BRONZEWING DISTRICT, WESTERN AUSTRALIA

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LOCATION

Bronzewing is located within the Yandal greenstone belt of the Archaean Yilgarn Craton, about 500 km north of Kalgoorlie and 80 km northeast of Leinster, at 27°23′S, 120°59′E on the SIR SAMUEL (SG51-13) 1:250 000 sheet. The district examplifies some of the important exploration problems in the northeastern Goldfields. This account is largely derived from Varga *et al.* (1997) and Anand *et al.* (2000).

PHYSICAL SETTING

Geology

The Yandal greenstone belt, within which the Bronzewing district is located, is part of the Norseman–Wiluna belt and consists of mafic to ultramafic basal units and felsic upper parts. The local geology is dominated by upper greenschist facies rocks, commonly massive tholeiitic pillow basalts and dolerite. Ultramafic and gabbroic bodies are also present at the west and northwest part of the main deposit. A north-striking diorite body intrudes the sequence to the southeast of the Discovery Pit (Figure 1) (Phillips *et al.*, 1998).

Geomorphology

The contemporary landscape of Bronzewing district has a subdued relief with wide, flat valleys separated by low hills less than 50 m high. Ferruginised, silicified and relatively unweathered Archaean greenstones form ranges of low hills, strike ridges and broken slopes. The regolith in the Bronzewing district was influenced by the Lake Maitland drainage system to the northeast and its tributaries including Bates Creek. Bates Creek flows northwards adjacent to the Bronzewing Pits (Figure 1) with a gradient of less than 1 m in 1 km and has many braided channels in sandy alluvium. Further north, in the Sundowner area, the creek turns eastward to cut through the north-trending greenstones and Banded Iron Formation (BIF) and flows into the Lake Maitland system of salt lakes and playas. Beneath the modern alluvial

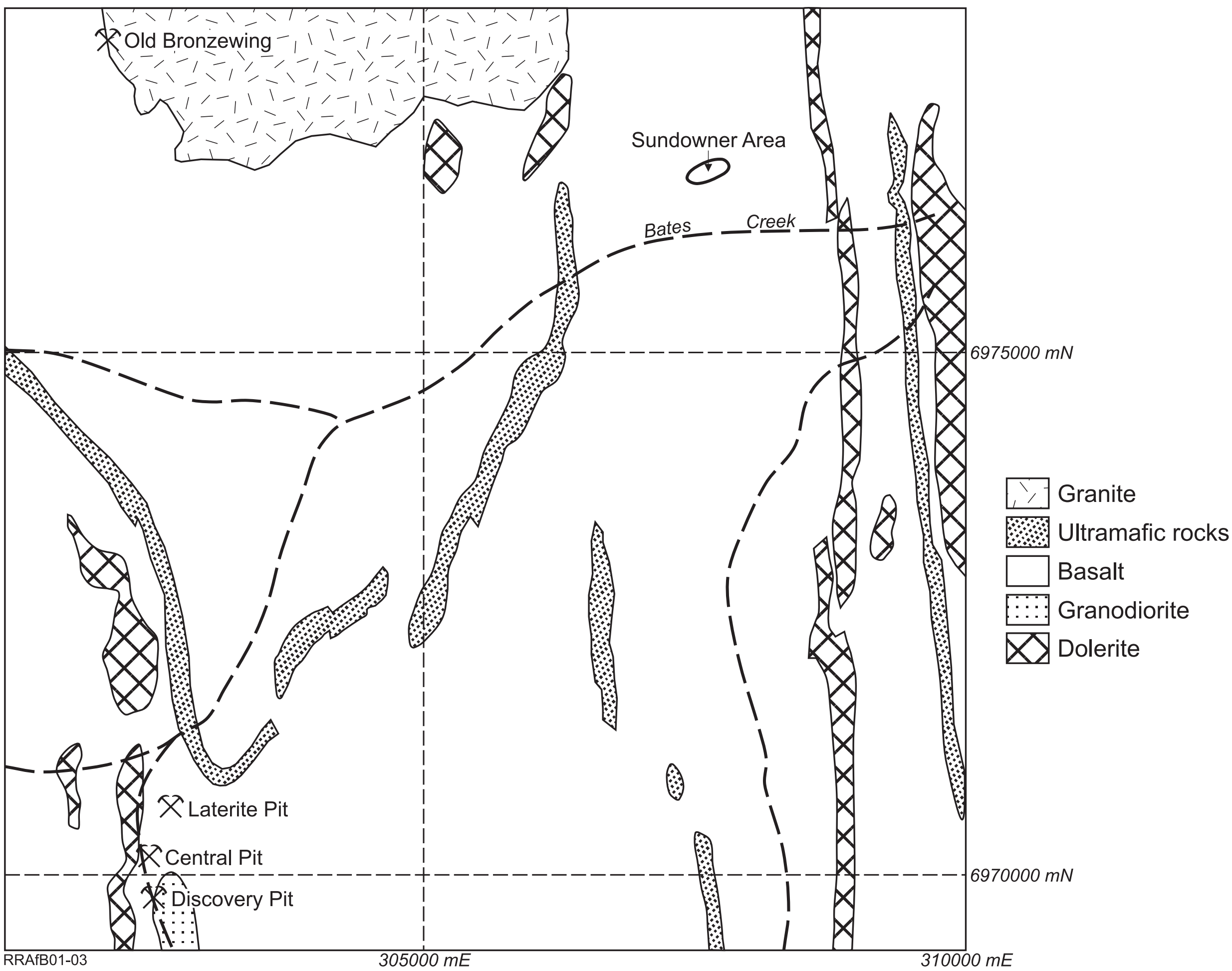

Figure 1. Local geology of the Bronzewing district.

