

## LATERITIC WEATHERING AND SECONDARY GOLD IN THE VICTORIAN GOLD PROVINCE

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Three periods of deep chemical weathering and formation of duricrusts (including ferricreted bedrock and sediments on palaeoplains) are recognised in the Victorian gold province, the first having produced a Mesozoic regolith. The second formed the Norval Regolith which is interpreted to have formed during an extended period of very high rainfall when western Victoria had low relief; this deep weathering possibly ended with Eocene uplift. It is mostly represented by remnants of ferricreted surfaces overlying pallid zones to 30 m deep. Bauxite, nickel laterite, supergene gold enrichment and most Victorian whiteware clays and many brick clays appear to be related to this event. The Karoonda Regolith of Pliocene age formed during the third period and is represented by widespread ferricreted and mottled surfaces, but mostly thin pallid zones, on uplifted plains surrounding the highlands. This formed after a brief resurgence of high rainfall followed by a more arid regime. The role of these weathering events in gold enrichment is uncertain but possibly locally important, and the geochemistry of the regoliths are useful in exploration for hypogene gold deposits. Features indicative of supergene gold mobility in Victoria include variations in the grain size, silver content, textures and grade of gold with depth, both in Tertiary palaeoplacers and hypogene gold deposits in Palaeozoic rocks. There is also an apparent spatial relationship between gold nuggets, for which the province is noted, and weathering features.

**Key words:** laterite, gold, nugget, geochemistry, Norval Regolith, Karoonda Regolith, Victoria, supergene, regolith, clay

### INTRODUCTION

Explorationists have not traditionally considered deep lateritic weathering and associated supergene enrichment of gold to be features of the Victorian gold province. However, there is evidence for deep weathering, at least partly lateritic, in the Mesozoic and during at least two further periods during the Cainozoic. There is also evidence for the widespread presence of secondary gold in the weathering zone, as well as some features suggestive of gold enrichment. This paper discusses evidence for the presence and timing of lateritic and other deep-weathering profiles in Victoria and reviews evidence for gold mobility in this environment. The numerous localities referred to, and geological features, are indexed in Douglas and Ferguson (1988), and the gold geology has been reviewed in Phillips and Hughes (1996).

Lateritic weathering is used in this paper in the broad sense of a ferruginous zone overlying a deeply weathered saprolite, with or without additional features such as subprismatic ped structures and root casts characteristic of a palaeosol. Ferruginisation which could have originated by precipitation from formation waters or by oxidation of diagenetic sulphides is clearly distinguished from laterite in the text.

### TERTIARY FLUVIAL SEDIMENTS OF THE HIGHLANDS

Tertiary fluvial sediments of the Victorian highlands reflect stripping of deeply weathered profiles. Some formed in low-relief areas where high water tables existed, and were themselves deeply weathered during later weathering events.

### GREAT WESTERN FORMATION (WHITE HILLS GROUP)

The formation name White Hills Gravel has been applied to disconnected gravel deposits of uncertain age over a broad region, and is therefore an unsatisfactory formation name outside its type area at Bendigo. Nevertheless these rocks are restricted to a particular, if broad, time interval. They are therefore upgraded to group status here (White Hills Group), and are named the Great Western Formation in the Ararat area (Figures 1, 2). The younger age limit of the White Hills Group is uncertain, and it may be as old as Palaeocene or even Mesozoic (Williams 1983; Joyce 1992; Cherry & Wilkinson 1994; Cayley & McDonald 1995; Willman 1995; Taylor et al 1996). The White Hills Group could have formed over as much as 45 My, in the interval between mid-Cretaceous uplift and the stripping of a lateritised palaeoplain which is thought to have existed in the Paleocene-early Eocene, or more probably over a short time interval within this period.

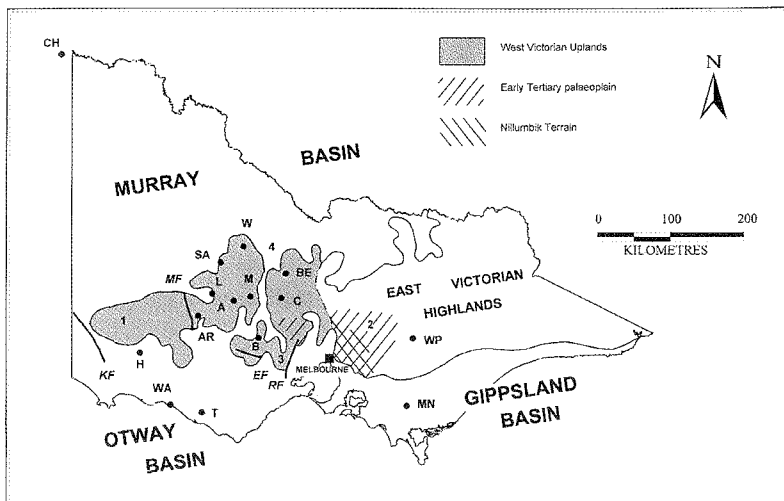


Figure 1: Locality map, showing the outline of mostly Palaeozoic rocks of the West Victorian Uplands and East Victorian Highlands. **Physical features:** Dundas Tablelands (1), Kinglake Plateau (2), Brisbane Ranges/Steiglitz Plateau (3), Loddon River Valley (4), modified from Jenkin (1976, 1988). **Faults:** Kanawinka (KF), Moyston (MF), Enfield (EF), Rowsley (RF). **Towns:** Avoca (A), Ararat (AR), Ballarat (B), Bendigo (BE), Castlemaine (C), Chowilla (CH), Hamilton (H), Landsborough (L), Maryborough (M), Mirboo North-Boolarra (MN), St Arnaud (SA), Timboon (T), Wedderburn (W), Warrnambool (WA), Woods Point (WP). Remnants of the Norval Regolith and its possible equivalents are widely distributed in the West Victorian Uplands, the Early Tertiary palaeoplain, Nillumbik Terrain and South Gippsland (e.g. at MN). The Karoonda Regolith is extensively preserved in the Dundas Tableland and throughout the Murray Basin (e.g. at CH). It is also present on reactivated palaeoplain north and south-west of Ararat, south of the Enfield Fault and extending to east of Melbourne (e.g. via the Steiglitz Plateau), and fringing the Gippsland Basin (piedmont downs) and Otway Basin (e.g. Timboon).

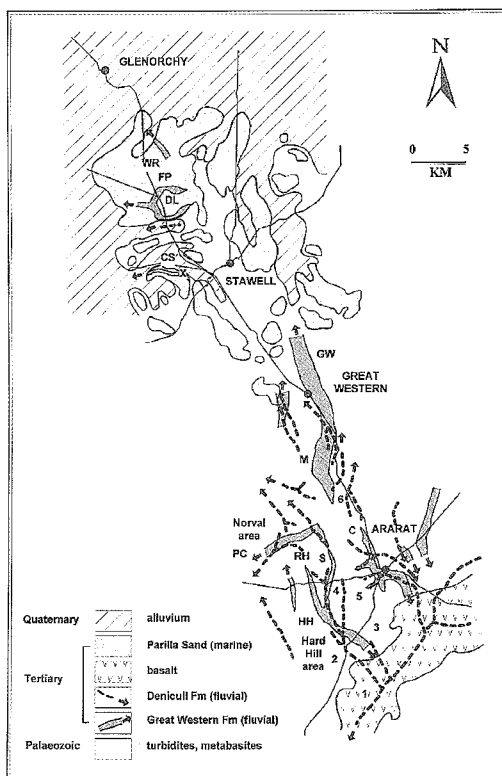


Figure 2: Geology of the Ararat-Stawell area. Palaeodrainages of the Great Western Formation and Denicull Formation extend north and south of a palaeodivide near Ararat, close to the present topographic divide. **Parilla Sand:** West's pit (X). **Great Western Formation palaeoplacers:** Hard Hill (HH), Red Hill (RH), "Springfield" (S), Port Curtis (PC), Cathcart (C), Murphy's (M) and Great Western (GW). The Commercial Street (CS), Deep Lead (DL), Four Posts (FP) and Welcome Rush (WR) palaeoplacers are possibly this age and are overlain by Parilla Sand at Stawell. **Denicull Formation palaeoplacers:** The Langi Logan (1), Cathcart (2) and Nil Desperandum (3) palaeoplacers are partly covered by basalt, the Heather Belle (4), Driver's (5) and Milkman's Flat (6) palaeoplacers are not. The Norval Regolith predates the basalt and Parilla Sand, which are both postdated by the Karoonda Regolith.

