THE REGOLITH GEOLOGY AROUND THE HARMONY GOLD DEPOSIT, PEAK HILL, WA

I.D.M. ROBERTSON[1], C. PHANG[1] AND T.J. MUNDAY[2]

[1]*Cooperative Research Centre for Landscape Evolution and Mineral Exploration, CSIRO Exploration and Mining, PMB Wembley, 6014, Western Australia.*
[2]*Cooperative Research Centre for Australian Mineral Exploration Technologies, CSIRO Exploration and Mining, PMB Wembley, 6014, Western Australia.*

ABSTRACT

The Harmony Gold Deposit lies beneath an extensive plain covered by polymictic lag and red soil. Drilling beneath this revealed a complex regolith comprising weathered Palaeoproterozoic basement, clay-rich valley-fill alluvial sediments and a veneer of colluvium-alluvium. A 3D regolith model was produced by logging the main regolith units. This provided a valuable guide to geochemical sampling and later interpretation. The basement consists of mafic and ultramafic metavolcanics and fine-grained metasediments that have been eroded and weathered. The higher parts and ridges of this buried basement are ferruginous saprolite; the axes of palaeovalleys eroded into it are largely saprolite and mottled zone and are very deeply weathered. Lateritic residuum occupies the flanks of the palaeovalleys.

The palaeovalleys have been partly infilled with smectite- and kaolinite-rich sediments, probably derived from the surrounding saprolites. Hematitic, manganiferous and dolomitic mega-mottles have developed in these sediments and the tops of some valley-fill sediments contain ferruginous nodules and pisoliths. All this indicates intense post-depositional weathering, both at the surface and at oxidation fronts within the sedimentary pile. Parts of the valley-fill sediments were eroded prior to deposition of colluvium.

The colluvium varies from 0.5 m thick over parts of the Harmony deposit to 20 m over the palaeovalleys. Some alluvium occurs where the cover is deepest. This cover presents a significant hindrance to exploration. The base of the colluvium is complex in places, being a mixture of saprolite blocks included in a palaeosol.

Key words: Regolith, chemical weathering, landform evolution, palaeosols, colluvium, alluvium, saprolite, three-dimensional models, smectite, Harmony Gold Deposit, Glengarry Basin, Peak Hill, Western Australia,

INTRODUCTION

The Harmony deposit (previously known as the Contact deposit) is located 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. The deposit is hosted by Palaeoproterozoic rocks of the Bryah Basin. The deposit was discovered in 1991 by RAB drilling the contact between the Ravelstone and Narracoota Formations, and by sampling buried ferruginous lateritic residuum. Mining of a reserve of 2.15 Mt at 3.6 g/t Au commenced on 3rd July 1995.

The Harmony deposit is concealed by a thin cover of colluvium over a basement of deeply weathered Palaeoproterozoic rocks. These are now represented partly by lateritic duricrust and by an eroded regolith of mottled zone, saprolite and ferruginous saprolite occurring as a number of buried low ridges and valleys. The valleys were subsequently partly filled with clay-rich sediments.

The objective of the study was to investigate the nature and stratigraphy of the regolith and to evaluate the residual and cover materials as geochemical sample media. The results of the geochemical part of the investigation will be published separately. Extensive RAB and RC drilling around the deposit allowed a 3D inventory of regolith materials and a study of dispersion processes (Robertson et al. 1996) from which the content of this paper is drawn and where study methods may be found. Regolith terminology is drawn largely from the glossary of Butt and Zeegers (1992).

CLIMATE, REGIONAL SETTING AND LOCAL GEOLOGY

The region is arid and is characterised by irregular rainfall averaging 200 mm per annum (Figure 1) and lies north of the Menzies Line (Butt et al., 1977). Vegetation cover is thin and consists largely of mulga and other drought-resistant shrubs and some grasses. The 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.

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

The Peak Hill district is located in the western part of the Palaeoproterozoic Bryah Basin (Pirajno & Occhipinti 1995). The area comprises mafic and ultramafic volcanic rocks (Narracoota Formation), turbiditic sedimentary 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. Gold deposits here are epigenetic, mesothermal, lode types, hosted within high-strain zones in metasedimentary and/or metavolcanic rocks or along their contacts (Pirajno *et al.* 1995). Details of the Harmony mineralisation are given by Harper *et al.* (1998). The Harmony 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. BIF's of the Padbury Group form prominent ridges southwest of the area.

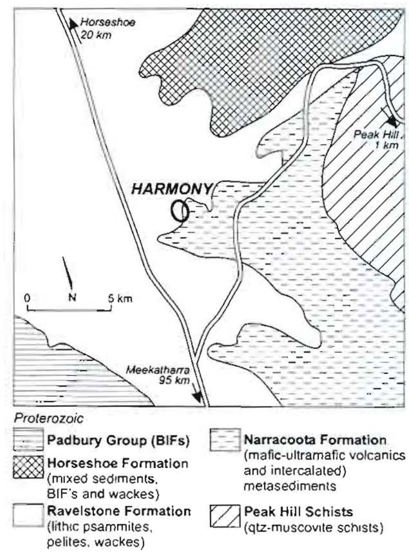

Figure 2: *District bedrock geology of the area around the Harmony Au deposit adapted from Robinson (1992) and Pirajno and Occhipinti (1995). The Harmony deposit lies on the contact between the metavolcanics of the Narracoota Formation and metasediments of the Ravelstone Formation.*

DISTRICT REGOLITH GEOLOGY

A regional regolith map (1:250 000) was prepared by the Geological Survey of Western Australia (Subramanya *et al.* 1995). This broad scale provided insufficient detail for exploration. The regolith distribution and landforms were remapped at 1:25 000 around the Harmony Deposit by interpretation of colour air photographs (1:25 000) and Landsat TM imagery and checked by field traverses. A simplified map is given in Figure 3; the complete version was part of a detailed study (Robertson *et al.* 1996). Two major geomorphic provinces were identified. These are i) an area of transported regolith, which includes the depositional plain on which the Harmony deposit is located, and ii) an area of subcropping and outcropping *in situ* regolith.

TRANSPORTED REGOLITH

The Harmony deposit is located beneath a broad colluvial-alluvial depositional plain of coalescing sheet-wash fans which have been aggraded by infrequent sheet flow and channeled stream flow, with subordinate wind erosion, comprising about 30% of the mapped area. Sheet wash has been dispersed along the surfaces of gently inclined fans that make up the depositional plain. Drainage channels over these are shallow, ill defined and seldom active. Wanderrie[1] banks are common. Here, sands and clays are mantled by a fine- to medium-grained polymictic lag. Other parts are characterised by a medium to coarse lag of ferruginous and manganiferous lithic fragments, lithic clasts, brown to black nodules, pisoliths and some ferruginous saprolite fragments and abundant quartz. This is set on a red-brown sandy-clay loam.

[1] Sandy banks aligned along the contours, perpendicular to the sheet flow direction (Mabbutt 1963).

The sheet-wash deposits are underlain by extensive tracts of coarse colluvium-alluvium which were deposited on weathered Palaeoproterozoic basement and subsequently hardpanised[2] (Figure 4A). The colluvium-alluvium consists of poorly sorted ferruginous granules and lithic clasts, in a silty-clay matrix. The ferruginous fragments include nodules, pisoliths and lithic clasts. Several facies in the colluvium-alluvium indicate varying conditions of deposition. The low hills of the Horseshoe Formation and, to a lesser extent, of the Narracoota Formation are sources of much of this detritus.

