HARMONY-PEAK HILL GOLD DEPOSIT, WESTERN AUSTRALIA

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INTRODUCTION

The Harmony gold deposit lies approximately 9 km west of Peak Hill and some 90 km north-northeast of Meekatharra (Figures 1 and 2) at 25°39'10"S, 118°37'50"E in the Baxter Mining Centre (PEAK HILL 1:250 000 Map Sheet; SG50-08). Although hosted by Palaeoproterozoic rocks, the Harmony gold deposit is very similar in regolith-landforms and exploration problems to extensive colluvial-alluvial plains of the northeast Yilgarn Craton.

The following is drawn from a combined report on the regolith geology and geochemistry around the Harmony Au deposit (Robertson *et al*., 1996), summaries of which were subsequently published (regolith geology by Robertson *et al*., 1999, and geochemistry by Robertson, 2001). The objective was to investigate the nature and stratigraphy of the regolith and to evaluate the residual and cover materials as geochemical sample media. This was made possible by some very detailed exploration drilling by Afmeco Mining and Exploration Pty Ltd.

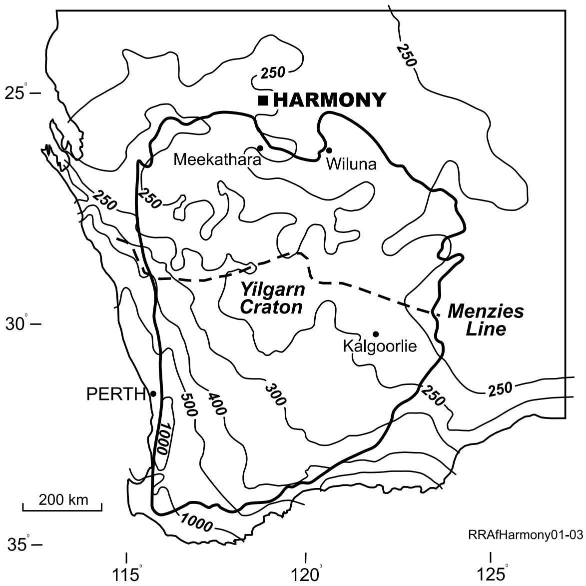

Figure 1. Location map of the Harmony Au deposit in relation to the southwest of Western Australia, the Yilgarn Craton, the Menzies Line and the average annual rainfall as contours.

PHYSICAL SETTING

Geology

The Peak Hill district is located in the western part of the Palaeoproterozoic Bryah Basin (Pirajno and Occhipinti, 1995). The area comprises mafic and ultramafic volcanic rocks (Narracoota Formation), turbiditic metasedimentary rocks, banded iron-formation (BIF) and associated clastic sediments (Horseshoe and Ravelstone formations), all of which are intensely deformed and metamorphosed to the low to mid-greenschist facies. The Harmony Au deposit lies at the contact between Narracoota Formation metavolcanics (mafic-ultramafic) and the Ravelstone Formation metasediments (turbidites). To the northwest of the deposit, calcareous, manganiferous shales and subgreywackes of the Horseshoe Formation outcrop. BIFs of the Padbury Group form prominent ridges southwest of the area.

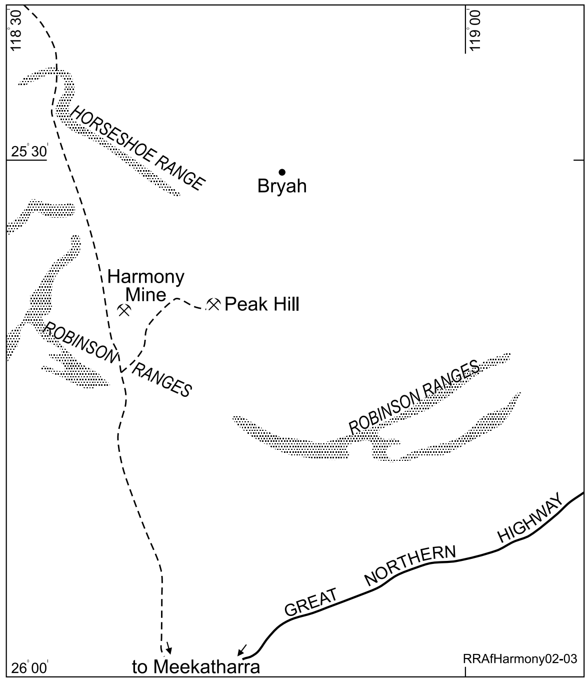

Figure 2. Location map of Harmony in the Peak Hill Mining District, showing the surrounding ranges and main roads.