Deposits of these coarse, often well-rounded fluvial gravels in which vein quartz is commonly the dominant lithology, are now found on hills and ridges, and high on the sides of modern valleys (Brown 1987, Joyce 1992), but appear to have formed in broad paleovalleys. They have been extensively mined for gold in some areas, e.g. Ararat. The mature quartz gravels have been interpreted as products of initial erosion and reworking of the deep regolith of the Mesozoic palaeoplain of the West Victorian Uplands (Figure 1), in which the only solid material to survive the previous intense chemical weathering on the palaeoplain was reef quartz (Ollier 1988). Others interpret the gravels as the end products of such erosion, after extensive dissection of the palaeoplain to depths of 430-700m (Cayley & McDonald 1995; Taylor et al. 1996). The presence of well-rounded vein quartz boulders (some more than a metre in diameter) is thought to indicate a high energy environment (Marlow & Bushell 1995), such as broad, active river systems in areas of fairly modest relief and very high rainfall (Cayley & McDonald 1995; Taylor et al. 1996).

Outliers of the Great Western Formation define broad palaeovalleys which flowed both north and south in the immediate vicinity of a low-relief palaeodivide, situated slightly north of the present divide at Ararat (Carey & Hughes 1997; Figure 2). The palaeovalleys were partly controlled by north-north-west strike faults, and east-west valleys were also present. However the palaeodivide is 300-600 m below the projected position of a Mesozoic palaeoplain, which had therefore already been removed in the Ararat area. The angularity of quartz pebbles and cobbles close to the palaeodivide indicates direct derivation from adjacent quartz reefs in Palaeozoic bedrock, rather than reworking of a quartz lag derived from the palaeoplain. The ferruginous and other duricrusts superimposed on these gravels (including in their headwaters), and on adjoining Palaeozoic rocks, aided in their preservation. These duricrusts and deep pallid zones occur beneath the gravels, but are absent from adjacent valley walls at higher elevation, and presumably reflect the high water tables in the valleys prior to uplift of the area and incision of younger, deeper valleys. Lateritisation therefore occurred in an area of low relief, subsequent to mid-Cretaceous uplift of the Mesozoic palaeoplain and major erosion.

#### **DNICULL FORMATION (LODDON RIVER GROUP)**

The Calivil Formation (the "deep lead" facies) is another formation name which is of restricted usefulness outside of its type locality, since it has been applied to

sediments which probably range from Eocene to Pliocene in age, in numerous separate, north-draining palaeovalleys. Equivalents in the south-draining palaeovalleys have been informally named "sub-basaltic gravels" (Taylor et al. 1996). A group name, the Loddon River Group, is adopted here to include the Calivil Formation, the "sub-basaltic gravels", and equivalent sediments of the Ararat area which are here named the Denicull Formation.

The Loddon River Group in highland areas consists of relatively unweathered Palaeozoic lithic clasts in addition to vein-quartz pebbles and detrital laterite fragments (Williams 1983; Macumber 1991). This group was deposited in much narrower channels and deeper palaeovalleys than modern valleys or those of the White Hills Group. Sediments of the Loddon River Group derived their well-rounded quartz-pebble population (and some of their gold) from the previously lateritised White Hills Group (Cayley & McDonald 1995). This provenance can be demonstrated in the Denicull Formation of the Ararat area (Figure 2), where some older White Hills Group valleys have been utilised by the Loddon River Group (although a significant part of the pebble population is thought to be derived from Palaeozoic rocks).

The Loddon River Group was deposited in drainages which extend up to 45 km south and 130 km north of the divide. Meandering channels were present in many north-flowing streams, but south-flowing streams had steeper gradients and straight courses. River capture may have occurred as the divide migrated northwards. Gradients were steeper than for the White Hills Group, especially for parts of the Trunk-Pitfield and Buninyong-Mount Mercer palaeoplacers, which occupied gorges in the vicinity of the Enfield Fault south of Ballarat (Figure 1). The valleys of these two palaeoplacers appear to have re-established themselves after major uplift which post-dated deposition and ferruginisation of the Moorabool Viaduct Formation of Pliocene age, south of the Enfield Fault, but prior to infilling of the valleys by basalt flows. This is consistent with continuing deposition of the Loddon River Group into the Pliocene as suggested by Taylor et al. (1996) for the Calivil Formation.

#### **PALAEOPLAINS AND HIGHLANDS UPLIFT**

The history of palaeoplains is relevant to the weathering surfaces formed upon them. Uplift is relevant to the stripping of the weathering profile and to fluvial sediments, which then formed part of the regolith and underwent weathering. Major events in the West Victorian Uplands included (i) formation of a Mesozoic

plain, (ii) mid-Cretaceous uplift, (iii) formation of an Early Tertiary plain and its uplift, and (iv) Late Tertiary regression and uplift

An extensive Mesozoic plain existed when south-eastern Australia was continuous with Antarctica. The exact age of this palaeoplain is uncertain, but is probably at least as old as Triassic volcanics on its surface in Victoria (Hills 1975). The Southern Ocean opened as Antarctica rifted from Australia, with initial rifting of the Otway Basin, south of the present West Victorian Uplands, commencing at 158 Ma (Late Jurassic). Rifting farther east then formed the Gippsland Basin, south of the East Victorian Highlands (McNicol 1989; Cooper 1995). These basins and the associated Bass Basin were filled in the Early Cretaceous by sediments derived from contemporaneous volcanic sources to the east (Constantine & Holdgate 1993), rather than from the adjoining areas of palaeoplain. Rapid uplift of the Mesozoic plain to the north probably first occurred during mid-Cretaceous inversion, followed by stripping of a 1-2 km thickness from the southern flank of these newly developed highlands. The Murray Basin, north of the present highlands, developed later during Palaeocene subsidence, subsequent to Late Cretaceous rifting of the Tasman Sea and formation of the Great Divide of eastern Australia (Ollier & Pain 1994).

Extensive remnants of the Mesozoic palaeoplain exist as "high plains" in the Eastern Victorian Highlands (Ollier & Pain 1994) and as minor, isolated remnants at slightly lower elevations west of Melbourne in the West Victorian Uplands (e.g. Mount Cole-Mount Buangor; Joyce 1992; Cayley & McDonald 1995; Figure 1). Fission track and vitrinite reflectance data indicate that major mid-Cretaceous (95 Ma) uplift of the palaeoplain occurred eastwards from the western margin of the Lachlan fold belt (the Moyston Fault; Cayley 1995; Figure 1) to the Gippsland Basin (Foster & Gleadow 1992; Cooper 1995). The elevation range over which dated basalts were erupted indicate that the Eastern Highlands had a minimum relief of 600 m before the late Eocene and a relief of over 1000 m by the Oligocene (Wellman 1974).

The highlands west of Melbourne (the present West Victorian Uplands) were greatly reduced in elevation by the Palaeocene-early Eocene (i.e. during the 45 My between uplift and the mid-Eocene). The entire Otway Basin south of the uplands underwent alternating, widespread Palaeocene-early Eocene non-deposition, erosion, basaltic volcanism and wrench-faulting, reflected in seismic and palynological data. A plain

formed to the north by this time and was lateritised (O'Brien 1987; McNicol 1989; Cooper 1995), with deposition of kaolinite in the basin (Abele et al. 1988). This is probably when the undated fluvial sediments of the White Hills Group formed to the north in the West Victorian Uplands (Taylor et al. 1996), although these may extend back into the Late Cretaceous. Deep weathering of the Norval Regolith, described here, continued until after deposition of the White Hills Group.

The Otway Basin recommenced subsidence after the early Eocene with a return to more open marine conditions. A second period of uplift of the West Victorian Uplands is indicated at this time by the present topographic relief, which appears to significantly exceed that in existence during deposition of the White Hills Group, and by the even greater relief of the palaeovalleys of the Loddon River Group. This interpretation receives further support from reference to a deeply-weathered Eocene palaeoplain (a pre-Older Volcanic Terrain) in the Melbourne area (Hills 1975; Jenkin 1988), and from Oligocene and Eocene ages indicated for sediments which overlie the Loddon River Group (King 1985) which Taylor et al. (1996) suggest is evidence for this timing. Also, by Oligocene time the valleys of the Loddon River Group would have been backfilled because of rising sea level (Cayley & McDonald 1995). The sea retreated from the Murray Basin in the mid-Miocene, with formation of the mid-late Miocene Mologa Surface across the Loddon Plain and the Campaspe Plain north of the uplift (Macumber 1991). No lateritisation is associated with this surface.

A marine regression occurred in the Otway Basin in the mid-late Miocene (Taylor et al. 1996). A late Miocene-Pliocene marine incursion in the western Murray Basin led to deposition of the Loxton Sand and the Parilla Sand (Macumber 1991), and there was a marine transgression from the south-east in the Otway Basin at this time. This affected the area south of Ballarat (e.g. Rokewood), farther north than the Miocene shoreline, with deposition of the marine Moorabool Viaduct Formation and fluvial equivalents. The northern limit of deposition of the Moorabool Viaduct Formation was closely controlled by the Enfield Fault, which either formed or was reactivated at this time (Smith et al. 1997), concurrent with the onset of Newer Volcanics volcanism (Cayley & McDonald 1995). The Pliocene units were deposited on weathered Palaeozoic bedrock and Loddon River Group, which locally had already been covered by the oldest, late Miocene, valley flows of the Newer Volcanics.