The sheetwash deposits in the vicinity of the Harmony Mine (Figure 4B) consist of medium to coarse, ferruginous, polymictic clasts set in a fine sandy-clay loam (Figure 4A) forming an extensive plain (Figure 4B). To the southwest of the Harmony Mine, these sheetwash deposits give way to hardpanised colluvium that is being eroded by the present drainage system. Probable fossil termite mounds and burrow structures are found here which penetrate the upper metre of colluvium. Bioturbation in the upper part of the colluvium is important. It has served to carry some of the geochemical signal from the basement to the surface at Harmony, but only where the colluvium is extremely thin (<1 m).

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

In situ regolith

A significant proportion of the area is characterised by *in situ* regolith. The dominant units include residual soils developed over saprolite, ferruginous saprolite and saprock. Prominent outcrop and extensive subcrop commonly occur in the Robinson and Harmony ranges, to the southwest and northeast of the Harmony deposit. These are generally characterised by very coarse lag, including boulders and cobbles of partly weathered bedrock. Small areas of ferruginous lateritic duricrust also occur.

Immediately south of the Harmony deposit, colluvium mantles a long, gentle, concave slope which rises to a gently bevelled, south-facing crest or breakaway where a pisolitic duricrust is developed. The bedrock comprises metasediments of the Ravelstone Formation and the duricrust developed on them is clay rich and consists mainly of quartz, kaolinite, goethite and barite. The pisoliths consist of a conglomerate of tiny, subangular, hematitic granules and kaolinite balls, indicating a complex processes of formation. Late barite occurs in very fine solution channels in the pisoliths.

Towards the base of the breakaway, structures, circular in plan, of varying sizes, occur in the weathered metasediments. They contain nodules and pisoliths that may have originated from a previously overlying duricrust or colluvium. They seem to be linked to biological activity. An erosional plain has developed to the south of the breakaway where the regolith comprises a ferruginous saprolite, mantled by a coarse, blocky, quartz-rich, polymictic lag, including ferruginous lithic fragments. Over the Peak Hill Schist, there are sporadic outcrops of quartz veins, ferruginous saprolite and saprolite which shed a lag of subangular blocks and cobbles onto a gently sloping erosional plain.

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 gravels and ferruginous saprolites. Fe-rich duricrusts (developed over mafic volcanics of the Narracoota Formation) tend to be 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 in addition to those described above. Their composition commonly reflects the original composition of the underlying sediments. Iron-rich and manganiferous duricrusts occur; examples are illustrated in detail by Robertson *et al.*, (1996).

To the northeast of the Harmony deposit, in low hills developed on mixed sediments of the Horseshoe Formation, thick, massive to vermiform, manganiferous, lateritic duricrusts have developed in places. These were mined for manganese in 1948-1969 (Subramanya *et al.* 1995). Several origins have been proposed for

[2] Hardpanisation: Induration by silica (hyalite) of a variety of transported or residual host materials (hardpan defined in a glossary by Butt and Zeegers, 1992).

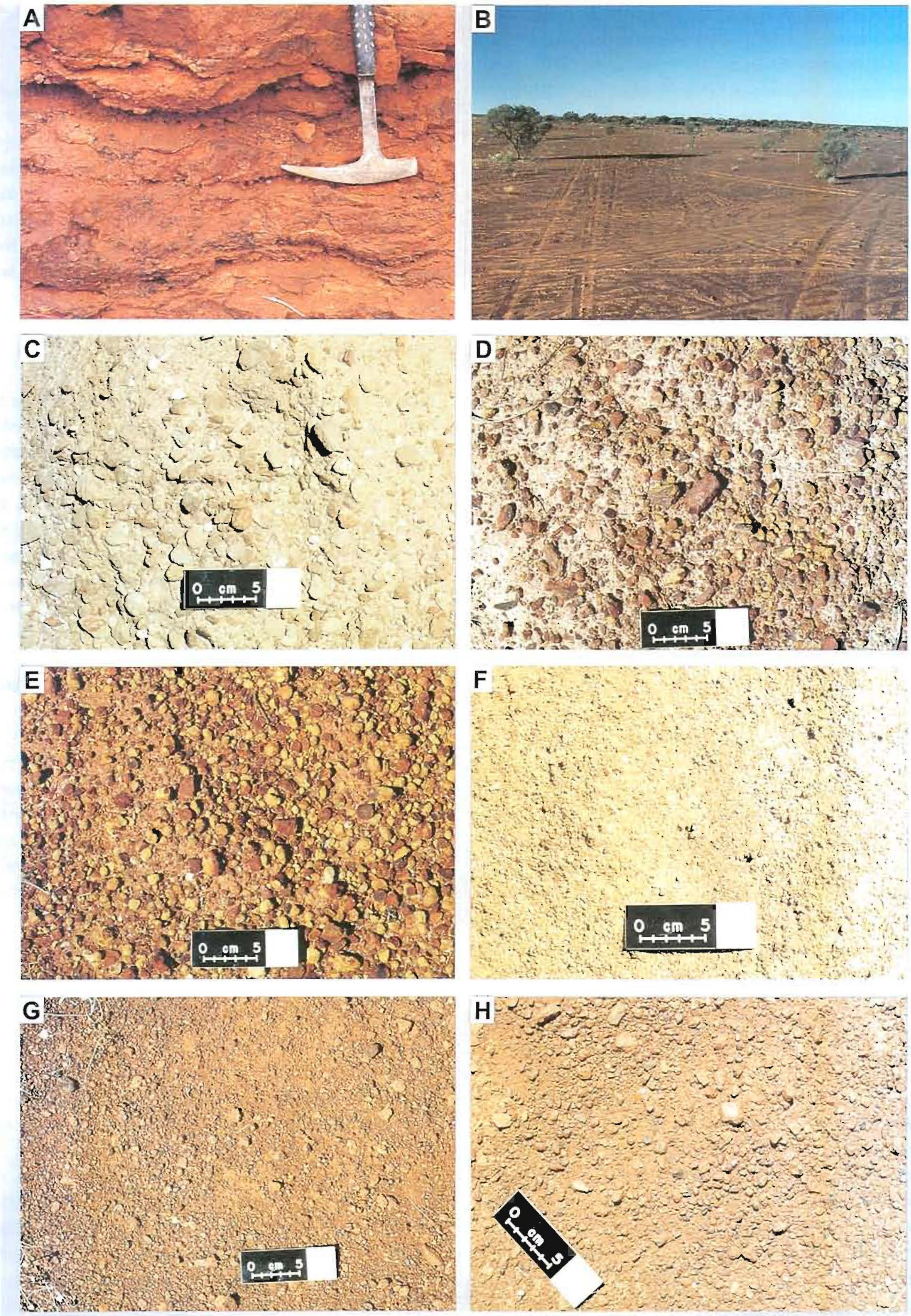

Figure 4: *Surficial and Drilled Materials*

A. Laminated, hardpanised colluvium exposed in stream section to the south-west of the Harmony Pit. AMG co-ordinates 662385E, 7160925N.

B. Ground oblique looking northeast towards location of Harmony Deposit prior to mining which is sited in the middle ground. AMG co-ordinates 669855E 7159005N.

C. Saprolite. RAB-drilled chips of kaolinite-rich saprolite, slightly stained with goethite, clearly showing the schistose fabric of the metavolcanics (Narracoota Formation) in powdered material of a similar composition. Drillhole 263H829 at 7-8 m depth down hole: local co-ordinates 9640 mE 12080 mN.

D. Mottled zone. Deep red-brown, hematite-rich, mottles and elongate nodules with a thin, yellow cutan of goethite-rich clay as fragments and chips in powdery, white kaolinite. RAB drillhole 263H440 at 23-24 m depth down hole: Local co-ordinates 8855 mE 12421 mN.

