of undifferentiated, micritic carbonate accumulations, or alternatively detrital clasts of bedrock or quartz, as in the case of coated grains. The abrasion of outer nodular coatings suggests some detrital reworking, however the similarities between the fabrics of the carbonate matrix and the type of carbonate facies fragmented into the angular core of many nodules indicate transport has not been extensive. Transport was possibly restricted to localised churning and volume changes within the profile and local breakdown of adjacent hardpan facies and massive, tabular facies (such as in the Corona profile). Some carbonate nodules feature a void space in their centre, suggesting either carbonate nucleation and growth on a carbonate "plugged" void space, or in many other cases that voids represent shrinkage and cracking due to dessication. The inner lining of many of these voids commonly contain calcified filaments, visible with the aid of a hand lens. Similar filaments have been described in detail by Phillips et al. (1987) and Phillips & Self (1987) and interpreted as calcified fungal hyphae and the remains of other micro-organisms.

CARBONATE RHIZOLITHS

Carbonate accumulations that are root-like in morphology, are termed carbonate rhizoliths. They are usually elongated in a near to vertical orientation, up to

Figure 3(a): *Photographs of selected morphological facies for regolith carbonate accumulations. a) nodular carbonate facies from the Marnpi profile*

Figure 3(c): *Photographs of selected morphological facies for regolith carbonate accumulations. c) laminated hardpan facies from the Nine Mile profile*

Figure 3(b): *Photographs of selected morphological facies for regolith carbonate accumulations. b) carbonate rhizoliths from a cutting on the India-Pacific railway line approximately 20 kilometres west of Broken Hill station*

Figure 3(d): *Photographs of selected morphological facies for regolith carbonate accumulations. d) tabular massive facies from the Limestone Station pits.*

several centimetres in diameter, and rarely show internal structure. Some are found associated with the carbonate silt facies although they more commonly form discrete, indurated carbonate accumulations within a less indurated matrix. Carbonate mineralogy is usually dominated by calcite.

This is a frequently described regolith carbonate morphological facies and a number of mechanisms for its development have been suggested (e.g. Johnston 1967; Klappa 1980). The most widely accepted controls involve: water loss adjacent to plant roots, ionic exchange, the influence of organic acids, soil bacteria and symbiotic hyphae, water channelling along roots and the infilling of root casts after plant death.

CARBONATE HARDPAN FACIES

Carbonate hardpans are hard, relatively impervious layers of indurated regolith carbonate. Their internal morphology is usually complex, incorporating coalesced nodules, coated grains and other carbonate indurated fragments. They usually occur in close association with the base of the nodular carbonate facies, however they can occupy a variety of settings.

The upper surface of hardpans usually features a discontinuous laminar carbonate subfacies, preferentially developed within depressions in the hardpan surface. In some cases this may also develop along the interface between regolith and fresh bedrock. Individual laminae are generally several millimetres in thickness, are mostly micritic and well defined with sharp contact boundaries between adjacent laminae or adjacent carbonate facies. The mineralogy of laminae is typically dominated by calcite. Laminar carbonates typically develop by carbonate accretion on indurated surfaces, often attributed to precipitation from ponded water possibly with some contributions from biological processes associated with lichens, cyanobacteria or root mats (Klappa 1979). The laminated subfacies may be disrupted into carbonate boulders (boulder carbonate facies), or flat blocks ("biscuits" using the terminology of Phillips et al. 1987).

Beneath the laminated subfacies the main part of the hardpan generally consists of an extensively indurated subfacies, typically including coalesced carbonate nodules and coated grains. The carbonate mineralogy of this facies is variable between calcite-rich and dolomite-rich end members. Where nodules have weakly coalesced and feature large void spaces variably filled with a carbonate silt matrix, they are referred to as having a "honeycomb" morphology (Netterberg 1969). Where a majority of the void spaces are filled by carbonate minerals, a densely indurated hardpan results. This indurated hardpan commonly overlies the carbonate silt facies, although in some cases carbonate nodules and coated grains are found immediately beneath it. The boundary with the underlying carbonate silt or nodular facies is usually gradational.

Some harpan facies observed during this study consisted of a dense network of filaments and rods up to a millimetre in diameter and therefore visible in hand specimen. Calcite is the dominant mineral in these biologically influenced accumulations. These filaments and rods resemble fungal hyphae, suggesting a strong biological control on their development.

The hardpan facies represents the "plugging" of the regolith profile, by the accretion and eventual coalescence of regolith carbonate accumulations (e.g. Gile et al. 1966; Machette 1985; Arakel 1982; 1995). Ponding on the surface of the "plugged" hardpan horizon then results in the deposition of the laminated subfacies. Similar ponding along hydromorphic barriers such as the regolith-bedrock interface accounts for the presence of this facies at the base of some regolith profiles covering fresh bedrock.

