DEEP WEATHERING OF DEPOSITS IN THE YILGARN AND CARLIN GOLD PROVINCES

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Weathering (also known as supergene oxidation) has played a significant role in making Western Australia and Nevada major beneficiaries of the 1980s global gold boom. Gold production from the Yilgarn Craton has risen from 10t to 200t per annum since 1980. Initially, this was due to mining of oxide ores from deeply lateritised terrains. Since 1990 the growth has depended upon deeper ores discovered after better appreciation of the regolith processes. In the Yilgarn, weathering is typically 100 to less than 300 m deep with an upper oxidised and leached interval, and a thicker saprolitic interval characterised by fabric preservation and chemically reduced mineral assemblages. The carbonate and especially the pyrite associated with many primary gold deposits facilitate deeper weathering near mineralisation. Distinguishing criteria for different parts of the regolith profile include the proportions and crystallinity of kaolinite and illite-smectite clays.

The rise in gold production from Nevada, also to 200t Au per annum, is mainly due to development of the Carlin gold province. These deposits are predominantly hosted by sedimentary rocks of Ordovician to Devonian age that include mudstone and lesser limestone. Near-surface mineralisation is free-milling (non-refractory), and hosted in bleached kaolinite-Fe-oxide rich material. At depth, gold ore is dark in colour due to carbonaceous material and arsenian pyrite, and the gold is refractory to conventional cyanide treatment. There is considerable debate about the origin of the deposits of the Carlin gold province with mineralising ages including 40 Ma, 110 Ma and 155 Ma being suggested. Fluid inclusion studies have confirmed an H_2O-CO_2-H_2S, low salinity fluid as the transporting agent for gold during the main ore stage. Pressure estimates of 0.5-1.5 kbars indicate a deeper origin than classical 'epithermal' deposits.

Since the 1980s, the bleached interval in Carlin-type deposits has been recognised as the product of weathering and this interval can extend to the full depth of individual 300 m deep pits. Drill cores from several of these deposits reveal ore intervals that are highly fractured, friable, quite porous and/or totally granulated to sand up to 800 m depth, and individual clasts of unoxidised material that are coated by kaolinite and Fe-oxide indicating penetration of the weathering fluids down cracks to great depth. Hydrogen isotope data confirm the circulation of meteoric water to over a kilometre depth, possibly during the Tertiary.

The dark refractory ores in Carlin deposits occur deep in some pits, but in other places appear completely surrounded by bleached oxide ores. We suggest that there is strong evidence to suggest they have been influenced by weathering resulting in their extreme porosity and meteoric water signature.

A very deep weathering scenario for the deposits of the Carlin province, perhaps to 1.5 km depth, is compatible with the 3000 m of topographic relief in north-central Nevada and the highly reactive nature of carbonate and sulphide minerals that initially comprised the primary gold deposits. Deep weathering would also explain the juxtaposition of oxidised and reduced ore assemblages in most deposits, free-milling intervals that wrap the present land surface regionally, ore formation conditions equivalent to 4 or more kilometres depth, and 20-30 percent porosity in rocks at 1 kilometre depth. Weathering might also explain why there is a plethora of geochronological numbers from 350 to 18 Ma.

Key words: gold, weathering, regolith, Yilgarn, Carlin, metamorphic, refractory.

INTRODUCTION

The importance of weathering in the Yilgarn Craton of Western Australia, especially for the gold industry, has been recognised for many years. This is in no small way due to the pioneering studies of Anand, Butt, Mann, Smith and their CSIRO colleagues (Butt & Smith, 1980; Smith, 1982; Mann, 1984; Webster & Mann, 1984; Webster, 1986; Lawrance, 1988; Butt, 1989a & b; Anand, 1993; Anand & Smith, 1993 Anand, 1998; Mann, 1998) during industry collaborative projects and now through the Co-operative Research Centre for Landscape Evolution and Mineral Exploration (CRC-LEME). It is becoming clear, as the ideas developed in Western Australia are applied and transferred to elsewhere, that weathering might be equally important in other gold provinces around the world.

This contribution brings together published data and many new observations of our own that relate to weathering in the Carlin gold province of Nevada. We use the framework for understanding regolith processes that has been developed in Western Australia, and combine this with our studies of the primary mineralising processes that have led to the formation of Archaean, slate-belt and Carlin-type gold deposits (Kuehn & Rose, 1992, 1995; Phillips & Powell, 1993; Phillips, 1993). The SEG field conference on 'Carlin-type gold deposits' in Elko, Nevada brought together most researchers involved within the Carlin gold province, and provided an up-to-date summary of current opinions on this group of deposits (Vikre et al., 1997). One over-riding impression conveyed by many speakers was the lack of an overall coherent genetic model that could integrate the various geological aspects of Carlin-type deposits. We have provided information on the Carlin geology and genesis to demonstrate that the genesis is not well understood for this major province, and that new interpretations may have important implications. In our contribution, we provide the evidence that leads us to believe that the deposits of the Carlin gold province are much more deeply weathered than previously appreciated, and this may account for some conflicting aspects of the current genetic models. Our contribution does not extend to deposits in Nevada outside the Carlin province, but it would be unusual if weathering had failed to influence other deposits of Tertiary or older age. It is worth noting the extensive research and considerable economic importance of weathering in the development of porphyry copper deposits of western USA.

Economic Importance of Yilgarn and Carlin Gold Provinces

Western Australia and Nevada stand out as the two great beneficiaries of the 1980s global gold boom. During a time in which South African gold production declined, that of USSR did not increase, and many other gold producers rose slightly or remained static, the production of Western Australia and Nevada rose sharply taking Australia and USA into the top three gold-producing nations. These two states now produce about two-thirds of their respective country's gold. The gold production from Western Australia is primarily from gold deposits in greenstone belts of the Archaean Yilgarn Craton. All-time gold production from the Yilgarn Craton is 4000 t with almost half having come from Kalgoorlie.

Historically, gold production from Nevada has been from low sulphidation epithermal deposits (e.g. Round Mountain), 'gold-plus' deposits with significant Ag and base metals (e.g. Comstock), and especially 'Carlin-type' deposits (e.g. Gold Quarry, Carlin, Genesis, Goldstrike). Deposits on the Carlin Trend in north-central Nevada have produced 1000t Au since discovery of the Carlin deposit itself in 1961 and the start of mining in 1965. Reserves on the Carlin Trend stand at 1600t and resources a further 700t making an endowment approaching 3500t (or 107 Moz; Teal & Jackson, 1997). Three further trends (Independence, Getchell, Battle Mountain-Eureka Trends) have also produced gold from similar deposits but all three trends are subordinate to the Carlin Trend in production and reserves. The trends are approximately 50 km apart and up to 100 km in length. Mining since 1965 has mostly been via open pits, but underground mining is active (e.g. Miekle, Deep Star, Rain) and likely to increase in future. From recent drilling, mineralisation appears to continue to 2km depth distinguishing these deposits from the vertically-restricted class of 'epithermal' gold deposits (White & Hedenquist, 1995).

Reasons for the recent successes in Western Australia and Nevada are several and relate to high gold prospectivity, government policy, environmental issues, infrastructure, mining capabilities, and personnel. The new technologies of carbon-in-pulp, carbon-in-leach and heap leach methods became available globally in the 1980s, but took on special significance in Western Australia and Nevada because of the nature of the gold deposits and gold ores. These favourable characteristics of the ore bodies and ores owe much to weathering processes today and throughout Mesozoic and Tertiary times. Regolith studies are well-developed in Western Australia and the economic importance of weathering to the gold industry is widely appreciated: recognition of the role of weathering has been slower to evolve in Nevada, but significant shifts of thinking have occurred since 1980 and are likely to continue.

Table 1: *Production of some major gold producing countries for 1980, 1990 and 1996 showing the substantial rise in gold production from Western Australia and Nevada. Virtually all WA gold is from the Archaean Yilgarn Craton, except a declining contribution from the Proterozoic Telfer mine. Nevada gold production includes 'low sulphidation'- type deposits such as Round Mountain.*

	Gold Production		
	1981	1992	1996
South Africa	638	614	495
USA	44	322	329
Nevada	16	203	216
Australia	18	239	289
Western Australia	12	182	221
Canada	53	157	164
Russia		237	130
China		118	145
Indonesia		44	92
Brazil	35	77	64

It is interesting to recall that Western Australian production was predicted to decline dramatically when the weathered 'oxide' ores were depleted in the late 1980s (this decline did not eventuate, Table 1). It is equally interesting to recall that weathering in the Carlin gold province was considered negligible until the early 1980s and the upper bleached interval with its free-milling gold was attributed to primary (hypogene) processes (Radtke et al., 1980; Radtke, 1985): this interval is now generally accepted as due to weathering (Bakken & Einaudi, 1986; Kuehn, 1989).