E. Ferruginous lateritic residuum. Broken, deep red-brown pisoliths and nodules with thin, yellow-brown cutans in a light-brown clay. Some of the clay was probably washed down from above. RAB drillhole 263H440 14-15 m depth down hole: Local co-ordinates 8855 mE 12421 mN.

F. Mottled clays which fill the Waste Dump palaeovalley. Fine chips of yellow-brown and white, puggy clay in a clay pulp. Some of the clay is mottled with a light-brown stain of goethite. RAB drillhole 263H1033 12-13 m depth down hole: Local co-ordinates 8920 mE 11680 mN.

G. Colluvium. Dark brown chips, pisoliths and lithorelics derived from ferruginous lateritic residuum from which the cutans have been abraded. This is set in a slightly lighter brown pulp of quartz, goethite and fine mica. RAB drillhole 263H440 1-2 m depth down hole: Local co-ordinates 8855 mE 12421 mN.

H. Interface. Gravelly base of the colluvium and top of the duricrust which is rich in pisoliths and nodules. A few have retained parts of their cutans but considerable abrasion is evident in others. RAB drillhole 263H837 3-4 m depth down hole: Local co-ordinates 10160 mE 12159 mN.

these materials. MacLeod (1970) and Blockley (1975) considered them to be deposits infilling drainage lines, or fossil lakes and swamps formed on a dissected Tertiary plateau. They were classified as bog manganese ores. More recently, Gee (1987) considered them to have resulted from a lateritic enrichment from primary manganese in underlying shales and siltstones of the Horseshoe Formation. Although field relationships with other regolith materials support the latter hypothesis, there is evidence for lateral migration and accumulation of manganese. In some of the old mine pits, manganiferous duricrusts lie directly over Fe-rich, massive to vermiform duricrusts and ferruginous saprolite. The contact is generally angular.

Different types of manganiferous duricrusts indicate various degrees of Mn mobilisation. Generally, cauliflower-pisolitic manganiferous duricrusts are developed over nodular or vermiform duricrust which, in turn, are underlain by a massive, manganiferous duricrust in places. The manganiferous, vermiform duricrust contains cryptomelane, goethite and hematite with colloform growth rings within pisoliths. The spatial extent of all duricrusts found in the study area is generally very limited and their occurrence patchy (Figure 3).

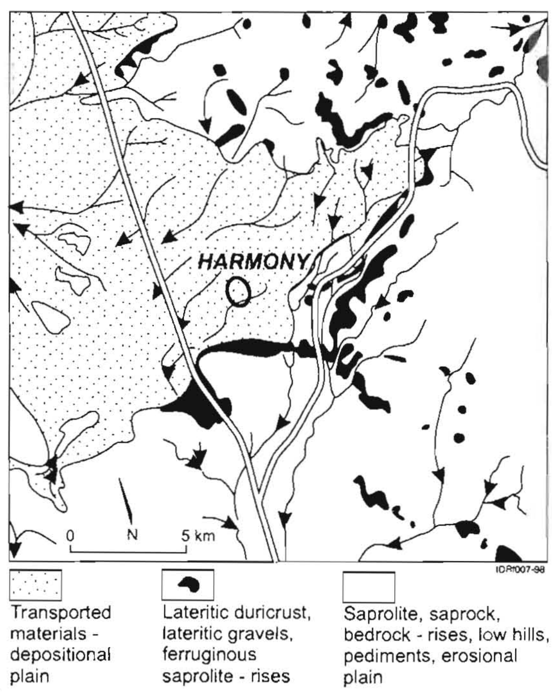

Figure 3. *District regolith geology of the area around the Harmony Au deposit showing the distributions of the residual terrain (relict and erosional landforms) and the depositional plain covering the Harmony mineralisation.*

LOCAL REGOLITH GEOLOGY

In the immediate vicinity of the Harmony deposit, 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, 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 ferruginous lateritic residuum, having 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.

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

PALAEOTOPOGRAPHY

Contours of the buried interfaces and isopach maps of the thicknesses of the regolith units provided a palaeotopographic model to indicate the spatial disposition of regolith materials (Figures 5A-E). The outline of the Harmony pit and the most recent interpretation of the contact between the metavolcanics and the metasediments, obtained from drilling (see Figure 6A), was added.

The 'palaeotopography' provided by these contour maps has some limitations. The 'surfaces' that they represent may be used to approximate the form of the topography of a basement prior to a particular sedimentary event. Only those parts of the surfaces that were subsequently blanketed and not eroded later are faithfully preserved. The exposed parts would have suffered some erosion since and so must be regarded as 'minimum' surfaces. These 3D relationships provide an improved understanding of landscape development, may be used to guide sampling of the most appropriate medium, assist in understanding dispersion processes, predict dispersion directions and, thus, to help interpret geochemical data. A schematic representation of the regolith around the deposit is shown in Figure 7A as a cut-away 3D model.

The palaeosurface (Figure 5A) of the residual profile on the basement (including the top of the saprolite and associated mottled clays and lateritic residuum) shows that the deposit is on a west-northwest trending palaeohigh. The highest part of this palaeohigh is occupied by ultramafic rocks of the Narracoota Formation and its resistance may be related to slight surface silicification prior to erosion. The basement palaeosurface had a relief of about 40 m within the study area.

The modeled palaeotopography contains two palaeovalleys. A major, deep palaeovalley, referred to as the Waste Dump palaeovalley, parallels the trend of the palaeohigh and lies to the south of the Harmony deposit. A west-northwest flow direction from the volcanics into the metasediments is implied from trends in the topography of the valley floor and a greater valley width to the west (Figure 5A). Another, apparently shallower and sub-parallel palaeovalley, lies north of the deposit. 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 structures (faults, shears) and lithological differences in the basement.

WEATHERED PROFILES ON THE BASEMENT

The palaeohigh consists largely of weakly indurated, grey and light yellow-brown ferruginous saprolite (Figure 4C). The floors of the palaeovalleys are particularly deeply weathered and have been eroded into mottled zones and clay-rich saprolites which, in drillspoil, consist of varying proportions of dark red or yellowish brown nodules and powdery, white kaolinite (Figure 4D).

Lateritic duricrust and lateritic gravels are preserved on the flanks of the palaeohigh (Figure 5C); they occur neither in the axes of the palaeovalleys, nor on the palaeohigh itself. Combined, they vary in thickness, are generally about 8 m thick but, in places, reach 19 m, where they are likely to have an upper, slumped or transported component. The nodules are generally dark red in drillspoil with distinctive, yellow-brown cutans (Figure 4E).