The sea retreated again from the Murray Basin in the early or mid-Pliocene. The Karoonda Regolith then formed (Kotsonis 1995), associated with the Karoonda Surface, extensively lateritising exposed areas of Parilla Sand (and of Moorabool Viaduct Formation in the Otway Basin). The Parilla Sand was tilted, and the Moorabool Viaduct Formation tilted and uplifted 150 m in association with uplift of the highlands south of Ballarat (Taylor et al 1996)

### WEATHERING SURFACES

In the West Victorian Uplands deep weathering profiles and duricrusts are discontinuous and vestigial (Ryall et al 1980), and are largely absent farther east, in the East Victorian Highlands. Nevertheless, remnant ferruginous, siliceous and clay duricrusts and deep kaolinitic profiles are widespread on Palaeozoic sedimentary rocks and Tertiary gravels and sands in the western half of Victoria. They are less abundant in highland areas, possibly because they have been largely eroded from these areas, although their distribution suggests that their development was at least partly confined to, and largely controlled by, broad palaeovalleys in the highlands. Nevertheless, remnant pallid zones are present even on the highest part of the uplands near Beaufort and Ballarat, especially on Palaeozoic granites. Palaeozoic granite plutons with both negative and positive topographic relief coexist throughout the region, and deeper weathering of the former may have resulted from a higher modal-biotite content which increased their susceptibility to weathering (Hill 1996), although the presence of accessory pyrite could have been a factor.

Three periods of deep chemical weathering associated with palaeosurfaces can be recognised in the West Victorian Uplands, and these have produced: (i) regolith of the Mesozoic palaeoplain, (ii) the Norval Regolith, interpreted to be of Palaeocene-early Eocene age, and (iii) the Karoonda Regolith of Pliocene age. These do not necessarily represent the only periods of deep chemical weathering, but are the only three that can be clearly differentiated. The Karoonda Regolith may be superimposed on the Norval Regolith in some areas adjoining the Murray Basin and on the Dundas Tableland. Other palaeosurfaces are recognised elsewhere (e.g. the mid-late Miocene Mologa Surface of the Loddon Plain and Campaspe Plain, with which no deep weathering profile is associated; Macumber 1991). Mineralogical studies of these profiles are in progress.

### PALAEOSOLS OF THE MESOZOIC PALAEOPLAIN

Isolated remnants of a deeply weathered horizon of red soil have been reported slightly below 1000 m above sea level (a.s.l.) in west-central Victoria (Taylor et al 1996). Initial results from palaeomagnetic dating of regolith from the granitic plateau of the Buangor Dome in this area indicate a probable Cretaceous age (Joyce 1992). Deep Mesozoic weathering of post-Jurassic, pre-Eocene age has also been recorded from a bore in the Gippsland Basin (Bird & Chivas 1993). A zone of kaolinitic weathering up to 30 m deep has been reported on Ordovician rocks of the eastern Loddon Plain, where they underlie the Palaeocene-Oligocene Renmark Group (Macumber 1991). This zone might relate to weathering of the Mesozoic palaeoplain, or alternatively to development of the Norval Regolith (see below) in the Early Tertiary.

### THE NORVAL REGOLITH AT ARARAT

The Norval Regolith is defined here from its geological relationships in two areas west of Ararat (see Appendix and Figure 2). A pallid zone with an overlying iron-rich duricrust (Figures 3,4) is superimposed upon both Palaeozoic bedrock and the Great Western Formation (White Hills Group). Gravels of the Great Western Formation are typically ferruginous (Figure 4) rather than clearly ferricreted, but the ferruginous zones are laterally continuous with adjacent ferricreted bedrock (Figure 3) and appear to have had a common origin. This regolith of ferricreted bedrock and sediment, and kaolinitic saprolite, defines subhorizontal to undulatory surfaces in these areas (e.g. 340-360 m a.s.l. at Norval). The regolith originally occurred within broad palaeovalleys, which are still clearly defined between higher valley walls of less weathered Palaeozoic rocks. The regolith is dissected, and the Denicull Formation (Loddon River Group) occurs in terraces at a lower elevation. There is evidence for erosion of the Norval Regolith into the younger Denicull Formation, which was deposited in valleys which contain overlying lava flows as old as late Miocene (see Appendix). The Norval Regolith can be clearly distinguished from the younger Karoonda Regolith by this age relationship, and by the presence of tiger mottling (Figure 5) and other features, characteristic of the Karoonda Regolith, which overlie the Denicull Formation in the same area.

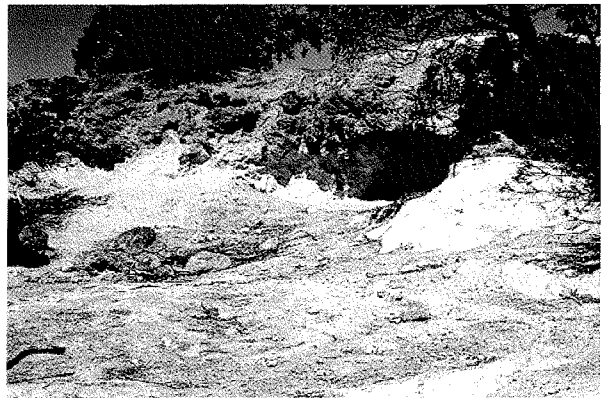


**Figure 3:** Remnant cap of massive ferricrete of the Norval Regolith, below which a 20 m thick saprolite of kaolinised Palaeozoic mafic rock(?) is heavily ferricreted along former joints, Norval, Ararat. Elsewhere in the area remnants of Tertiary sand and gravel are weakly ferruginised or altered to massive ferricrete. The deeply dissected, sub-horizontal, ferricreted Norval Surface has been eroded to unweathered bedrock in some drainages. The surface is interpreted as the floor of a very broad palaeovalley. Pick for scale.

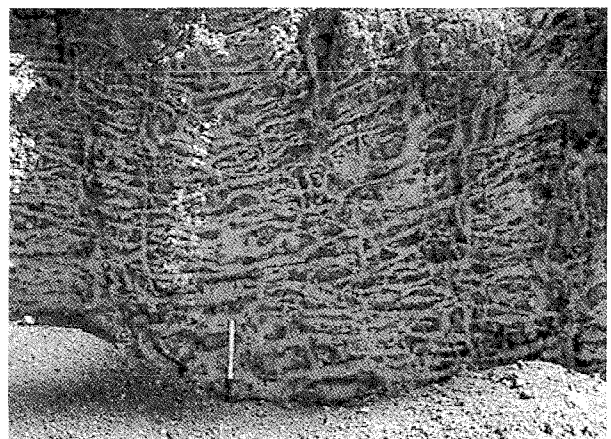
Weathering profiles on the Great Western Formation at other localities near Ararat display additional features such as clay duricrusts, ped structure and well defined ferricrete duricrusts (see Appendix). These are assumed to represent the Norval Regolith but no timing criteria are available (i.e. they could represent the Karoonda Regolith, a combination of both, or an intermediate event).

#### THE NORVAL REGOLITH ELSEWHERE IN VICTORIA

Many workers have recognised ferricrete within the upper 1-2 m of gravels of the White Hills Group throughout the goldfields region (e.g. Taylor et al. 1996; Cayley & McDonald 1995), and also the presence of a pallid zone 6-9 m deep, possibly of Eocene age, in underlying Palaeozoic rocks (e.g. Smythesdale and Scarsdale near Ballarat; Williams 1983, King 1985). Taylor et al. (1996) recognised that this weathering was controlled by broad, shallow valley floors.



**Figure 4:** Weathering typical of the Norval Regolith throughout the goldfields of the West Victorian Uplands. Weakly ferruginised quartz pebble conglomerate (Great Western Formation) overlying deeply kaolinised saprolite (Palaeozoic turbidites), 30 m thick, interpreted as the floor of a palaeovalley. Hard Hill, Ararat. Note old gold working 1 m high at base of conglomerate.



**Figure 5:** Tiger mottling typical of the Karoonda Regolith in the Ararat-Stawell area (West's Pit, Stawell). The upper mottled zone consists of alternating maroon and pale brown layers, and overlies a strongly indurated clay duricrust (not visible). A few iron pisoliths occur in the mottled zone, but are quite abundant at surface. Pick for scale.