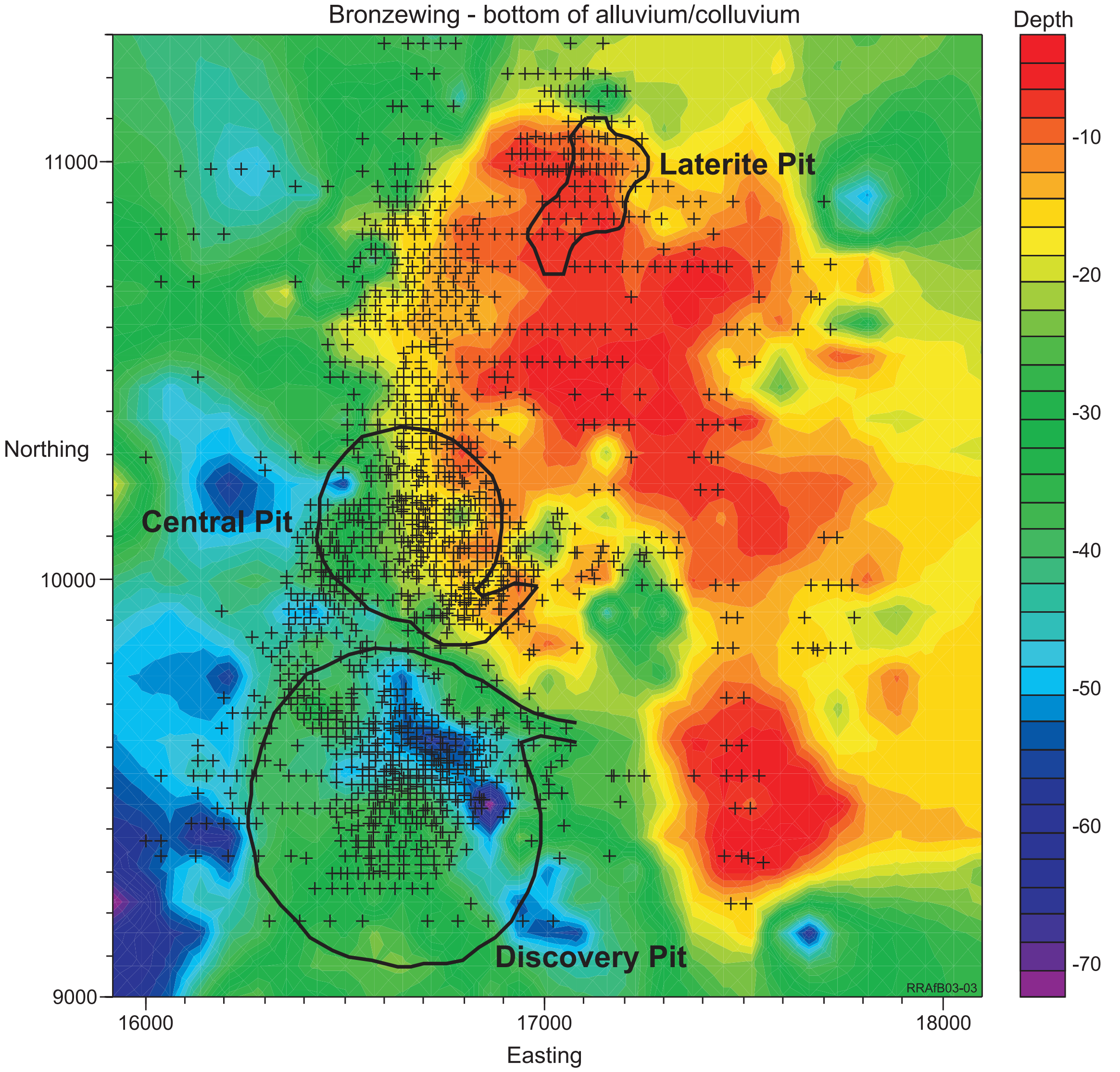

Figure 2. Thickness of transported overburden derived from drilling, indicating palaeotopography in the Bronzewing district.

plains of these tributaries is evidence of steep sided channels, that in places are oblique to the modern water course flow directions. Palaeochannels are incised into weathered regolith. The position of these channels have been influenced by large scale structures that may or may not be associated with mineralization. The channels lie beneath, but only partly mirror, modern drainage patterns. Paleochannels exposed in pits and drilling are up to 100 m deep and can be traced by drilling for several kilometers. High resolution aeromagnetic data have greatly facilitated mapping of these paleochannels. Extensive maghemite-rich gravels in paleochannel sediments coincide with dendritic patterns visible in imaged aeromagnetic data. Detailed stratigraphy and distribution of magnetic gravels in the paleochannels have provided sufficient detail to enable mapping the dendritic buried drainage systems (Wildman and Compston, 2000). Flanking the channels are extensive areas of sheetwash covered with a polymictic lag of ferruginous nodules, lithic and quartz fragments.