Geomorphology

The Harmony deposit is located within a broad colluvial-alluvial depositional plain (Figure 3), bounded to the west by the westerly extent of the Robinson Ranges, to the north by the southerly extension of the Horseshoe Range and to the east and south by rises and low hills.

Climate and vegetation

The region is arid and characterised by irregular rainfall averaging 200 mm/yr (Figure 1) and lies north of the Menzies Line (Butt *et al*., 1977). Vegetation is sparse and consists of mulga and drought-resistant shrubs and grasses.

REGIONAL REGOLITH-LANDFORM RELATIONSHIPS

Erosional regimes

The dominant erosional regimes include residual soils developed on saprolite, ferruginous saprolite and saprock. Prominent outcrop and extensive subcrop commonly occur in the Robinson and Horseshoe ranges, to the southwest and northeast of the Harmony deposit. These generally have very coarse lag, including boulders and cobbles of partly weathered bedrock with small areas of ferruginous lateritic duricrust (relict regime).

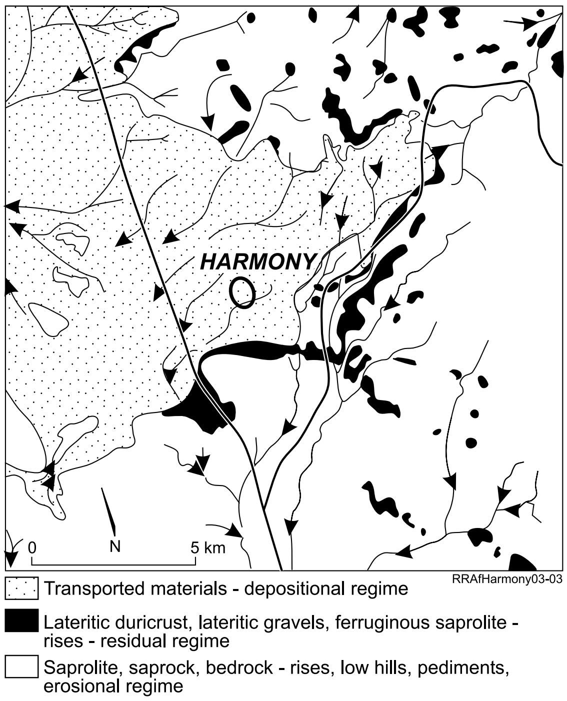

Figure 3. District regolith geology of the area around the Harmony Au deposit showing the distributions of the residual terrain (relict and erosional landforms) and the depositional plain covering the Harmony mineralisation.

South of the Harmony deposit, colluvium mantles a long, gentle, concave slope which rises to the south to a gently beveled, south-facing crest or breakaway of pisolitic duricrust. The bedrock comprises metasediments of the Ravelstone Formation and the pisolitic duricrust developed on them is clay rich and consists mainly of quartz, kaolinite, goethite and barite. Towards the base of the breakaway, pothole structures of varying sizes, occur in the weathered metasediments. They contain nodules and pisoliths that may be relics of a previously overlying duricrust or colluvium.

To the south of the breakaway, there is an erosional plain where the regolith is ferruginous saprolite, mantled by a coarse, blocky, quartz-rich, polymictic lag, including ferruginous lithic fragments. Over the Peak Hill Schist, there are patchy outcrops of quartz veins, ferruginous saprolite and saprolite which shed a lag of subangular blocks and cobbles onto a gently sloping erosional plain.

Relict regimes

Low rises occur to the east and southeast of the Harmony deposit. Here, the regolith has developed over mafic and ultramafic metavolcanics of the Narracoota Formation and consists of Fe-rich, lateritic duricrust, lateritic gravel and ferruginous saprolite. Iron-rich duricrusts developed over Narracoota Formation mafic volcanics are black, massive and silicified, with abundant hematite and goethite.

Sediments of the Ravelstone and Horseshoe formations and the Padbury Group have weathered to a range of duricrusts, some Fe-rich and manganiferous. Their composition reflects the original composition of the underlying sediments. To the northeast of Harmony, in the low hills on the Horseshoe Formation, thick, massive to vermiform, manganiferous, lateritic duricrusts have developed. These were mined for manganese (Subramanya *et al*., 1995). In some of the old mine pits, manganiferous duricrusts lie directly over Fe-rich, massive to vermiform duricrusts and ferruginous saprolite. The duricrusts are patchy and of limited extent.

