David J. Gray, J.E. Wildman and G.D. Longman

Selective and partial extraction analyses of transported overburden for exploration

SELECTIVE AND PARTIAL EXTRACTION ANALYSES OF TRANSPORTED OVERBURDEN FOR EXPLORATION

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1. Introduction

Selective extractions are techniques for the controlled dissolution of particular soil phases that can be used to investigate how trace elements are distributed. These extractions have been used for geochemical exploration, because it has been perceived that elements associated with mineralization (especially those hosted by sulphides) are more readily released during weathering than those in barren rocks (hosted by silicates), more widely dispersed and held by secondary minerals and hence likely to be preferentially released by extraction solutions. In contrast, many of the new extraction techniques currently being introduced for geochemical exploration are partial rather than selective digests: *i.e.*, they extract part of a phase or phases, rather than a selected mineral. It is claimed that these new methods have a high efficacy in the location of buried or otherwise hidden orebodies. There has been significant interest in these methods because, if effective, they would offer an inexpensive and easy method for exploration in areas of transported overburden. This study, using selective extractions for carbonates, Mn oxides and amorphous Fe, varying HCl treatments, the CSIRO Iodide extraction for Au, mobile metal ions (MMI) and Enzyme Leach, has been designed to examine the chemistry of partial and selective extractions and the mineralogical implications more fully. Particular questions are: whether soil extraction anomalies exist over buried mineralization; can these anomalies be observed using different techniques; what is the primary cause of the anomalies?

2. Study sites

Seven different sites (Figure 1) have been used for the extraction tests, grouped as follows:

(i) *Northern* (N Yilgarn and margins) -
  Baxter: 90 km N of Meekatharra, in early Proterozoic basin on the northern margins of the Yilgarn Craton, primarily mafic and ultramafic volcanics;
  Fender: 28 km WNW of Cue, hosted by a regional volcanic and sedimentary sequence in an attenuated greenstone belt about 830 m wide;
  Bronzewing: 400 km N of Kalgoorlie, within a sequence of mafic volcanics and minor sediments, which are intruded by felsic porphyries.
(ii) *Central* (close to and north of the Menzies line) -
  Curara: 70 km SSW of Mt. Magnet, in a tonalitic porphyry stock, bound to the E by mafic amphibolite schists;
  Safari: 200 km NNE of Kalgoorlie, in a greenstone assemblage containing a wide variety of volcanic and volcaniclastic rocks.
(iii) *Kalgoorlie region -*
  Steinway: 15 km W of New Celebration, in mafic andesites with trachytes, porphyritic tuff and black shales, overlain by a minor palaeochannel system;
  Apollo: 25 km S of Kambalda, high-Mg basalts / dolerite beneath a palaeochannel.

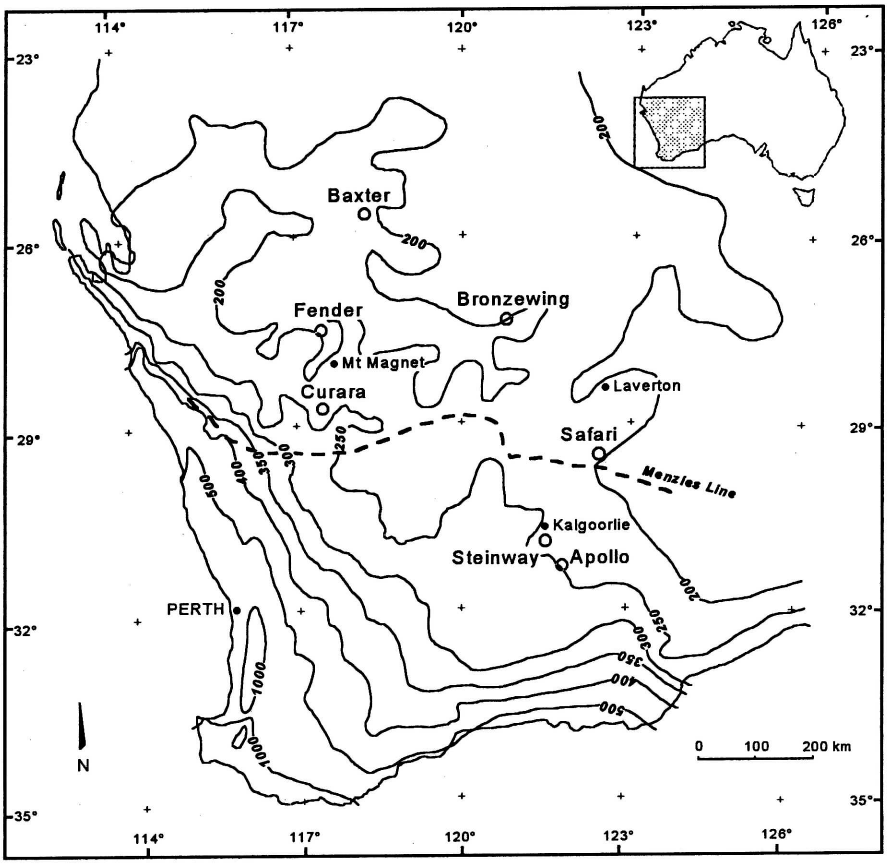

Figure 1: Location of selective/partial extraction investigation sites, with rainfall (mm) in ohyets.

This investigation was conducted as part of CRCLEME/AMIRA Project 409 (Butt *et al.*, 1997), and readers are referred to this and other reports from this project for full site descriptions. The primary references and abridged site descriptions are given below.