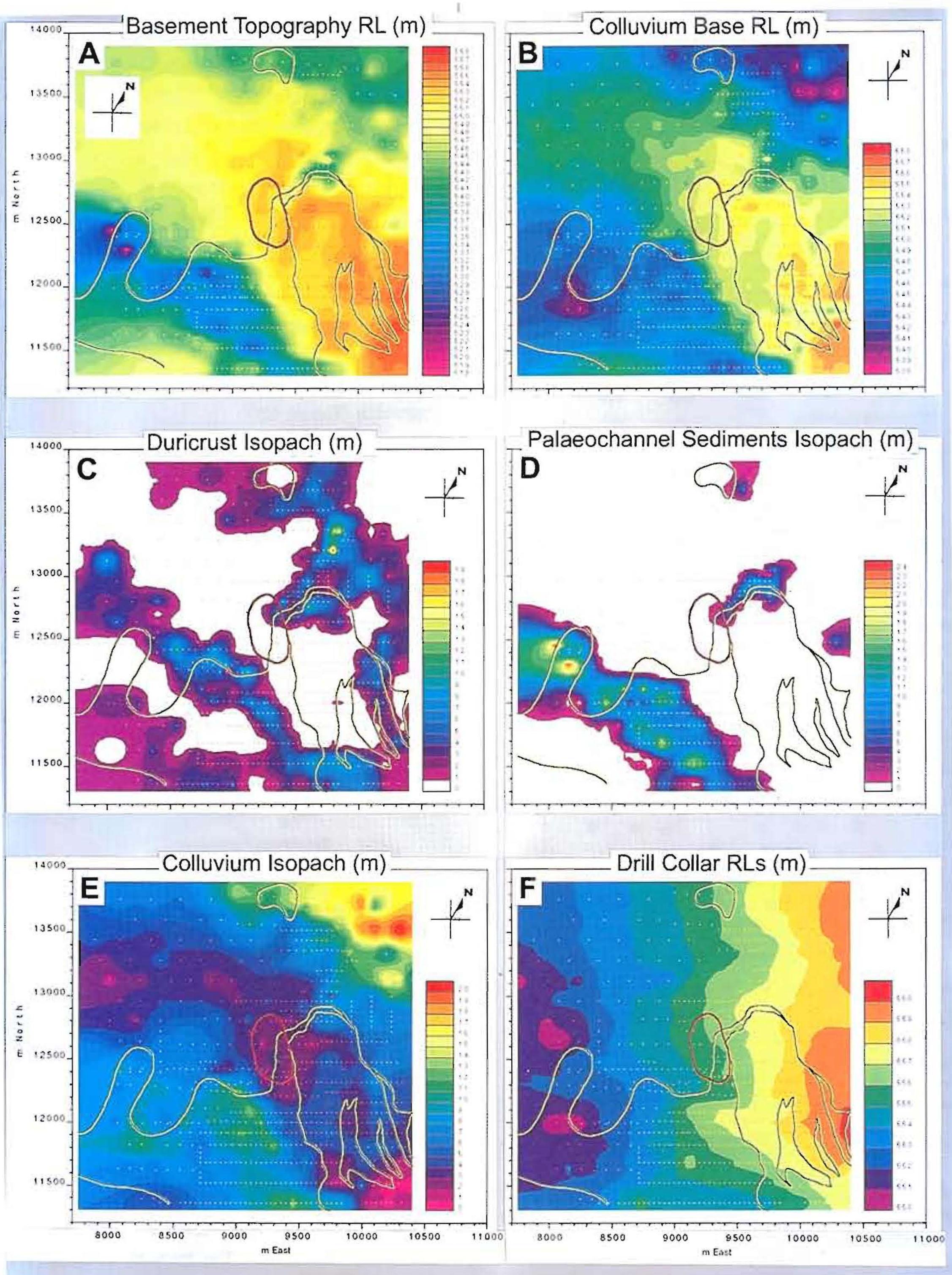

Figure 5: *Colour contour maps of the palaeotopography and isopach maps of some regolith units around the Harmony deposit show the palaeotopography of the residual profile (A), the palaeotopography prior to deposition of the colluvium (B), the distributions and thicknesses of lateritic duricrust (C), valley-fill sediments (D) and colluvium (E) and the present surface (F). The bedrock geology (Figure 4A), pit outline and data points have been added.*

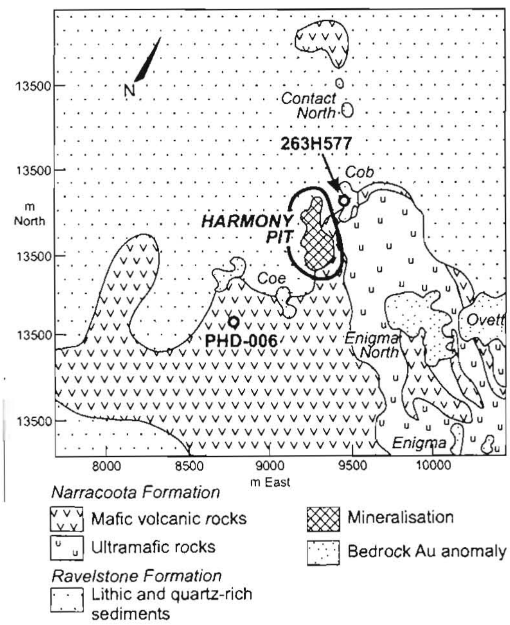

Figure 6A: *Local geology of the area surrounding the Harmony pit as determined by Plutonic Operations Ltd from intensive RAB drilling with known bedrock geochemical anomalies, the locations of drillholes PHD-006 and 263H577 and the outline of the Harmony mineralisation.*

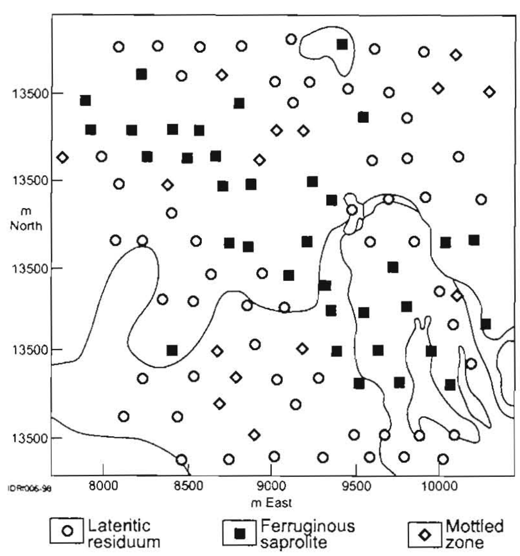

Figure 6B: *Outline of bedrock geology (from Figure 6A) with sampled drillholes and nature of the top of the residual regolith.*

Valley-fill sediment

The palaeovalleys have been partly filled with clay-rich sediments, generally about 10 m thick but reaching 24 m locally (Figure 5D). Mostly, these consist of soft, puggy, grey, green or light-brown clays (Figure 4F) which are slightly mottled and have a tendency to crack on drying. A very thin layer of sand occurs at the base in a very few places. These valley-fill sediments are extensive in the Waste Dump palaeovalley but are developed only in patches (Figure 5D) in the northern palaeovalley, probably partly removed by erosion. The residual regolith beneath the valley-fill sediments consists largely of mottled clays, clay-rich saprolite and some lateritic duricrust, with very little ferruginous saprolite (Figure 6B).

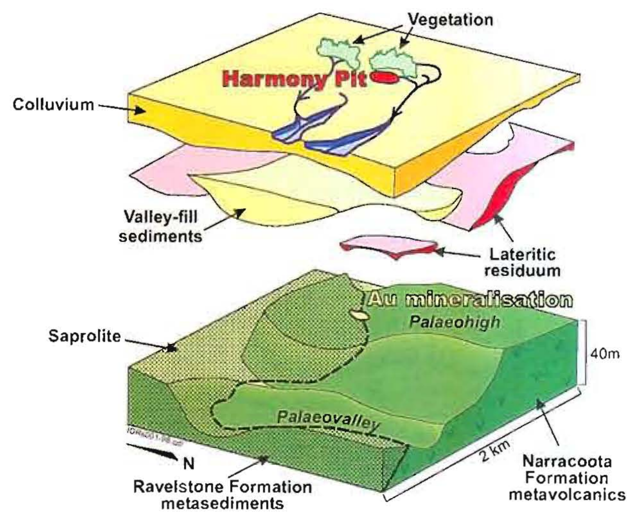

Figure 7A: *Block model of regolith relationships around the Harmony Au deposit. Proterozoic metavolcanics and metasediments, with Au mineralisation located at their contact, have been eroded and lateritised. Palaeovalleys have been partly filled with clay-rich valley-fill sediments, which have also 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.*

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. The thickest colluvium (Figure 5E) 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 and the Harmony deposit. The relief, prior to deposition of the colluvium, is shown in Figure 5B. The palaeohigh, below the colluvium, is dominated by weakly silicified ferruginous saprolite formed on mafic and ultramafic rocks. The palaeo-relief is muted (15 m) compared to 40 m on the basement.