Hills (1975, p. 310, 322) refers to a south-sloping, Early Tertiary palaeoplain (Figure 1) north-east (the Kinglake Plateau) and north-west of Melbourne (near the Blackwood Ranges, Woodend and Trentham). It reaches 650-700 m a.s.l. in the north, extending to lower elevations near the coast where it passes south beneath marine Tertiary cover (Brighton Group). This Early Tertiary palaeoplain is at least 500 m lower than the Mesozoic palaeoplain to the north-east of Melbourne (which is, for example, 1220 m a.s.l. at Healesville-Warburton). North-west of Melbourne the Early Tertiary surface is 300-350 m below Mesozoic palaeoplain remnants which occur

south-west of Avoca at nearly 1000 m a s l (e.g. Mount Cole, Mount Lonarch and Mount Avoca; Taylor et al. 1996). This Early Tertiary surface appears to have been affected by two periods of weathering. The first is represented by a cover of deep brown soil, developed on the Kinglake Plateau at 275 m a s l., and farther west, which may be temporally equivalent to the Norval Regolith. The second, Pliocene, event equates temporally with the Karoonda Surface and affected the Brisbane Ranges/Steiglitz Plateau in the south-west at 400-150 m a s l. (Bolger 1981). Some workers distinguish this plateau as lower and younger than the Early Tertiary palaeoplain, but this surface may have already been deeply weathered in the Early Tertiary (Gill 1964).

Remnants of the Early Tertiary palaeoplain are probably represented by the Murrumbidgee Terrain (Gill 1964; Neilsen 1967), or pre-Older Volcanic Terrain (Jenkin 1988; Ferguson 1988), which includes the area immediately north-east of Melbourne (where it is lower than the Kinglake Plateau), and the Blackwood, Gisborne and Macedon areas. Hills (1975) considered this terrain to have developed by erosion of the southern margin of the Early Tertiary palaeoplain. This low-relief surface was dissected prior to extrusion of the Older Volcanics of earliest Miocene age (Gill 1964), and could be Eocene (Ferguson 1988). A deep, white, kaolinitic profile, interpreted as the deep pallid zone of a lateritic profile but lacking an upper ferruginous layer, is associated with this surface. White sections are 6-9 m thick but may have originally been thicker, and have been completely removed over much of the area. This profile is the source of most white firing clay used for whitewares in Victoria (Ferguson 1988). Brown and grey-blue weathered saprolite, up to 15-20 m thick, underlies the kaolinite in the Melbourne area and is characterised by changes in chlorite, breakdown of sulphides to sulphates, and deposition of goethite along joints and permeable beds (Ferguson 1988). The saprolite is widely exposed by deeper erosion at the north end of the Murrumbidgee Terrain, south of the Kinglake Escarpment, and is the source of most brick clay of the Melbourne area.

Ferguson (1988) attributed similar clays in granite areas at Lal Lal and Pittong, near Ballarat, to this Early Tertiary phase of weathering. This conflicts with the oxygen isotope data of Bird and Chivas (1989), which indicate an age younger than mid-Tertiary, although the geological data are ambiguous. Palaeocene-Eocene ligneous, kaolinitic clays of sedimentary origin, 60 m thick at Lal Lal, appear to be derived from the adjacent kaolinised granite (Ferguson 1988).

Small bodies of bauxite up to 11 m thick have formed by deep weathering of Lower Tertiary basalt and tuff (Older Volcanics) near Boolarra and Mirboo North, South Gippsland (Figure 1). The Older Volcanics belong to the late Palaeocene-early Eocene Thorpdale Province (Wellman 1974) and are overlain directly in places by coal seams of the Latrobe Valley Formation (middle Miocene), sand and gravel. Some workers (e.g. Bell 1960) have suggested that the bauxite is not lateritic in origin but formed by groundwater movement adjacent to later faults, subsequent to deposition of the overlying rocks. The presence of apparently unoxidised coal in continuous, direct contact with the upper surface of the bauxite (illustrated in Bell 1960) is more consistent with the bauxite having formed by lateritisation between the Eocene and early Miocene, as suggested by earlier workers. However, oxygen isotope data are more consistent with an age younger than mid Tertiary (Bird & Chivas 1989).

The Woodstock Surface of Tertiary age in northern Tasmania (Noldart 1975) is partly developed on Palaeocene-Eocene sediments (Gill 1964), and a kaolinitic profile with local bauxite is present to over 30 m depth. Nickel laterites are currently being evaluated where this surface overlies serpentinite, and these cannot be younger than Early Tertiary (Summons et al. 1981). A major phase of ferruginous weathering also occurred prior to the middle Eocene in South Australia (Drexel & Preiss 1995).

The weathering profiles discussed above might have formed over an extended interval of time in the Early Tertiary, but approximate in age to the Norval Regolith (an event as brief as that which formed the Karoonda Regolith is not implied here).

#### **THE KAROONDA REGOLITH AT STAWELL-ARARAT**

The second major regolith, represented by the Karoonda Regolith and equivalents, is developed on early Pliocene sediments (e.g. Macumber 1991) and possibly basalt over a large part of southern and western Victoria. It is also present at Chowilla in South Australia (Figure 1), where a palaeomagnetic age of 2.5-3.4 Ma has been obtained on ferricrete (Drexel & Preiss 1995).

The Karoonda Regolith is widespread in the Ararat-Stawell district (see Appendix and Figure 2). It differs in appearance from the Norval Regolith at many localities because of the lack of a distinct pallid zone, though the materials involved (e.g. gravel and sand of the Denicull

Formation and Parilla Sand) are probably not amenable to development of such a zone. Tiger mottling (see Appendix and Figure 5) is associated only with this regolith, and clay duricrusts and ped structure are common, confirming that it is a palaeosol. A weathered saprolite underlies massive ferricrete where the Karoonda Surface has developed on rocks more susceptible to chemical weathering (Figure 6), but the depth of the pallid zone is typically less than that of the older Norval Regolith.

The Karoonda Regolith of the Ararat area is distinguished from the Norval Regolith by its development on younger rock types (Denicull Formation and the Parilla Sand). However, these regoliths cannot be clearly distinguished in some parts of the Stawell area, where deep weathering is developed on palaeoplacer gravels of uncertain age.

#### THE KAROONDA REGOLITH ELSEWHERE IN VICTORIA

The lateritic podsol of the Karoonda Surface in low-lying areas is developed on an extensive, well-developed, low-relief lateritic surface. This surface is silicified and ferruginised to varying degrees, and is clearly of pedogenic origin. In the Murray Basin, including north of Stawell and east to at least Landsborough and Bendigo, the Karoonda Regolith is developed on the Parilla Sand of late Miocene-Pliocene age, where it forms a profile up to 15 m thick. Modern redistribution of iron has also occurred in the Parilla Sand, with deposition of ironstone from formation water in low-lying areas of the Mallee (Macumber 1991), and can be distinguished from laterite. A profile equivalent to the Karoonda Regolith occurs on a surface at a higher elevation in the Glenelg Zone to the south-west, the Dundas Tableland, which was uplifted in the Pliocene or Pleistocene (Bush et al. 1995a). This is the Dundas Surface (Kenley 1988) which also formed, together with its lateritic profile, south-west of Ararat (extending south-west of Lake Bolac; King 1985). Remnants of this lateritic profile extend westwards to the escarpment of the Kanawinka Fault (Figure 1). The rocks have been completely weathered and altered to massive ironstone and pisolite in some areas (Figure 6), with underlying clay-rich, mottled and leached pallid zones to depths exceeding 20 m; fresh bedrock exposures are confined to the creek beds of deep valleys. The lateritic profile overlies flat-lying Tertiary sediments farther to the west (probable equivalents of the Parilla Sand; Abele et al. 1988). Laterite development appears to pre-date the Whalers Bluff Formation of the area, which is not lateritised, so this weathering ended by mid-late Pliocene time.



**Figure 6:** Ferricrete of the Karoonda Regolith overlying mottled, kaolinised saprolite (Devonian felsic volcanics). The ferricrete is strongly pisolitic near surface, and more than one age of ferricrete could be present. Boral quarry, Hamilton North (Dundas Tablelands). Person for scale.

Early or middle Pliocene basalts of south-western Victoria are also deeply kaolinised. The dissected landscape south of Hamilton has up to 15 m of kaolinitic weathering profile developed on early Pliocene basalt (3.9–4.4 Ma K/Ar), with mottled clay and nodular ironstone (Abele et al. 1988; Jenkin 1988). This profile consists of an upper red, iron-rich zone, an intermediate mottled zone and a lower pallid zone, but lacks any indurated zone. It has been suggested that this weathering might have slightly post-dated that of the Karoonda Surface, which is at a lower elevation in the same area (Gibbons & Gill 1964); however its age is consistent with the Karoonda Regolith. Slightly younger basalts of Hamilton (e.g. 2.2–2.6 Ma) and elsewhere in south-western Victoria (e.g. Portland 3.1 Ma), have very thin, red and kaolinitic weathering zones, and have been termed “transitional krasnozems” by Gibbons and Gill (1964).