2.1. Harmony deposit, Baxter

Gray (1995), Robertson *et al.* (1996)

The Harmony Deposit is approximately 90 km N of Meekatharra and located within a depositional plain. The climate is semi-arid, characterized by low irregular rainfall averaging 200 mm pa. Vegetation cover is thin, mainly consisting of mulga and other drought resistant shrubs and grasses. The deposit is located on the contact between the folded mafic and ultramafic Narracoota Volcanics and a thick turbidite sequence of fine-grained lithic, feldspathic and mafic wacke of the Ravelstone Formation (Figure 2). Both have been moderately metamorphosed, and are part of the Proterozoic Glengarry Basin.

In 1997 the deposit had a calculated reserve of 2.148Mt @ 3.6g/t Au. Primary stratabound gold mineralization is associated with quartz veining, and is hosted within a mafic sequence at the top of the Narracoota Volcanics. The deposit is low in sulphides, with pyrite >> pyrrhotite. Mineralization also occurs as a near-surface, relatively flat-lying supergene deposit, occurring mainly within the volcanic saprolite, lateritic residuum and extending into the base of the overlying colluvium. The depth of oxidation is variable but averages about 80 m, with the water-table at 30 m.

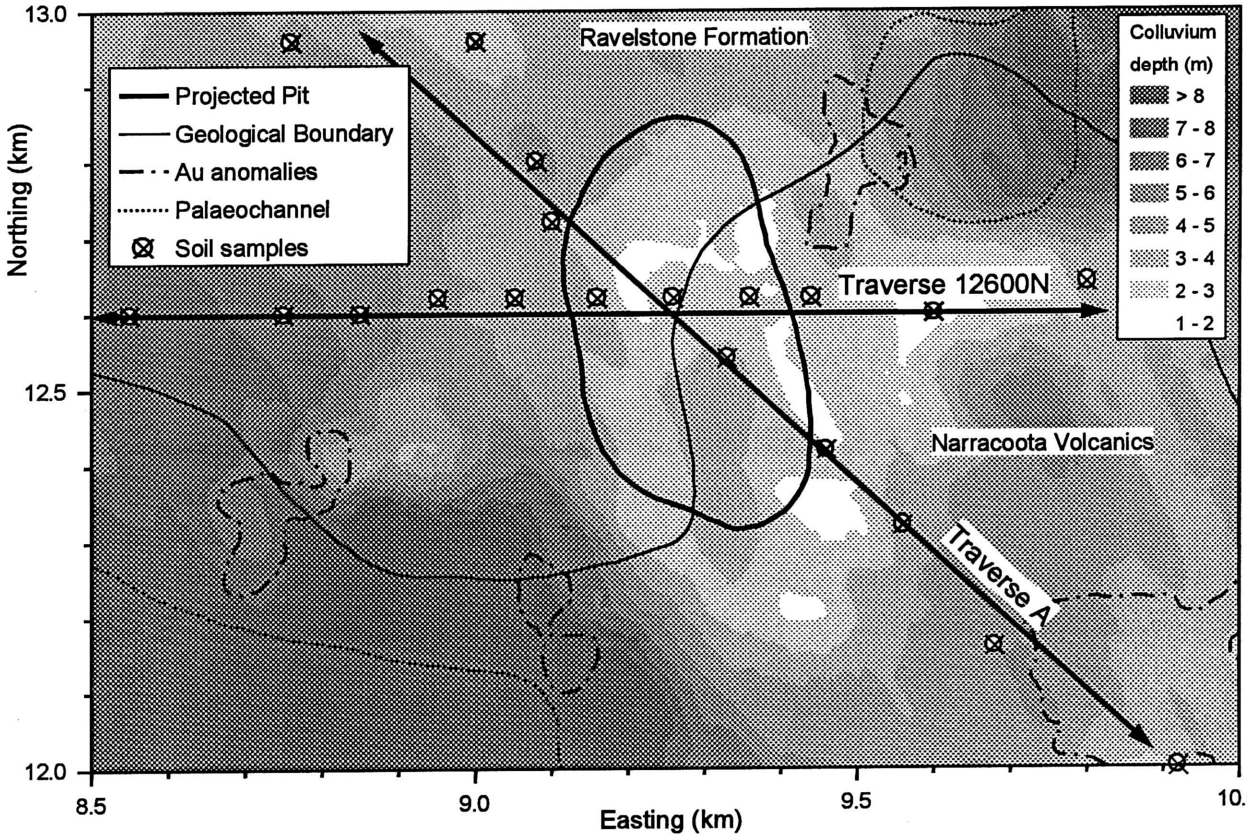

Figure 2: Soil samples from Baxter used for the partial extraction study, with geology, projected pit, other Au anomalies, position of palaeochannels and depth of colluvium shown.

The transported overburden in the vicinity of the Harmony Deposit is a variably thick, red-brown, colluvial-alluvial blanket (Figure 2), with thickest cover (7-12 m) over the palaeochannels. The colluvium on the palaeohigh (0.5-3.0 m) lies directly over a basement of ferruginous saprolite, saprolite and saprock. Ferruginous duricrust is developed on the flanks of the palaeohigh and is complete with lateritic nodules and pisoliths. The colluvium over the palaeochannels is underlain by various mottled clay sediments, which may by subdivided into an upper unit of dark puggy clays, and a lower unit of pallid clays with silica. Beneath the palaeochannel sediments, thick mottled zones and clay-rich saprolites have developed. Most soils tested are dominated by the > 2000 µm fraction (removed before partial extractions; Section 3.1), with the < 75 µm fraction also very important. This fine fraction showed weak Au, W, Ta anomalies over Harmony, though only where the colluvium is particularly thin (0.5 - 1.0 m).

