BALLARAT GOLDFIELDS REGION, VICTORIA

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INTRODUCTION

The Ballarat goldfields lie 120 km northwest of Melbourne, centred at latitude 37º34'S and longitude 143º52'E within the BALLARAT (SJ54-8) 1:250 000 scale map sheet (Figure 1). The Ballarat goldfield was the second largest gold producer in Victoria after Bendigo, and is similar to the many other deposits of Victoria's "Golden Triangle" (Taylor, 1998). The following summary of the regolith and its development through time is based on regional geological mapping (Taylor *et al*., 1996; Taylor *et al*., 2000) that included some basic regolith mapping (Taylor and Joyce, 1996). A more detailed investigation that covers the immediate goldfield area and included some geochemical characterisation has recently been carried out (Radojkovic and Bibby, 2003).

PHYSICAL SETTING

Geology

The Ballarat goldfield lies in the Bendigo Zone of western Victoria, hosted in the kilometres-thick Lower Ordovician Castlemaine Group, which is a greenschist grade sequence of quartz-rich turbidites. The rocks were deformed in the Silurian and then intruded in the Devonian by numerous post-tectonic I-type granites

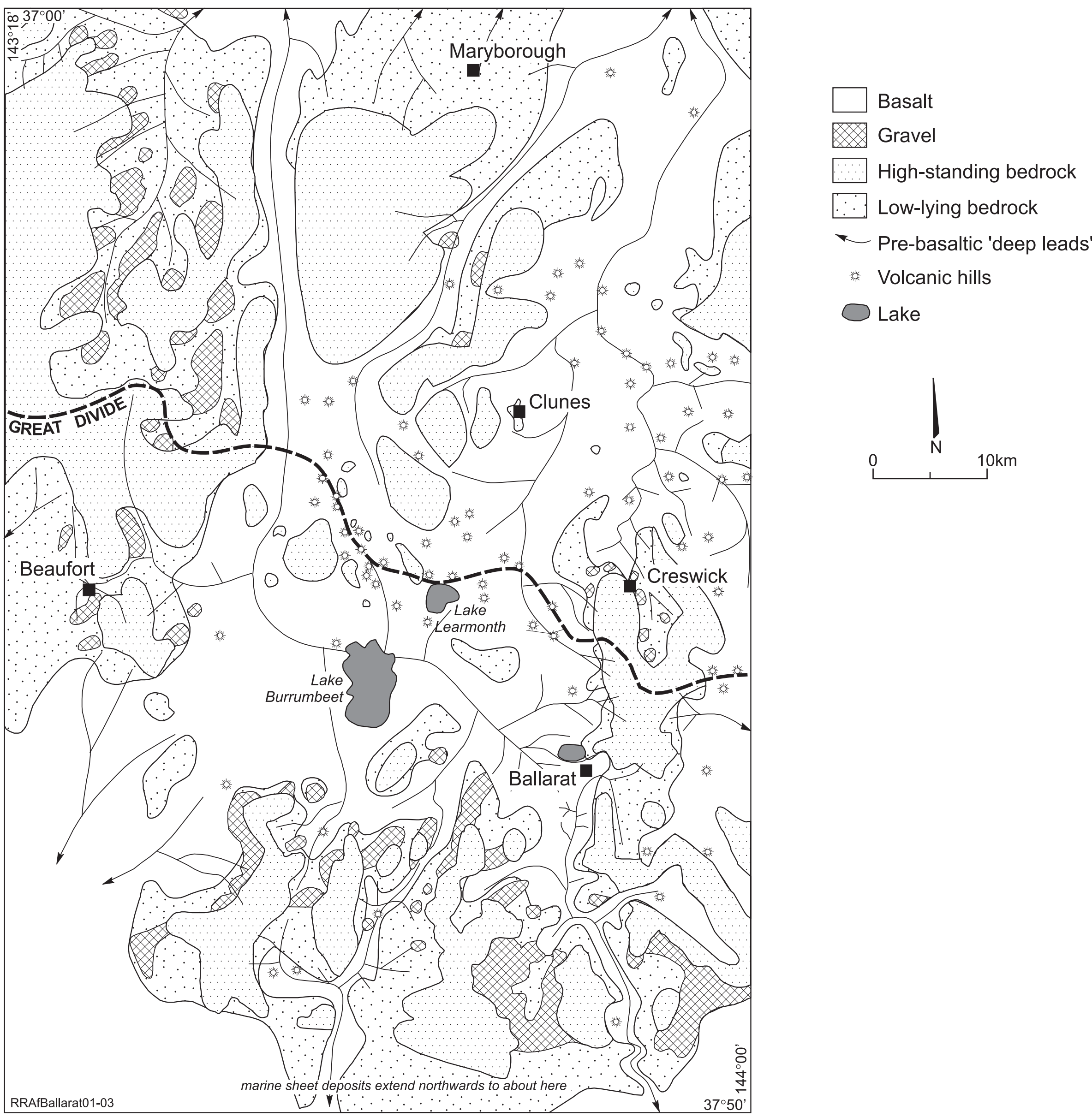

Figure 1. Simplified map showing the broad distribution of the major types of regolith units; the Palaeozoic bedrock, Cenozoic gravels and Cenozoic basalt.