BOULDER CARBONATE FACIES

This facies consists of discrete boulder and cobble sized blocks of carbonate indurated regolith, usually within a matrix of powder carbonate or nodular carbonate facies. Many blocks are coated with a carbonate skin and are subrounded to subangular reflecting dissolution and reprecipitation along block margins. Examples where this facies is well developed occur within the Corona Profile. Previous studies describing this facies interpret its origins as being due to the disruption and dissolution of hardpans (Netterberg 1967; 1980; Goudie 1983). Some of this material within the blocks has a similar morphology to carbonate hardpan facies suggesting that this interpretation is also applicable in this region. Many other blocks, such as in the Corona profile appear to have resulted from the breakdown of a tabular, massive, groundwater carbonate accumulation. In this case the carbonate blocks are accommodated ("jig-saw-fit" arrangement).

POWDER CARBONATE FACIES

This is usually structureless, fine grained, unconsolidated to weakly consolidated carbonate material. This facies is also often referred to as "carbonate silt" facies, referring to its typical gransize and unconsolidated nature. It is typically found in the lower parts of profiles, such as gradationally underlying carbonate hardpans. In thin section it consists of micrite, commonly including quartz clasts and gypsum crystals throughout, and some carbonate nodules and coated grains, particularly in the upper parts of this facies. Carbonate mineralogy is usually dolomite or magnesium-rich calcite.

Some previous studies reporting the presence of this carbonate facies interpret it as representing an aeolian addition to the regolith (e.g. Phillips & Milnes 1988). In this region, however, it usually grades into a carbonate hardpan. A floating fabric of quartz and bedrock pebbles and coarse sand clasts suggests that this facies represents a secondary carbonate precipitate within predominantly alluvial material. Aeolian material is mixed into much of this alluvial material and is a significant primary source of the carbonate, however the ultimate development of this facies is mostly due to secondary carbonate precipitation (reprecipitation), in some cases derived from aeolian sources. This facies probably represents an area of the regolith that receives reduced inputs of carbonate from the downward movement of surface waters due to "plugging" of the upper parts of the profile by hardpans. As a result carbonate induration has not advanced to the extent of hardpan and nodular facies. The relatively high magnesium and sulphate contents, reflected in the abundance of dolomite and gypsum, may reflect some groundwater contribution to the diminished pedogenic input for waters associated with the development of this facies.

TABULAR MASSIVE CARBONATE FACIES

Lensoidal carbonate accumulations commonly occur as mounds or domes within thick alluvial sequences. Internal structure is typically massive. They consist of both micrite and densely crystalline microspar. The main carbonate mineral is typically dolomite, however calcite-rich varieties of this facies also occur. At Corona an abundance of ankerite is related to the proximity of this profile to the "Corona ironstone" (Gilligan 1972) and associated iron-rich groundwaters.

These carbonates commonly form along the interface between bedrock and alluvium, penetrating bedrock joints and schistosity and in some cases disrupting bedrock fabric. Shrinkage cracks and dissolution features are abundant. The thickness of this facies varies, although it is often thicker in coarser grained, more permeable lithologies, or along hydromorphic boundaries, such as bedrock-alluvium interfaces and along bedrock fractures and schistosity planes.

This carbonate facies corresponds to the groundwater carbonate type, also referred to as phreatic, valley and channel types (Mann & Horwitz 1979; Carlisle, 1983; Arakel 1986; Wright & Tucker 1991). It is interpreted as forming from carbonate-rich groundwaters, usually within the capillary fringe zone directly above laterally moving, subsurface waters (Wright & Tucker 1991). Groundwaters in the Broken Hill and Cobar regions are typically saline, thereby accounting for the abundance of sodium and magnesium in this facies.

SEPTARIAN MAGNESITE ACCUMULATIONS

Areas of western New South Wales with mafic and ultramafic bedrock typically feature septarian accumulations of magnesite within the shallow regolith. The mineralogy is remarkably pure magnesite with very few of the accumulations examined containing detrital quartz or minerals derived from the local bedrock lithologies. Cracks within the accumulations may have been derived from dessication of the carbonate. The weathering of the mafic and ultramafic bedrock is obviously a major source of the magnesium for these carbonates. Examples of magnesite -rich regolith occur across the area of the Thackaringa Serpentinite body west of Broken Hill (Figure 4) and in association with parts of the Little Broken Hill Gabbro, southeast of Broken Hill. Magnesite appears to be more widespread throughout profiles in the Cobar region, ocurring in profiles that feature different carbonate minerals such as calcite and dolomite.

Figure 4: *Magnesite-rich regolith carbonate accumulations in the regolith overlying the Thackaringa Serpentinite, west of Broken Hill*

REGOLITH CARBONATE PROFILES AND VERTICAL VARIATIONS

The regolith profiles featuring regolith carbonate accumulations from the Broken Hill region show some consistent variations with depth.

The vertical organisation of morphological facies in profiles is extremely variable, however some general trends can be identified. The Limestone Station and Nine Mile profiles show the greatest range of morphological facies. In both of these profiles nodular carbonate and coated grains form the uppermost facies, which successively overlie laminated, hardpan and carbonate silt facies (Figure 2). In the very lowermost part of the Limestone Station profile, usually directly overlying the regolith-bedrock interface is a massive tabular facies. In the Marnpi profile nodular carbonate and coated grains are the most extensive regolith carbonate facies. Many of the concentric overgrowths of the carbonate nodules have joined overgrowths on adjacent nodules suggesting that some of the nodules have coalesced to form a thin and discontinuous hardpan, which overlies a weakly consolidated carbonate silt facies. At Corona the profile consists of a thick, massive, carbonate facies overlain by boulders and nodules consisting of fragments of hardpan with concentric carbonate overgrowths.