The groundwaters at the Harmony deposit are neutral (pH 6-8) and have very low salinity (mean 0.04% TDS), and as such they are distinct from the saline acid groundwaters of the southern Yilgarn. The low salinity at Harmony means that the dominant mechanism for mobilization of Au in the southern Yilgarn, namely through the formation of halide complexes, is not expected to be significant. Other important mechanisms for Au mobilization (*i.e.*, formation of complexes with organic ligands or thiosulphate) are also unimportant because of the low organic matter content of the groundwater and the negligible degree of present day sulphide oxidation.

Soil samples for the partial extraction tests were taken from two traverses (Figure 2), at 12600N and Traverse A, running from the NW to the SE of the study area. The traverses intersect close to the centre of the mineralized area. Colluvium thickness varies from 1 to 8 m, being greatest in the western part of traverse 12600N.

2.2. Fender

Butt (1996)

Fender is approximately 2 km south of Big Bell, about 28 km WNW of Cue. It is hosted by a volcanic and sedimentary sequence in a steeply-dipping, strongly attenuated and overturned greenstone belt about 830 m wide. It is confined by granitic rocks to both east and west. The regional metamorphic grade is low to middle greenschist. Exploitable mineralization, estimated in 1997 at 248000t @ 2.4g/t Au, appears to be confined to the weathered zone, as a small 'laterite' resource in the southern part of the deposit, and weathered primary mineralization in saprock and saprolite (Figure 3). Primary mineralization is hosted by quartz-muscovite-potassium feldspar schists. In addition to Au, the primary mineralization is enriched in Ag, As, Sb, W, Mo, Tl, Zn and, surprisingly, Hg, a similar suite to that present at Big Bell.

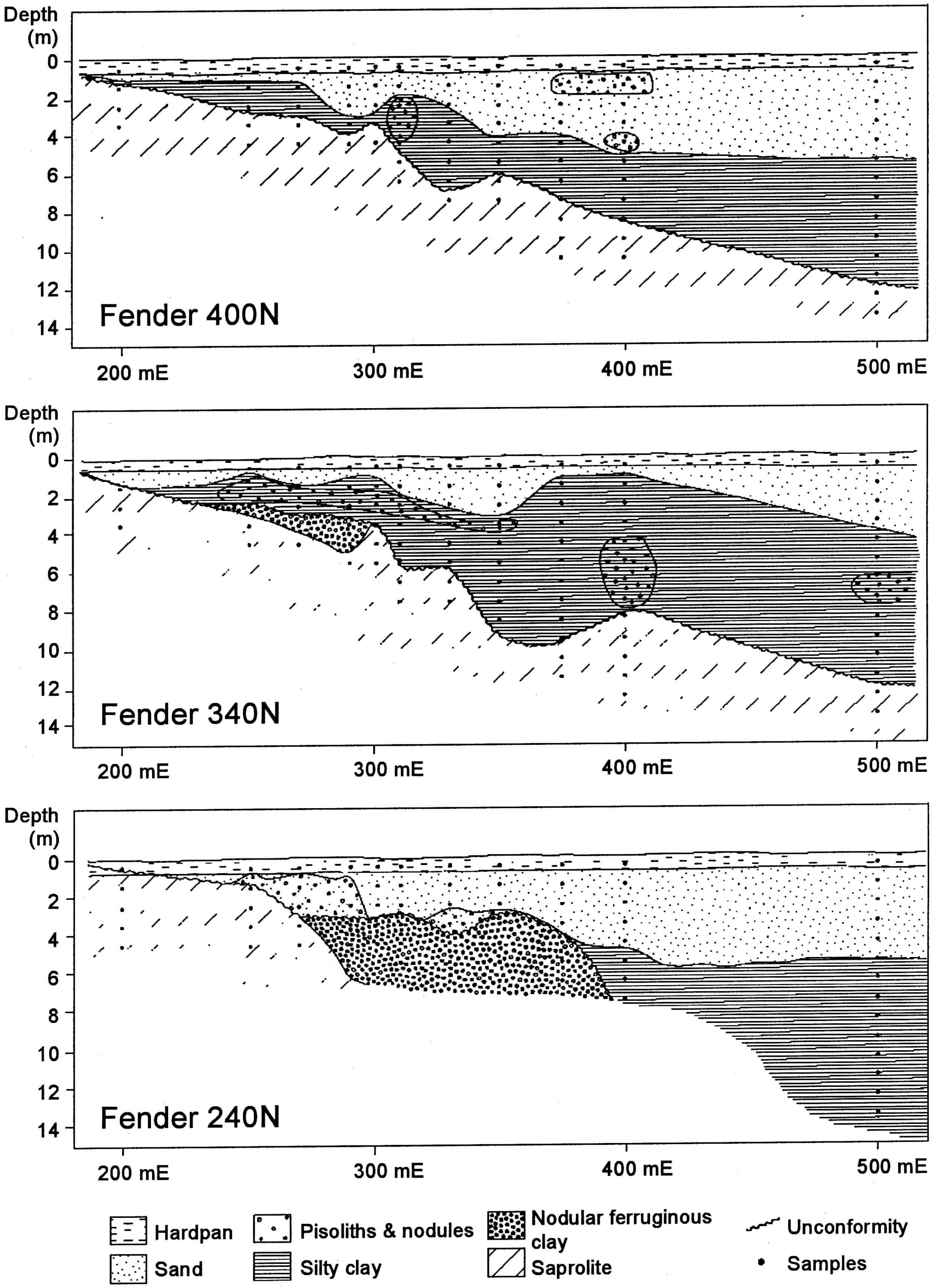

Figure 3: Regolith sections, Fender. 0 – 1 m samples were used for the extraction tests (from Butt, 1996).