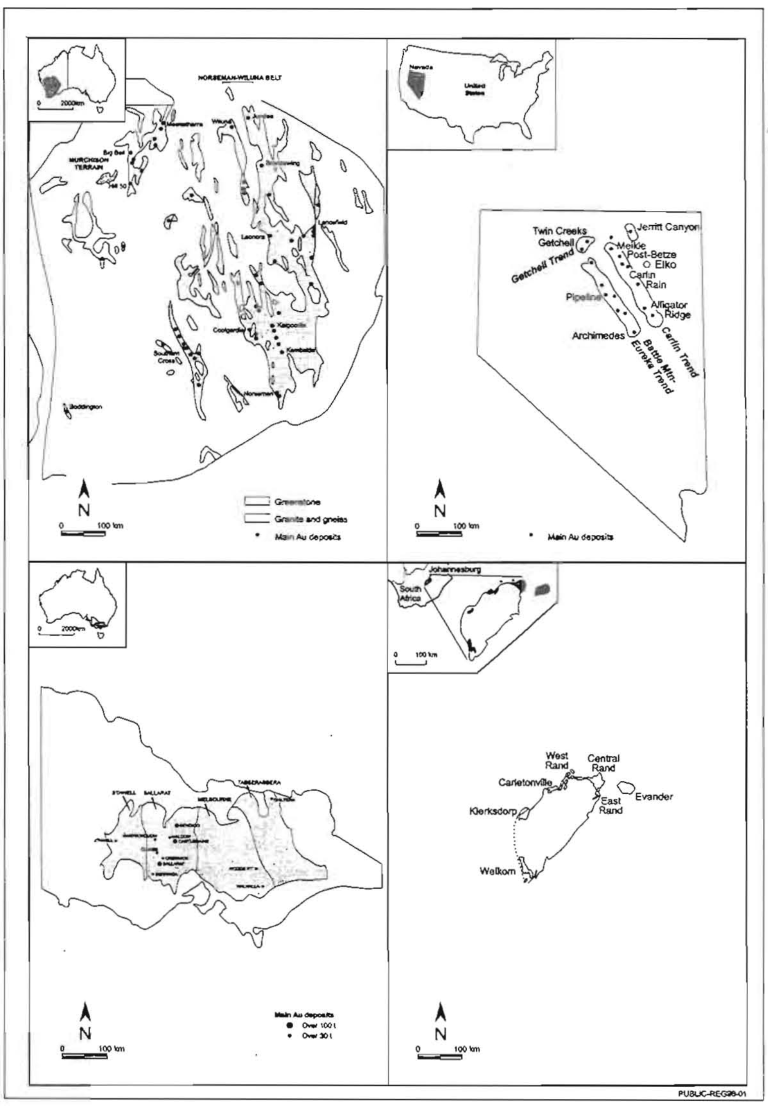

Figure 1: *Composite map of Yilgarn, Carlin, Victoria and Witwatersrand at same scale. Approximate gold production from each province is 4000 t, 1000 t, 2500 t, and 45,000 t, respectively.*

Archaean Greenstone Gold Deposits of the Yilgarn Craton

Gold deposits of the Archaean Yilgarn Craton are either in the greenstone belts, or within granite in which case they are spatially related to greenstone belt margins or fragments. Primary gold deposits are generally dominated by gold with subordinate silver and base metals (i.e. 'gold-only'; enrichment of Au > As, Ag, Hg > Cu, Pb, Zn), are structurally controlled, and occur in a variety of host rocks with Fe-rich rocks being the preferred host for the larger deposits (e.g. mafic rocks with 8 to15 or more wt % FeO). Apart from silicate minerals, the alteration mineralogy around Yilgarn gold deposits is dominated by pyrite, muscovite and carbonate minerals in the greenschist facies, and pyrite, pyrrhotite and biotite at higher metamorphic grades. The distribution of gold deposits within the Craton is heterogeneous with areas such as the Eastern Goldfields Province having significantly more larger and smaller gold deposits than other parts of the Craton. Most gold-only deposits appear to have formed from low salinity, H_2O-CO_2-H_2S fluids generated by the devolatilisation of greenstone belt material at several kilometres depth during greenschist facies to amphibolite facies progression (i.e. metamorphic model; Phillips & Groves, 1983; Powell et al., 1991). Exhalative models, lamprophyre-related models (Rock & Groves, 1988), and a 'continuum' model with some gold deposits formed under granulite facies conditions (Groves, 1993) do not appear to be able to account for the distribution and features found in greenstone gold deposits especially the fluids. The metamorphic model successfully predicts the low salinity H_2O-CO_2-H_2S fluid recorded from fluid inclusions and indicated by the metal ratios, and allows for incorporation of non-essential components (e.g. Pb, Sr, Nd) from other rock units or fluid types (Phillips, 1993). This metamorphic fluid is typically reduced, but does locally evolve to hematite - magnetite - siderite - pyrite assemblages (Phillips & Gibb, 1993). However, primary orpiment, realgar and arsenian pyrite appear absent throughout greenstone gold deposits and many other provinces derived from this same fluid type (Phillips & Powell, 1993).

Weathering in the Yilgarn Craton

The Yilgarn Craton is traditionally thought of as being deeply weathered, and it has been the birthplace of many techniques that have helped to characterise different components of the regolith. Much of the regolith research has been driven by the requirements of exploration in weathered terrains. The research has addressed the profound changes brought about during weathering of primary rock types, the role of weathering in modifying existing ore deposits, and the potential for weathering processes to generate new ore deposits by secondary processes. The regolith over much of the Yilgarn Craton is the product of a complex history of weathering under a variety of climatic conditions and over a long period of time. Several well-defined regolith types occur which relate to a deeply weathered veneer and to its modification by erosional and depositional processes. These regolith materials were either horizons of a deep profile developed by in situ weathering of basement rock or consist of transported debris derived from eroded local weathering profiles. Modification of the weathering profiles has occurred throughout the Yilgarn Craton, but the extent of this varies (e.g. regolith variations between the Kalgoorlie district, the northeast Yilgarn, and the southwest Yilgarn). These variations include the relative abundance of clay types, soils, red-brown hardpans, pedogenic carbonates, lateritic duricrust and lateritic gravels (Anand & Smith, 1993; Anand, 1998).

Over most of the Yilgarn, the current climate is arid with few surface streams and, for the eastern half, a general drainage trend that is towards saline lake systems then eastwards to the arid Nullabor Plain. There is very little relief over the eastern Yilgarn and the elevation is generally 300-550 m above sea level. Local topographic complexities are generally due to variations in rock types. Careful mapping of the 'base of alluvium' (i.e. the unconformity at the base of the transported cover that might include alluvial, colluvial, aeolian or lake sediments) indicates a much more rugged palaeo-topography below the cover than the present surface would otherwise suggest. Palaeochannels of 100 m or more depth are becoming widely recognised and many of these channels are parts of much larger lake systems draining the eastern Yilgarn. Some channels have very steep sides, are only a few hundred metres wide, and are traceable by drilling and geophysics for many kilometres (e.g. Wildman et al., 1998, Sundowner area adjacent to Bronzewing). The intimate topographic link between the individual palaeo-drainage channels, the major lake systems draining towards the Nullabor Plain and ultimately sea-level (past and/or present) appears to have provided a control on the overall depth of weathering in much of the Yilgarn Craton. Weathering to 50-200 m is widespread, but weathering to much greater depths is either localised, subtle, or not well-substantiated.

In principle, for deep regolith profiles to form, the rate of chemical weathering and downward progress of the weathering front must exceed the erosion rate. The relief must be sufficient for there to be adequate drainage to allow leaching of the products of chemical weathering. Hence, tectonic stability, arid climate and moderate relief all play a role in facilitating deeper weathering. Stability and climate favoured weathering in the Yilgarn Craton, but relief may have been the ultimate determinant of the maximum depth of weathering.

The importance of regolith mapping in understanding relationships in the Yilgarn Craton has been stressed by Smith et al. (1992) and Anand et al. (1993). Grouping mapped regolith units into interpreted regolith landscape regimes (relict, erosional and depositional: RED scheme) provides a valuable surface classification of the regolith in appropriate terrains. The RED scheme (Craig et al., 1992; Anand & Smith, 1993) provides a valuable first stage of surface classification of the regolith and landform (Figure 2). The scheme is based on mapping, stratigraphy and detailed characterisation of regolith in several type districts including Mt Gibson, Boddington, Lawlers, Bottle Creek and Bronzewing - Mt McClure. The surface classification is then supplemented by details of the vertical variation in the regolith, and in most areas this relies heavily on drilling data. A generalised lateritic weathering profile consists of fresh rock passing upwards into saprock, saprolite, clay zone, mottled zone, lateritic duricrust and lateritic gravel. However, in detail, profiles are variable (Anand, 1998).