(VandenBerg *et al*., 2000; Figure 2A). Veneers of Cenozoic gravel deposits, that are often rich in placer gold, patchily overlie the bedrock. Much of the region is covered by Cenozoic flood basalts.

Geomorphology

Dissection of a Mesozoic palaeosurface (Figure 2B) led to the development of new landscapes in the Cenozoic (Figure 2C). Since the landscape is so youthful, the geology still has a strong control on the geomorphology. The region straddles the east–west oriented Great Divide, which is a chain of undulating bedrock hills (the Midlands) with up to several hundred metres of relief (Figure 2C). The granites form either topographic basins or high hills depending on their resistance to erosion. Scattered in the low parts of the landscape, still crudely delineating their depositional valleys, are the Cenozoic fluvial deposits (Figure 2D). Much of this low-lying landscape was recently covered by basalt (Figure 2E), which in places forms localised plains (northward extensions of the Western Victorian Volcanic Plain).

Climate and vegetation

The climate is temperate with warm summers and cool, wet winters with an annual rainfall of about 500–800 mm. The mean daily temperature ranges are 12–26°C in January and 4–10°C in July. The bedrock hills with poor siliceous soil are covered in stringybark eucalypt woodland with little understorey, whereas the fertile basalt soils have been cleared for agriculture.

REGOLITH–LANDFORM RELATIONSHIPS

Following geological mapping, a 1:100 000 scale regolith map of the Ballarat area was produced by interpretation of radiometric data and soil maps, with ground control from regolith profiles exposed in numerous road cuttings (Taylor and Joyce, 1996). There are three major types of regolith units: Palaeozoic bedrock, Cenozoic gravel deposits, and Cenozoic basalt (Figure 1). The present landscape reflects a configuration that developed in the early Cenozoic after Australia–Antarctic break-up. It consists of interfluve ridges of bedrock aligned north–south along the tectonic grain. The intervening broad shallow valleys contain the Cenozoic gravels and most of the basalt (Figure 1). As a general rule, the high-standing bedrock of the ridges is less weathered than the low-standing bedrock of the valleys. A deep weathering profile of pallid and mottled zones beneath a ferruginised cap is well preserved in many places and probably dates back to the early Cenozoic. In the south of the area, a topsoil of grey, sandy loam caps many of the regolith profiles. This may be wind-blown, formed during arid glacial periods in the Quaternary.

Palaeozoic bedrock units

Palaeozoic bedrock comprises about 50% of the area, with numerous natural and man-made exposures. Regolith formed from Palaeozoic bedrock varies from pallid saprolite through to incipiently weathered bedrock, with this variation largely controlled by elevation in the landscape. Low-lying regions are deeply weathered, whereas high standing regions are less weathered, although the freshest rocks occur in some of the deeply incised modern streams to the south of Ballarat that have cut through the weathering profile.