The palaeosurface of the residual profile on the basement shows that the Bronzewing deposit is on a north and east trending palaeohigh (Figure 2). Within the 2.0 x 2.5 km minesite area at Bronzewing, the present topography varies by only 7 m between Bates Creek in the west to the low hill on which the plant has been constructed in the east. The bed of Bates Creek was once approximately 50 m below the present surface and a palaeochannel ran from the southeast to the northwest of the deposit area. The flow directions of Bates Creek and the palaeochannels were probably controlled by north-trending bedrocks and cross-cutting faults. The basin to the southwest of the deposit area was the site of clay and silt deposition over the present Discovery orebody.

Climate and vegetation

The climate is semi-arid and has irregular average rainfall of 200 mm/yr. Vegetation is mainly *Acacia* spp with *Eucalyptus* spp and *Santalum* spp. in defined creeks.

REGOLITH–LANDFORM RELATIONSHIPS

The regolith distribution and landforms were mapped at 1:50 000 scale around the Bronzewing deposit. Simplified map (Figure 3) describes the local area and conceptual regolith-landform

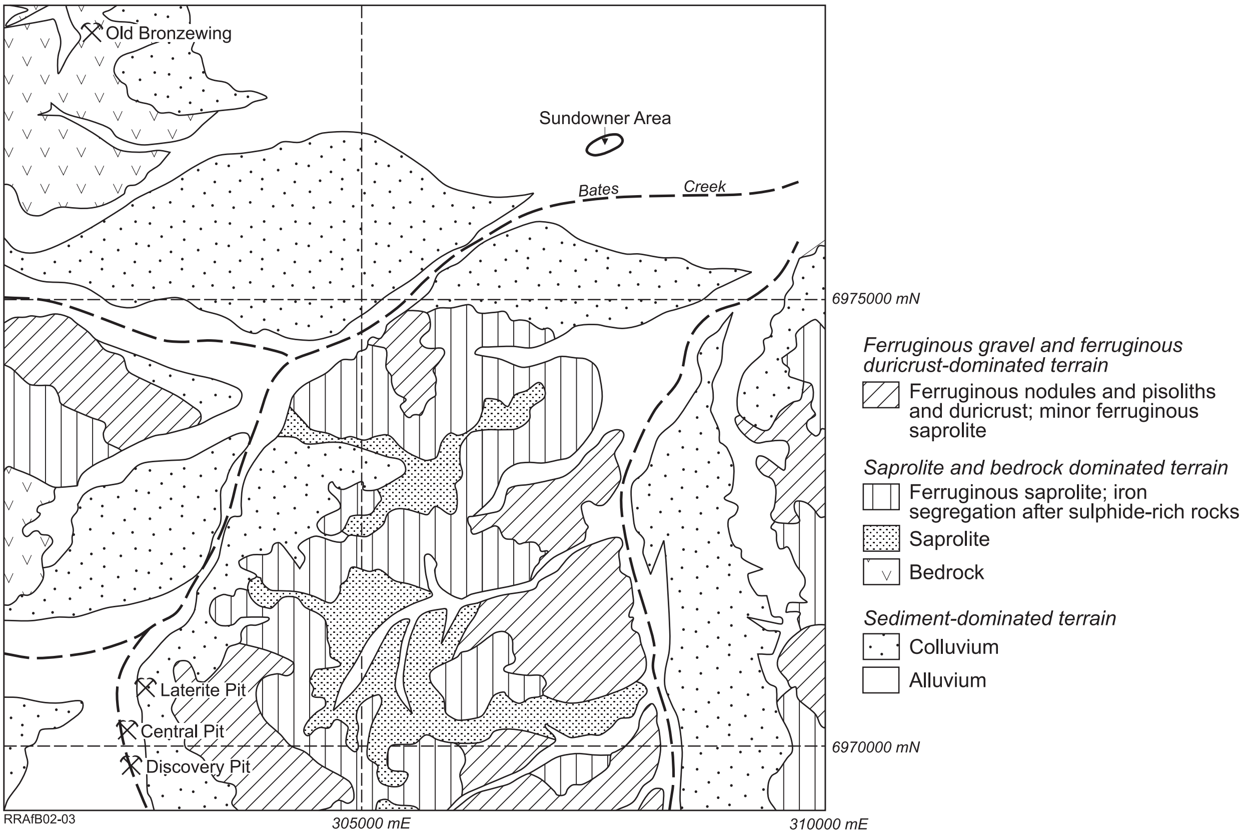

Figure 3. Simplified regolith–landform map of the Bronzewing district.

relationships are shown in Figure 4. Regolith–landform mapping units can be placed in three major geomorphic regimes. These are:

(i) A regime dominated, in the upper regolith, by ferruginous gravel and duricrust developed in weathered Archaean bedrock, or younger sediments that have themselves been weathered and/or indurated by Fe oxides. These commonly overlie mottled clay zones and saprolite. In places, remnants of palaeochannel sediments occur as ferricrete ridges composed of goethite-cemented ferruginous clasts; some of these now occupy topographically high areas because of relief inversion (Figure 4).