The upper part of the colluvium has been silicified to a red-brown hardpan. It consists of sand- and granule-sized, matrix-supported, subangular to subrounded nodules and ferruginised lithic clasts, with some minor quartz, in a silty matrix of quartz, kaolinite, mica and Fe oxides. In drillspoil, the colluvium is seen to be rich in brown, polymictic granules with abraded cutans and fragments of ferruginous lithorelics (lacking cutans) in a brown, clay-rich pulp (Figure 4G). 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 (Figure 4H).

Present surface

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 (Figures 5F and 7A). 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.

REGOLITH STRATIGRAPHY AND CHARACTERISTICS

Initially, the regolith stratigraphy was known only from RAB drill cuttings. However, following the discovery of the Harmony deposit, the regolith and bedrock were investigated by diamond drilling, some of which was cored from surface. Most of the diamond drilling was concentrated on the palaeohigh, proximal to the Harmony deposit, giving several sections through the thin colluvial cover and ferruginous saprolite. Here, there are some complex relationships between the colluvium and the basement, where they are separated by a mixed zone of 0.2-0.7 m thickness, comprising blocks of saprolite in a matrix of earthy colluvium, which could represent a palaeosol. However, there were no cored stratigraphic sections through the thicker colluvium and the valley-fill sediments, marginal to this palaeohigh and distant from Harmony, until a special-purpose triple-tube diamond hole (DDH PHD-006) was drilled in the Waste Dump palaeovalley at the end of 1995. Despite intersecting smectite-rich clays, the core recovery was good, with minor loss confined to poorly consolidated sand and the interfaces between soft and relatively hard materials. Numbers in parenthesis in the following description refer to the stratigraphic core segments of Figure 8.

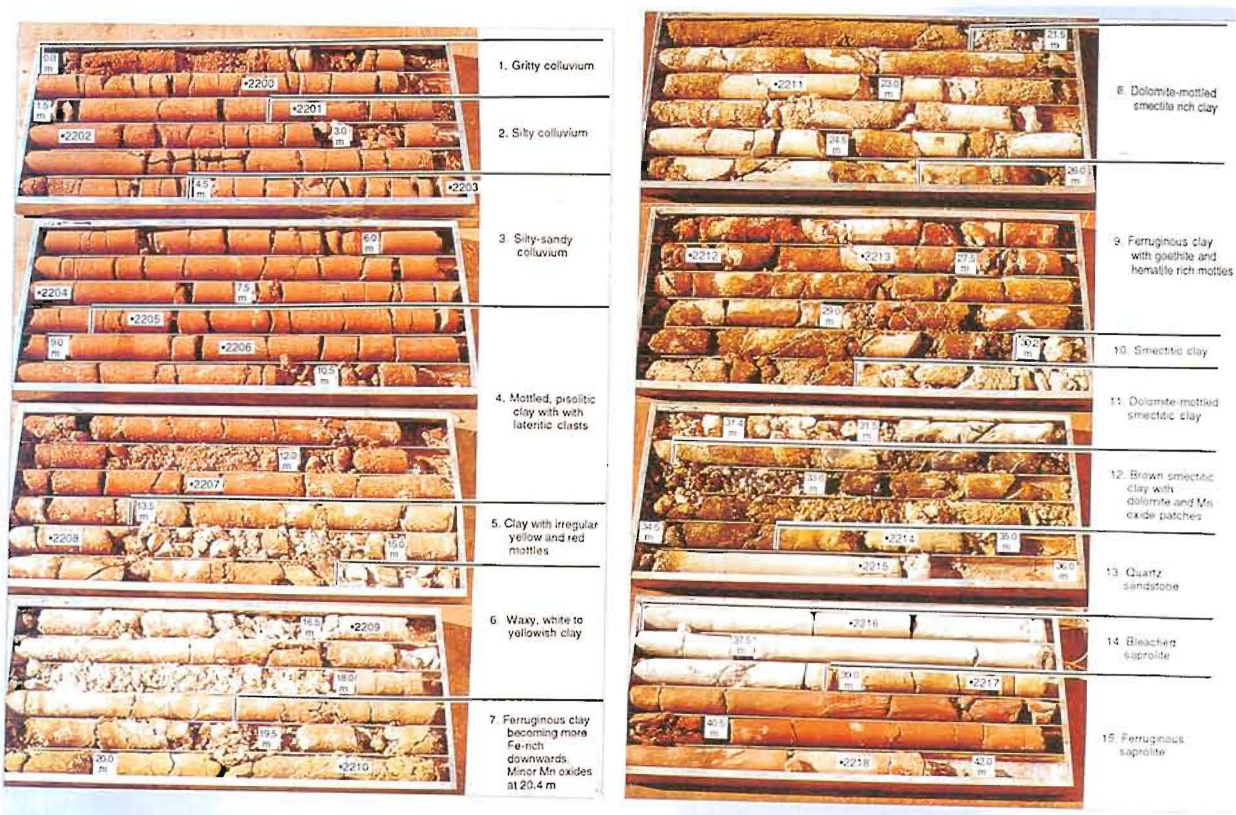

Figure 8: *Composite photographic record of the drillcore of DDH PHD-006 from the Waste Dump palaeovalley, prior to sampling. Major stratigraphic units are numbered (see text), down-hole depths are shown and specimen locations are numbered. Collar location 8790 mE 12090 mN (local grid).*