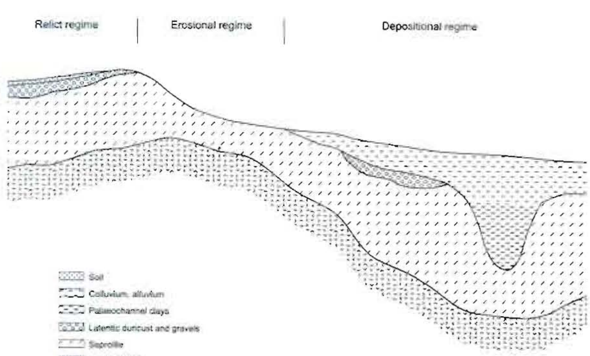

Figure 2: *Idealised cross-section from the Yilgarn Craton illustrating the major regolith components, including relict, erosional and depositional landform regimes (based on studies by CRC-LEME). The vertical scale on this figure is such that the relief is approximately 100 m and the thickness of depositional cover generally 0-100 m. Aspects of this model apply readily to the Basin and Range province of western USA except that the vertical scale would be 10-20 times that applicable for the Yilgarn Craton.*

In most regolith profiles, a major change is from oxidised to reduced (Fe^{2+}) iron-bearing minerals (i.e. mapped as the 'base of complete oxidation'), and this is usually near the saprolite - clay zone boundary (Figure 3). In mafic rocks, the transition is from overlying dominantly ferric minerals (e.g. goethite, hematite, maghemite) to less-weathered material with ferrous minerals (e.g. chlorite). This transition is obvious in rocks of basaltic composition, but poorly defined in rocks with minimal Fe content such as granite. The base of complete oxidation commonly is at several 10s metres depth, and beyond 100 m depth in rare cases. The deepest (first) signs of weathering are usually the oxidation of primary sulphide minerals and the dissolution of carbonates (Nickel & Daniels, 1985).

Below the zone of oxidation is a transitional zone in which rock textures are relatively well-preserved, the rock is fragmented into clasts with less-weathered cores, sulphides may be present, porosity may have developed from carbonate dissolution and Fe is in its reduced state (Figure 3). This lower part of the regolith profile in which primary rock fabrics are preserved (i.e. saprock and saprolite) is generally thicker than the upper interval (pedolith; Anand & Butt, 1988).

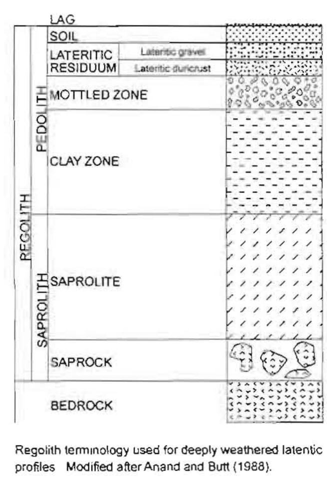

Figure 3: *Idealised stratigraphic column of a weathering profile in the Yilgarn Craton. This highlights the considerable proportion of the weathered profile below the most oxidised interval where rock fabrics are lost (i.e. below the pedolith).*

Clay types vary throughout the profile and above different rock types suggesting dynamic growth and/or destruction at essentially ambient temperatures. Within the Yilgarn Craton there are substantial differences in the regolith profile above mafic and above sedimentary rock types. In general, the upper part of the profile is dominated by kaolinite, with more illite-smectite in the saprolite and saprock intervals. Where there is transported alluvium in the profile, kaolinitic clays above the unconformity usually increase in crystallinity and decrease in bound water with increasing depth. In residual material (below the unconformity), crystallinity increases and bound water decreases in kaolinite downwards towards the saprolite; but in the lower saprolite and saprock, other clay types dominate over kaolinite (e.g. smectite).

There are many examples where the base of oxidation is deeper near sulphide accumulations than it is in surrounding terrain, and this depression has been attributed to acid ground waters developed from the oxidation of sulphides (Mann, 1984). The presence of pyrite and carbonate minerals in gold deposits plays a critical role in this depression of the base of oxidation. This is partly due to the tendency for pyrite breakdown to generate acid, and the role this acid plays in carbonate breakdown:

$$FeS_2 + 3.75\ O_2 + 3.5\ H_2O = Fe(OH)_3 + 2SO_4^{2-} + 4H^+ \quad 1.$$

(the oxidation and dissolution of pyrite to form ferric hydroxide and lower the pH)

$$CaCO_3 + 2H^+ = H_2O + CO_2 + Ca^{2+} \quad 2.$$

(dissolution of carbonate promoted by lower pH).

The interplay of sulphide ores, alteration around ore bodies, and distal country rocks has been recognised as a strong influence on weathering for many years. The weathering of sulphides generates acid conditions in a process analogous to an electrochemical cell (equation 1; Nickel et al., 1974), and massive sulphide ores are an end member where this sulphide influence is dominant. Carbonates, however, tend to neutralise any acid, and hence the weathering above massive sulphide deposits (i.e. which approximate carbonate-free systems) may contrast considerably with the weathering over nearby distal ores and alteration in which carbonates are common (Thornber et al., 1981). Gangue minerals within the sulphide ore thus affect the weathering pH, and this in turn influences the weathering style, depth, and element mobilities. Massive sulphides produce acid conditions, whereas any carbonate in disseminated sulphide ores keeps the weathering neutral or even alkaline, and in carbonate alteration without sulphides conditions are alkaline and carbonate minerals relatively stable.

Acid, saline ground waters over parts of the Yilgarn Craton have facilitated dissolution of gold in the regolith profile and led to gold remobilisation above many deposits (Mann, 1984; Butt, 1989a). This is particularly so around Kalgoorlie where highly saline waters easily leach gold and many other elements. However, in the northeast of the Yilgarn Craton where rainfall is lower and the ground waters are less saline and closer to neutral, the solubility of gold in the regolith is significantly less.

The regolith over the Yilgarn Craton today owes much of its character to past climatic conditions, particularly the more humid conditions leading up to the middle Miocene. During humid conditions there was deep lateritic weathering, and subsequently the laterite profiles were substantially modified during the more arid conditions following the Miocene. Increased aridity led to falling water tables, more saline ground waters and the importance of the gold-chloride complex in these waters. This all had significant impact on gold mobility and redistribution (Mann, 1984, 1998; Butt, 1989a). The practice of drilling to 'refusal' (Eshuys & Lewis, 1995) has followed from recognition of the importance of gold depletion in parts of the regolith profile. 'Refusal' in rotary air blast drilling is typically achieved by 120 m depth in much of the Yilgarn Craton, thus indicating the normal depth to 'mostly unweathered' rock (i.e. saprock).

Carlin Gold Province

Here, the term 'Carlin deposit' refers to the first mine of its type found in 1961 near the town of Carlin, Nevada; 'Carlin Trend' refers to the 100 km line of gold deposits that includes the Carlin deposit and follows the usage of Teal & Jackson (1997); 'Carlin-type' deposits refer to gold deposits with the characteristics outlined by Teal & Jackson (1997) and of course potentially include similar deposits in other parts of the world. 'Carlin gold province' refers to the geological part of north-central Nevada that includes a high concentration of Carlin-type deposits aligned in four main trends (in the sense of 'province' used by Phillips & Hughes, 1996). The terms 'Great Basin' and 'north-central Nevada' are reserved for geographical meaning. This terminology is consistent with the global use of the word 'Carlin' to identify this group of gold deposits in north-central Nevada.

There is considerable variability between different deposits that are termed 'Carlin-type deposits', but they share features such as high Au/Ag ratios, enrichment of Au > As, Hg, Ag, Tl, Sb > Cu, Pb, Zn, W, Te, Bi, and structural and host rock control. These features are also

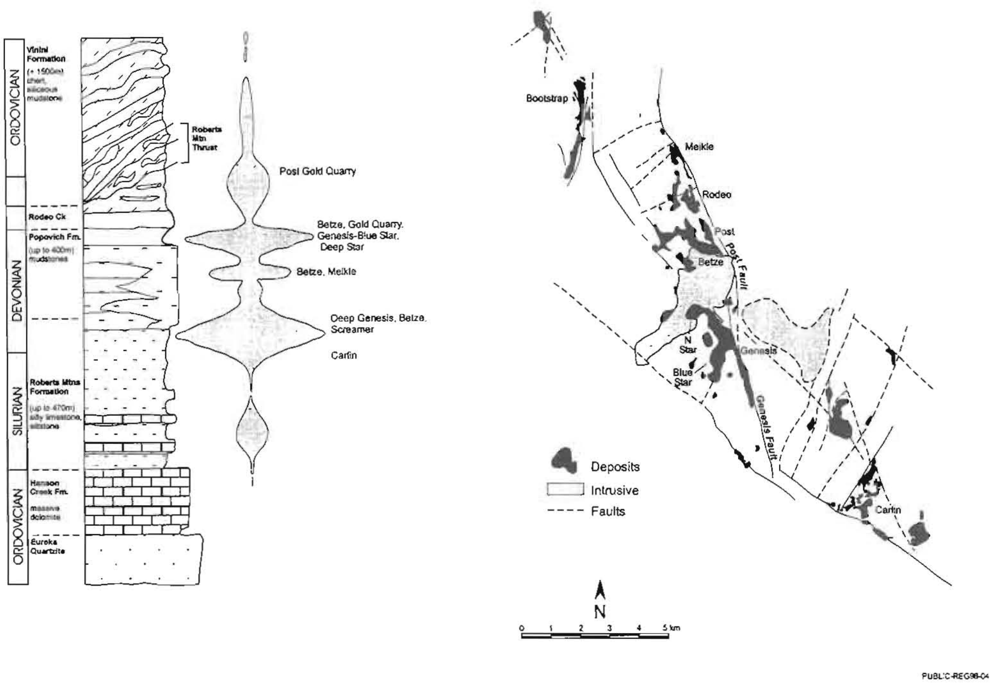

Figure 4. *Map of part of the Carlin Trend showing location of major Carlin-type deposits, and a stratigraphic column showing the position of significant Carlin-type gold mineralisation (after Armstrong et al., 1997; Teal and Jackson, 1997).*