(ii) A regime on pediment slopes and low hills dominated by saprolite and ferruginous saprolite, with, in some areas, extensive bedrock, either exposed or mantled by shallow soil. Iron segregations related to sulphide-rich and/or Fe-rich rocks form a blocky ferruginous lag on saprolites developed from mafic bedrocks. Locally, greater relief variation, such as breakaway scarps, is the result of differential stripping of deeply weathered regolith. Below the breakaways, the gentle, often imperceptible, slopes of the main trunk valleys are produced by active but intermittent drainage and by localised deposition of sediments.

(iii) Sediment-dominated regimes within which the Bronzewing Pits are located, whose upper regolith is comprised of colluvium and alluvium. The sediments have either been derived from breakdown of weathered Archaean bedrocks from the upland areas or the reworking of younger sediments and may themselves have been subjected to extensive post-depositional weathering (Figure 4). Wanderrie banks (Mabbutt, 1963) occur on depositional plains. These have resulted from differential deposition from unconfined sheet floods, which have segregated the coarse fraction into low, sandy rises, preferred by mulga plant communities. Detailed stratigraphy from drilling in these areas has indicated the variable nature of the substrate. Beneath this colluvial–alluvial cover are concealed (a) earlier depositional regimes, consisting of megamottled, clay-rich materials and sand, confined to palaeochannels and (b) extensive areas where weathered profiles, some with lateritic residuum, are preserved.

The stratigraphy has been compiled from interpretation of drill cuttings and pit faces. In the Discovery Pit, 20–35 m of sediments directly overlies ferruginous saprolite (Figure 5). The sedimentary cover is 15–20 m thick in the southwest of Central Pit (Figure 5) and thins toward the northeast to <5 m in the Laterite Pit. The sediments are interpreted to have been derived from the northeast as alluvium, and from the subdued breakaway to the E as colluvial talus, shed during sheetwash erosional events.

The transect through Discovery Pit on 9400 mN (local grid)

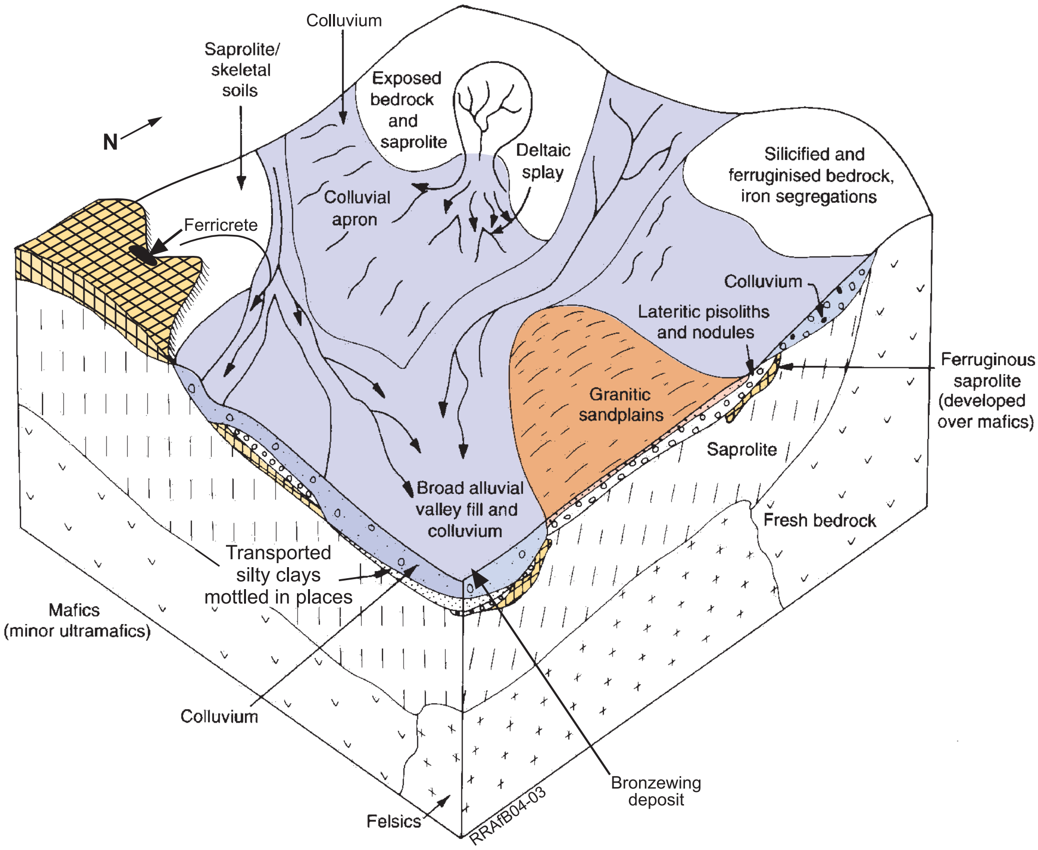

Figure 4. Idealised block diagram model showing regolith–landform relationship for the Bronzewing district.

(Figure 5) starts in the braided channels of Bates Creek and also intersects a dolomite-filled tributary palaeodrainage that cuts through the north side of Discovery Pit. The present surface, dominated by sandy and silty colluvium and alluvium, drops only 4 m from east to west across the 2 km transect. Ferruginous saprolite marks the base of the transported overburden except above the Fe-poor granodiorite unit. On the west side of Discovery Pit, a layer of green smectites with siliceous nodules occur at or above the residual regolith–transported overburden interface. Above the nodular zone, a lens of dolocrete, up to 15 m thick, appears to be continuous across the pit and to have a very similar upper surface RL as dolocrete in the Central Pit. The dolomite is biogenic, formed in lacustrine environments (Anand *et al.,* 2000). At the boundary of the dolomite and the overlying megamottled clays there is a thin layer (0.5 m) of green smectite that also fills the non-ferruginous part of the mottled clay above. The smectite oxidises to a khaki colour on exposure and crumbles to form a layer over the dolomite on the pit face. Towards the top of the green smectite clay, dense black goethitic nodules (1–10 cm diameter) form at a redox front.