MINERALOGY

Calcite and dolomite vary systematically with depth in most profiles (Figure 2). Calcite is generally the most abundant carbonate mineral in the upper parts of the regolith, whereas dolomite increases with depth in the profile. This is also reflected in the changes in the abundances of calcium and magnesium in the profile. The progressive decrease in the Ca/Mg ratio with depth and the corresponding changes in the abundances of calcite and dolomite have been described from previous studies of regolith carbonates (e.g. Weatherby & Oades 1975; Hutton & Dixon 1981; Milnes & Hutton 1983). Hutton & Dixon (1981) attributed this trend to the dissolution of carbonate near the ground surface by percolating rainwater and the reprecipitation of calcite in the upper part of the profile due to changes in pH or pCO_2. Calcite will also precipitate from soil solutions before dolomite, so downward percolating waters will precipitate calcite higher in the profile than dolomite. Biological controls could also be important, although the processes and mechanisms involved here are unknown. In all of these situations the remaining solution moving down the profile will undergo relative magnesium enrichment, therefore favouring dolomite precipitation. The presence of a well developed hardpan could also have some control on the vertical transition from calcite to dolomite-rich carbonate accumulations. Carbonate facies within and below this indurated horizon tend to be dominated by dolomite, whereas calcite is more common in overlying facies. The hardpan could be an important hydromorphic barrier restricting the access of more calcium-rich surface waters to the lower parts of the profile. Lower parts of the profile are also more likely to receive inputs of more magnesium-rich waters from an underlying fluctuating watertable.

The morphology of the calcite and dolomite crystals also varies. Calcite is mostly characterised by micritic and anhedral crystals, whereas dolomite crystals are typically subhedral. This suggests rapid formation of calcite during movement of solutions and rapid dessication in the upper part of the profile. Impurities such as clay minerals may also prevent euhedral crystal growth. The subhedral form of most of the dolomite crytals suggests that crystallisation was slower, perhaps due to restricted or impeded water flow at depth in the profile or changes in the degree of saturation or supersaturation of the parent solutions.

Minerals typically associated with insoluble detrital grains such as aluminosilicates and quartz may show irregular variations in the profile. The major elements silicon, aluminium, iron and minor elements such as titanium, zirconium, manganese, potassium and phosphorus are mostly associated with detrital components in the regolith. These elements show irregular variations in the profile reflecting the mixture of alluvial, colluvial and aeolian deposits of the regolith host materials. The most prominent and widespread of the sedimentary host facies in all of these profiles is the uppermost deposit. This deposit features poorly developed pedogenic features, and relatively little carbonate compared to most of the underlying profile. The common occurrence of glass, pottery and metal materials indicates that this is a post-European settlement deposit. The remainder of the Marnpi, Limestone Station and Nine Mile profiles are developed within a series of dominantly alluvial sediments mixed with aeolian additions, whereas the Corona profile is developed within sediments of mainly colluvial origin with some aeolian additions.

LANDSCAPE SETTING AND LATERAL VARIATIONS IN REGOLITH CARBONATE ACCUMULATIONS

Some uncertainties exist concerning the importance of landscape setting for the development of various features of regolith carbonate accumulations. Ruellan (1970) and Yair et al. (1978) stress the importance of lateral variations in carbonate facies and thickness with changes in landscape position. These studies relate catenary distribution patterns to moisture changes resulting from variation, with semi-indurated carbonate mottles and nodules to compact hardpans. Yair et al. (1978) related catenary distribution patterns to the distribution of moisture from infiltration and runoff under semi-arid conditions. Thin calcrete horizons occur on convex slopes and are due to less effective infiltration and greater runoff and erosion, whereas thick profiles on low-angle slopes and in basal footslopes reflect enhanced infiltration. However, in a review featuring Australian examples, Milnes (1992 p 340) claims that there is "... no evidence for the lateral migration of carbonate in a catenary sense, ..."

Detailed regolith mapping emphasising regolith carbonate accumulations was conducted in the Limestone Station area. A regolith carbonate toposequence summarising the results of this mapping is shown in Figure 5. This toposequence shows that landscape setting is a major control on lateral variations in features of regolith carbonate accumulations. Towards the axis of the Umberumberka Creek valley, regolith carbonates become increasingly thicker, continuous, complex and magnesium (and dolomite)-rich. This corresponds to a thickening of the regolith profile facilitating greater water infiltration, vertical leaching and water holding potential, as well as greater inputs from lateral moisture flow, such as in groundwaters. This is consistent with the findings of other studies that also recognised a concentration of magnesium and presence of groundwater carbonate types in depressions and the axis of valley systems (e.g. Ruellan 1970; StArnaud & Herbillon 1973; Mann & Horwitz 1979; Carlisle, 1983).