Massive ferruginisation of the Moorabool Viaduct Formation of uppermost Miocene-Pliocene age, south of Ballarat, lacks development of any significant underlying pallid zone in some areas (e.g. Dereel), and its origin by weathering is uncertain in these areas and might be partly related to iron deposition during lateral groundwater migration. Elsewhere, to the east and west (e.g. south-east of Dereel and south of Linton), it is more clearly a laterite with an underlying kaolinitic saprolite, and would therefore correspond temporally to the Karoonda Regolith. Ferruginisation was followed by significant Pliocene uplift of this area south of the Enfield Fault, to form a tableland resistant to erosion which is being dissected today (Taylor et al. 1996).



The Karoonda Regolith is probably also equivalent to: (i) an early Pliocene lateritic profile developed on Port Campbell Limestone in the Warrnambool area (Orth 1988), (ii) a lateritic profile with indurated zones at Camperdown (Gibbons & Gill 1964), and (iii) a lateritic profile on the Timboon Surface in the Otway Basin of south-western Victoria (Gill 1964). It is also represented eastwards in the Otway Basin (Hills 1975) to Anglesea, south-west of Melbourne. The Timboon Surface caps the scarp of the Rowsley Fault (Figure 1), e.g. near Bacchus Marsh, and on the Brisbane Ranges/Steiglitz Plateau where laterite is developed on the Moorabool Viaduct Formation (Bolger 1981). It appears to pre-date Pliocene uplift along the fault (Gill 1964; Hills 1975). A Pliocene weathering surface in the Melbourne area has produced metahalloysite clays with goethite concretions (Ferguson 1988), and strong ferruginisation of sands of the Brighton Group (Gill 1964; Neilsen 1967), which are equivalent to the Moorabool Viaduct Formation (Abele et al. 1988). The main lateritic weathering event which affected the piedmont downs of Gippsland appears to be mid-Pliocene (Jenkin 1976). This includes deep lateritic weathering of Tertiary sediments, including Pliocene sediments, marginal to the Gippsland Basin (Jenkin 1988). All of these profiles therefore correlate temporally with the Karoonda Regolith.

#### UNCLASSIFIED DEEP WEATHERING

A post-Older Volcanic (i.e. earliest Miocene) surface in the Melbourne area, termed the Nunawading Surface (Gill 1964), has been superimposed on the earlier Nillumbik Terrain prior to deposition of the Brighton Group. This profile consists of a mottled zone with an underlying kaolinitic pallid zone 1-5 m thick (Ferguson 1988). The clay mineral alteration is not as profound as on the pre-Older Volcanic surface and consists of kaolinite-illite which gives a more plastic ceramic clay. Gill (1964) considered the timing of this surface to be mid-Tertiary, as suggested by kaolinitic weathering of earliest Miocene basalt at Moonee Ponds Creek, below Pliocene ferricrete. The data do not conclusively demonstrate that this weathering is unrelated to the overlying ferricrete, so the possibility that it might be equivalent to the Karoonda Regolith should be investigated.

#### CONCLUSIONS

Deep weathering of the Mesozoic palaeoplain and uplift was followed by the fairly clearly defined lateritic weathering event of the Norval Regolith. This caused deep weathering of Palaeozoic rocks and overlying White Hills Group on broad valley floors, and was apparently related to high water tables in such positions. The

palaeoplacer gravels of the Loddon Valley Group have partly stripped these surfaces (Cayley & McDonald 1995; Taylor et al. 1996) prior to the burial of these palaeoplacers by late Miocene basalt, so this is not the event represented by the later Karoonda Regolith. Cessation of this event after further uplift in the mid to late Eocene is favoured.

A second major weathering event, development of the Karoonda Regolith, produced ferricrete throughout much of the western part of Victoria in the Pliocene, extending eastwards near the coast to Gippsland. Pallid zones, where developed, were shallow. Other deep weathering events might have occurred in the Tertiary but have not left any widespread record.

#### RELATIONSHIP OF WEATHERING TO PALAEOCLIMATE

Development of weathering profiles only occurs when weathering proceeds faster than the rate of erosion, so the lateritic profiles discussed can be expected to correlate with certain combinations of climate and topographic relief. Past climates in Victoria have been partly deciphered from palaeontological (e.g. palynological) and stable isotopic evidence. Climate is related to deep weathering and laterite formation because of the dependence of these processes on rainfall, temperature and vegetation. Deep kaolinitic weathering profiles imply high water tables, and rainfall in excess of evaporation, but with temperature possibly not being critical. The formation of ferruginous horizons and crusts is associated with fluctuating water tables and seasonal regimes (Ryall et al. 1980). Such duricrusts can retard subsequent erosion and assist in preservation of weathering profiles.

Australia had migrated towards the South Pole during the Permian, with resulting glaciation, but by the Triassic the climate was probably cool temperate in Tasmania and Victoria, despite their high latitude, and became warmer and more humid towards the end of the Cretaceous (Veevers 1986). Australia was still at high latitudes in the early Cainozoic, suggesting that high temperatures may not be required for ferruginisation and deep kaolinitic weathering. This is supported by arguments, based on the oxygen isotopic composition of clays formed by Cainozoic weathering, that these clays did not form under tropical to sub-tropical conditions (Bird & Chivas 1989). High rainfall and temperate climates prevailed in the south-east of Australia throughout the Palaeocene and Eocene (Veevers 1986), and the deep weathering imposed on the White Hills Group might have

formed at this time and only ceased after Eocene uplift. *Nothofagus*-dominated forests were probably still widespread in Antarctica and throughout the southern half of Australia.

The climate in the Murray Basin to the north, which was forested throughout the Tertiary, has broadly followed a pattern of high water tables in the Early Tertiary, followed by seasonal regimes and then the onset of drier conditions (Ryall et al. 1980). Very high precipitation prevailed throughout the Early Tertiary followed by step-like decreases beginning in the late Oligocene-early Miocene (Martin 1989; Mackay & Eastburn 1990), conditions being cooler in Victoria during the Oligocene. This corresponded to widespread Antarctic glaciation, with removal of effectively all vegetation from Antarctica. The widespread rainforest disappeared in the mid-late Miocene when the sea retreated from the Murray Basin and it was warmest, and was replaced with eucalypt wet sclerophyll forest (Ryall et al. 1980). Rainfall was more seasonal and precipitation had decreased. The Mologa Surface, with which no lateritisation is associated, formed at this time. Rainfall then increased for a brief interval in the late Miocene-early Pliocene and there was a brief resurgence of *Nothofagus* rain forest as far west as Balranald (Ryall et al. 1980). This wetter period, with high summer rainfall, correlates with the late Miocene maximum transgression in the Murray Basin and a global rise in sea level. Rainfall dropped again as the sea retreated in the early Pliocene. "Lake Bungunnia" formed in the western part of the basin, and the Karoonda Regolith developed in the period to the middle Pliocene. Precipitation dropped still further in the Plio-Pleistocene when the area became open woodland and grassland (Ryall et al. 1980). The present dryland salinity has occurred since the early Pleistocene. Since the mid-Pleistocene there have been fluctuations between the present climate and cold, arid conditions, corresponding to the waxing and waning of glaciers in the northern hemisphere (Mackay & Eastburn 1990). Lake Bungunnia began to dry up at this time.

The reported deep Mesozoic weathering is therefore consistent with the limited climatic data available for that period. The proposed formation of the Norval Regolith in the Palaeocene-Eocene corresponds to a period of high rainfall and temperate climate in south-eastern Australia, and was probably aided by low topographic relief and terminated by uplift. The lateritic profile most tightly constrained in time, the Karoonda Regolith, corresponds to a brief resurgence of high rainfall followed by a decline to much drier conditions than before, so appears to be closely related to significant climatic change.

## SECONDARY GOLD AND GOLD ENRICHMENT

Primary gold deposits of Victoria are typically sulphide-poor quartz veins of simple mineralogy which occur in Palaeozoic turbidites, mostly of the Ballarat zone in west-central Victoria (Phillips & Hughes 1996; Hughes et al. 1997).

A number of features are suggestive of Cainozoic solution and redeposition of gold in the weathering zone and immediate subsurface environment in Victoria, and were recognised by some early workers (e.g. Junner 1921). These are: (i) variations in gold-silver ratios in alluvial deposits and the supergene zone of primary deposits, (ii) coarsening of gold in the weathering zone, (iii) colloform, arborescent and botryoidal gold textures, (iv) abundant perfectly crystallised gold in alluvial deposits and in the weathering zone of primary deposits, (v) an abundance of gold nuggets in some deeply weathered areas adjoining the Murray Basin, and (vi) gold concentration in fossil trees and possibly in diagenetic pyrite.