Megamottled clays overlie the dolomite in the middle of the palaeochannel and nodular gravels towards the edges. Mottling (1 m x 10 cm) is more extensive in the middle of the palaeochannel, where it extends upwards into overlying gravels, and is denser towards the base of the unit. It was formed by mobilisation and segregation of Fe by a combination of tree roots and reduced groundwaters. At the sides of the channel, the kaolinite in the leached part is replaced by calcium carbonate. Above the megamottled zone, red clayey alluvium, of variable thickness (5–15 m), has the same matrix as the mottled clays but has not been mottled. Such red clays, presumably derived from an older soil, may have been a source for the hematite of the underlying megamottles. The clays may have been a uniform red brown and became white on reduction below the water-table and mottled in the vadose zone. The red clayey unit grades upward into a ferruginous gravelly colluvium that contains polymictic gravels composed of sub-rounded to rounded ferruginous clasts, vein and detrital quartz, lithic fragments and clays; 60% of the material is over 2 mm in size. The nodules have partly worn cutans. Importantly the unit contains many maghemite-rich nodules, which allow the channels to be mapped by aeromagnetic surveys.

The uppermost sandy–silty unit is 10–12 m thick. Sub-horizontal to horizontal laminations have developed within the top 5–6 m, commonly marked by thin coatings of precipitated Mn-oxides. These result from a surficial process referred to as 'hardpanisation', which includes partial cementation by amorphous silica, clay and Fe oxides. The shallow sandy clayey soil contains ferruginous granules and occasional quartz fragments.

At Sundowner (Figure 1), the transported overburden reaches a depth over 100 m (Figure 5). The materials above a depth of 50 m are similar to those at Bronzewing, 12 km to the south,