Depositional regimes

The Harmony deposit is located beneath a broad colluvial-alluvial depositional plain of coalescing sheet-wash fans. Drainage channels over these are shallow, ill defined and seldom active. Sandy banks aligned along the contours, perpendicular to the sheet flow direction (Wanderrie banks of Mabbutt, 1963), are common. The sands and clays are mantled by a fine- to medium-grained polymictic lag or by a medium to coarse lag of ferruginous and manganiferous lithic fragments, brown to black nodules, pisoliths and abundant quartz. This is set on a thin red-brown sandy-clay loam.

The sheet-wash deposits are underlain by hardpanised coarse colluvium-alluvium on weathered Palaeoproterozoic basement. The colluvium-alluvium consists of poorly sorted ferruginous granules and lithic clasts, in a silty-clay matrix. The low hills of the Horseshoe and Narracoota formations are sources of much of this detritus.

Colluvial fans and footslopes occur in the low hills of the Robinson and Horseshoe ranges. These consist of coarse to blocky clasts (>200 mm), a lag of ferruginous, lithic fragments and quartz. Similar materials occur in drainage depressions underlain by the Narracoota Formation and Peak Hill Schist. Over metavolcanic rocks of the Narracoota Formation, there is a medium to coarse polymictic lag of lateritic nodules, pisoliths, hardened mottles and ferruginous saprolite, with lesser quartz and ferruginous, lithic fragments set in a red, silty-clay soil. Quartz and ferruginous lithic clasts are dominant in colluvium derived from the Peak Hill Schist.

The sheetwash deposits around Harmony consist of granules and gravels of ferruginous, polymictic clasts in a fine sandy clay loam. To the southwest of Harmony, these sheetwash deposits give way to hardpanised colluvium that is being eroded by the present drainage system. Probable fossil termite mounds and burrow structures penetrate the upper metre of colluvium. Bioturbation in the upper part of the colluvium is important as it carried some of the geochemical signal from the basement to the surface at Harmony where the colluvium is extremely thin (<1 m).

The regolith in 3D

Because of the complexity of the sub-surface regolith, and the very extensive drilling around the Harmony deposit, a 3D regolith stratigraphic model was developed for the site. A total of 708 drillholes were logged, over an area of 2.6 km^2, noting the major regolith units (colluvium, valley-fill sediment, lateritic duricrust), various unconformities and the nature of the residual profile.