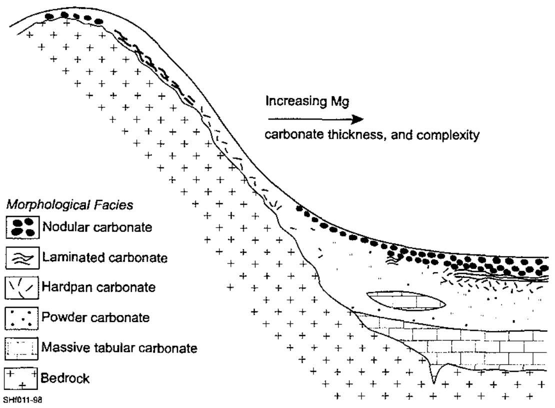

Figure 5: *A toposequence of regolith carbonate accumulations from the Limestone Station area*

Elsewhere in the Broken Hill region, the depth of regolith appears to be a major control on the lateral variations in regolith type In valley systems with thin regolith (usually less than 3 m) and low topographic relief, dolocretes and groundwater carbonate types are typically found In valley systems where the regolith is deeper (usually greater than 3 m) and landscape relief is greater regolith carbonate accumulations are more common near the landsurface. This contrast can be seen by comparing the relatively more manganese-rich Limestone Station profile with the calcareous Marnpi profile. Both profiles are located close to the axes of major valley systems, however the stream gradient and local landscape relief is greater in the Marnpi profile facilitating greater groundwater throughflow rather than ponding In the sites with shallower regolith, and therefore where the hydromorphic boundary corresponding with the bedrock interface is closer to the landsurface, the local water table is also more likely to fluctuate and occasionally rise to the upper, pedogenic parts of the profile. This will not only bring with it more magnesium-rich groundwaters to this part of the profile, but with a reduced hydrological gradient will also reduce the amount of leaching and vertical differentiation of calcium and magnesium-rich carbonates The more shallow regolith profiles in the sites where the regolith carbonates have been examined in this study, may therefore account for the presence of more magnesium-rich profiles than many of those reported from similar studies in Western Australia where groundwaters are typically at greater depth in the regolith (such as profiles shown in Anand et al 1997 and Lintern & Butt 1997)

DISCUSSION: Consideration Of Some Environmental Controls

At the first order level, regolith carbonate accumulations will form when vadose and shallow phreatic waters become saturated with respect to particular carbonate minerals The literature features a myriad of scenarios for how this may occur (see Goudie 1973; 1983; Milnes 1992; Wright & Tucker 1991 for reviews of many of these) The most frequently suggested mechanism, particularly for pedogenic types, involves concentration by evaporation and evapotranspiration The influences of micro-organisms and CO_2 degassing are also important (Klappa 1979a; 1979b; 1980; Phillips et al 1987; Phillips & Self 1987; Wright & Tucker 1991) Groundwater types are typically accounted for by derivation from carbonate-rich groundwaters, with precipitation enhanced by common ion effects from mixing with saline solutions, CO_2 degassing and water loss through evaporation within the capillary fringe of aquifer systems In reality regolith carbonate accumulations develop due to the influence of a variety of controls and their interactions

The development of environmental conditions suitable for the formation of regolith carbonates is largely controlled by a balance between:

(i) the degree of leaching of carbonates, which is mainly proportional to the amount of rainfall, but also to landscape setting and factors such as groundwater pH; and,

(ii) the availability of the chemical constituents of carbonates, mostly derived from bedrock weathering (particularly of primary carbonates, and mafic lithologies), reworking of older regolith carbonate accumulations, aeolian accessions, rainfall chemistry, surface runoff, bioclasts and other biological concentrations

Regolith carbonate accumulations will develop and be preserved in the landscape so long as the rate of carbonate leaching and physical erosion is less than the rate of carbonate addition This may be due to changes in the rates of a variety of processes Climatic controls on the development of regolith carbonates and morphoclimatic relationships, particularly with semi-arid and arid climates, are asserted in most previous studies (e.g Goudie 1973; 1983; Young 1976; Semeniuk & Searle 1985; Milnes 1992) These studies thus emphasise restricted leaching of carbonates as the dominant environmental control Considering the large variety of controls on the development of regolith carbonate accumulations this is a serious, and in many cases a misleading, simplification

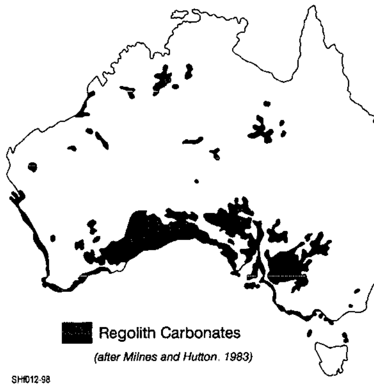

Figure 6: *Distribution of regolith carbonates in Australia (after Milnes & Hutton, 1983)*