The ferruginous nodular clays and ferruginous saprolite host the laterite resource in the south of the deposit, and are enriched in Au, As, Sb and, in part, W. Arsenic (100->300 ppm) and Sb (30->130 ppm) give the most widespread anomaly, which extends to the surface 200 m west of the deposit. Gold enrichment (100->6000 ppb) is also quite extensive, but has no surface exposure, whereas W (10-16 ppm) is confined to the centre of the ferruginous nodular clays, possibly indicating the position of the primary source.

Rocks in the vicinity of the deposit are weathered to 40-60 m depth. Nodular lateritic residuum, continuous with the buried nodular ferruginous clay, and saprolite both outcrop about 200 m to the west (Figure 3). The site is on the margin of a colluvial-alluvial plain which slopes gently to the north and east. The deposit itself is entirely overlain by a thin cover of transported overburden, although residual regolith is exposed within 200 m west of the mineralized unit. The sediments are 3 to 8 m thick over the deposit, thickening to over 13 m, 200 m to the east, with 1-5 m of fine- to coarse-grained sandy clay, sand and gravel, overlying 1-8 m of silty clays. Both the sands and, particularly, the silty clays contain detrital lateritic gravels. The sands are weakly silica-cemented in the top metre to form hardpan and some deeper sediments are mottled; there is no pedogenic carbonate. The sediments contain feldspar and are probably derived from the granites to the west.

Soil and hardpan over Fender are developed in the top metre of the sandy sediments (Figure 3). Over the laterite resource (240N), these sands are less than 3 m thick and the overlying soil/hardpan is weakly anomalous in Au (10-27 ppb compared to <5 ppb background). The As, Sb and W contents of the soils are at background abundances over mineralization, but As and Sb contents increase to the west, reflecting the contribution of shallowly buried and outcropping lateritic residuum to the soil. To the north, where the sands and silty clays overlie saprolite, Au, As, Sb and W are at background abundances although, again, As and Sb contents increase to the west.

The vegetation around Fender consists of scattered shrublands dominated by *Acacia* and *Eremophila* spp, with ephemeral grasses and herbs. The region is characterized by a warm semi-arid climate, with hot summers and mild to cool winters. The mean annual rainfall at Cue is 224 mm, with a weakly bimodal distribution (January-February and May-June).

Samples of the top 1 m from all three traverses (240N, 340N and 400N) were used for the partial extraction tests. The holes were specially drilled to avoid cross-over contamination.

2.3. Bronzewing

Varga *et al.* (1996)

The Bronzewing Au deposit is located in the Yandal Greenstone Belt, about 400 km north of Kalgoorlie at approximately 120°59.5′E 27°23.1′N. The deposit is situated on an alluvial plain adjacent to the Bates Creek drainage and slopes very gently NE in a broad undulating terrain of low relief. The few hills are secondarily silicified or relatively fresh Archaean greenstone sequences. Locally, greater relief is provided by breakaways. The climate is semi-arid, with hot summers and mild winters. The mean annual rainfall of 205 mm falls mainly in the summer months during erratic local thunderstorms. The area is subject to both drought and short-term floods.

Gold mineralization occurs within a sequence of mafic volcanics (basalts, dolerites) and minor sediments, which are intruded by felsic porphyries. The mineralization is associated with a dense stockwork of quartz veining and alteration of the host sequence, and is accompanied by pyrite, pyrrhotite and minor chalcopyrite and scheelite. The predominant foliation of the host rocks is N-S and primary mineralization generally follows this structural orientation.

The use of lateritic residuum and ferruginous saprolite sampling methods was an important factor in drawing initial attention to the area, eventually leading to the discovery of the Bronzewing Au deposit in 1992 by the Creasy-Great Central Mines N.L. Joint Venture. Drilling for buried geochemical halos in laterite included initial intersections of 4.65 g/t Au. Pre-mining reserves at Bronzewing were calculated to be 9.137Mt @ 4.6 g/t cut or 9.137Mt @ 5.7 g/t uncut. Four mineralized zones have been found - the Western, Central, Laterite, and Discovery, of which the later three are now pits. The buried lateritic residuum contains Au to ore grade, which sometimes extends into the colluvium.

The transported overburden consists of colluvium and alluvium and covers much of the weathered Archaean sequence (Figure 4). The thickness of the transported overburden reflects the palaeotopography. There are three principal units:

1. Red-brown sandy, silty, clay soils, 1 m thick, developed on the colluvium and alluvium.
2. Alluvial channel deposits, colluvial talus and sheetwash. The unit fines towards the top and can be subdivided into an upper silty and a lower gravelly component. Hardpanization is generally restricted to the upper silty component.
3. Fine silty lacustrine clays that appear to occupy a palaeochannel and have been subjected to intense post-depositional mottling.

Where fully preserved, the residual profile beneath the transported overburden has a 2-5 m thick lateritic horizon consisting of ferruginous gravels, mainly pisoliths and lithic nodules, set in a silty clay matrix. The nodules were formed by the fragmentation and collapse of the underlying ferruginous saprolite. The ferruginous saprolite, a few metres thick, grades downwards into saprolite. Fresh rock is encountered at 80 to 120 m depth.

Bulk soils were collected from 30-50 cm depth. The < 250 µm fraction consists mainly of aeolian silt-sized quartz, kaolinite and hematite. The hematite is present as fine sand to clay-sized particles, as fine coatings on quartz grains and, presumably, within the clay matrix. No significant concentrations of Au or pathfinder elements are present in the soil; the Au content rarely exceeds the detection limit of 5 ppb.