Contours of the buried unconformities and isopach maps of the

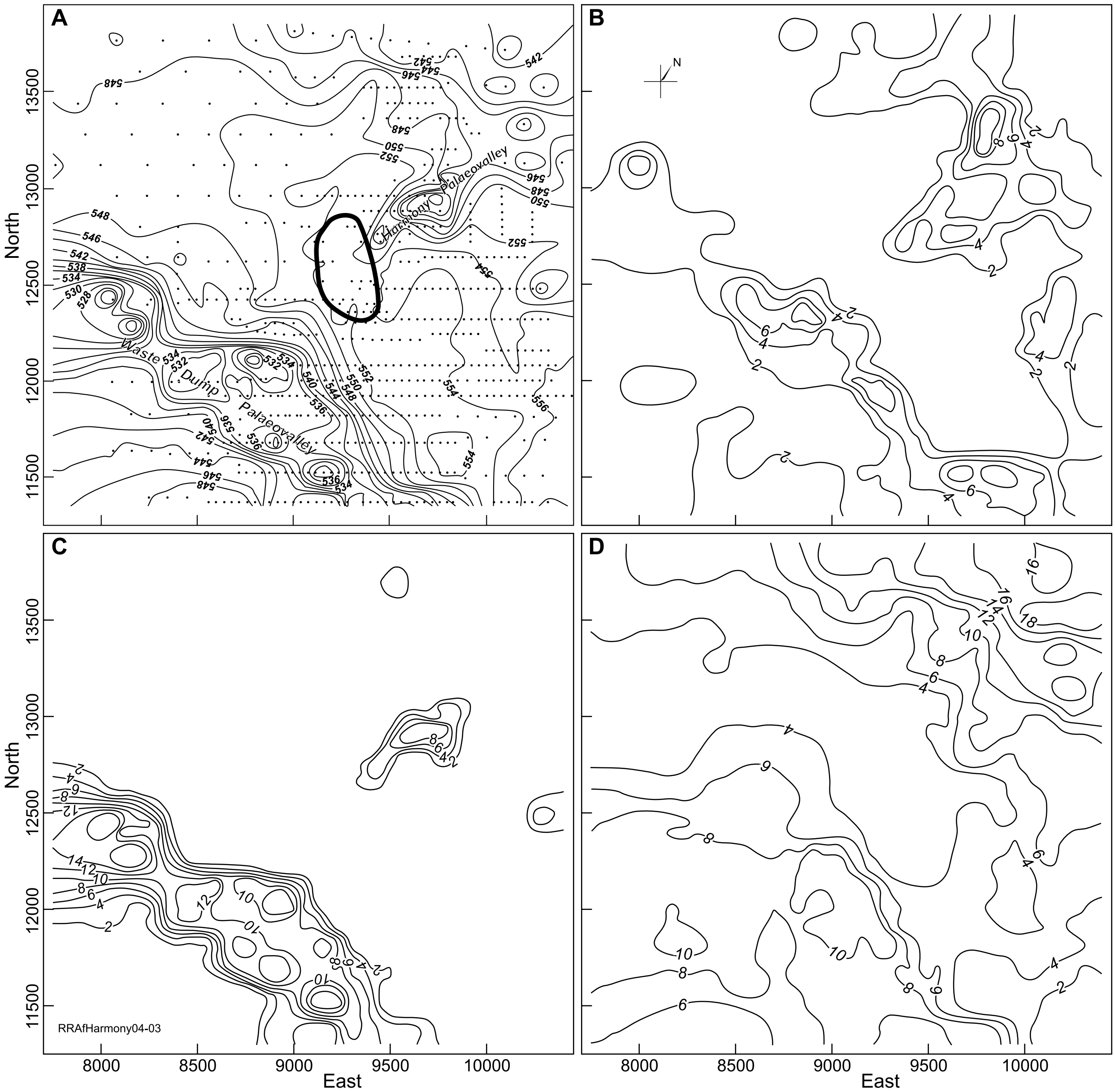

Figure 4. **A**. The palaeotopography prior to deposition of the colluvium. **B**. The distributions and thicknesses of lateritic duricrust. **C**. The distributions and thicknesses of valley-fill sediments. **D**. The distributions and thicknesses of colluvium. The bedrock geology, pit outline and data points have been added.

thicknesses of the regolith units provided a model of the spatial disposition of regolith materials and the palaeotopography (Figure 4). These 3D relationships provide an improved understanding of landscape development and may be used to interpret geochemical data by predicting mechanical dispersion.

The palaeosurface (Figure 4A) of the residual profile shows that Harmony is on a west-northwest-trending palaeohigh. Surface silicified ultramafic rocks occupy the highest part. The basement palaeosurface had a relief of about 40 m within the study area.

There are two palaeovalleys. A major, deep palaeovalley (Waste Dump palaeovalley) parallels the palaeohigh and lies to the south of Harmony. Another, apparently shallower and sub-parallel palaeovalley, lies north. A small branch of this, the Harmony palaeovalley, drains the Harmony deposit to the north-northeast, locally incising the palaeohigh. The alignment of the palaeovalleys is probably related to underlying structure and lithology.

REGOLITH CHARACTERISICS

In the immediate vicinity of Harmony, the regolith consists of a surface-hardpanised, red-brown colluvium of variable thickness, overlain by a polymictic lag that has been sorted into different size fractions by sheetwash. Beneath this, the degree of complexity varies considerably (Figure 5), as revealed by detailed drilling. In places, particularly close to the Harmony deposit, the colluvium directly overlies ferruginous saprolite, saprolite and saprock, developed on Palaeoproterozoic rocks. Elsewhere, notably to the north and south, the colluvium is underlain by various mottled clay sediments that infill palaeovalleys cut into the Palaeoproterozoic basement. Parts of the basement saprolites are mantled by buried