common to Archaean greenstone gold provinces, slate-belt gold provinces, and the Witwatersrand goldfields (Phillips & Powell, 1993). Specific features of the Carlin-type deposits that have been cited as characteristic include carbonate dissolution, argillic alteration of primary silicate minerals, silicification, gold enriched sulphidation of iron in host rocks to form pyrite, arsenical pyrite (Teal & Jackson, 1997), and 'invisible' gold. We will suggest that several of these features can be explained by weathering.

The Carlin-type deposits also have a geographical link: they are in four linear trends within an area of 150 km square in north-central Nevada (Figure 4). This elementary observation takes on some importance when comparing the difficulty of defining 'Carlin-type' with the same difficulty experienced in other major gold provinces.

Regional geology of the Carlin gold province

The regional geology of the Carlin province is dominated by windows of Palaeozoic sedimentary rocks, Mesozoic intrusions of various compositions, all otherwise covered by Cainozoic volcanic and sedimentary rocks. The Palaeozoic rocks form an Ordovician to Carboniferous sequence of fine to medium grained clastic rocks and limestone, thrust over by Ordovician chert and siltstone (Roberts Mountain Thrust). The interpreted sedimentary depositional model comprises shelf limestone grading outwards and upwards to mudstone (Armstrong et al., 1997). There is undoubted original calcareous material in the sequence, but there is also evidence for substantial post-burial addition of carbonate. This has probably been responsible for the current difference of opinion as to whether the sequence is mainly mudstone or limestone (cf. stratigraphic columns of Armstrong et al., 1997, figure 2; and Teal & Jackson, 1997, figure 3). Petrographic work is particularly important in determining whether this carbonate is original or secondary.

Gold mineralisation is commonly focused around the Roberts Mountain Thrust, especially in siltstone below this structure; however, steep-dipping structures which post-date thrusting also play an important role. The Palaeozoic succession is folded and faulted with multiple orientations of brittle-ductile shear zones, faults and breccias. The general tectonic setting during sedimentation was a Cambrian to Early Carboniferous stable continental margin, with an ocean and eugeosynclinal setting to the west. The Late Devonian to Early Carboniferous Antler orogeny involved east-directed compression with western successions thrust over eastern strata.

There are two main periods of igneous intrusive activity recorded in the Carlin province, i.e. Jurassic (160-150 Ma) and Tertiary (35-40 Ma). There are also Miocene and younger volcanic rocks. The Jurassic intrusive rocks include intermediate to mafic dykes, lamprophyres and kilometric-scale, diorite stocks. One of the latter, the Goldstrike stock is unfoliated (see Figure 6e) and appears to lack the brittle-ductile shear zones found elsewhere in mineralised areas of the Carlin Trend. The Tertiary activity included rhyolite dykes and granodiorite. Surrounding some of these stocks of both intrusive periods are 100 m wide zones of calc-silicate hornfels formed from contact metamorphism of the limestone and calcareous mudstone of the Palaeozoic succession.

Mineralisation in the Carlin gold province

Palaeozoic rocks are easily the dominant host rock for gold. Sedimentary rocks of Ordovician, Silurian and especially Devonian age host Carlin-type mineralisation. Regionally and locally there is a concentration of mineralisation in the siliclastic rocks rather than in thick limestone (see Teal & Jackson, 1997, figure 1), with minor mineralisation in Palaeozoic basalt at Twin Creeks mine (Bloomstein et al., 1991) and in various weathered intrusive rocks at Goldstrike. Although all deposits appear structurally controlled, there is considerable variation of structural setting between Carlin-type deposits including breccias, shear zones, folds, faults, extensional veins and disseminated strata (Teal & Jackson, 1997).

One of the striking features of the deposits on the Carlin Trend is the lack of a strong association with igneous activity (Ilchik & Barton, 1997), with some deposits very close to igneous bodies and others quite removed. Despite major deposits such as Goldstrike being immediately adjacent to the Goldstrike pluton, the Carlin Trend continues 10s km from this pluton with very similar gold deposits along its length. The Goldstrike pluton, a diorite stock dated at 158 Ma, is gold-bearing in its outer 15 m adjacent to strong mineralisation in the surrounding metasedimentary rocks, and locally near structures cutting the stock. However, despite this hornblende plagioclase intrusion appearing to be an ideal host rock based on its relatively Fe-rich chemical composition, its competency, and its position on the Carlin Trend, gold grades in the bulk of the stock are substantially lower than in surrounding rock types.

Figure 5(a): *Betze-Post pit showing bleached 'oxide' upper unit representing extensive weathering and equivalent to the 'pedolith' zone in Western Australian terminology. The darker, lower part of the pit walls have some rock fabric preservation (here equated to the saprolite zone). The dark colour is a result of carbonaceous material and/or arsenian pyrite.*

Figure 5(b): *Gold Quarry pit showing a wedge of Tertiary Carlin Formation in the upper central pit wall (light colour). Red and yellow colours of the oxide ore continue to great depth and are interspersed with darker carbonaceous and/or pyrite-bearing material.*

Figure 5(c): *Gold Quarry pit near 300m depth. Dark refractory ore with carbonaceous material and/or arsenian pyrite surrounded by lighter coloured oxide material comprising kaolinite and Fe oxides.*

Figure 5(d): *Gold Quarry pit showing kaolinite-Fe oxide material representing strong weathering at 300m depth.*

Figure 5(e): *Genesis pit looking south showing Tuscarora anticline left of centre, and the steep Gen Fault (also known as Post Fault) on the far left (both structures marked).*

Figure 5(f): *North Star pit with extensive dark metasediments of the Popovich and Rodeo Formations containing carbonaceous material and/or pyrite.*

Figure 5: *Photo mosaic*

Throughout the 80 km length of the Carlin Trend, the upper 10s to 100 m of open pits comprise a bleached interval rich in kaolinite with Fe oxides ('oxide' material). Oxide ores in this bleached interval are extremely important economically as they occur at shallow depth and have cyanide-extractable gold; and as such have been the primary focus of the first three decades of open pit mining. This oxidised zone generally follows the topography (i.e. is present in every open pit operation for the top 10s to 100s m regardless of elevation); this is despite exhumation from the site of gold deposit formation at several kilometres depth. There is typically a fairly sharp contact of this bleached interval with very dark ores (Figures 5a-f; 6a-f). In core from 300-800 m depth, several mineralised intervals are very friable, and contain kaolinite and Fe-oxides on the surfaces of individual clasts.*

Below the bleached zone is a dark interval with abundant black pyritic shale containing refractory gold. This ore requires different extraction methods to the bleached ores that include pressure oxidation and roasting to recover all the gold. The refractory gold is associated with dark (in places black) ores containing arsenian pyrite, carbonaceous material, local realgar and orpiment, with much of the refractory gold being within the arsenian pyrite (Arehart et al., 1993a). Importantly, the gold is within the arsenian-rich rims to pyrite grains, with minimal gold in the core pyrite itself. Further minerals include introduced silica, arsenian pyrite, dolomite, 'illite' and/or kaolinite, with common quartz veining that is typically as thin veinlets of limited length. In general, the refractory ore is vertically below the bleached interval, but locally one ore type can surround the other (Figure 5c).

High degrees of porosity are a characteristic of both the oxide and carbonaceous ores (typically 10 to 30 percent porosity), and this porosity locally continues to the base of open pit mining (300 m) and in drill holes to 1.5-2 km depth (Figure 6). The porosity in the ores results from calcite and lesser dolomite dissolution and is common to many but not all gold deposits (e.g. Screamer deposit has calcite present). Outside this decalcified zone, calcite veins are common but there is much less pyrite here, and subordinate economic gold. Thus the decalcification that leads to the porosity shows a close correlation with the ore intervals and higher pyrite concentrations.