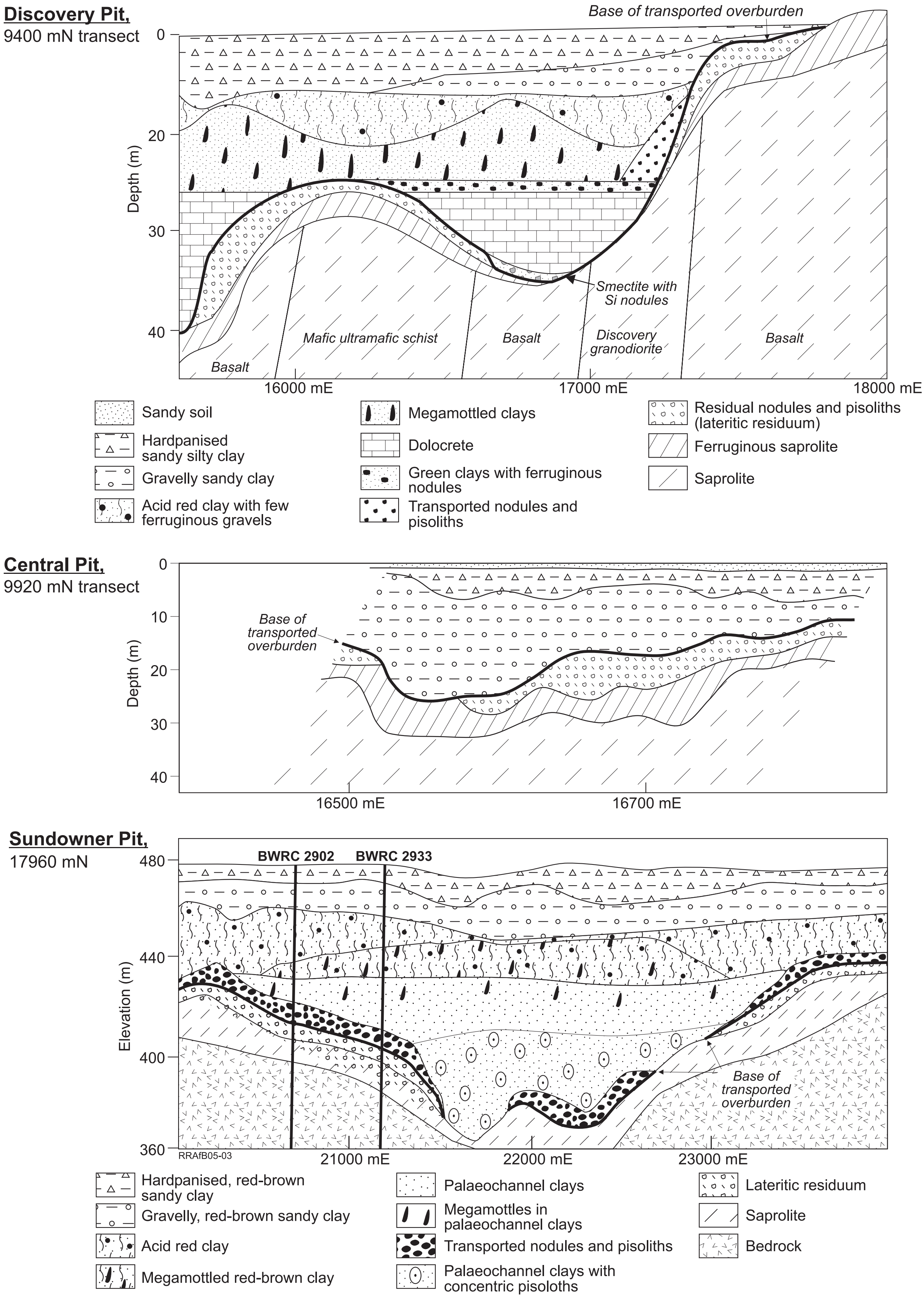

Figure 5. Regolith stratigraphy for the Discovery and Central Pits, and the Sundowner prospect.

except for the input of feldspar and coarse quartz from a granitic area to the northwest of the drainage. Below 50 m is puggy goethitic clay dominated by small spherical pisoliths 0.5–5 mm in diameter. Some have a single thin cutan (<1 mm), but most have multiple cutans. Pisoliths may have a variety of cores including hematite–maghemite fragments, ferruginous clay, organic debris, quartz or a mixture of these. Nuclei can be simple, e.g. representing a single particle or may be complex, consisting of composite particles. Nuclei may be either regular or irregular and are surrounded by concentric goethite or hematite-rich cutans, which are more and more circular in section. Only the first few cutans closely follow the small external irregularities of the nucleus; the cutans further from the nucleus become more and more regular and circular. Rarely, a band of quartz may be sandwiched between two concentrically banded zones. The number of laminae in the cutans of pisoliths varies greatly, depending on grain size, but generally there are 10 or more. In places, there are two sets of cutans; broken hematitic cutans are encased by *in situ* concentric goethitic cutans. There is a small proportion of rounded and water worn quartz sand grains (about 1 mm) in the clays. The boundary of transported overburden and residual materials below the puggy clay is marked by 8m of ferruginous gravels.

REGOLITH CHARACTERISATION

Soils developed in sediments consist mainly of aeolian sand and silt-sized quartz grains, kaolinite and hematite with minor amounts of feldspar, muscovite and calcite. Mottles developed in palaeochannel clays are dark brown to reddish maroon and consist of hematite, quartz and kaolinite with minor amounts of goethite. They are generally massive but some show hematite pseudomorphs after wood fragments.

The residual profiles on mafic and ultramafic rocks vary in thickness from 60–90 m and consist of lateritic nodules and pisoliths and/or nodular duricrust, collapsed mottled saprolite, mottled saprolite, ferruginous saprolite, saprolite and bedrock. The nodules are generally angular and platy fragments of mottled saprolite, composed mainly of hematite, goethite, kaolinite, gibbsite, quartz and anatase. Nodules may contain recognisable pseudomorphs after primary minerals (e.g., mica) or relict schist and have about 1 mm thick yellow cutans. Mottled saprolite consists of red, hematitic, tabular, ferruginous fragments (10–70 mm) aligned with the structure of the bedrock, generally also visible in the saprolite below. Common pseudomorphic replacement of structurally aligned primary minerals in the bedrock by hematite and goethite has resulted in preservation of primary fabrics within incipient *in situ* nodules and pisoliths of ferruginous saprolite. Towards the top, mottled saprolite has been subjected to solution weathering, resulting in a marked, mesoscopic porosity to form coarse, generally vermiform voids. Some voids are lined with goethite and secondary silica. Amalgamation of these coarse voids leads to the ultimate collapse of the mottled saprolite. The base of the collapsed mottled saprolite is very irregular and has pendants penetrating the mottled saprolite. The collapsed mottled saprolite, is a condensed, largely residual horizon, composed of fragments of mottled saprolite (as large nodules) and pisoliths. Further weathering, micro-fragmentation and minor lateral transport gives rise to the small nodules and pisoliths that lie above it. The angularity of the nodules tends to increase down the profile. Near the surface, nodules tend to be dark brown to black but are yellowish brown to brown in collapsed saprolite. These nodules and pisoliths have evolved by partial collapse, involving both vertical and some lateral movement, following chemical wasting.

Ferruginous saprolite is yellowish brown to reddish brown, composed largely of kaolinitic clay, variably impregnated by goethite. The saprolite is generally 50–70 m thick. Primary bedrock fabric and structure are generally well preserved and can be traced through saprock to fresh bedrock. Cream, light yellow or grey-brown clays are typical of the upper saprolite. They are composed of kaolinite, smectite and quartz; smectite increases in abundance with depth. Near the base, creamy buff, light green or khaki-cream coloured, slickensided clays and saprock fragments of weathered chloritic basalt pass into the fresh bedrock. The lower part of the saprolite consists of chlorite, feldspar, quartz, calcite, mica and pyrite.

DATING

Palaeomagnetic dating of the ferruginous saprolite from the Central pit at Bronzewing indicates Late Cretaceous and Miocene weathering (Table 16; Anand and Paine, 2002).