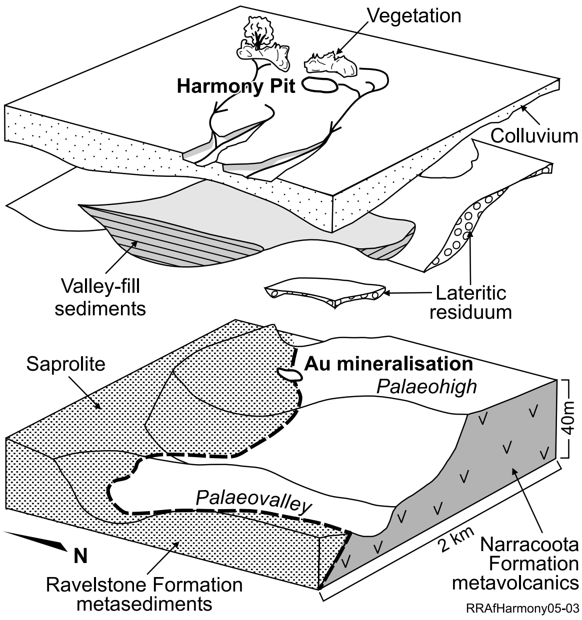

Figure 5. Block model of regolith relationships around the Harmony Au deposit. Proterozoic metavolcanics and metasediments, with Au mineralisation located at their contact, have been eroded and lateritised. Palaeovalleys have been partly filled with clay-rich valley-fill sediments, which have also been lateritised. Finally, the palaeotopography has been filled in and blanketed by colluvium-alluvium to leave a very flat plain, completely concealing the Au mineralisation and the complex regolith.

ferruginous lateritic residuum, with nodules and pisoliths coated with pale brown, clay-rich cutans. Horizons containing lateritic nodules and some pisoliths, with cutans, also occur at the top of the valley-fill sediments.

Weathered profiles on the basement

The palaeohigh consists largely of weakly indurated, grey and light yellow-brown ferruginous saprolite (buried erosional regime). The floors of the palaeovalleys are particularly deeply weathered and have been eroded into mottled zones and clay-rich, coarsely cleaved saprolites of muscovite, quartz and kaolinite with a few disaggregated quartz veins.

Lateritic duricrust and lateritic gravel (buried relict regime) are preserved on the flanks of the palaeohigh (Figure 4B), but not in the axes of the palaeovalleys or on the palaeohigh itself. The buried lateritic residuum is generally about 8 m thick but locally reaches 19 m, where it is likely to have an upper, slumped or transported component. The nodules are generally dark red in drillspoil with distinctive, yellow-brown cutans.

Valley-fill sediment

Thin, rarely developed, unbedded basal sands are well sorted and closely packed, consisting of a small size range (0.1-3.0 mm) of quartz, minor quartzite grains and a trace of rounded tourmaline. The larger quartz grains are well rounded; the smaller grains are angular to shard-like. The intergranular space is filled with very fine-grained kaolinite.

The palaeovalleys have been largely filled with clay-rich sediments, generally about 10 m thick but reaching 24 m locally (Figure 4C). Mostly, these consist of soft, puggy, grey, green or light-brown clays that tend to crack on drying and have small grains of quartz and a trace of tourmaline. Their lower parts are mottled with dolomite and their upper parts with hematite and goethite.

The uppermost parts of the valley-fill clays are very strongly mottled with nodular to pisolitic hematitic goethite, within a matrix of greenish-white clay ooliths. At the top, the pisoliths have thin, partly abraded cutans of light brown clay, indicating minor transport or reworking. These valley-fill sediments are extensive in the Waste Dump palaeovalley but are developed only in patches (Figure 4C) in the northern palaeovalley. They were probably partly removed by erosion.

Colluvium

After deposition of the valley-fill clays and subsequent erosion, there has been extensive deposition of a dark brown, gravelly to silty colluvium that has infilled the remaining palaeolows and thinly buried the paleahigh. The thickest colluvium (Figure 4D) has been deposited over the palaeovalleys, where it generally reaches a thickness of 7-12 m and, locally, 20 m but it is only 0.5-3.0 m thick over the palaeohigh.

The upper eight metres of brown colluvium consist of an upper, gritty-sandy part and a lower silty-sandy part. The gritty-sandy colluvium contains matrix-supported, polymictic, subangular to subrounded goethitic and ferruginous clay fragments (1-3 mm) with some quartz in a porous, brown clay matrix. The ferruginous clasts include remnant mica, Fe oxide pseudomorphs after fibrous silicates and some pseudomorphs after secondary coarse, accordion clay fabrics. The matrix is a pale pink to yellow-brown, clay-rich silt, consisting of quartz, kaolinite and Fe oxides. Some pores are lined with brown, goethitic clay. The clasts and matrix of the silty sandy colluvium are similar to those above but the proportion of coarse, clastic material is less. The clasts are set in a dull brown matrix of kaolinite, quartz, Fe oxides and anatase. The upper part of the colluvium has been silicified to a red-brown hardpan.