The distribution of regolith carbonates in Australia suggests that the controls on their development are more complex (Figure 6) Australian regolith carbonates are more widespread across the south of the continent, in association with coastal calcarenite dune complexes (Crocker 1946; Fairbridge & Teichert 1952), and further inland in association with a wide range of geological and landscape settings The coastal calcarenites provide an abundant source of the required chemical components, and as a result, regolith carbonate accumulations are common even in temperate, high rainfall areas (e g the south coast of Victoria) Adjacent to the coast the aeolian additions to the regolith are an important chemical source for regolith carbonate development combined with decreased leaching in arid areas (Phillips & Milnes 1988) In the arid and semi-arid parts of central and northern Australia the occurrence of regolith carbonate accumulations is much more restricted, largely limited to local areas featuring suitable substrate sources (such as carbonate or mafic bedrock lithologies) or derived from concentrations from lateral sources (e g groundwater aquifers and discharge areas such as valley and lake systems)

The identification of the sources of the constituents of carbonate minerals has been the subject of considerable debate The carbonate is mostly accounted for from the abundance of carbon dioxide in the atmosphere and dissolved in waters, and also released from respiring plant roots The primary sources of the cation species, which are most commonly calcium and magnesium, may be:

i aeolian additions (e g Dan 1977; Gile 1961; Gile et al 1965; 1966; Reeves 1970; Gardner 1972; Phillips & Milnes 1988)

ii sea spray and rain (Crocker 1946; Hingston & Gailitis 1976; Hutton 1979; Warren 1983)

iii weathering and redistribution from a parent material source (Milnes 1992; Milnes et al 1983)

iv deflation from carbonate-rich lakes (Hutton & Dixon, 1981; Milnes & Hutton 1983; Milnes et al 1987)

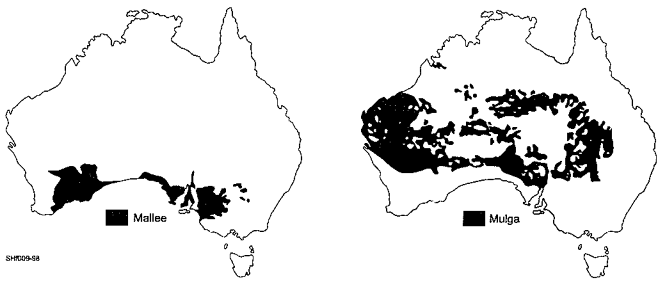

Figure 7: *The general distribution of mulga (Acacia aneura) and malle (Eucalyptus spp) communities in Australia (after Specht, 1981)*

In Western Australia marked differences in the distribution of regolith carbonate accumulations of dominantly pedgenic and groundwater types have been recognised (Butt et al 1977; Carlisle, 1983) The transition in this distribution broadly conforms to the Menzies Line with groundwater carbonate accumulations dominant to the north and pedogenic groundwater types dominant to the south This is an east-west trending transitional zone, close to the town of Menzies, across which there are marked changes in soil types, vegetation, groundwater chemistry and climate (Table 1)

Table 1: *A summary of environmental differences north and south of the Menzies Line in Western Australia.*

	NORTH OF MENZIES LINE	SOUTH OF MENZIES LINE
Soils (Butt et al., 1977; Carlisle, 1983)	Neutral to acid, includes red-brown hardpans	Neutral to alkaline includes carbonate-rich soils
Regolith Carbonates (Butt et al.,1977; Carlisle, 1983)	Minor Groundwater Carbonates	Pedogenic Carbonates
Groundwater chemistry (D.Gray pers. comm., 1997)	Moderate to low salinity, neutral - alkaline	Saline to hypersaline, neutral - acid
Average Rainfall (Carlisle, 1983)	170-250 mm	200-500+ mm
Annual Potential Evaporation (Carlisle, 1983)	>3300 mm	<3300 mm
Rainfall Seasonality (Carlisle, 1983)	Summer Maximum	Winter Maximum
Vegetation (Carlisle, 1983)	Mulga dominated	Mallee and Salmon Gum dominated

A similar subdivision extends across South Australia and into western and central New South Wales (Figures 6 and 7). In western and central New South Wales this subdivision passes between Broken Hill and Tibooburra near Fowlers Gap Station and to the east towards Cobar. Further east of Cobar this subdivision is not well defined. To the south pedogenic carbonate accumulations such as those described here from near Broken Hill and Cobar are widespread, whereas as to the north they become less common and instead groundwater carbonates and red-brown hardpans are more common. This appears to contradict the association of carbonate development with aridity, as to the north annual rainfall is much less and evaporation rates much higher. This division is also reflected in the vegetation communities. For example, Mulga (Acacia aneura) communities are extensive in the neutral to slightly acid soils to the north, whereas mallee eucalypts and nelia (Acacia loderi) are more extensive in the alkaline soils to the south (Figure 7). In transitional areas mulga tends to grow on bedrock rises where soils are more leached of carbonate, with mallee or chenopod shrubs occupying lower parts of the landscape. The distribution of a number of fauna species appear to also be controlled by this subdivision.

Accounts of the controlling factors on the formation of this subdividing zone are likely to reflect important controls on the development of regolith carbonate accumulations in this area and equivalent regions. The recognition of controlling factors for this subdivision have had limited success where this subdivision has been previously recognised in Western Australia. Carlisle (1983) related the subdivision mostly to differences in rainfall seasonality and its consequences on the retention of water in soils. Although admitting that the cause of this distribution pattern is unclear, Lintern & Butt (1997) suggested that changes in rainfall seasonality across the Menzies Line and its influence on vegetation growth and soil conditions may be responsible. The full mechanism however may also take into account the primary source of the chemical constituents of regolith carbonate accumulations.