Figure 6(a): *Mixed sections of core from unmineralised mudstone of the Popovich Formation in the Betze-Post area (mostly 400m depth).*

Figure 6(b): *Weakly mineralised core from the Rain area showing fragmented pieces of mudstone from 700m depth.*

Figure 6(c): *Mineralised core from Rain area showing porosity and highly fragmented nature of material even at 800m depth. Note: core blocks are in feet.*

Figure 6(d): *Mineralised core from Rain area illustrating granulated nature of material at 700m depth.*

Figure 6(e): *Goldstrike granodiorite from Betze-Post area with fresh amphibole and plagioclase (pluton dated at 158 Ma).*

Figure 6(f): *Quartz veining unrelated to gold mineralisation within the Goldstrike granodiorite, North Star pit.*

Figure 6: *Photo mosaic*

There is well-established evidence for a meteoric water signature in the deposits of the Carlin province based upon δD values in fluid inclusions in ore minerals of -100 to -150 per mil, which is much lighter than metamorphic or magmatic values (typically - 40 to -80 per mil). This meteoric signature is supported by oxygen isotope work, and is common in both the upper oxidised ores AND in the deeper refractory ores including in realgar and orpiment (Radtke et al., 1980; Ilchik & Barton, 1997).

A survey of many of the world's gold provinces has suggested that several have characteristics similar to the Carlin-type deposits of north-central Nevada. Similarities between the central section of the Victorian gold province (e.g. Melbourne zone) and deposits of the Carlin gold province have already been alluded to by Hughes et al. (1997). The comparison has already been made between the Carlin ore fluids and those of Witwatersrand, greenstone and slate-belt gold provinces (Phillips & Powell, 1993). The recent conclusion that sulphidation of Fe-rich wallrocks was an important process in the formation of the Twin Creeks mineralisation in Nevada is significant (Stenger et al., 1998), because this is the same process implicated over the last decade in the formation of many Archaean greenstone (e.g. Phillips & Groves, 1984; Neall & Phillips, 1987), and Victorian slate belt gold deposits (Phillips & Hughes, 1998).

Origin of Carlin-type mineralisation

Several paragenetic stages of mineralisation are recognised in and around the deposits of the Carlin gold province. A localised occurrence of sphalerite-galena-barite with very minor gold is interpreted as diagenetic or earlier, and formed from early saline fluids well before the gold event (Emsbo et al., 1996): this early origin is supported by cross-cutting geological relationships (Kuehn & Rose, 1992). In many of the Carlin-type deposits (e.g. those of the Carlin Trend), pyrobitumens are common and are evidence for earlier migration of hydrocarbons; these now indicate an over-mature ('dead') oilfield. Migrating ore fluids may have exploited similar fluid pathways to the hydrocarbons.

Most present genetic models suggest that two stages of gold mineralisation occurred:

1. **Main Ore Stage** characterised by pyrite, muscovite (illite), and gold, with fluid inclusion evidence of a low salinity fluid dominated by H_2O-CO_2, and with essential H_2S. The best estimates of P-T are 0.5 to 1.5 kbars and 200-220°C (Kuehn & Rose, 1995; Cline et al., 1997; Lamb & Cline, 1997).
2. **Late Ore Stage** is characterised by a significantly different group of minerals to that of the Main Ore Stage such as realgar (AsS), orpiment (As_2S_3), stibnite (Sb_2S_3), barite ($BaSO_4$), kaolinite, other clays and calcite veins.

The low salinity, H_2O-CO_2-H_2S fluid inferred for the Main Ore Stage is critical in regard to genetic models for Carlin-type deposits. This type of fluid is not widely recorded in nature except that it is typical of other major gold-only provinces and is best explained by metamorphic devolatilisation (Phillips & Powell, 1993). The fluids responsible for the Late Stage ores in the Carlin province are typical of a low temperature, relatively more oxidised environment, and considered aqueous with a strong meteoric component (Cline et al., 1997).

The age of gold mineralisation in the Carlin province has long been contentious, and still remains less-well constrained than most other gold styles, even including those of Archaean age. For Carlin-type mineralisation, the Mesozoic and Tertiary ages that are commonly inferred for the major hydrothermal gold mineralisation represent a range from 160 to 35 Ma (contrast this with the smaller absolute range for Archaean Kalgoorlie gold of 2660 to 2600 Ma). Although the bulk of gold from the Carlin Trend is within rocks that pre-date the Antler orogeny (350 Ma), weak gold mineralisation in the Goldstrike stock (158 Ma; Figure 6 e) has traditionally been cited to support a maximum age for gold introduction. There are few potential host rocks of Carboniferous to Jurassic age to provide timing constraints (one example is at the Rain deposit). In other studies of Carlin-type deposits, mineralisation in Tertiary igneous rocks is taken to indicate a Tertiary age for mineralisation. However, the picture is more complex; for example, gold distribution in the Genesis pit is partially controlled by branches of the Gen Fault which itself offsets the Tertiary Carlin Formation and is 'Basin and Range' in age (ca 17-14 Ma; Figure 5 e). This last observation is not easy to rationalise with other constraints on the timing of mineralisation unless the Gen Fault is older and has been reactivated and/or the control on gold by the Gen Fault is a later effect (perhaps weathering). Extensive use has been made of Ar-Ar dating of muscovite-illite particularly from the carbonaceous ore. A mineralised dyke from Goldstrike has been dated at 39 Ma using Ar/Ar methods on a biotite (Emsbo et al., 1996). Not all the field data are completely consistent as some lamprophyres are undeformed and unaltered adjacent to mineralisation, yet inferred to be ca 150 Ma; furthermore, there are many muscovite-illite ages that are quite old (see Table 3). The explanation that these old illite ages are preserved from the detrital stage is not yet convincing.

Ar/Ar dating has been used to infer five separate mineralising events at the Twin Creeks and the Getchell deposits: these are at 95, 92, 83, 75 and 42 Ma (Groff et al., 1997). The mineral assemblages cited for each of these phases can be related to the scheme of Main Ore Stage and Late Ore Stage of Kuehn & Rose (1995). The resulting paragenetic scheme (Groff et al., 1997) illustrates the difficulties of building geological models from geochronological numbers without an independent and over-riding geological and paragenetic framework.

The concerning aspect of the wide age discrepancy for gold mineralisation in the Carlin province comes from potential links to major tectonic events. Most of the world's gold-only deposits, including Carlin-type, occur in orogenic zones (as opposed to platform or basin settings) and bear a relationship to deformation and thermal processes on a scale at least as large as the gold province (Kerrich & Cassidy, 1994). The Antler, Humbold, Sevier, Laramide and Basin and Range orogenies have all influenced the lower Palaeozoic host rocks of the Carlin gold province. The 160 Ma to 35 Ma uncertainty bracket for Carlin province mineralisation means the Carlin gold-forming process remains unconstrained within a whole series of possible tectonic events from Jurassic to Tertiary age, or possibly earlier. Hence it is very difficult to integrate Carlin mineralisation with the tectonic development of western USA or relate the Carlin gold province to the many other gold deposits in the region (e.g. 'low sulphidation epithermals', hot springs, Au-Ag deposits, Mother Lode, Cripple Creek).

Despite their global importance and extensive study, the origin of Carlin gold is described as 'enigmatic' (Ilchik & Barton, 1997). The lack of a mutually-agreed and testable genetic model for deposits of the Carlin gold province appears to be conceded by many of those working on, and familiar with, these deposits. This uncertainty is in no small way linked to the enormous uncertainty in the age of mineralisation (Teal & Jackson, 1997, p. 23), and uncertainty of tectonic setting during mineralisation. Genetic models to account for the formation of Carlin-type deposits invoke magmatically derived fluids (Sillitoe & Bonham, 1990; Henry & Boden, 1997), meteoric fluids (Ilchik & Barton, 1997) or metamorphic fluids (Kuehn & Rose, 1992, 1995; Phillips & Powell, 1993; Cline et al., 1997). Epithermal models have been widely invoked in the past (e.g. Radtke et al., 1980; Radtke, 1985), but ore continuing to 1-2 km depth, the importance of brittle-ductile shear zones, and the fluid inclusion data (Kuehn, 1989; Kuehn & Rose, 1992, 1995) make conventional epithermal models unlikely. Outstanding problems to do with understanding the formation of Carlin-type mineralisation include the juxtaposition of oxidised and reduced mineral assemblages as part of Carlin gold mineralisation in so many deposits, the concentration of deposits in rocks of pre-Pennsylvanian age, the juxtaposition of lithostatically and hydrostatically pressured regimes, the extensive porosity, and the inference of carbonate dissolution by an acidic fluid rich in CO_2. It also needs to be resolved whether an acidic fluid moved through the large footwall section of carbonate-bearing rocks to where it deposited the gold. The orientation and position of the Carlin Trend and other trends are not well related to any tectonic features or processes at the traditionally inferred times of gold mineralisation.