## GOLD NUGGETS

Central western Victoria is renowned for its abundant gold nuggets. Prior to the use of metal detectors, 1327 alluvial gold nuggets of greater than 20 oz (0.6 kg) were recorded, but many more were presumably found (Bowen & Whiting 1975). Some were very large, e.g. 625 over 50 oz (1.6 kg), 335 over 100 oz (3.1 kg), 45 over 500 oz (15.6 kg) and 12 over 1000 oz (31.1 kg). The four largest nuggets were the 2280 oz (70.9 kg) Welcome Stranger nugget from Moliagul, supposedly the largest single nugget found in the world, the 2195 oz (68.3 kg) Welcome nugget from Ballarat East, the 1744 oz (54.2 kg) Blanche Barkly nugget from Kingower and the 1716 oz (53.4 kg) Precious nugget from Rheola-Berlin. The main nugget-producing fields, with the number of nuggets over 50 oz (1.6 kg) given in brackets, were Dunolly (126), Rheola-Berlin-McIntyres (112), Wedderburn (40), Ballarat (38), Poseidon, near Tarnagulla (30), Bendigo (23), Kingower (21) and Rokewood (18). The majority of nuggets are from the main north-south zone of "indicator" fields (see below) of Dunolly-Moliagul, Wedderburn, Ballarat, Tarnagulla, Inglewood and Bealiba (Figure 1). An additional 118 slugs of gold greater than 20 oz (0.6 kg) were systematically recorded from quartz reefs, the largest being 18.8 kg, but this number of slugs is probably a major underestimate, most being documented from the Ballarat East field (references to much larger bodies of gold in quartz reefs are common in mine reports from other goldfields).

The major Victorian gold nuggets found in the past have commonly been assumed to be of hypogene rather than supergene origin, although no studies of Victorian gold nuggets appear to have been undertaken. Evidence advanced for a hypogene origin includes the presence of large nuggets (or slugs) in quartz veins at depths as great as 395 m in the Woah Hawp Canton mine, Ballarat East, and the fact that quartz was attached to some eluvial or alluvial nuggets (e.g. the Welcome Stranger nugget, Moliagul). These observations are suggestive, but not proof, of a hypogene origin for at least some of the nuggets, and an alternative model of supergene enrichment in quartz veins is discussed below.

Supergene origins for gold nuggets, such as their growth in Tertiary alluvial gravels, have been suggested from the last century to the present day (e.g. Williams 1983; Swensson 1990). This is particularly true for the "Golden Triangle" area, e.g. near Wedderburn, where large nuggets occur in numerous small outliers of high-level, lateritised White Hills Group gravels adjoining the Murray Basin (Bush et al. 1995b). Large nuggets are still being found in this area today, e.g. a \$100,000 nugget of unknown mass in 1996. However, grains of coarse gold (up to many grams) observed from gravels of the White Hills Group in other areas (e.g. Buninyong and Amphitheatre) commonly have a waterworn or rounded, if pitted (Swensson 1990) appearance, casting some doubt on this interpretation. Also, there is a clear decrease in the coarseness of gold in many palaeoplacers with distance from known sources in adjacent Palaeozoic bedrock, which would not be expected if the coarse gold formed in the palaeoplacers prior to weathering. Conversely, data from fragmentary reports can be interpreted to suggest that both coarse and fine gold may have been precipitated in duricrusts (e.g. ferricrete "cement") overlying palaeoplacers. This is suggested because of: (i) the higher stratigraphic level, (ii) lower silver content (e.g. Smyth 1869), and (iii) lack of "waterworn" textures of fine gold in the ferricrete relative to the underlying, more clearly alluvial, gold. Large tonnages of this ferricrete "cement" were crushed and its gold recovered (e.g. Stawell, Berringa). Silica "cement" from the uppermost layers of Tertiary gravels at Moliagul contained "a number of fresh, sharp nuggets" and these have obviously grown *in situ*" (Cahill 1988). The nature of material described as "cement" is uncertain at some localities, so some descriptions in the literature are ambiguous (e.g. some has formed by oxidation of diagenetic sulphide; Swensson 1990).

At least some chemical modification of alluvial gold is probable, as it was already recognised during the last century that many eastern Australian nuggets contained less silver than was present in the gold of nearby quartz veins (Liversidge 1893, quoted in Mann 1984), and invariably the average fineness of placer gold in Victoria is greater than that of primary reef gold from the same district (Junner 1921).

#### **GOLD IN OXIDISED ORE ZONES**

In many districts, e.g. Tarnagulla, Rheola, Dunolly, Wedderburn, Inglewood and the Pyrenees (near Avoca), the majority of reefs became low grade and uneconomic in the primary sulphide zone (Junner 1921; Figure 1). However, gold grades of 3-8 oz/t (93-248 g/t) were common at shallow depths, e.g. 30-60 m, locally reaching hundreds to thousands of oz/t (i.e. greater than 60 kg/t) in small tonnages, e.g. Maldon, Bendigo. Although many veins were narrow and would have been more expensive to mine at depth, it is unlikely that this grade distribution reflected only the economics of mining, since such grades were rarely encountered in deep mines (e.g. deeper mines averaged 15 g/t, and 30 g/t was considered high grade, admittedly averaged over larger tonnages than in the shallow mines). Less spectacular near-surface gold enrichment, systematically varying with depth, was recorded in other fields (e.g. Castlemaine, Stawell, Walthalla-Woods Point) and recognised by Junner (1921).

A number of large nuggets have been found at surface within, and immediately overlying, auriferous quartz veins, e.g. 810, 805 and 785 oz (i.e. 24-25 kg) nuggets above one vein at Rheola. Rich concentrations of slugs and veinlets of gold occur below surface within quartz veins, e.g. an approximately 400 oz (12.4 kg) concentration at William Australia's open-pit mine, Ballarat East, found in 1996 (L. Dickinson, pers. comm.). The presence of quartz attached to some large nuggets at surface, and of large nuggets in quartz veins at significant depth (e.g. Ballarat East) do not preclude the possibility of growth of supergene gold in the lode channels of primary auriferous quartz veins.

Thin, bedded, graphitic, pyritic, chlorite-rutile and ferruginous horizons ("indicators") were reported to be an important control of hard-rock nuggets typical of "pocket" (presumably cavity-filling) deposits in "indicator" fields such as Dunolly-Moliagul, Rheola, Wedderburn, Ballarat, Tarnagulla and Maryborough. This included the Woah Hawp Canton and North Woah Hawp mines, Ballarat

East (Junner 1921) discussed below. Some gold slugs associated with "indicators" in bedrock lack associated hydrothermal quartz, although most occur where quartz veins intersect "indicators". These goldfields are all in areas affected by weathering associated with formation of the Norval Regolith or the Karoonda Regolith, and are mostly marginal to the Murray Basin and Otway Basin, as are other nugget fields such as Bendigo, Kingower and Rokewood. The coarse gold "pockets" were abundant above 60 m depth, and were rare below 120 m except at Ballarat East (e.g. they were almost all above water level at Maryborough and Wedderburn). The silver content of the gold in some cases was lower than in deeper mines at the same locality, suggesting supergene processes. The majority of recorded slugs in quartz reefs are from the Ballarat East field, which is the "indicator" field mined to greatest depth, and a remarkable 68% of these slugs were recorded from within 50 cm of the intersection of a quartz reef and an "indicator" (the locations of the remainder are unrecorded; Bowen & Whiting 1975). Features in the Woah Hawp Canton and North Woah Hawp mines, Ballarat East, are unusual and do not preclude a supergene origin for the gold slugs (Junner 1921). These mines produced 50 of the 70 slugs of gold of more than 50 oz (1.6 kg) from the Ballarat East field. The mines adjoined each other and were exceptional for their number of faults which post-dated quartz veins, the presence of marcasite (not a primary sulphide) in deep mine workings, and the presence of masses of kaolin in the reefs at depths as great as 366 m (Junner 1921). These features suggest deep weathering associated with this faulted area, a requisite for supergene enrichment.

Although an original hypogene origin is probable for many nuggets and much of the coarse gold of eluvial, alluvial and "indicator" gold deposits, the above observations suggest that supergene enrichment processes, perhaps related to the weathering of the Early Tertiary Norval Regolith, might have formed at least some of this gold. However the rounded form of gold in White Hills Group gravels (but not necessarily in their ferricretes) suggests that much of this enrichment, if economically significant, pre-dated the incorporation of nuggets into the gravel.