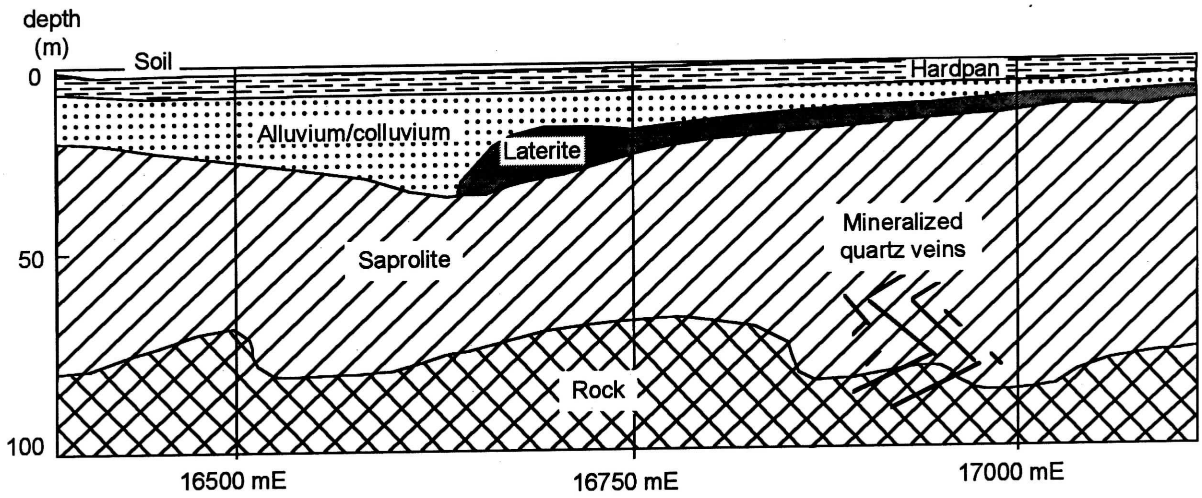

Figure 4: Regolith cross-section for Bronzewing traverse 9800N (modified from Varga *et al.*, 1996).

Size fractionation of the colluvium that occurs within 1 m of the residuum/colluvium interface, indicates that Au is concentrated in the > 2 mm fraction, and is depleted in the < 75 µm fraction, relative to the bulk sample. It can be inferred that the enrichment in the coarse fraction represents clastic dispersion of lateritic detritus. The palaeosurface represented by the unconformity has sufficient slope for the colluvium to have been derived from mineralized lateritic residuum upslope, thus accounting for the Au enrichment in the coarse fraction. There is no evidence to show that hydromorphic dispersion is currently accumulating Au, and the present fresh groundwaters are unlikely to be able to dissolve or disperse Au.

2.4. Curara Well

Gray (1996)

The Curara Well Au prospect is located some 420 km NNE of Perth and 70 km SSW of Mt Magnet. It is situated within the Wydgee Fold Belt immediately south of the Mount Magnet Greenstone Belt. Outcrop is extremely poor (< 1%). Exploration to 1997 identified a possible 100,000 oz laterite resource overlying mineralized bedrock. The prospect is located over a tonalitic porphyry stock that is bounded on its eastern side by a package of mafic amphibole schists. Detailed aeromagnetics have shown that the porphyry stock is cut by a number of NW-NNW trending fault splays off a regional shear that occurs to the east of the prospect. The laterite mineralization straddles one splay in particular, and the greatest tenor of mineralization is developed where a wedge of porphyry has been faulted off the main stock by this splay. The present day drainage system over the mineralized zone also follows this fault splay. Bedrock mineralization is present within both the porphyry fault wedge and the hanging wall mafic schists immediately to the east. The Au mineralization shows some association with thin (< 1 cm) quartz-actinolite veins. The overall percentage of sulphide (pyrite±pyrrhotite and trace chalcopyrite) associated with the mineralization is low (< 3%).

The majority of the prospect is covered by 0-10 m of alluvium and hardpanized colluvium, and 30 - 60 m of partially preserved lateritic regolith, with a deeper palaeochannel to the east (Figure 5). The buried residual profile is generally stripped back to lower laterite, nodular mottled zone or upper saprolite. The laterite mineralization is approximately 2.5 km S-N and 0.5 km W-E, and is dominantly hosted by the nodular mottled zone, with deeper supergene Au enrichment. The laterite outcrops in the south west corner of the anomaly, but over much of the deposit the laterite is covered by up to 10 m of sediments. Laterite Au enrichment defines the primary mineralization well.

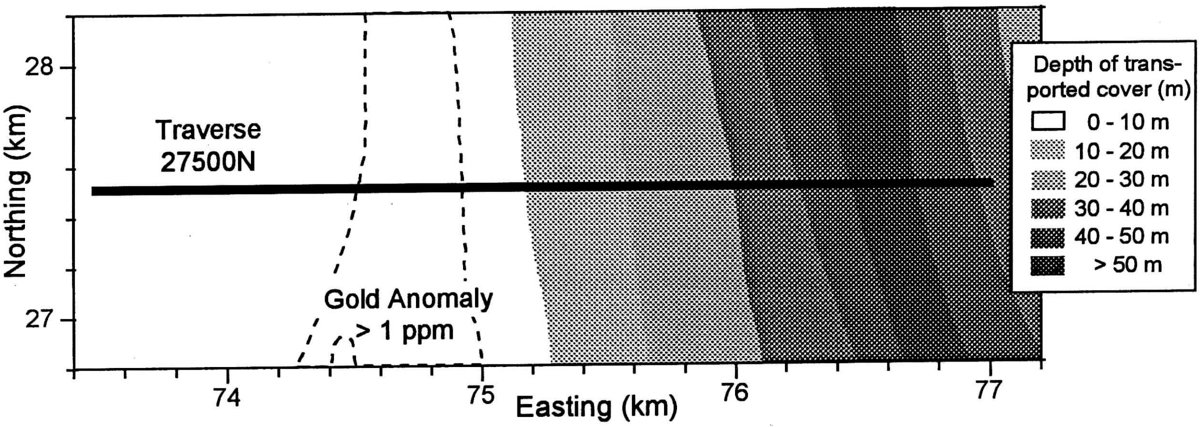

Figure 5: Main soil traverse, position of the laterite Au anomaly and depth of transported overburden at Curara (using data provided by CRA Exploration Ltd.).