Weathering In Deposits of the Carlin Gold Province

Most of Nevada and parts of surrounding states comprise the Great Basin, a geographic unit within the Basin and Range Province of western USA. The Great Basin is characterised by very few permanent surface streams and an internal drainage resulting in salt lakes. The elevation is from 500 m to 3500 m and the present climate is semi-arid. Outcrop on higher ground is sparse, and the 'Basins' are filled with thick sequences of undeformed Tertiary sediments. The filling of the 'Basins' is analogous to the filling of the palaeochannels on the Yilgarn Craton, although the scale is different: the vertical scale for Nevada is about twenty times that of the Yilgarn (see Figure 2). Both filling processes would be favoured by aridity, consequent reduction in the amount of surface waters, and resulting decreased sediment transport. The main difference today is that the equivalent of the 'Ranges' on the Yilgarn Craton are insignificant compared to the 'Ranges' in Nevada.

Evidence for weathering in Carlin deposits

There are several references in the literature to deep weathering in individual deposits of the Carlin province; and yet weathering was virtually unmentioned during the 'Carlin-type gold deposits' field conference (Vikre et al., 1997) and in a recent major overview (Teal & Jackson, 1997). At the Pipeline deposit, weathering extends to 245 m (Foo et al., 1996a) and at South Pipeline deposit to 550 m depth (Foo et al., 1996b.). At the Carlin deposit itself, oxidation to 250 m depth is preferentially developed along steep structures or permeable footwall beds (Kuehn & Rose, 1992). At Twin Creeks deposit, the redox interface in the weathering profile is at 120 m depth generally, but 500 m deep near sulphides. The importance of unravelling hypogene oxidation from supergene weathering has been very clearly elucidated in some earlier work (e.g. Seedorff, 1991, p.161; Arehart et al., 1992).

Juxtaposition of significant low grade copper mineralisation at the Mike deposit is not typical of the Carlin Trend, but provides clear evidence for weathering processes. Here the 100 m thick, Tertiary sedimentary rocks are weathered, and copper occurs over a 200 m horizontal interval in the underlying Palaeozoic succession (Teal & Branham, 1997). The copper mineralisation includes an oxide zone of malachite and native copper and a deeper supergene sulphide interval of chalcocite and covellite. Hence, supergene processes are recorded by the copper assemblages to at least 500 m below the Tertiary cover (Teal & Branham, 1997). The bulk of the current gold resource at Mike overlaps or lies above the copper mineralisation and includes highly porous ore that has lost calcite through dissolution.

Studies of alunite recognise the role of palaeoweathering (Folger et al., 1996): "The oldest supergene alunite, from the Gold Quarry deposit in the Carlin Trend yielded apparent ages of 30-27 Ma (Heitt, 1992)". Compatible with this conclusion is the statement by Arehart et al. (1992) based particularly on their research at the Post deposit: "From all available petrographic and geochemical data, it would appear that alunite in the micron gold deposits of Nevada is entirely of secondary supergene origin.". The nature of Carlin hematite, which is not specularite, has been used to conclude that this mineral is also unlikely to be primary, and that the primary ore fluids did not enter the hematite stability field (Seedorff, 1991). Brief mention has been made of a 'post-gold hydrothermal event' that has overprinted Miocene sediments and was of low temperature (below 150°C; Ferdock et al., 1997, p. 84-85): although conventionally attributed to a hypogene oxidation process, this event appears quite similar to Cainozoic weathering.

Modern day hot waters within the Meikle mine are creating cavities tens of metres wide in the immediate footwall of the Post Fault (i.e. an old structure reactivated around 20 Ma). These caverns appear to be forming from acid waters that are attacking carbonate: calcite and barite are precipitating locally. This dissolution is occurring to 500 m depth and we interpret the acidity as being due to the oxidation of sulphide minerals.

Clasts up to several centimetres diameter, that have been recovered during diamond drilling, have rinds of kaolinite and ferric oxide (hematite, limonite) and continue to 800 m depth in decreasing abundance (e.g. at Rain deposit; Figure 5). The assemblage represented on these rinds is that of the upper bleached zone in open pits that contains the free-milling gold, and probably represents the more-extreme downward extension of this bleached zone along cracks and fractures.

These isolated literature references and new field observations all suggest weathering in the Carlin province, but do not provide much indication of how extensive the deep weathering is. To determine this would require systematic mapping of various weathered and unweathered assemblages. Importantly, a model of deep weathering in the Carlin district has additional circumstantial support by providing plausible answers to some of the outstanding questions about Carlin geology and especially gold genesis.

Interpretation of bleached upper interval with free-milling (non-refractory) gold

The interpretation of the upper, bleached interval as the product of Cainozoic weathering appears to be relatively well accepted now (Bakken & Einaudi, 1986; Kuehn & Rose, 1992), although it has been controversial in the past. While some groups appear to have accepted the weathering origin of the upper bleached interval since the early 1980s (Bettles, pers. comm., 1998), others debated the issue during the 1980s interpreting this interval as the argillic part of an epithermal system (see Radtke et al., 1980, Radtke, 1985).

The evidence suggests that the bleached zone formed above the water table redox front, the dominant form of iron is Fe^{3+}, and the ground waters caused alkali removal and kaolinite stabilisation. This oxidised zone generally follows the modern topography (i.e. the oxidised interval is present in every open pit operation for the top 10s of metres at least, regardless of elevation): this is a significant piece of information given the deposits have been exhumed from their site of formation of primary mineralisation at several kilometres depth (Kuehn, 1989; Kuehn & Rose, 1995; Cline et al., 1997).

Our work suggests that locally weathering continues to considerably greater depth than previously recognised, i.e. at least to 800 m and probably to 1.5 km depth. Deeper bleached intervals are probably localised by the common fractures in and around mineralisation and reflect the abundances of sulphide and carbonate minerals in primary mineralisation. One of the most extreme expressions of this deep bleaching is the kaolinite and Fe-oxide rimmed clasts in drill core.

If the weathering interval above the water table redox front extends locally to 1 km or more, the question is begged of where and how deep the weathered interval below the redox front might be (see Fig 3).

Interpretation of dark refractory ores with arsenian pyrite and/or carbonaceous material

The genesis of the refractory ore is more controversial than that for the bleached mineralisation. Previously, this ore has been considered the result of one or more evolving primary mineralising events. This interpretation creates some difficulties explaining the evolution from a reducing to oxidising fluid, extensive porosity at several kilometres depth, calcite dissolution by a CO_2-rich fluid to cause the porosity, lack of a coherent genetic model for primary mineralisation, and a myriad of geochronological numbers for what is otherwise a relatively coherent gold mineralising style. Instead, we explore the possibilities that the dark interval has also been exposed to weathering processes.

We suggest that the porosity, realgar and orpiment, and kaolinite are products of weathering processes well after the main gold mineralising event. This is supported by the strong meteoric water signature in both the bleached ores and in the refractory arsenian-pyrite bearing ores. It is possible that the porous mineralisation, which is virtually all the non-silicified mineralisation in the Carlin-type deposits below the oxidised ores, post-dates the major gold and pyrite mineralisation and may in part be 'transition' zone material formed during the early stages of weathering below the water table redox front. This weathering is probably Tertiary in age although meteoric waters are still percolating to great depths today as evidenced by the large crystal filled cavities at the Meikle mine. This interpretation defines the transition zone of weathering in the Carlin provinces as the interval in which weathering has dissolved calcite but has not totally consumed sulphides and carbonaceous material through oxidation. The relatively late origin for this porosity helps overcome the paradoxical preservation of open spaces previously proposed to have been generated at initial formation depths of >4 km.

Interpretation of the Late Ore Stage mineralisation

The change from low salinity, H_2O-CO_2-H_2S fluid during the Main Ore Stage to a fluid that stabilised realgar, orpiment and barite (Kuehn & Rose, 1992, 1995) is not well understood. Three possibilities are tested here, and one of the main variables between the models is the role of meteoric waters. In the first model meteoric water is peripheral, in the second it is involved in massive influx during primary mineralisation, and in the third model there is significant meteoric water influx after and separate from primary mineralisation and as part of weathering.

The evidence for a substantial role for meteoric waters is in part based upon deuterium isotopes from kaolinite within realgar - orpiment bearing ores. This supports the influx of meteoric waters to the deepest levels of mineralisation (Ilchik & Barton, 1997), and is corroborated by light (18O values in late stage calcite-realgar veins (Kuehn, 1989).

Model 1. A progressive evolution of the Main Stage fluid into a fluid that stabilises the Late Stage minerals

This model invokes a progression from Main Stage to Late Stage ore without significant disruption. There is no complete explanation why or how the H_2O-CO_2 dominated Main Ore Stage fluid with H_2S and low salinity evolves into an oxidised fluid, especially at 4km depth. There is no parallel to such a progression in other gold deposits despite the fluids being similar (Phillips & Powell, 1993; notwithstanding hematite-bearing assemblages at some such deposits, e.g. Kalgoorlie; Phillips & Gibb, 1993). It is also unclear how any porosity would develop during the mineralising process at 4 km depth and then be preserved. This model requires an acidic ore fluid to have traversed a significant footwall carbonate sequence.