Descriptions indicative of supergene gold in deposits hosted by Palaeozoic rocks are not confined to the immediate proximity of quartz veins or "indicators". Within parts of mines where gold occurred in auriferous quartz veins, but separate from them, rich weathered patches ("pockets") of nuggety gold, e.g. to 36 oz (1.1

kg), and fine gold were found associated with hydrous manganese oxides (e.g. Walhalla-Woods Point). The fine gold was commonly loose and free from quartz. It also occurred as arborescent ("fern-like") and botryoidal gold, and as discrete gold crystals (Junner 1921). At St Arnaud, "finely-divided" (flour?) gold low in silver was associated with hydrated Mn-Fe oxides and cellular quartz in rich, near-surface ore, and with secondary silver, lead and copper minerals in rich ore e.g. 6-7 oz/t (186-218 g/t) at 43-52 m depth. Gold is silver-rich at depth in the lower-grade primary ore at St Arnaud (electrum in part), and gold at Walhalla-Woods Point is slightly more silver-rich than in the Ballarat-Bendigo region (Hughes et al. 1997); this might have accentuated the breakdown of gold during weathering at these localities. Colloform gold intergrown with secondary iron oxide has also been observed in central Victorian quartz veins during the present study.

Recent research indicates that gold has been redistributed to some degree in the oxide zone of deposits in which gold is enclosed in sulphide minerals at depth, such as Nagambie (Gillies 1990), Fosterville (McConachy & Swensson 1990) and Tallangalook. This evidence consists of (i) variations in Au:Ag ratios with depth, (ii) the coarser grain size of gold particles in the oxidised zone relative to the primary zone, (iii) the presence of colloform gold textures in the weathering zone, and (iv) the presence of free gold in the weathering zone, overlying the hypogene zone in which gold is entirely locked as submicron gold in sulphide minerals.

#### **GOLD IN PALAEOPLACERS (DEEP LEADS)**

There is also evidence that gold was mobile in palaeoplacer (deep lead) systems. The presence of gold in diagenetic pyrite which has replaced the roots, branches and stems of fossil trees is well recorded from the palaeoplacers of central Victoria (e.g. Newbery 1868). Diagenetic pyrite is also widespread and locally abundant in sediments of the palaeoplacers, together with minor native copper and at least some perfectly crystallised diagenetic arsenopyrite. The arsenopyrite occurs in the Geera Clay of the Murray Basin (Brown & Radke 1989) and in the Denicull Formation at Ararat. Native copper has been reported in palaeoplacer mines at Ballarat West, Clunes and Sulky, and was collected in one treatment plant at Creswick for extraction of its gold. One tonne of pyrite concentrate collected from the Great Northern Junction shaft on the Deadhorse palaeoplacer, Mount Rowan (Ballarat North), yielded 6.4 oz Au, but this included "blanketings" (a possible source of fine gold

trapped on fabric). This was probably diagenetic pyrite, which one author (MH) has observed as coarse euhedral crystals associated with abundant fossil leaves from another Victorian palaeoplacer (Tanjil). Elsewhere, diagenetic pyrite reportedly contains no significant gold (Swensson 1990). Wire-gold and colloform, very fine-grained gold, as well as coarser gold, have been observed within some deep lead cobbles. Examples occur in the Chiltern area (Dickson 1996), where minor quantities of gold were recovered from the cobbles, and immediately underlying ferricrete in the Ballarat area. The cobbles consist of only moderately weathered Palaeozoic metasedimentary rocks which lack quartz veining, and a supergene alternative to their commonly assumed hypogene origin should be considered. An unusual form of extremely fine-grained alluvial gold, in which each grain was crystallised, was found in the same palaeoplacer as the cobbles at Chiltern (Hunter 1903).

These observations leave little doubt that gold was mobile in the supergene zone and palaeoaquifers of Victoria during the Cainozoic. However despite the observation of secondary gold, and the probable enrichment of hypogene ore at shallow depths, there is no direct evidence that supergene gold enrichment of major economic significance, i.e. sufficient to form an economic ore body in 1990s terms, has occurred in direct genetic and spatial association with laterite in Victoria. Investigation of the numerous gold nuggets now being found in Victoria is hampered by secrecy or uncertainty surrounding their source and the difficulty of observing them, or of obtaining specimens for detailed study (e.g. a botryoidal gold nugget of uncertain origin, reputedly Dunolly, observed by MH). Research in progress includes the study of gold from lateritised White Hills Group gravels.

#### COMPARISON WITH WESTERN AUSTRALIA

There are similarities between the history of lateritisation in Victoria and that in Western Australia, but also three differences of possible relevance to gold genesis and economics. The first is that lateritisation in Western Australia was more prolonged and the average depth of chemical weathering of the rock mass was greater (although oxidation and formation of clay during weathering in some Victorian vein systems may have occurred at depths exceeding 250 m). The second is that the deeply weathered regolith has subsequently been more extensively stripped in Victoria (by uplift and stream erosion in the uplands, and by marine erosion in low-lying areas). The third is less certain: the only confirmed period

of aridity and salinisation in Victoria (i.e. with the required high chloride concentration for gold mobility) is the last 0.5-1.0 My (Martin 1989). This is a much shorter interval in time than in Western Australia where such conditions were already present in the early Pliocene. However, salinisation may have been associated with earlier deep weathering in Victoria although it has not been recognised in the geological record.

Some of the essential requirements for dissolution of gold in lateritic environments include high concentrations of chloride ion, low pH (e.g. <4) and high Eh (i.e. high  $fO_2$ ; Mann 1984). pH values of 2-3 can exist in groundwater at shallow depth, with pH 6 at depth where there is significant ferrous iron and little  $O_2$  (and where gold would have limited solubility). Present-day groundwater in the south-west Yilgarn craton of WA can have > 0.1 M  $Cl^-$  and pH < 4 (Mann 1984). Similar groundwater exists in northern Victoria today, and high chloride ion concentrations are present in Victorian soils. Acid groundwaters with pH 4.5 to less than 3.5 occur extensively in the Parilla Sand aquifer of north-western Victoria and in Palaeozoic bedrock aquifers of central Victoria (Macumber 1991). These are commonly restricted to the upper parts of the Parilla Sand aquifer (e.g. 25-40 m below the water table), and can increase 3-4 pH units at depth. Acid groundwaters with pH 3-4 are high in chloride ion (e.g. 15%), soluble Fe (e.g. 15-40 ppm) and sulphate (1.8%) at depths of 10-16 m in the Parilla Sand. At depths of 50-67 m waters are similar except that they have pH 7.5 and contain only 1-2 ppm Fe (i.e. ferrollysis is indicated; Macumber 1991). There is evidence in Victoria that iron, partly from the Karoonda Regolith, is being extensively redistributed in the near-surface environment today, with some waters with pH 2.3 and 200 ppm Fe actively precipitating iron oxides at surface (Macumber 1991). Since high Eh is common in most near-surface environments, potentially all three of the required conditions for gold mobilisation exist in Victoria today, although it is unknown whether these conditions were met in Victoria during the Tertiary.

#### APPLICATION TO EXPLORATION

If significant supergene enrichment of gold has occurred in Victoria it is most likely to be of economic significance today in areas where more of the Tertiary regolith remains. These areas include the extensive, poorly-exposed north-western margin of the highlands, adjoining the Murray Basin. The area which might contain true laterite-related gold enrichment of economic proportions is limited by subsequent erosion and by the

original lateritic profile being shallower than in Western Australia, but such target areas exist and are predictable. Gold enrichment may also have been a factor in ore bodies mined in major goldfields of the upland areas. Although this has limited application to exploration in these areas today, recognition of enrichment and depletion at specific depths may be relevant, e.g. to shallow, bulk-tonnage targets. Also, some low-lying areas previously drilled using shallow RAB/aircore holes, which might have drilled into depleted zones, may need to be re-evaluated.

An understanding of regolith development and distribution, particularly as ferricrete and calcrete duricrusts, is very relevant to geochemical exploration in the lowland areas adjoining the Murray Basin. Initial results suggest that the geochemistry of these materials can be used in exploration for underlying hypogene gold deposits in these areas, e.g. at Bendigo (Metex Resources N.L. 1996).

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## APPENDIX: LATERITE TYPE LOCALITIES

### THE NORVAL REGOLITH AT ARARAT

The Norval Regolith is defined here from its geological relationships in two areas west of Ararat. These are at Norval in the north, where it is best exposed around Mine

Battery Road, and at Hard Hill in the south, near Denicull Creek and Phillips Flat roads (Figure 2). Grid references (G R ) correspond to topographical mapsheet 7423-2-N (Ararat North 1:25 000) unless otherwise indicated.