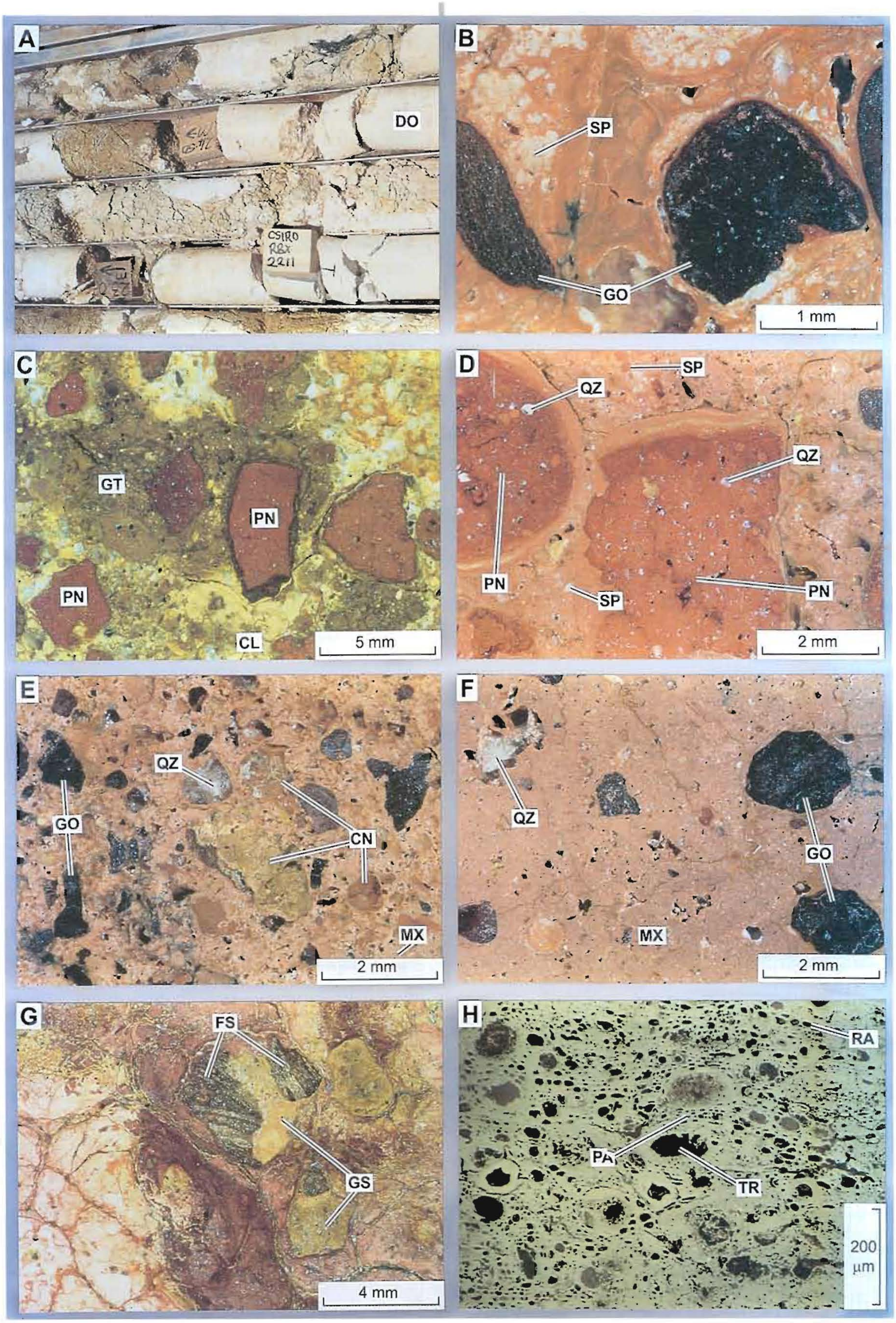

figure 9: *Lithologies of Valley Fill Sediments of Diamond Drillhole PHD-006*

A. *Large, white dolomite mottles in grey-brown smectitic clay. Large compound nodules or mottles of dolomite (DO) in cracked, light-grey, waxy smectitic clay from the depth range 23-26 m. Photograph of drillcore.*

B. *Ferruginous nodules in spherulitic smectitic clay. Goethite-rich nodules (GO) lie in a matrix of smectitic clay spherules (SP). Despite being outwardly varied, the goethite-rich nodules, which contain included mica, are mineralogically and texturally quite similar internally. Voids have been infilled with finely laminated clays. Specimen RBX-2206 from 9.35 m depth. Close-up photo of polished surface in oblique reflected light.*

C. *Mottled, nodular clay. Hematitic clay nodules (PN) are set in a matrix of yellow and white smectitic clay (CL). Parts of the clay are goethite stained (GT). Specimen RBX-2208 from 14.35 m depth. Close-up photo of polished surface in oblique reflected light.*

D. *Mottled pisolitic clay. Small subrounded goethite fragments and larger pisolitic nodules (PN) of hematitic clay, with included quartz grains (QZ) and coated with pale-brown, laminated clay, are set in a matrix similar to the colluvium (compare Figures 9E-F) but contain a few clay spherules (SP). Specimen RBX-2205 from 8.18 m depth. Close-up photo of polished surface in oblique reflected light.*

E. *Gritty-sandy colluvium. A mass of polymictic, angular to subrounded, yellow, clay nodules (CN), goethite-rich clasts (GO) and minor quartz (QZ) are set in a matrix (MX) of smaller fragments, quartz grains, clay and mica. Specimen RBX-2200 from 1.35 m depth. Close-up photo of polished surface in oblique reflected light.*

F. *Silty-sandy colluvium. A few subangular to subrounded goethite-rich clasts (GO) and quartz (QZ) set in a fine-grained matrix (MX) of quartz, clay and mica. This is similar to Figure 9E, in clasts and matrix, but the proportion of large clasts is much less. Specimen RBX-2203 from 5.30 m depth. Close-up photo of polished surface in oblique reflected light.*

G. *Clay with hematitic mottles and fossil wood. Details of compound nodules containing both fossil wood (FS) and attached goethite-stained sediment (GS) set in hematitic clay mottles which are encased in cracked and slightly Fe-stained clay. Specimen RBX-2212 from 27.05 m depth. Close-up photo of polished surface in oblique reflected light.*

H. *Fossil wood cross section. Large, round, central tracheid vessels (TR) surrounded by numerous, small, round parenchyma packing cells (PA) separated by chains of elongated ray cells (RA). The cell walls have been delicately replaced by goethite. Specimen RBX-2212 from 27.05 m depth. Photomicrograph in normally reflected light.*

WASTE DUMP PALAEOVALLEY

Basement

DDH PHD-006 penetrated the top six metres of a clay-rich saprolite of the slightly schistose mafic metavolcanics of the Narracoota Formation (Figure 8) before drilling was terminated. The lower part of the saprolite is coarsely cleaved, reddish brown, hematite bearing, and mottled with grey (15). The upper part is highly bleached white or very pale grey (14) and contains a few disaggregated quartz veins. The saprolite has a uniform mineralogy, being rich in muscovite, quartz and kaolinite. The colour differences are due to minor variations in hematite content; the bleaching may be related to leaching of Fe oxides by groundwater just below the permeable, sandy base of the valley-fill sediment.

Valley-Fill Sediment

At the base of the valley-fill sediment is a very thin (1.2 m) unbedded, grey, fine-grained sand (13). It is relatively clean, 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 crystals. The larger quartz grains are well rounded; the smaller grains are angular and vary from equant to shard-like. The intergranular space is filled with very fine-grained kaolinite. The upper part of the sand is particularly fine grained and stained with goethite, presumably from the overlying ferruginous material.

The sand is overlain by 2.8 m of brown smectite and kaolinite clay which is goethitic, manganiferous and dolomitic in places (12). This is followed by a thin band (1.3 m) of dolomite-mottled smectitic clay (11), by 0.5 m of a slightly mottled light greenish-grey clay (10) and 4.5 m of waxy, pale-grey to slightly greenish smectitic clay with large, compound 'mega-mottles' of goethite, hematite and dolomite (9). This mottled zone could represent an old water table where Fe was precipitated from groundwater at an oxidation front.

Above this interval is a substantial zone of dolomite-mottled smectitic clay (Figure 9A), consisting of approximately 60% of fused nodules of very fine-grained dolomite forming masses about 0.3 m in size (8), internally cemented with similar but slightly coarsergrained dolomite. This is followed by friable goethite- and hematite-stained clay (smectite and minor kaolinite) with a few remaining streaks of unstained, waxy clay (7). A few goethite-rich granules (1-2 mm) are set in the clay along with glassy quartz (<0.5 mm) and a trace of tourmaline. Minor Mn oxides occur at 20.4 m. This is followed by more smectitic and kaolinitic clay (6), slightly stained with Fe oxides. Above this, the clay (5) becomes progressively more mottled with hematitic nodules (1-20 mm) and yellowish goethite granules, and is less smectitic.

The mottled clays (4) become progressively more Fe rich up core. The contact between the mottled and pisolitic top of the valley-fill clays and the colluvium is sharp and is marked by a distinctive fabric change but this could be missed easily in drill cuttings, as the materials on either side of the contact are quite similar. The upper parts of the valley-fill clays are strongly mottled and nodular (Figures 9B and C) within a matrix of greenish-white clay ooliths[3]. The nodules of hematitic goethite contain varying amounts of very small mica flakes. The matrix has been extensively dissolved and the voids infilled with a brown, laminated kaolinite with a slight sheen (Figure 9B). At the top, the pisoliths have thin, partly abraded cutans of light brown clay (Figure 9D), indicating minor transport or reworking. Although this matrix contains ooliths of ferruginous or white clay, it has some similarities to the matrix of the colluvium above and forms a transitional zone, probably formed by downward settling of clays from the colluvium.