Initially, the regolith stratigraphy was known only from RAB drill cuttings but it was later investigated by diamond drilling, some of which was cored from surface. Several sections through the thin colluvial cover and ferruginous saprolite on the palaeohigh, proximal to Harmony, showed some complex relationships between the colluvium and the basement. Here they are separated by a mixed zone 0.2-0.7 m thick of blocks of saprolite in a matrix of earthy colluvium, which could represent a palaeosol.

In drillspoil, the colluvium is rich in brown, polymictic granules with abraded cutans and fragments of ferruginous lithorelics (lacking cutans) in a brown, silty, clay-rich pulp. Drill intervals through the unconformity at the base of the colluvium contains a mixture of colluvium and the underlying regolith (lateritic duricrust or ferruginous saprolite). Here, some granules have thin, partly worn cutans.

Soil and present surface

Soil developed on the colluvium is closely related to its colluvial-alluvial substrate, being rich in coarse, ferruginous lithic fragments and granules. Its composition reflects that of the remote source of the colluvium. In contrast, the fine, silty portion (75-250 µm) is largely quartz-rich, with some small ferruginous granules; it is probably aeolian in part. Aeolian input may have occurred during colluvial action, during soil formation or both. The clay-rich fraction consists of quartz, mica, kaolinite and Fe oxides.

The present surface, with a total relief of 10 m across the study area (2.8 km across), is gently inclined to the west-southwest and is incised by west-southwest flowing drainages. This surface is mantled by a patchily developed, polymictic lag of ferruginous lithorelics, BIF fragments, ferruginous lateritic residuum and quartz that has been partly sorted by sheetwash and aeolian action.

PALAEONOLOGY AND AGE

Yellow-brown granules of goethite-replaced fossil wood occur among pink, clay-bearing ferruginous mottles at 27.05 m within the valley-fill clays of diamond drillhole PHD-006. Some contain attached, exogenous, goethitic, quartz-rich sediment. The cell patterns and their scale are typical of woody tissue. Cross sections show larger, sap-carrying, tracheid vessels surrounded by smaller parenchyma or packing cells and some evidence for ray cells. This material probably formed stem or root material and tracheid vessels imply a primitive vegetation (cycad, fern or conifer) (J.K. Marshall, pers. comm; 1996).

This woody tissue could have been incorporated into the sediments as (i) already fossilised detritus (ii) woody detritus that was fossilised in place or (iii) plant material that was growing in the clays at some time after their deposition and was fossilised later. The first hypothesis seems the more likely in view of (i) the attached exogenous sedimentary material, (ii) the marked contrast between the goethite replaced fossils and the hematite-clay mottles that surround them, (iii) the sharp contact between the two materials and (iv) the fragmentary nature of the fossil material.

An unsuccessful attempt was made to palaeomagnetically date some of the ferruginous, mottled material from 27 m +0.5 m (B. Pillans pers. comm; 1996). Only one specimen had stable, positive (reversed) magnetic declination, suggesting an age of >0.78 Ma. The others did not have stable magnetisations.

REGOLITH EVOLUTION

The present, relatively flat surface around Harmony indicates little of the complex regolith beneath. However, the polymictic lag implies a depositional area where further investigation would have to be by drilling and costeaning.

Residual regolith

The Palaeoproterozoic basement of metavolcanics and metasediments was subjected to the same deep lateritic weathering as the Yilgarn Craton to the south. Fluvial systems then incised this to leave deep palaeovalleys to the north and south of a palaeoridge of resistant, silicified metavolcanics. Incision probably occurred while weathering continued, leaving a regolith of ferruginous saprolite on the high ground and mottled materials beneath the palaeovalleys. Lateritic duricrusts are patchily preserved on the palaeovalley flanks.

Transported overburden

Valley fill sediments

The valley-fill sediments appear to have been deposited in a low-energy environment. A few, very restricted, probably fluvial sand layers were found in some palaeovalley axes (Figure 6). The remainder are clays (kaolinite and smectite) with small quantities of minute (0.5 mm) quartz grains distributed throughout without any apparent bedding or sorting. Either bedding and sorting was destroyed by bioturbation, subsequent to sedimentation, or a process occurred that could deposit both clay and sand simultaneously such as a debris flow, as suggested by Robertson (1990) for Campaspe Formation clays in eastern Queensland.