The close association between this subdivision and the boundary between the extents of summer dominated and winter dominated rainfall is striking. A recent study of rainfall chemistry along a north-south transect through central Australia also reveals major chemical differences between these two rainfall regimes (Keywood 1995; Keywood et al. 1997). To the south, winter dominated rainfall is largely derived from the Southern Ocean and therefore has a strong marine chemical signature, and therefore an abundance of calcium and magnesium. Areas to the north are beyond the extent of regular winter dominated rainfall and feature summer dominated rainfall largely derived from north of Australia. As the summer rain-bearing system passes over northern Australia its marine chemical signature is dramatically diminished within approximately 200 kilometres of the north coast. At the southern extent of this rainfall regime (immediately north of the Menzies Line and in northwestern NSW) the rainfall has a very low marine chemical signature, and therefore provides very little calcium and magnesium to the regolith (Figure 8). Rainfall chemistry rather than seasonality or quantity may therefore be a major control on the distribution of regolith carbonates along this subdividing zone. Further analysis of rainfall samples from across the subdividing zone in western NSW, and strontium and carbon isotope studies are needed to test this hypothesis.

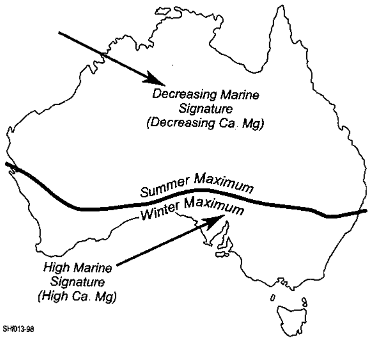

Figure 8: *Australian seasonal rainfall regimes and sources*

Although rainfall may be a major source of the chemical constituents and therefore a control on the development and distribution of regolith carbonate accumulations, other factors are also important throughout western and central New South Wales. Aeolian accessions are widespread across this region and are responsible for the reworking and redistribution of regolith carbonate accumulations (particularly leeward of ephemeral lake systems). Weathering of bedrock is also a major chemical source, as shown by the association of magcretes with ultramafic rocks near Broken Hill, and the often observed extensive development of regolith carbonate accumulations associated with areas featuring calcic amphibolites (Hill et al 1997). Secondary redistribution by biological processes are also important.

DISCUSSION: MINERAL EXPLORATION SIGNIFICANCE

CARBONATE - GOLD RELATIONSHIPS

An association between regolith carbonate accumulations and gold has been established from regolith studies in Western Australia and South Australia (Lintern & Butt 1993; 1997; Anand et al. 1997; 1998). Gold content in the regolith is shown to closely correspond with calcium content. Anand et al. (1998) consider the origin of the carbonate accumulation as the main control on this association with pedogenic carbonates recognised as the favoured sampling media ahead of groundwater types.

Figure 2 shows the vertical trends in calcium, magnesium, iron and gold for the four profiles studied in the Broken Hill region. For all of the profiles there is a close association between calcium and gold within the profile. Similarly, results from the Cobar region show an association between calcium content of regolith carbonates and gold (Figure 9). The gold content does not correspond to the iron content suggesting that the gold is not associated with iron oxide and hydroxide minerals, as it may be in many other regolith sampling media. The relationships with magnesium are more complex. When the magnesium content is lower than calcium, particularly below approximately 5 wt%, the association between regolith carbonates and gold appears to be strongest. At greater magnesium concentrations the relationship is weaker. The association between magnesium and gold at low magnesium contents reflects the association of small amounts of magnesium with calcium in calcite. At higher magnesium contents the dominant carbonate mineral is dolomite which is typically associated with more saline solutions with high pH. Ca/Mg ratios and carbonate mineralogy may therefore be important for discriminating and comparing differences in the relationship between regolith carbonate accumulations and gold.

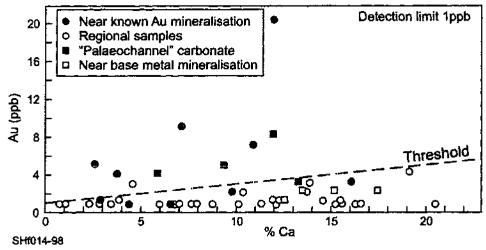

Figure 9: *The relationship between gold and calcium content for regolith materials associated with regolith carbonate profiles from the Cobar region*

The differences in morphology of regolith carbonate accumulations also suggests a correspondence in their association with gold. Figure 10 shows that at Broken Hill nodular carbonate facies tend to have higher calcium contents relative to magnesium and are more closely associated with gold. The groundwater and pedogenic carbonate facies from the lower parts of the profile tend to have higher magnesium and lower gold contents. This illustrates the ability of morphology, mineralogy and chemistry to reflect environmental conditions of regolith carbonate formation. It also shows the importance of accounting for all of these features when comparing regolith carbonate samples. The nodular facies is usually more calcium and therefore more calcite-rich and appear to be the most comparable facies to sample for gold exploration. It must be stressed, however, that the results here are from relatively few profiles.