Model 2. Mixing with meteoric water during the Main Stage event leading to stabilisation of the Late Stage minerals

This model invokes mixing of a typical 'gold-only' fluid with descending meteoric waters late in the mineralising event. Although this accounts for the fluid inclusion and isotope evidence, the model might have difficulties explaining the descent of meteoric waters from a hydrostatic regime into a deeper lithostatic regime in which brittle-ductile processes are inferred, unless perhaps some throttling mechanism is invoked (Kuehn & Rose, 1995). There is also difficulty seeing how the porosity has been retained through later events including exhumation. This model requires an acidic ore fluid to have traversed a significant footwall carbonate sequence.

Model 3 (preferred). Main Stage assemblage undergoes later weathering, involving meteoric water influx, to generate the Late Stage minerals

This model invokes a typical 'gold-only' mineralising process under lithostatic conditions, probably before the Tertiary. The fluid was H_2O-CO_2 dominant with H_2S and low salinity; the dominant alteration minerals were muscovite-pyrite-calcite±dolomite. During the Tertiary weathering, meteoric waters influenced the landscape and were particularly reactive with sulphides, in turn becoming acidic and then highly reactive with calcite. This reaction and the disposition of fractures around mineralisation provided deep access of the meteoric waters in and around the orebodies. The considerable topographic relief provided a substantial head to drive water penetration. Porosity was developed during this weathering and is thus a relatively late feature formed under hydrostatic conditions. The water table redox front is 100 to 300 m below the present land surface except within the gold deposits where it is much deeper in some mineralised zones.

Ilchik and Barton (1997) have already presented a detailed hydrological model for meteoric water migration in the Carlin province, but instead of invoking it as the gold transporting agent, we are interpreting it as the weathering process after gold formation, and the agent of substantial modification to existing deposits.

Summary: The vertical profile found in deposits of the Carlin gold province appears best explained if the dramatic visual change at the base of the oxide ores marks the base of complete oxidation rather than the base of weathering, and the underlying, mostly refractory material is interpreted as weathered for many hundreds of metres below this level. Hence the top of fresh rock may not have been reached in many parts of the Carlin Trend.

This interpretation has the saprolith (Figure 3) in the Carlin province as including the interval in which weathering has begun but has not totally consumed sulphides, carbonates and carbonaceous material through oxidation and acidification. The relatively late origin for the porosity helps overcome the paradoxical preservation of open spaces previously proposed to have been generated at depths of more than 4 km. Model 3 also removes the need to have juxtaposed over-pressured fluids with meteoric water circulating under presumably hydrostatic conditions.

Table 2: *Factors supporting deep weathering of gold deposits in the Carlin province.*

In favour of deep weathering	• porosity. • oxidised mineral assemblages. • kaolinite - Fe oxide assemblages. • hydrogen isotope data. • oxygen isotope data.
Problems explained by deep weathering scenario	• source and pathway of acid fluids. • source of oxidising fluid.
Issues that are potentially resolved by deep weathering	• dating: the uncertainties for Carlin gold exceed any other major gold province (>100My). • genetic model: refinement beyond current range of magmatic or metomorphic or meteoric. • tectonic setting during mineralisotion: Basin and Range or Laramide or Sevier or Humboldt or Antler? • origin of realgar and orpiment during late stoge processes.

Model for weathering in the Carlin gold province

The postulated weathering in the Carlin province probably reflects an earlier Cainozoic period during which the climate was less arid: this would provide more surface water in turn leading to 'Basins' with less sediment fill. The net result would be greater relief through which ground waters could move. These meteoric waters would have reacted vigorously with any sulphide-bearing ore deposit they met, and become acidic. The acidic waters would react strongly with calcite to remove this carbonate and leave the rock porous, and the oxidising condition would redistribute arsenic. In places, this weathering profile has been covered by Tertiary Carlin Formation sediments, but there is also evidence in the Carlin Formation suggesting it also has undergone weathering (e.g. opal, jarosite, antimony hydroxides and oxides, marcasite, iron hydroxides, clays and zeolites; Ferdock et al., 1997 and earlier discussion).

The near-surface 'oxide' ores were originally considered as a late stage of the main mineralising event (Radke et al., 1980); they are now widely regarded as the product of weathering of typical Carlin-type gold and sulphide mineralisation. This is compatible with the observation that the interval of oxide ore follows the topography despite considerable present-day relief and significant erosion (possibly 3-4 km) since ore deposit formation. Jasperoids at the top of this zone could be another product of this weathering resulting from silica replacement of carbonate in an arid environment.

Although we have emphasised some similarities between the regolith in Western Australia and Nevada, there are significant differences. In Western Australia, the profile passes downwards from Fe-rich laterite to bleached material to saprolite; whereas in Nevada, jasperoids pass downwards into bleached material and then decalcified, porous and leached material and dark refractory ores. Some of the differences can be accounted for by contrasting the widespread mafic rocks that host gold in the Yilgarn with the common sedimentary host rocks in the Carlin province. Fully understanding these differences is a remaining and important issue.

Implications of Weathering in the Carlin Province

Is kilometre-deep weathering reasonable?

Although weathering in the Yilgarn Craton is usually thought of as being relatively 'deep', the weathering being suggested here for the Carlin gold province is substantially deeper.

Deep weathering is virtually an inevitable consequence of stable high relief, and climate change can lead to significant relief change. Kilometric-scale penetration of meteoric waters has already been recorded in other geological settings in North America. Limestone cave systems (interestingly also relying upon calcite dissolution) are known to vertical depths of 1 km or more. Isotope studies in several shear zone and vein-related gold deposit systems have shown deep meteoric fluid ingress overprinting vein quartz but not necessarily the surrounding alteration minerals (Goldfarb et al., 1991; Kyser & Kerrich, 1991), again representing evidence for locally deep penetration of meteoric waters. The substantial elevation of parts of Nevada (up to 3500 m above sea level), and low base level (around 500 m) during more humid periods, are important in the deep weathering scenario. The downward penetration of rain waters from the mid to upper elevations would be facilitated by pre-existing faults and shear zones (including around gold deposits) and by soluble rock forming material (e.g. calcite in and around gold deposits) and the main limit on weathering depth would be the base level of streams in this part of the western USA around 500 m.

In our weathering model, the deepest weathering is at the gold deposits and coincides with abundant pyrite that generated acidic waters to dissolve calcite. The weathering is less deep in the surrounding halo where there is more calcite and less pyrite, and in country rocks. This is similar to the findings of Thornber et al. (1981) in the Yilgarn Craton where they noted the important interplay of sulphides and carbonate in influencing weathering depth and element mobilities.

Implications for gold in the Carlin province

Some of the critical timing relationships for Carlin-type mineralisation come from the gold distribution in samples that are likely to be weathered. This is relevant when geological relationships are being used to determine if a certain rock unit pre-dates or post-dates the main gold mineralising event. Units that post-date the primary gold mineralising event may still be gold mineralised by redistribution during weathering. Unfortunately, most studies do not make it clear what care has been exercised in using the distribution of gold in weathered rocks to reflect the gold distribution at the mineralising primary stage. The presence of pyrite and carbonaceous material alone is insufficient evidence to conclude that the rocks have not been subjected to weathering processes.

The migration of gold in the weathered zone is influenced by salinity of ground waters (Mann, 1984; Webster & Mann, 1984; Webster, 1986; Mann, 1998). In low salinity ground waters inferred for the Carlin province today, gold mobility may be limited compared to the parts of the Yilgarn Craton that have saline waters such as around Kalgoorlie. This conclusion is compatible with the lack of strong gold enrichment and depletion zones and the paucity of nuggets in the Carlin province, but does not rule out different weathering conditions in Nevada during the Mesozoic and Cainozoic. The relatively uniform gold fineness throughout the Carlin gold province, and with depth, also suggests little silver-gold partitioning by saline ground waters (Mann, 1984). The micron sized nature of Carlin gold in the oxide zone is here attributed to breakdown of gold-bearing arsenian pyrite, and the negligible supergene migration of gold. Thus, the weathering episode exerts a profound effect on the economics of Carlin metallurgy and even the late appreciation of this major gold province.

The economics of gold mining in Nevada is intimately linked to the role of arsenic. In the bleached oxide ore zone, arsenic is either leached or in a form that does not encapsulate gold; in the dark ore zone, arsenian pyrite leads to gold ores being refractory. This behaviour is compatible with As being mobile in oxidising conditions and precipitating upon entering deeper, more reducing environments (Heinrich & Eadington, 1986). Several aspects of As behaviour remain unresolved, including why the contrast in its distribution in the regolith profiles of Western Australia and Nevada. Possibly, the high iron contents of Archaean greenstone belts have played a role in stabilising As in the regolith and this process may have been less effective in the less-Fe-rich Carlin sequence. In the Yilgarn, the As is concentrated in ferruginous zones of the regolith, whereas in the Carlin province such zones appear to be less-well developed.