The angular to shardy quartz grains in the clays are remarkably similar to the quartz of the basement saprolite. The basement saprolites consist of kaolinite, muscovite and quartz and the valley-fill sediments consist of kaolinite, smectite and quartz. It is likely that the palaeovalleys were filled with locally derived, finely comminuted saprolite detritus under conditions of sluggish stream flow or possibly episodic debris flow conditions. Weathering of this sediment continued, possibly with some bioturbation. The basal sand could have been concentrated from the saprolite by fluvial action and the valley-fill clays were formed from locally derived saprolite detritus without concentration. Muscovite, in the original sediment, could have reacted with dissolved bases and silica, under conditions of restricted drainage, to produce smectite. However, it is probable that most smectite was formed from

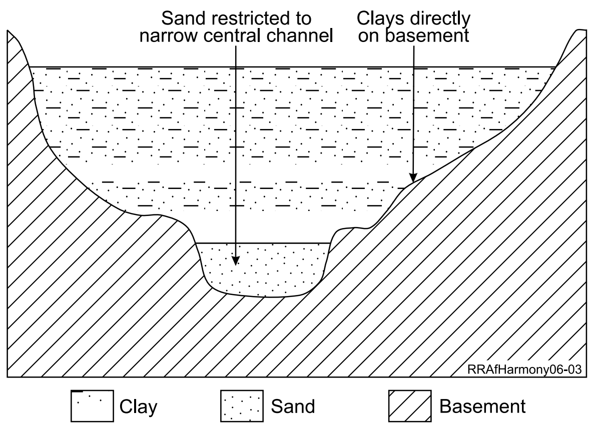

Figure 6. Relationships between sand and valley-fill clay to the basement. Generally, smectitic clays lie directly on the basement, the sands occupy a narrow, central channel.

kaolinite. This implies variations in pH, from acidic to alkaline, depending on the availability and the quantities of weathering muscovite. Temporary alkaline conditions and excess dissolved Ca, Mg and HCO_3^- in the groundwater would favour deposition of dolomite with the clays and this has occurred.

The valley-fill sediments have had a complex weathering history and show signs of oxidation fronts, including the development of manganiferous layers, mottling with goethite and hematite and even lateritic duricrust in their upper parts, all of which could be confused easily with similar phenomena in the residual regolith.

In the north, the upper layers of the valley-fill sediments were eroded, whereas they are largely complete in the south. In the south, the lateritic materials, formed in the top of the valley-fill sediments, are complex, with a mixture of *in situ* clay-rich pisoliths and some apparently exogenous nodular material. The latter may have been released by dissolution of the matrix of an existing *in situ* lateritic duricrust, followed by collapse and minor transport. This would carry with it any associated Au. The matrix of the ferruginous parts of the upper valley-fill sediments contains both physical and geochemical evidence of illuviation of fine-grained materials from the colluvial-alluvial cover.

Colluvium-alluvium

Thin colluvium covers the Harmony Deposit but the thicker sediments over the palaeovalleys were probably alluvial. Structures in the colluvium, seen in pit faces and in diamond core, indicate shallow but broad lenses of gravelly material, typical of sheet flow.

The base of the colluvium (Figure 7) varies from a simple, sharp, erosive unconformity to a complex mixture of saprolite and colluvium, nearly a metre thick, probably comprising saprolite blocks included in a palaeosol, which was later buried by the colluvium. This important interface provides a particularly useful geochemical medium in which greater dispersion occurs than in the underlying saprolite of eroded and buried areas (Robertson et al., 1996; Robertson, 2001).

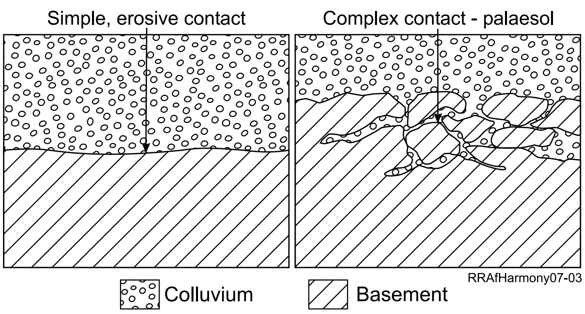

Figure 7. Simple, erosive and complex contacts between basement and colluvium. In the latter, the base of the colluvium is probably a palaeosol.

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