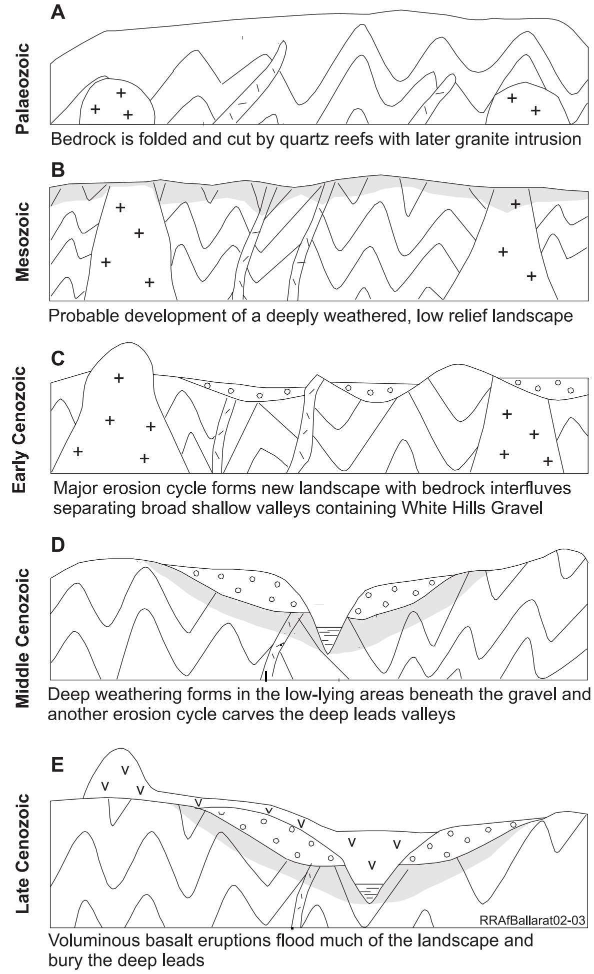

Figure 2. Landscape evolution through time with deep weathering represented by shading.

Intensely weathered bedrock occurs low in the landscape directly beneath remnants of early Cenozoic gravel deposits. These areas would originally have been valley floors in the early Cenozoic landscape and it was probably the focussing of groundwater into these regions which caused the intense weathering. The original sandstone and mudstone of this bedrock is now a soft, mottled to pallid, kaolinitic saprolite up to a few tens of metres thick, in which original bedrock features can be obscured. There is a duplex soil with grey sandy loam with abundant quartz fragments over a cracking clay subsoil.

On low hills and valley sides there is less weathered saprock that has a higher proportion of primary minerals and less altered clays. The stiff, reddish-yellow saprock may extend to depths of a few tens of metres, in which original bedrock features such as bedding and quartz veining are still recognisable. There is a duplex soil with a grey loam with abundant quartz fragments over a swelling clay subsoil.

The bedrock ridges, hornfels rims and resistant granite hills consist of slightly weathered bedrock. There is a thin residual lag of slightly ferruginised bedrock float and abundant fragments of vein quartz scattered upon a thin stony soil. In the south, deep and ongoing stream incision has exposed fresh bedrock below the weathering front. In these steep-sided gorges the hard, fresh rock retains its original grey colour, exhibits minor alteration of the primary minerals and has a thin stony soil.

Cenozoic sedimentary units

Cenozoic sedimentary units consist of a series of sheet-like or channelled fluvial gravel deposits, although an extensive sheet of finer grained marine rocks onlap the bedrock from the south (Figure 1). The extent of the Cenozoic sediments been reduced by erosion but they still cover about 15% of the map area. All of these units have been variably ferruginised and silicified by lateral and vertical groundwater movement of material.

The oldest unit is the early Cenozoic White Hills Gravel, which forms deposits of coarse quartz conglomerate up to 30 m thick in broad meridional palaeovalleys. This unit is scattered throughout the Midlands, often as elevated hill caps or hill fringes. The surface of the gravel is strongly silicified and ferruginised into a duricrust that forms a resistant cap protecting the weathered bedrock below. Beneath the gravel duricrust, the lower parts of the gravel are usually mottled and rest unconformably upon the highly weathered bedrock. At the base of the gravel there is commonly a concentration of alluvial gold that has been extensively worked in the past. This unit has a stony duplex soil similar to that developed upon the bedrock.

The "deep leads" are the channel deposits of a widespread middle Cenozoic dendritic drainage system that is now largely buried by basalt. The unit is richly auriferous because it contains gold derived from bedrock and gold that was reworked and concentrated from the White Hills Gravel. The deep leads sit low in the landscape and have been conduits for groundwater movement so that the deep lead gravels are now highly ferruginised or silicified. There are only a few small exposures where younger streams have incised through the cover units to reveal this hardened material which lacks soil.

Littoral to shallow marine sediments of late Cenozoic (Miocene–Pliocene) age encroach northwards over the bedrock towards Ballarat. The deposits consist of somewhat calcareous sandstone and marl. Dissection of the sheet deposits by modern streams back to the bedrock has locally formed a dissected plateau. Along the margins of this plateau the marine sand has been strongly ferruginised by groundwater to form a mottled ferricrete that overprints the original rock texture. Patchily distributed thorium anomalies visible in radiometric imagery mark these areas of intense ferruginisation. Away from the ferruginised plateau margins, the rocks often have pallid weathering zones and may contain thin silcrete bands. A duplex soil consists of a thin sandy loam over a cracking clay subsoil with ironstone concretions.

Quaternary colluvium of poorly sorted gravel to clay has been shed from bedrock hills to form aprons overlying or abutting the young lava flows that had impounded earlier streams. Where sourced from earlier auriferous deposits the colluvium is rich in nuggetty gold. The deposits have a reddish mottled to kaolinitic profile, often with shiny clay skins. There is a duplex soil of sandy loam over a cracking clay subsoil. The aprons shed from the granites consist of well-sorted coarse granitic sand. The quartz grains are preserved but the feldspars and mafic minerals are weathered to a kaolinitic clay below a slightly ferruginised cap. These have a gradational soil of coarse sandy loam over a cracking clay subsoil.