### Norval

The important features of the Norval type area are (i) the former continuity of a local subhorizontal and undulatory Norval Surface, remnants of which can be observed at a similar elevation in the landscape throughout the area (340-360 m a.s.l.), and (ii) the development at this surface of ferricreted bedrock and sediment, and kaolinised saprolite

Three outcrops at Norval are particularly informative:

1. At Mine Battery Road (G.R. XD643737), a lateritic profile of a pallid zone with overlying ferricrete is superimposed on a probable mafic rock of Cambrian age (Figure 3). The pallid zone is bleached to white and consists of clay (presumed kaolinite) with original rock textures still preserved. The ferricrete is massive and featureless in hand specimen, and overlies and extends downwards along former joints into the pallid zone.
2. Nearby at G.R. XD644742, the pallid zone is white sandy clay, developed upon probable Cambrian diorite, which is overlain by thin (5-20 cm) remnants of ferricrete, including some ferricreted Tertiary sandstone. The pallid zone has numerous grey to pale grey, texturally similar features, possibly caused by Recent bioturbation (probable root casts) and/or filling of fractures. Nearby at G.R. XD645741, sandy pebble/granule conglomerate of the Great Western Formation (White Hills Group), less than 1 m thick, is now ferricrete in which breakage is usually through the grains.
3. At Port Curtis Hill (G.R. XD638744), Great Western Formation (quartz pebble conglomerate, less than 1 m thick) overlies granitic saprolite. The matrix of the conglomerate is quartz sand and clay with minor ferruginisation. The adjacent hill to the south has numerous small outcrops of massive and fine-grained to sandy-textured ferricrete developed on Great Western Formation and Palaeozoic granite. Farther south, probable eluvial gold has been sluiced from the decomposed granite at the base of the weathered profile.

Drilling in the Norval area indicates remnants of a thoroughly leached (less than 25 ppm Cu+Pb+Zn) pallid zone in Palaeozoic rock which is mostly 9-20 m thick (e.g. 20 m thick beneath the gravel cap of Port Curtis Hill).



### Hard Hill

The important features of the Hard Hill area are (i) the development of the Norval Regolith on the Great Western Formation and underlying Palaeozoic rocks on the floor of a clearly defined palaeovalley, (ii) the presence of saprolitic Great Western Formation and Palaeozoic rocks, and (iii) evidence for erosion of this regolith into the younger Denicull Formation, which has been covered by younger, dated, basalt flows

At the Hard Hill quarry, Denicull Creek (G.R. XD669669), intensely kaolinised Cambrian metapelite is overlain by quartz-lithic, pebbly cobble conglomerate of the Great Western Formation (White Hills Group), 1.5 m thick. The cobbles, mainly metapelite, and the matrix are altered to white clay (presumed kaolinite). This is overlain by weakly ferruginised quartz pebble conglomerate, which locally directly overlies the Cambrian rocks (Figure 4). Drilling in this area indicates that the thoroughly leached (less than 25 ppm Cu+Pb+Zn) remnant pallid zone in Palaeozoic rock beneath the gravel is more than 500 m wide, and 18-30 m thick across the former floor of the Great Western Formation palaeovalley. The present valley, the palaeovalley of the Denicull Formation, and the palaeovalley of the Great Western Formation have been superimposed on each other between higher, much less weathered, parallel ridges of Palaeozoic rock to the east and west. The pallid zone material and its ferruginous cap now occupy a low rise in the centre of the valley, bounded by two Denicull Formation palaeoplacers (Cathcart and Heather Belle), and therefore represent original deep weathering of the valley floor

Younger Denicull Formation (Loddon River Group) palaeoplacer gravels at Ararat are partly sourced from older gold-bearing gravels of the Great Western Formation. This includes the area immediately adjacent to Hard Hill (Hunter 1913), where Denicull Formation gravels of the Cathcart and Heather Belle palaeoplacers are 30 m lower in elevation than the Great Western Formation. The Cathcart palaeoplacer joins the Langi Logan palaeoplacer farther east, where its gravel is overlain by basalt which slightly farther north is dated at  $6.07 \pm 0.11$  Ma (late Miocene; Cayley & McDonald 1995; Figure 2). This constrains the upper age of the Norval Regolith. Deep weathering of basalts which overlie the Langi Logan palaeoplacer (Cayley & McDonald 1995) is possibly that of the Karoonda Regolith

### Other Areas at Ararat

The road cutting by "Springfield" (G.R. XD672722) on Rhymney Road, Cathcart, shows pebble conglomerate of the Great Western Formation (White Hills Group) in a probable headwaters tributary of the Hard Hill palaeoplacer, overlying Cambrian metapelite (the "Springfield"

palaeoplacer; Figure 2). The unconformity has relief of approximately 1 m. The quartz-lithic conglomerate is indurated primarily by clay (i.e. it is a clay duricrust), though it is also iron-pigmented. The metapelite is weathered to kaolin, with all original structure destroyed. Instead, vertically elongate subprismatic pedis are well developed, and mottling and rare root casts are present. We interpret the top of the metapelite as a palaeosol, but its timing relative to gravel deposition is uncertain. Red Hill palaeoplacer (G.R. XD647716) is very proximal Great Western Formation, and is probably also part of the headwaters of the Hard Hill palaeoplacer. It consists of a clay-indurated, lenticular pebble/granule conglomerate and massive mudstone. Murphy's palaeoplacer (G.R. XD657804) is interpreted as the upstream part of the Great Western palaeoplacer, and contains approximately 50 cm thickness of heavily ferricreted Great Western Formation.

## THE KAROONDA REGOLITH AT STAWELL-ARARAT

### West's Pit, Stawell

West's pit (G.R. XD547965, topographical mapsheet 7423-4-1, Illawarra 1:25,000) provides important stratigraphic evidence for distinguishing the Karoonda Regolith from the older Norval Regolith. A weathering profile is developed on clayey pebbly sand of the Parilla Sand (Miocene-Pliocene), suggesting a maximum Pliocene age of formation for the Karoonda Regolith, younger than the youngest units which display the Norval Regolith (e.g. Great Western Formation).

The weathering profile consists of an upper mottled zone and a lower, poorly exposed, clay duricrust. The mottled zone is a spectacular example of tiger mottling (R. MacEwan, pers. comm. 1998), where the mottling is strongly elongate in a roughly horizontal plane (Figure 5). Maroon-coloured layers alternate with pale grey layers in these mottles. Although commonly subhorizontal, the mottling is arcuate in many parts of the pit and reaches a dip of up to 45°. Frequent vertical orange-brown pipes cross-cutting the mottling are probable root casts. Few iron pisoliths occur within the maroon mottles, but they are quite abundant at surface.

### Byron's Pit, Denicull Creek

The soil profile formed on gravels and sands of the Denicull Formation (Loddon River Group) at Byron's pit, Denicull Creek (XD674652), immediately south-east of Hard Hill, well illustrates the characteristics of the Karoonda Regolith. It contains an upper layer of Fe-pisolithic brown soil, approximately 1 m thick, which displays brown/maroon tiger mottling. This overlies a strongly indurated clay duricrust, of similar thickness, of

mainly pale grey clayey gravel, which displays minor tiger mottling and contains thick cutans, abundant root channels and slickensides. The relative timing of this surface (i.e. younger than the Norval Regolith) is given by its development on sediments which have been derived in part by erosion of the Norval Regolith at Hard Hill.

#### **OTHER AREAS**

1. On the Western Highway at Deep Lead, north of Stawell (G.R. XE528015, topographical mapsheet 7423-4-1, Illawarra 1:25,000), a ferricrete forms part of the Karoonda Regolith. The highway road-cutting, approximately 1.5 m deep, exposes kaolinitic Cambrian metapelite underlying gravels, sands and silts of the Parilla Sand. Ferricrete occurs as a discontinuous sheet up to 80 cm thick, generally as a ferruginous quartz pebble conglomerate.
2. A road cutting at the intersection of the Western Highway and McDonald Road, north of Ararat (G.R. XD695758, topographical mapsheet 7423-1-5, Stawell South 1:25,000) exposes saprolitic Cambrian metapelite in which original textures can be identified. This is overlain on an unconformity of gentle relief by conglomerate and sandstone (Denicull Formation, possibly the Milkman's Flat palaeoplacer) which has a clay duricrust imposed upon it just below the present surface. The Denicull Formation is strongly consolidated due to the presence of matrix clay, and the strongest ferruginisation occurs at the basal contact. The clay duricrust is pale grey or mottled pale grey/orange, with a discontinuous tiger-mottled (maroon/brown) zone preserved on its top. The Denicull Formation includes pebble/granule conglomerate with chips of detrital ironstone (probably from the Norval Regolith) important amongst the predominant vein quartz and minor lithics.
3. Nil Desperandum palaeoplacer, Ararat-Warrnambool Road (G.R. XD685660). The Denicull Formation at this locality exhibits tiger mottling immediately below the surface, mainly in fine-textured sediment but also in some gravels. Maroon/tan mottling passes down into maroon/light grey mottling 30 cm below the surface. Vertically elongate subprismatic pedes are present.
4. Driver's palaeoplacer (G.R. XD701711), probably part of the Denicull Formation, is exposed in a creek below the Oliver Gully Reservoir, Ararat. A pale grey clay duricrust, approximately 1.5 m thick, occurs just below the top of the preserved profile, below which clay is present as matrix in the predominant pebble conglomerate and pebbly mudstone.