The area has a semi-arid climate, with an average annual rainfall of approximately 230 mm. Rainfall variability is high and results mostly from frontal systems from the west and south-west in winter and from patchy, convectional storms and cyclone-related rain-bearing depressions in summer. Summers generally are dry and hot to very hot; winters are cool to mild, with a few frosts. The vegetation is dominated by mulga and turpentine and by various types of poverty bush (*Eremophila* spp).

The soils were collected by spade, after scraping away the top 1 to 2 cm, including litter and humus, to approximately 20 cm depth. Three traverses were used for a previous study (Gray, 1996), of which one, at 27500N (Figure 5), was used in this investigation.

2.5. Safari prospect, Mt Celia

Bristow *et al.* (1996)

The Safari Prospect is located 200 km NNE of Kalgoorlie and 9 km NE of the margin of Lake Raeside and is situated on a broad, sandy, colluvial valley which slopes gently SW. The vegetation is medium to dense woodland of *Acacia* and *Eucalyptus* spp. The climate is semi-arid, and the mean annual rainfall of 200-250 mm falls variably throughout the year, resulting from frontal systems in winter, or convectional storms and cyclone-related depressions in summer.

The bedrock geology of the Safari Prospect consists of a greenstone assemblage comprised of a wide variety of volcanic and volcaniclastic rocks. These rocks are heterogeneously deformed and generally strike NNW and have nearly vertical to WSW dipping tectonic foliation, and sub-horizontal to down-dip mineral lineation. Porphyritic syenite, coarse granodiorite and ademellite intrude the greenstone sequence, which has been metamorphosed to amphibolite facies beside the larger plutons. Elsewhere, the regional metamorphism is lower greenschist facies.

Drilling to 1997 indicated a resource of 1.08Mt @ 3.3g/t Au. The mineralization is hosted by andesite to dacite metavolcanic rocks, now largely represented by quartz-chlorite-sericite ± carbonate schists that are bound to the west and east by serpentinized komatiite and talcose schists. Gold is primarily associated with quartz veins within an anastomosing shear. High concentrations of Au (maximum 31 ppm) are usually accompanied by enrichments of Pb (maximum 1100 ppm), although, in general, correlation with grade is not particularly good. Not specifically related to Au grade are general enrichments of As (maximum 1000 ppm), S (maximum 1.1 %) and W (maximum 79 ppm).

Most of the residual regolith consists of saprolite with a variable clay content, although in isolated areas in the north of the prospect, there are deep profiles with highly ferruginous upper horizons. Incipient mottling is present throughout the saprolite and the upper few metres are commonly indurated by silica and/or carbonate. Fresh rock is generally encountered 10 - 20 m below the unconformity. Anomalous Au occurs in the saprolite just below the unconformity (Figure 6), especially where it directly overlies primary mineralization (eg. 1200 ppb in a quartz vein from the top 2 m of the saprolite). The mean Au contents of the top 1 m give a very strong anomaly peaking over mineralization (1000 ppb), with a reasonably elevated and noisy background (10 - 50 ppb).