The nodular and pisolitic fabric at the top indicates intense weathering of the upper part of the valley-fill clay sediments, with development of a mottled zone and pisolitic structures. This appears to have been an event either continuous with or more recent than the weathering of the bedrock. This weathering was followed by some leaching, subsequent collapse of this weathered zone and very minor transport of the lateritic material, leading to broken cutans. Deposition of the colluvium followed, with further matrix dissolution and eluviation of clay from the matrix of the colluvium into voids in the upper part of the valley-fill sediment. This is also reflected in the chemical composition (Robertson *et al.* 1996).

There is a small proportion of quartz sand grains in the valley-fill clays that are rounded and water-worn; these are generally about 1 mm in size. Most of the smaller grains (0.5-0.2 mm) are subrounded to angular and appear to have resulted from breakdown of composite metamorphic quartz grains. This quartz occurs throughout the smectitic clays; its abundance decreases down the profile and it is similar in size and shape to the quartz sand at the base of the sequence and to quartz in the saprolites of the basement.

Colluvium

The upper eight metres consist of brown colluvium that may be divided into an upper, gritty- sandy part (1) and lower silty-sandy parts (2 and 3). 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 (Figure 9E). The 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.

In the silty-sandy colluvium, the clasts and matrix are very similar to those of the gritty-sandy colluvium but the proportion of coarse, clastic material is much less (Figure 9F). These are set in a dull-brown matrix of kaolinite, quartz, Fe oxides and anatase. Some voids in the matrix are lined with a light-brown, laminated clay.

Chemical Composition

Compared to the transported materials, the saprolite on the metavolcanics of the Narracoota Formation are enriched in Rb and K and have a much greater K/Rb ratio.

The colluvium is slightly richer in Zr (>170 ppm) than the valley-fill sediments. Enrichments in other elements, namely Pb, P, K, Rb, Th and the REE (La, Ce) also distinguish the colluvial sediments from the valley-fill sediments. Leaching and clay illuviation have imprinted some of the geochemical characteristics of the colluvium onto the mottled and pisolitic upper parts of the valley-fill sediments. This is very clearly shown by K, Rb, Pb, P, La, Th and Ce, which decrease in abundance progressively downwards from the contact. The two dolomitic layers within the valley-fill sediments are distinguished by greatly increased Ca (10-17% CaO) and Mg (14-23% MgO) contents, which have diluted all other elements. Details of this chemistry are given by Robertson et al., (1996).

Drillhole PHD-006 is located down the palaeo-slope from the Harmony Au deposit and the Coe Au anomalies (Figure 6A). Gold is preferentially enriched in the upper, pisolitic part of the valley-fill sediment (maximum 224 ppb) and in the lower part of the colluvium (maximum 125 ppb). The Au contents of the remainder of the valley-fill sediments (mean 25, maximum 74 ppb Au) and the basement saprolite (maximum 33 ppb) are relatively low. There has been ample opportunity for mechanical dispersion down slope of Au-rich detritus into the sediments and lower colluvium. In addition,

[3] Defined in a glossary by Butt and Zeegers (1992)

later hydromorphic dispersion may have introduced Au from primary sources into neo-formed ferruginous materials during weathering of the upper part of the valley-fill sediments and along the contact with the colluvium. Thus, lateral, largely mechanical but possibly partly chemical dispersive origins for this Au are likely. The highly manganiferous (0.8-2.5% MnO) clays are hydromorphically enriched in Cu, Zn, REE, Co and Ni.

Palaeontology and Age

Yellow-brown granules of fossil wood, now replaced entirely by goethite, were found among pink, clay-bearing ferruginous mottles at 27.05 m (Figure 9G) within the valley-fill clays of diamond drillhole PHD-006. Some contained attached, goethitic, exogenous, quartz-rich sediment. The cell patterns and their scale are typical of woody tissue. Cross sections (Figure 9H) show patterns that may be interpreted as larger, sap-carrying, tracheid vessels surrounded by smaller parenchyma or packing cells and some evidence for ray cells. The larger vessels are tracheid vessels rather than xylem, which are indicated by their lensoid form in near longitudinal sections. This material probably formed stem or root material and the presence of tracheid vessels rather than xylem implies a relatively primitive vegetation (cycad, fern or conifer) with no evidence of the higher, flowering plants (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 attempt was made to palaeomagnetically date some of the ferruginous, mottled material from 27 m ±0.5 m (B. Pillans pers. comm; 1996). Although friable, three ferruginous specimens were treated with stepwise alternating field demagnetisation. There was no agreement between the three specimens. Only one specimen had stable, positive (reversed) magnetic declination, suggesting an age of >0.78 Ma. The others did not have stable magnetisations.

Harmony palaeovalley

A small palaeovalley drains north-northeast from the Harmony deposit and is exposed in the northeast pit wall (Figure 7B). It has a floor of lateritic duricrust and has been filled with the characteristic mottled, puggy (plastic) clays, which are directly overlain by 2-3 m of colluvium. The white, pale yellow or pale pink, clays are similar to those of the Waste Dump palaeovalley, and contain hematitic and goethitic mottles and a few dark red-brown hematitic granules. The clays contain small, subangular grains of glassy quartz and are very similar to those of PHD-006. The clay sediments consist of quartz, smectite, kaolinite, goethite and hematite with minor anatase. A little calcite (calcrete) occurs from 8.5-11.5 m but there are no dolomite nodules. As there are no ferruginous, pisolitic materials in the upper parts of the valley-fill clays, these sediments may have been partly eroded prior to deposition of the colluvium.

A highly ferruginous cementation of the lateritic duricrust is also exposed in the pit, a few metres below the base of the valley-fill sediment (Figure 7B). The extent of this lenticular layer closely matches that of the palaeovalley and probably marks a redox front where Fe was precipitated and indurated the surrounding lateritic duricrust. Similar ferruginous cementations have been described at Lawlers (Anand et al. 1991). The residual lateritic duricrust consists of goethite, hematite, gibbsite, minor quartz and kaolinite; there is no smectite.

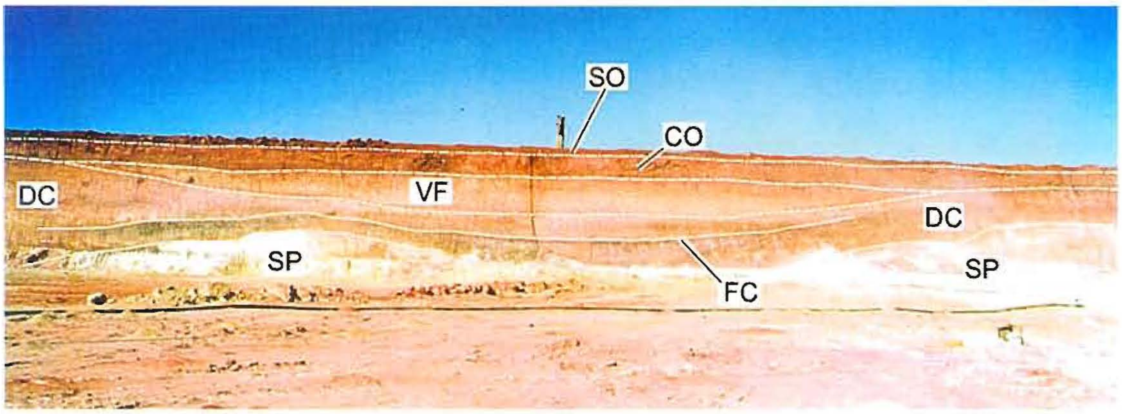

Figure 7B: *A section across the Harmony valley-fill sediments (VF) as they appear in the northeast wall of the Harmony pit. This is underlain by duricrust (DC), ferricrete (FC) and saprolite (SP) and overlain by colluvium (CO) and a thin soil (SO).*

Soil

Soil developed on the colluvium is closely related to its 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.