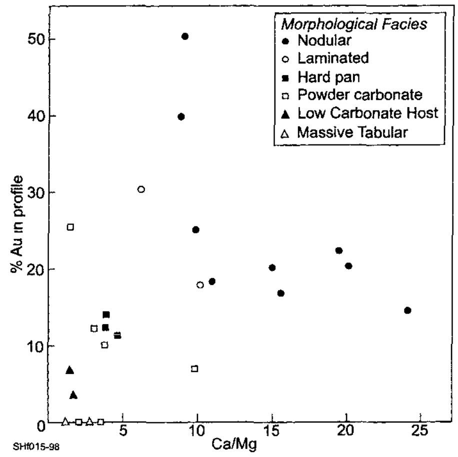

Figure 10: *The relationship between calcium/magnesium ratio and percentage gold in particular profiles for regolith carbonate morphological facies from the Broken Hill region. The percentage gold value represents the proportion of gold that a single sample contributes for the total gold content for the profile that it comes from. In other words: Au% = (SAu / PAu) 100%. Where SAu is the gold content for a sample, and PAu is the total gold content for the profile where the sample comes from. This therefore provides a crude basis for comparing results between different profiles with high and low gold contents, emphasising the relationships between gold content and carbonate chemistry and morphology, rather than regional gold variations between different profiles.*

Explanations for the low gold contents of regolith carbonate accumulations with high-magnesium and dolomite contents are not entirely clear. Differences in carbonate mineralogy will reflect differences in environmental chemistry and conditions that are likely to influence the behaviour of gold in the regolith. Gold mobility in the regolith is largely controlled by the presence of biological ligands, thiosulphates and halides. The presence of magnesium-rich carbonates can be, to a large part, related to origins from saline solutions, as is also reflected by their greater abundance in the axis of valley systems, groundwater carbonates and the lower parts of pedogenic profiles. Halides associated with saline solutions are a well known influence on gold mobility in the regolith where, for example, gold may complex with chloride (Mann 1984). This however is typically associated with groundwaters with low pH rather than the groundwaters with a high pH encountered in these profiles. Gold mobility associated with thiosulphate and organics is more important in alkaline, mildly oxidising conditions (Granger & Warren 1969; Goldhaber 1983; Mann & Webster 1990). Alternatively the gold may simply be coinciding with carbonates inthe upper parts of profiles where both carbonates and gold will similarly accumulate from evaporating soil waters.

A possible control could also be the influence of salinity on microorganisms and other biological processes. Gold appears to be most closely associated with parts of the regolith carbonate profiles where biological processes are most prevalent (e.g. upper pedogenic facies, nodules with calcified biological remains). Areas of regolith carbonates are also noted for supporting the greatest biological crust cover and number of lichen and bryophyte species in arid and semi-arid Australia (Figure 11; Rogers 1982; Eldridge & Tozer 1997). An ability for these types of organisms to accumulate gold has been previously reported (Bischoff et al. 1992). The ability of many of these organisms to concentrate trace metals may be strongly influenced by environmental salinity. For example the presence of chorine in saline solutions inhibites metal uptakes (e.g. Wong et al. 1979), and may be toxic (e.g. Babich & Stotzky 1978) to some microorganisms. Many of the local plant species, although having some tolerance of salinity, also exhibit a toxic response to high salinities therefore restricting their contribution to biological activity in areas with saline regolith. Saline solutions, reflected by the development of high magnesium carbonate minerals such as dolomite, may therefore inhibit biological concentration and retention of gold within regolith carbonate accumulations.

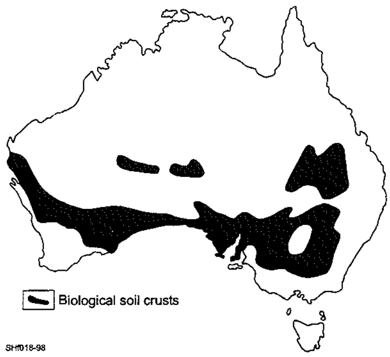

Figure 11: *The distribution of biological soil crusts in Australia (after Rogers, 1982). Note the similarities with the distribution of regolith carbonate accumulations (Figure 6).*

APPLICATION OF GENETIC MODELS

As previously stated, Anand et al (1998) consider the recognition of either pedogenic or groundwater genetic types of regolith carbonate accumulations to be the most important consideration for determining suitable regolith carbonate sampling media for gold exploration Results from this study support this to some extent with calcite-rich, pedogenic morphological facies, such as nodular carbonates, having a close association with gold In some cases however, the interpretation and classification of a carbonate as a specific genetic type may not always be clear and simple (Figure 12) For example some regolith carbonate materials may represent a combination of different genetic processes The following two examples from the Corona and Limestone profiles illustrate this complexity