REGOLITH-LANDSCAPE EVOLUTION

Regolith records a complex history including multiple weathering, truncation and burial (Figure 6). The regolith in the Yandal belt can be explained by progression from a moist, humid to possibly temperate climate with high water tables to the presently arid and semi-arid conditions. The humid climate during the Cretaceous to mid Miocene gave rise to extensive, deep lateritic weathering. However, the origin of regolith in tropical climates is not universally accepted (e.g., Taylor et al., 1992). Deep weathering may occur in cooler climates, but over long periods. The drier climate since the late Miocene (Bowler, 1976), and some minor uplift, have lowered water-tables, slowed chemical weathering, and eroded the land surface.

Pre-Tertiary topography and weathering: Palaeomagnetic dating of the ferruginous saprolite from the Central pit at Bronzewing indicates Late Cretaceous and Miocene weathering. This is consistent with K–Ar and $^{40}Ar/^{39}Ar$ dating of Mn minerals of weathering profiles from elsewhere in Australia (Dammer *et al*., 1999) that suggest that weathering occurred during the late Cretaceous. It is thought that the Mesozoic landscape on greenstones comprised broad, shallow valleys that were surrounded by an elevated granitic and marginal greenstone hinterland. Broadly contemporaneous weathering of topographically higher

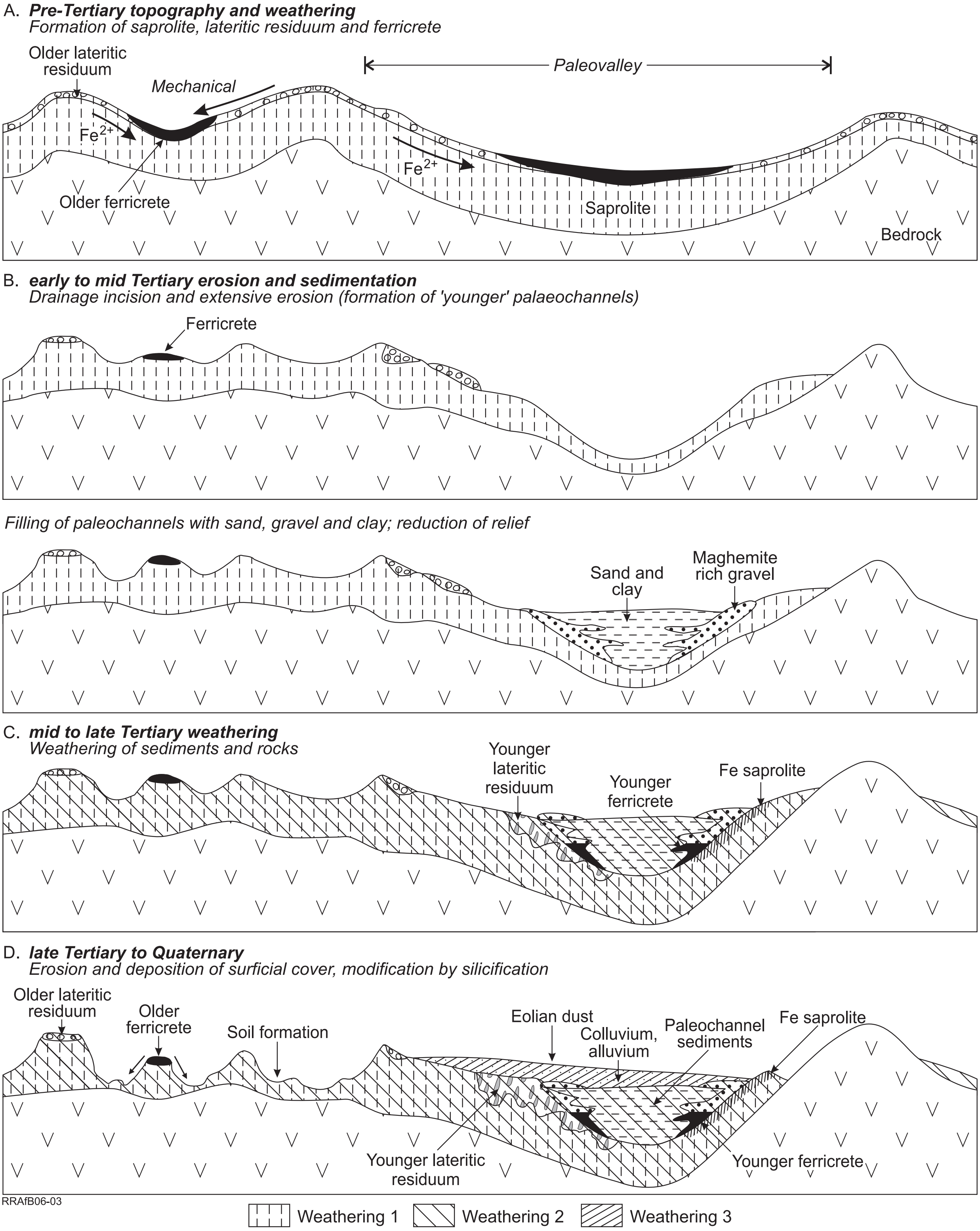

Figure 6. Interpreted history of regolith–landform evolution of the Bronzewing district. Rates of weathering and erosion were continuous, but their relative importance would have changed over time.

parts and palaeovalleys formed saprolite, lateritic residuum and ferricrete; the valleys were prone to ferruginisation. Ferricretes form dendritic palaeodrainage patterns often revealed by shallow, noisy signals in aeromagnetic data caused by maghemite. These elevated ferruginous regolith units are mostly relics of a former depositional surface. Lateritic residuum and ferricrete were subsequently eroded and deposited into 'younger' palaeochannels within the palaeovalleys as detrital ferruginous gravel, some of which subsequently became ferruginised to form ferricretes.