Implications of a weathering origin on radiometric dates in the Carlin province

Much of the material used for radiometric studies is selected from arsenian pyrite, realgar and/or orpiment bearing ores in open pits. Although these rocks contain a meteoric hydrogen isotope signature (Ilchik & Barton, 1997) they may still give a gold mineralising age if the meteoric water was an integral part of the main mineralising process: the same does not apply if the meteoric signature is due to much later weathering. In our assessment, the presence of pyrite in carbonaceous material is not sufficient evidence on its own of being below the weathered zone; instead, the open pits could be many hundreds of metres above the real base of weathering in ore zones. The extreme porosity of the rocks and the absence of calcite ('decalcification') adjacent to structures indicate that these rocks have seen large quantities of ground water. Many 'ages' that come out of dating illitic clays form clusters, but the meaning of these numbers from potentially weathered material remains uncertain. Overall, the validity of many radiometric samples as providing a date on the main mineralising event appears doubtful.

Radiometric dating of deposits in the Carlin province has commonly driven genetic models (e.g. Groff et al., 1997). A different approach would be to use dating to test between possible genetic models developed by independent methods. This approach would eventually lead to a chronological framework that is consistent with, and receiving independent support from, the geological framework.

The model for weathering will similarly influence the interpretation of stable isotope data, such as the +5 to +25 per mil sulphur isotope values.

Dating of highly weathered material by Ar-Ar methods applied to micas

Much of the material used for Ar-Ar dating from Carlin-type deposits (e.g. from Twin Creeks) would be classified by us (i.e. NP and DT) as 'significantly weathered' by Yilgarn standards if it was being sampled from a Western Australian gold deposit. It would be interpreted as containing oxidised and reduced minerals, and coming from below the water table redox front, i.e. below the 'base of complete oxidation'. For such samples, information collected from primary fluid inclusions tends to be more robust than information from stable and radiometric isotopes related to clay assemblages. There is a need to re-examine the premise that the mineralisation event(s) in the Carlin province (over 200°C) was inadequate to reset pre-existing micas (especially given the reordering, growth and consumption of mica and clay minerals occurring at ambient temperatures in the Yilgarn regolith). If this assumption proves to be invalid, then more weight should be placed upon some of the older geochronological numbers. A geologically late weathering event between 0-40 Ma would then explain many of the younger numbers, especially from finer grained material (Folger et al., 1996). Bringing weathering into the ore-forming and ore-modifying succession might also resolve some of the disputes about Mesozoic versus Tertiary ages for Carlin-type mineralisation (Wilson & Parry, 1995, 1997; Mako, 1997).

District/Trend	Deposit/Mine	Host	Stratigraphic age of	Isotopic age of Country Rocks	Method mineralisation	Reference
Carlin						
	Carlin	Roberts Mountain Fm	Silurian - Devonian	233	K/Ar	Kuehn, 1989
	Carlin	Intermediate Dykes	Silurian	100 - 123	K/Ar	Kuehn 1989
	Betze / Post	Roberts Mountain Fm	Silurian - Devonian	85 - 194	K/Ar, 40Ar/39Ar mica	Arehart et al. 1993b
	Goldstrike	Limestone & mudstone	Devonian	117 Ma hydrothermal event in 158 Ma Goldstrike Stock	K/Ar, 40Ar/39Ar mica	Arehart et al. 1993b
	Genesis/ Blue star	Popovich Fm	Devonian	95 - 97	K/Ar Illite	Drewes 1993
	Mike	Roberts Mountain Fm	Silurian - Devonian	107 - 111	K/Ar K-feldspar	Branham 1994
Independence						
	Jerritt Canyon	Hydrothermolly altered andesite	M. Ordovician - L. Devonian	120 - 320	K/Ar & Ar/Ar whole rock / amphibole	Phinsey et al. 1996
	Jerritt Canyon	Basalt Dyke		40.8 - 39.2	Ar/Ar	Phinsey, et al. 1996
	Jerritt Canyon	Roberts Mountain Fm	L. Silurian - L. Devonian	149 - 221 and 330 - 340	40Ar/39Ar & K/ Ar on coarse and fine mica	Folger et al. 1996
	Jerritt Canyon	Hanson Fm	U.Ordovician-L Silurian	285 - 360 and 406 - 420	40Ar/39Ar on coarse and fine mica concentrate	Folger et al. 1996
Battle Mt - Eureka Trend						
	Archimedes	Porphyry	Ordovician	110(5	K/ Ar Sericite altered K-spar	Margolis,1997
	*Cortez	Roberts Mountain Fm	Silurian	34 - 38	?	Maher et al. 1993
Getchell						
	Getchell	Granodiorite	Cambrion - Ordovician	67 - 94	K/Ar	Silberman et al. 1974
	Twin Creeks	Comus Fm	Ordovician	41.5 - 42.2	40Ar/39Ar Adularia	Hall et al. 1997
	Chimney Creek	Etchart Ls	L Corboniferous Permian	99 - 117	K/Ar on mica	Osterberg and Guilbert, 1991
Bingham Utah						
	Mercur	Great Blue Ls	E. Carboniferous	98.4 - 226	K/Ar on illite	Parry et al. 1997
	Barneys Canyon	Pork City Fm	Permian	147- 159	K/Ar on illite	Parry et al. 1997

* To be checked

Table 3: *Summary of some radiometric numbers related to Carlin-type mineralisation*

What is meant by 'Carlin type'?

Several of the characteristics of Carlin-type gold deposits are shared by many other gold-only deposits. These features include element ratios between gold, silver and base metals, structural and host rock control, and sulphidation involving iron in host rocks. The distinguishing features of Carlin deposits include the dissolution of calcite, light hydrogen isotope signature suggesting meteoric waters, kaolinite-bearing assemblages and silicification, and all of these are here interpreted as products of the weathering process. The origin of the arsenian pyrite remains contentious but it has been established that this material has also been invaded by meteoric waters. If weathering is as pervasive as we suggest, and allowance is made for differing host rock types, many of the unusual features of Carlin type deposits might be accounted for by this weathering, and the Carlin type deposits would bear considerable similarity to other gold-only deposits. This can be illustrated by comparing gold deposits from the Yilgarn and Carlin provinces in which the host rocks are similar (Figure 7).

Figure 7: *Weathering profiles over similar black shale sequences in the Yilgarn Craton and Carlin gold province. Upper bleached kaolinite-Fe oxide interval and lower carbonaceous shale interval at Binduli gold mine, 10km west of Kalgoorlie. The host sequence is the Black Flag Beds, and the base of weathering (ie top of fresh rock) is below the pit base.*

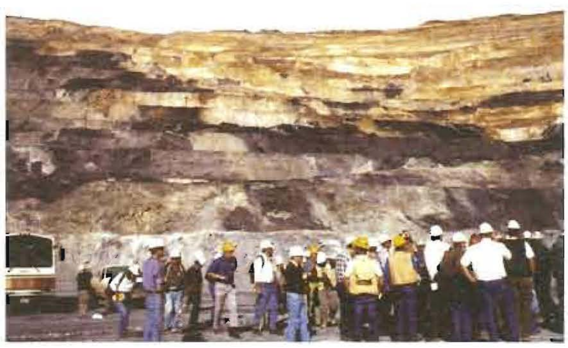

Figure 7: *Upper bleached kaolinite-Fe oxide interval and lower carbonaceous shale interval in the Betze-Post pit, Nevada (same as 5a, with sky removed). The host is fine grained clastic sedimentary rocks with carbonaceous materil. In both profiles, one regolit unit can virtually surround the other unit.*

Figure 7: *Photo mosaic*

SUMMARY

It appears that weathering in the Carlin gold deposits has been particularly deep, and that much of the economically important bleached and dark refractory ores may be part of the regolith profile. The deep weathering resulted from pyrite and calcite concentrations in and around the deposits, and might not extend uniformly across the whole district. We are forced to review our idea of the Yilgarn Craton as being deeply weathered. The differences in depth of weathering between the Yilgarn and Carlin provinces can, at least in part, be related to elevation and relief differences.

Weathering in the Yilgarn Craton is well-documented. For the Carlin province, there are isolated references to weathering but no comprehensive integrated overview despite the economic importance of weathering at Bingham and at Arizona porphyry copper deposits. Weathering in the Carlin province has affected the economics of gold mining including the differentiation of free-milling and refractory ores. A weathering model can also answer some of the questions surrounding the genesis of Carlin-type deposits, and might rationalise the unprecedented range of suggested ages for these Phanerozoic gold deposits. Weathering will profoundly effect what we come to understand as "Carlin-type gold deposits".

Weathering in the Carlin province appears to overprint a relatively typical mesothermal gold system and results in arsenic redistribution as realgar and orpiment, porosity due to calcite dissolution, common kaolinite, light hydrogen isotope signature, lower bulk densities (and gold grade increases) and a variety of relatively oxidised assemblages. The evidence for meteoric water ingress is in both the bleached and refractory ores.

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