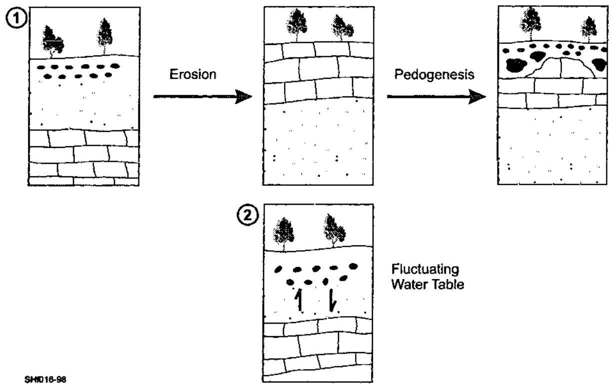

Figure 12: *Two scenarios where the genetic classification and geochemical derivations of regolith carbonate accumulations will be polygenetic and complex 1 Pedogenic modification of an earlier formed groundwater regolith carbonate accumulation; 2 Fluctuating groundwater additions to pedogenic regolith carbonate accumulations Even for these simplified examples a straightforward genetic classification of regolith carbonate sampling media would be a gross over-simplification*

The Corona profile is interpreted as originating as a tabular groundwater carbonate type that has then been modified by pedogenic processes, resulting in the development of blocky and nodular facies (Figure 2d & 12a) Although the upper parts of this profile resemble pedogenic carbonate types with nodular facies, interpretations of the chemistry of this part of the profile will reflect both its original groundwater and later pedogenic origins Although there is some systematic variation in calcium and magnesium contents with depth, the profile features relatively high magnesium contents throughout Field sampling and interpretations of carbonates such as this may be better made in the context of carbonate morphology and mineralogy as this can be objectively described in the field, rather than relying on often complicated genetic interpretations

The Limestone Station profile features pedogenic carbonate morphologies in all but the lowermost sections of this profile where a tabular, massive groundwater type occurs The lower parts of the upper pedogenic profile (including hardpan and carbonate silt facies) are dolomitic, reflecting vertical differentiation of calcium and magnesium in the profile as well as possible inputs from fluctuating groundwater levels The possible input of groundwater to the pedogenic zones is similar to the per ascensum model" of regolith carbonate genesis (Goudie 1973) The lower parts of this regolith carbonate profile, although featuring pedogenic morphological facies, could receive chemical inputs from pedogenic as well as groundwater systems Therefore, as was the case for the Corona profile, the recognition of genetic carbonate types is not straightforward

"FALSE ANOMALIES": THE IMPORTANCE OF INTEGRATING REGOLITH-LANDSCAPE SETTING

Exploration programs using regolith carbonate accumulations as sampling media often encounter problems with so-called "false anomalies" or "blind deposits". With "false anomalies" high gold contents in carbonate accumulations do not correspond with an underlying source of mineralisation, and "blind deposits" refer to cases where carbonate accumulations directly overlying mineral deposits do not reflect the underlying mineralisation Consideration of some of the environmental controls on physical and chemical dispersion pathways for different regolith carblonates may help account for some of these situations

The Marnpi profile contained the highest gold values for

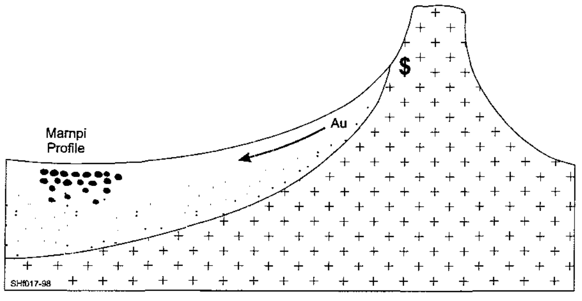

Figure 13: *A simplified example of how lateral dispersion may produce a geochemical anomaly that does not directly overlie a mineralisation source (often referred to as a "false anomaly") Obviously an understanding of lateral dispersion pathways (usually achieved with the aid of detailed regolith-landform mapping) is important to account for such anomalies*

the regions considered here. The mineralisation source for this anomaly however is not directly below this profile but instead is situated on adjacent bedrock ridges. Regolith mapping shows the colluvial and alluvial deposits in this area represent the style of dispersion from the mineralisation downslope to the Marnpi profile (Figure 13). Lateral dispersion and landscape setting may therefore be very important in accounting for "false anomalies". This is not suprising considering the well developed lateral variations and catenary variations in regolith carbonates described here. Rather than these anomalies being dismissed as "false" they perhaps more correctly represent cases where the environmental controls on chemical and physical dispersion pathways are not fully understood.

So-called "false anomalies" in some situations may also represent strong lateral dispersion from the area of mineralisation. Preliminary work at Cobar on carbonates related to palaeochannels, indicates significant down drainage dispersion of gold anaomalies. Alternatively, regolith carbonate accumulations overlying mineralisation may not be suitable sampling media or are not comparable with regolith carbonate accumulations sampled elsewhere in the region. This may arise if carbonates overlying mineralisation are dolomitic or of groundwater type. In other cases, however, dispersion pathways between the mineralisation and the overlying regolith may simply not interact, perhaps because mineralisation is beyond the zone of pedogenesis or interacting with weathering solutions.

CONCLUSION

A wide range of regolith carbonate types occur in western and central New South Wales. The response of these different types to different environmental conditions also reflect different physical and chemical dispersion pathways. Sampling of regolith carbonate accumulations has potential to be an important mineral exploration sampling medium in this region. However, consideration of differences in regolith carbonates (such as landscape setling, mineralogy and morphology) is important if these regolith materials are to be used successfully in mineral exploration.

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