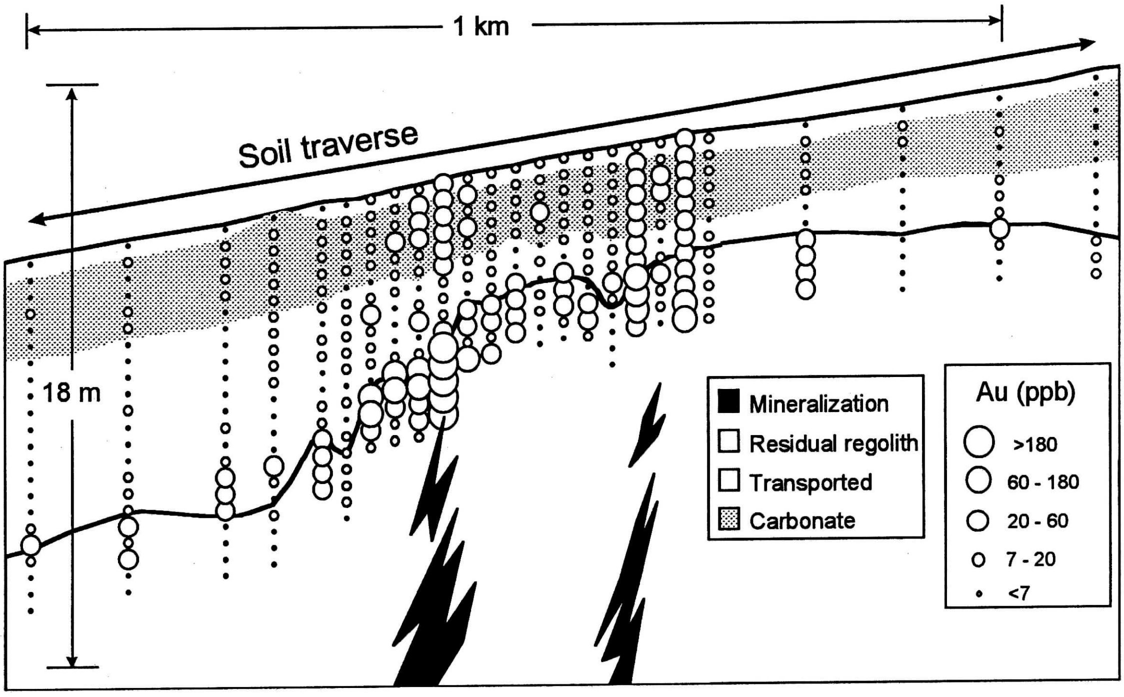

Figure 6: Soil traverse, regolith and mineralization at Safari, traverse 6732300N (from Bristow *et al.*, 1996).

The study area is completely blanketed by transported overburden except in the small area coinciding with the palaeohigh, where almost fresh Archaean bedrock outcrops. There is a uniform distribution of sheetwash and aeolian sand up to 1 m thick at the surface. The composition of the sediments is variable, and the thickness, including the sheetwash, is generally 5-10 m, reaching 20 m in the northern palaeovalley. The sediments below the sheetwash are a polymictic assemblage containing 2 - 10% coarse material, commonly towards the base, in a matrix of sand, silt and, in places, clay. The coarse fraction comprises angular, weakly weathered rock fragments near to the mineralization and indeed over most of the area, except in the northern palaeovalley where there is a mixture of ferruginous pisoliths, nodules and lithorelics. In places, drilling has intersected narrow lenses of coarse alluvial sand and gravel.

Post-depositional modification of the sediments is widespread; most significant is the widespread calcification from about 0.5 to 5.0 m below the surface. Beneath the zone of intense calcification, the sediments are commonly moderately to strongly indurated by silica and Fe oxides. Anomalous Au (22 - 60 ppb) is also present in the carbonate horizon, with enrichment strongest from approximately 0.5 - 2.5 m depth directly over mineralization. Concentrations of Au (>7 ppb) above background occur in the calcareous horizon for over 800 m across strike of the mineralization. Even in the top half metre, an anomaly with excellent contrast peaks directly over the primary mineralization, with concentrations exceeding 5 ppb for over 600 m across strike. Despite having higher absolute Au contents, preferentially sampled highly calcareous fragments do not increase anomaly contrast and the Au/Ca ratio in these is consistently lower than a bulk sample from the same interval.

The soil traverse used for the partial extraction study is shown in Figure 6.

2.6. Steinway

Lintern and Gray (1995a)

The Steinway prospect is located about 27 km SSW of Kalgoorlie at approximately 121°29'E 30°58'S. It is located adjacent to the regional contact between mafic-ultramafic rocks of the Saddle Hills Greenstone Belt, and the overlying intermediate to felsic volcanics and sedimentary rocks of the Black Flag Group. Mineralization at Steinway is twofold; *primary* mineralization is associated with quartz stockwork veining within mafic andesites/amphibolites, and *supergene* mineralization is located below a palaeochannel.

Climate is semi-arid with an unreliable mean annual rainfall of 280 mm. Vegetation consists of open woodland of *Eucalyptus* spp. and a sparse understorey that includes *Maireana* (bluebush). Steinway is located on a flat depositional plain, with higher areas rarely rising 5 m above it. Approximately 1 km to the S, an erosional area composed of mafic saprolite hosts the nearby Penfold Au mine and, 400 m to the W, another palaeochannel hosts the Greenback Au deposit. Present day ephemeral channels cross the depositional plain, generally flowing N to White Lake, a playa about 10 km distant. The ephemeral channels separate the Steinway and Penfold soil anomalies.

Fresh rock is encountered at about 50 m depth, with about 20 m residual regolith, consisting of saprolite, becoming more clay-rich towards the top (Figure 7). This is overlain by four sedimentary units. There is a basal sand and silty clay unit, between 25 and 30 m depth, overlain by massive clays between 5-25 m depth that contain zones of Fe-rich material such as mottles. A non-calcareous clay containing large amounts of ferruginous granules occurs between 2 and 5 m depth, and the uppermost unit consists of calcareous, clay-rich red soil with abundant ferruginous granules.