DISCUSSION AND CONCLUSIONS

Subsurface regolith-landforms and basement-related sampling media

The present, relatively flat surface around the Harmony Au Deposit indicates little of the complex regolith beneath (Figure 7A). However, the polymictic lag implies a depositional area where further investigation must be by drilling and costeaning. There is a considerable basement relief of 40 m, with the Harmony deposit lying beneath a palaeohigh of ferruginous saprolite. Deep palaeovalleys, to the north and south of the deposit, dissect this landscape and are underlain by saprolite and mottled zone. Lateritic duricrusts are preserved on the flanks of the palaeovalleys. There are at least three major residual regolith geochemical sampling media available immediately underlying the transported overburden. The sample media, which would be expected to be disparate in their geochemical backgrounds and dispersion characteristics, are:-

a) Ferruginous lateritic duricrusts, which tend to contain extensive geochemical halos of indicator elements adsorbed or incorporated in their component Fe oxides and oxyhydroxides;
b) Mottles from the mottled saprolite generally underlying the palaeochannels (these may be obtained by washing away the clays) and
c) Ferruginous saprolite from higher parts of the landscape.

Both sample media b and c tend to contain smaller geochemical dispersions but are also enriched, to different degrees, in indicator elements. Combining these media inadvertently may cause a significant geochemical leveling problem. Mapping regolith relationships and distributions, using exploration drilling, has revealed details of this sub-surface landscape and the sampling materials that would be expected, allowing the sampling strategy and subsequent data handling to be properly controlled.

Transported overburden

Cover materials include smectitic and kaolinitic clays, partly filling palaeovalleys, and a variable thickness of colluvium-alluvium covering all, including the palaeohigh that contains the Harmony Au Deposit. A thin soil veneer mantles this colluvium. Correct recognition of basement from these cover units is fundamental to exploration.

Valley-Fill Sediments

The valley-fill sediments appear to have been deposited in a very low-energy environment. Very restricted, thin sand layers were found at the base of a very few palaeovalleys. Although these sands were probably deposited in narrow, clearly defined channels (Figure 10A), they lack any current bedding. This bedding may have been obliterated by bioturbation near the time of sedimentation. Most of the sediments are waxy clays (kaolinite and smectite) and contain small quantities of minute (0.5 mm) quartz grains. These occurring together require a process that will deposit both clay and sand simultaneously. An alternate means of clay and sand sedimentation would be as a debris flow, as suggested by Robertson (1990) for Campaspe Formation clays in eastern Queensland. The term 'valley-fill' has been used for the clays, in preference to the term 'palaeochannel' for reasons made clear in Figure 10A.

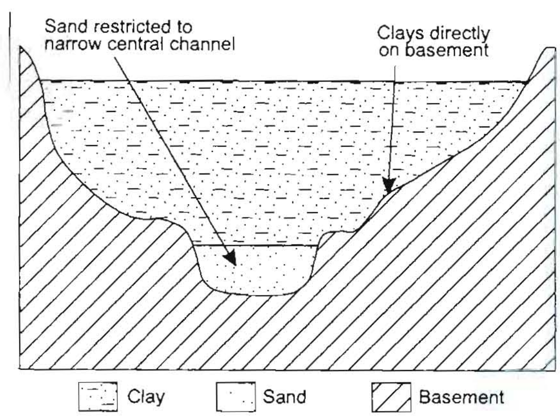

Figure 10A: *Relationships between sand and valley-fill clay to the basement. Generally, smectitic clays lie directly on the basement, the sands occupy a narrow, central channel.*

Most of the quartz grains in the clays are angular to shard-like, although a few larger grains show some rounding. There is a remarkable similarity between the abundance, size and appearance of the quartz of the basement saprolite and that of the valley-fill sediments.

The saprolites of the basement consist of kaolinite, muscovite and quartz; the valley-fill sediments of kaolinite, smectite and quartz. It is suggested that the palaeovalleys were filled with locally derived, finely comminuted saprolite detritus under conditions of sluggish stream flow or possibly even debris flow conditions. Weathering of this sediment continued, possibly with some bioturbation, keeping the quartz grains mixed in with the clays. It seems likely that the basal sand was concentrated from the saprolite by fluvial action and that 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 kaolinite.

1. $K_2Al_6Si_6O_{20}(OH)_4 + 0.8Si(OH)_4 + Mg^{2+}{}_{0.8} + (n-1)H_2O \rightarrow$

Muscovite — silicic acid — dissolved bases — water

$Mg_{0.8}Al_4(Si_{6.4}Al_{1.6})O_{20}(OH)_4.nH_2O + 0.2Al_2Si_2O_5(OH)_4 + 0.4OH^-$

smectite — kaolinite — alkalinity

2. $2.8Al_2Si_2O_5(OH)_4 + 0.8Si(OH)_4 + 0.8Mg^{2+} + (n-4.4)H_2O \rightarrow$

Kaolinite — silicic acid — dissolved bases — water

$Mg_{0.8}Al_4(Si_{6.4}Al_{1.6})O_{20}(OH)_4.nH_2O + 1.6H^+$

smectite — acidity

The above reactions imply variations in pH, from acidic to alkaline, depending on the availability and the quantities of weathering muscovite. Temporary alkaline conditions, brought about by reaction 1, and excess dissolved Ca, Mg and HCO_3- in the groundwater would favour deposition of dolomite with the clays.

The valley-fill sediments have had a complex weathering history and show signs of oxidation fronts, including 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 on the valley-fill sediments, are complex, with a mixture of in situ clay-rich pisoliths and some apparently exogenous nodular material. The first of these ferruginous materials may have been released by dissolution of the matrix of an existing in situ lateritic duricrust, followed by collapse and minor transport. The second type of ferruginous material could have been eroded from residual lateritic material from the adjacent slopes and deposited in the palaeovalley. 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 pedogenic materials from the colluvial-alluvial cover.

Colluvium

The layer of colluvium varies considerably in thickness, from 0.5 m over parts of the Harmony Deposit to 10-20 m over the palaeovalleys. Thick sediments in the valleys were probably alluvial but exposure was not available. The layer of colluvium provides a significant hindrance to exploration, effectively blocking physical transfer of geochemically anomalous material to the surface except where it is extremely thin (0.5 m). 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 10B) 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).

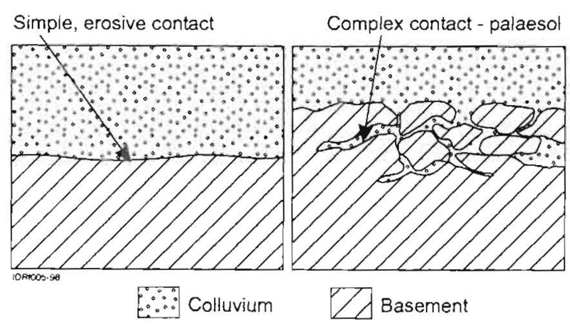

Figure 10B: *Simple, erosive and complex contacts between basement and colluvium. In the latter, the base of the colluvium is probably a palaeosol.*

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