Early to mid Tertiary erosion and sedimentation*:* By the Eocene, drainage incision along palaeovalleys on the weathered land surface had resulted in development of 'younger' channels that are less than 3 km wide and many kilometers long. These palaeochannels are younger than the 'palaeodrainage' system of broad, shallow valleys in which they occur and were probably incised during the final stages of the breakup of Gondwana in the early-mid Tertiary. Formation of the paleochannels involved limited stripping of regolith beyond the palaeochannel margins, removing much of the lateritic residuum and ferricrete. Incision of the paleochannels was most likely caused by stream rejuvenation following epirogenic uplift (Cope, 1975). A change occurred in allogenic conditions which caused the stream beds to rapidly aggrade.

The characteristics of the sediments indicates a complex history of deposition and subsequent modification by weathering. The palaeochannels have been partly filled with sand, kaolinite-and smectite-rich sediments, possibly derived from erosion of existing regolith, implying deep weathering prior to the Eocene. The sand facies represents the fluvial basal units (Kern and Commander, 1993). Thereafter deposition of thick clay occurred in lacustrine and shallow swampy environments. The landscape following deposition of these sediments probably comprised slightly elevated (but dissected) areas of pre-Tertiary terrain, surrounded by lower sediment-covered terrain.

Mid to late Tertiary weathering*:* The palaeochannel sediments and bedrocks then further weathered. Hematitic mottles, Mn nodules and authigenic smectites developed in palaeochannel sediments, indicating post-depositional weathering and diagenesis, both at the surface and at oxidation fronts within the sediments. Younger hematite-goethite-rich lateritic residuum that commonly occurs beneath the paleochannel sediments is thought to have formed during this period.

Late Tertiary to Quaternary erosion and sedimentation: Weathering under semi-arid to arid conditions was dominated by evaporation and restricted groundwater migration, accumulating weathering products in the regolith that would otherwise be leached. Water tables declined in upland areas and groundwater became rich in Fe in valleys, invading and impregnating the upper parts of the weathering profile and sediments to form younger ferricrete and ferruginous saprolite. In places, this process armoured the upper regolith setting the scene for topographic inversion by further erosion. Groundwater levels continued to fall in the highlands, contributing to leached upper saprolite by draining through the uppermost part of the profile. Erosion dissected parts of the land surface, exposing saprolite and saprock around the now-armoured paleovalleys. The colluvium and alluvium has been derived by dismantling the older regolith and is rich in ferruginous nodules and pisoliths. The lower parts are largely alluvial and the upper parts colluvial, probably dominated by sheet wash. The upper 1–5 m of colluvial-alluvial sediments were silicified, to a red–brown hardpan.

REFERENCES

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

Anand, R.R., Wildman, J.E., Varga, Z.S. and Phang, C., 2000. Regolith evolution and geochemical dispersion in transported and residual regolith - Bronzewing gold deposit. In: G.N. Phillips and R.R. Anand (Editors). Yandal Greenstone Belt. Australian Institute of Geoscientists. Bulletin 32. pp. 333-349.

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

Cope, R.N., 1975. Tertiary epeirogeny in the southern part of Western Australia: Western Australian Geological Survey. Annual Report for 1974; 40-46.

Dammer, D., McDougall, I. and Chivas, A.R., 1999. Timing of weathering-induced alteration of manganese deposits in Western Australia - evidence from K/Ar and $^{40}Ar/^{39}Ar$ dating. Economic Geology, 94: 87-108.

Kern, A.M. and Commander, P., 1993. Cainzoic stratigraphy in the Roe Palaeodrainage of the Kalgoorlie region, Western Australia. Geological Survey of Western Australia Professional Papers, 34: 85-95.

Mabbutt, J.A., 1963. Wanderrie banks: microrelief patterns in semi-arid Western Australia. Bulletin of the Geological Society of America, 74: 529-540.

Phillips, G.N., Vearncombe, J.R. and Murphy, R., 1998, Jundee gold deposit. In: D.A. Berkman and D.H. Mackenzie (Editors). Geology of Australian and Papua New Guinean Mineral Deposits. The Australasian Institute of Mining and Metallurgy, Victoria. Monograph 22. pp. 97-104.

Taylor, G., Eggleton, R.A., Holzhaur, C.C., Maconachie, L.A., Gordon, M., Brown, M.C. and McQueen, K., 1992. Cool climate lateritic and bauxite weathering. Journal of Geology, 100: 669-677.

Varga, Z.S., Anand, R.R. and Wildman, J.E., 1997. Regolith-landform evolution and geochemical dispersion at the Bronzewing deposit. CSIRO Division of Exploration and Mining. Restricted Report 308R. 85pp. (Reissued as Open File Report 108, CRC LEME, Perth, 2001).

Wildman, J.E. and Compston, D., 2000, Magnetic expression of palaeodrainage systems in the Yandal greenstone belt: implications for exploration. In: G.N. Phillips and R.R. Anand (Editors). Yandal Greenstone Belt. Australian Institute of Geoscientists. Bulletin 32. pp. 333-349.