Quaternary alluvium consists predominantly of dark organic clay with some gravel and sand. There is a subsoil of uniform dark cracking clay that often has a topsoil of sandy loam. Many alluvial flats have a veneer of post-settlement alluvium over the original soil. This layer usually consists of pale clay, silt and sand up to tens of centimetres thick with minimal soil. Its deposition is related to land disturbances such as clearing trees, over-grazing and mining since European settlement.

Cenozoic basalt flows

Late Cenozoic basalt flows cover about 55% of the map area, aggregating to a maximum thickness of about 150 m over pre-existing valleys but generally only to a few tens of metres over much of the region. These flows mask large areas of prospective bedrock and inhibit mineral exploration. The oldest flows were confined to the deep lead valleys, but in many places younger flows eventually overtopped these valleys to form localised volcanic plains. In the south, the flows debouched from the valleys onto the flat lying marine deposits to form an extensive plain. Regolith development has largely been by the *in situ* breakdown of the basalt, so thicker and increasingly mature clays soils have developed with age. The oldest flows have a uniform deep clay regolith with kaolinitic to mottled profiles. The younger flows have an undulating surface with emergent rock and thinner gilgai swelling clay soils. A reddish to black silty loam over a dark cracking clay subsoil with ironstone pisolites is variably developed.

REGOLITH CHARACTERISATION

In situ weathering of the rock types to form the regolith was dominated by hydrolysis, with breakdown of primary minerals through secondary minerals to swelling clays and finally kaolinitic clays in which all soluble elements have been leached.

The presence of substantial topography and high rainfall enabled fluvial and colluvial processes to play an important role in the re-distribution of weathering products via stripping of high standing areas and deposition in low lying areas. This may lead to complications for geochemical exploration because of the lateral movement of material by both physical surface processes and by chemical processes in groundwater.

The ongoing dissection of the Cenozoic fluvial units, which are often rich in placer gold, has redistributed large amounts of gold across much of the low lying bedrock and into the modern streams, and is likely to be a source of many "false" geochemical anomalies. The regolith of the high standing bedrock regions is uncontaminated by such material and thus geochemical anomalies in these regions are likely to represent a source in the nearby bedrock.

DATING

The classic deep weathering profile of pallid and mottled zones in the bedrock beneath the ferruginised cap of early Cenozoic White Hills Gravel remains undated by direct means. However, debris apparently eroded from this weathering profile comprises much of the dated middle Cenozoic deep lead deposits, suggesting that the weathering largely occurred in the early Cenozoic. Many of the young Cenozoic units, including alluvium in modern streams and lava flows dated at 6–2 Ma, have also undergone some ferruginisation which indicates that weathering is ongoing.

REGOLITH EVOLUTION

The present landscape and its regolith relate to several cycles of Cenozoic erosion and weathering that occurred after Australia–Antarctica break-up when an inferred deeply weathered and low relief Mesozoic landscape (Figure 2B) was dissected by re-energised drainages. By the early Cenozoic, dissection had produced a completely new landscape configuration with emergent meridional strike ridges of bedrock separating broad, shallow valleys filled with White Hills Gravel (Figure 2C). This landscape configuration has remained relatively intact to the present day and has largely controlled the distribution of the younger rocks. Shortly after deposition of the gravel, the low-lying parts of this landscape was itself deeply weathered. The surface of the gravel was silicified and/or ferruginised into a duricrust and the underlying bedrock was kaolinised to form mottled and pallid zones tens of metres deep (Figure 2D).

In the middle Cenozoic a new generation of smaller streams inherited the valleys of the early Cenozoic landscape (Figure 2D). The new streams carved deep, narrow valleys through the White Hills Gravel into the underlying bedrock and deposited the deep leads. The remnants of the White Hills Gravel were topographically inverted and are now perched about 30–80 m above the deep leads, with this depth of dissection probably reflecting the exhumation to fresher, harder bedrock.

Before the deep lead drainage system could destroy the earlier landscape by completely eroding it, the region was largely buried by voluminous outpourings of basaltic lava from late Miocene to Recent times (Figure 2E). These lava flows radically altered the earlier landscape, filling the deep leads valleys and essentially shutting down their well-established drainage system. The extensive drainage disruption by the basalt eruptions caused poorly sorted outwash to be deposited in swamps, lakes and streams around the fringes of the lava flows, and in the valley headwaters amongst the bedrock hills. In the last few million years drainages have been re-establishing a new system in which the Quaternary alluvium is accumulating

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