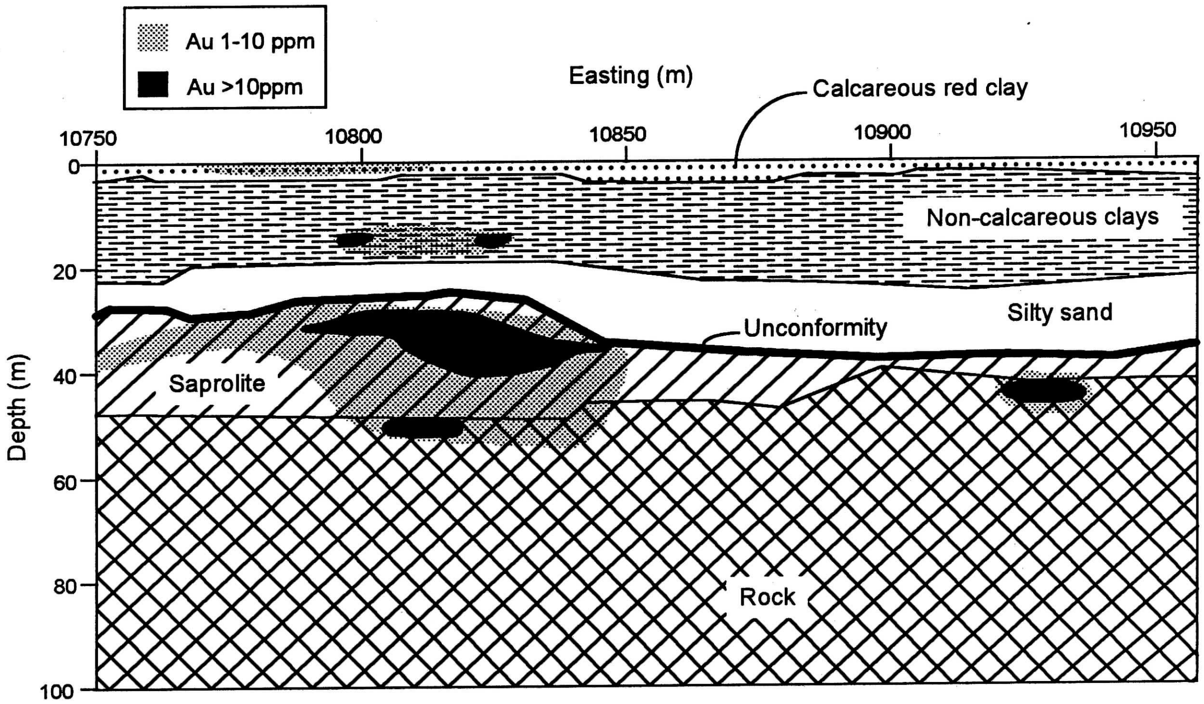

Figure 7: Soil traverse location, regolith and mineralization at Steinway line 4250N (modified from Lintern and Gray, 1995a).

Gold and Ca are probably associated in the upper horizons. Iron concentrations gradually increase with depth and, in the lower profile (below 0.5 m), Au may be associated with Fe. The Au anomaly in 0 - 1 m composite samples from Steinway reaches 150 ppb against a background of less than 20 ppb. The anomaly is over 150 m wide in an E-W direction and stretches over 1 km to the NW, following the direction of the palaeochannel, and appears spatially correlated to underlying mineralization (Figure 7). However, the presence of detrital broken pisoliths, lithic nodules and other transported fragments, and the random concentration of Au in these granules all suggest that the apparent association is coincidental. There are also high concentrations of Fe coincident and adjacent to the Au soil anomaly, and Cr, As, Sc and Sb appear to be associated with Fe. The REE, Zn, Co, and possibly Ni, tend to be associated with Mn.

Groundwaters at Steinway vary from moderately acidic (pH 5.8) to highly acidic (pH 3.4) and are saline. Halides (chloride and/or iodide) are important mechanisms for Au dissolution in such groundwaters. The groundwaters are also enriched in Al, Si, Mn, Fe, Co, Ni, Cu, Zn, Yb, Pb and REE, with the most acid groundwaters also enriched in U. These enrichments commonly occur where acid groundwaters contact mafic rocks. Anionic chalcophile elements, As, Mo, W, Sb and Tl are at low concentrations.

2.7. Apollo

Lintern and Gray (1995b), Lintern (1996)

Apollo is approximately 25 km SE of Kambalda, and 2 km E of Lake Lefroy, located in the western limb of the St Ives Antiform. The local bedrock consists of the Paringa Basalt, the Black Flag Group and the Condenser Dolerite, all of which strike NE, dip 70 - 80° SW and are metamorphosed to low grade. Mineralization is encountered at about 15 m depth and dips to

760 m or more to the W. It is confined to bedrock and saprolite, and is associated with albite alteration products within two NNE-trending mylonitic shear zones.

There is a palaeochannel 250 m to the S, where it cuts approximately E-W across the nearby Argo deposit. The U-shaped palaeochannel has a maximum depth of 60 m and average width of 400 m, and has been incised into the residual profile. The residual regolith profile consists of variably coloured, dark, clay-rich saprolite (Figure 8). The saprolite is generally between 20 - 30 m thick, though it is thinner beneath the palaeochannel. Gold contents of deeper saprolite exceed 500 ppb close to mineralization. The saprolite is covered by a unit of hard red and grey clays, with variable ferruginous mottling. This unit contains zones of indurated ferruginous and siliceous material, forming pans of variable thickness, generally between 2 and 7 m depth. It is covered by a calcareous clay-rich red soil, up to 2.0 m deep, that has a dark manganiferous horizon at 1.5 m depth. The soil is characterized by locally abundant calcrete nodules, 1-2 cm in diameter. Carbonates also coat the clays and lithorelics in the soil, and forms cutans on the nodules. Sandy aeolian topsoil, about 0.2 m thick, but up to 2 m thick in places, covers the calcareous soil

The climate is semi-arid with an unreliable average annual rainfall of 280 mm. Vegetation is sparse and composed of open woodland of *Eucalyptus* spp., the occasional *Casuarina* (she-oak), and small shrubs including *Eremophila* (poverty bush) and *Maireana* (bluebush). The landscape is typical of the floodplains bordering the salt lake regimes of the region. A broad colluvial plain with occasional clay pans drains the study area to the SW towards Lake Lefroy, where dunes cover large areas.

Ferruginous materials, including sediments and lithorelics, taken from the transported overburden have Au concentrations close to, or below, the detection limit of 5 ppb. However, Au concentrations are slightly higher (7 and 10 ppb) in the south, where depth to mineralization is less. Gold concentrations are not related to Fe content, which varies from 18 to 31%. The highest concentrations of Au appear in the calcareous horizon. Arsenic is not significantly associated with mineralization, and As concentrations are generally low. In contrast, Zn concentrations are strikingly elevated in soils over mineralization (maximum 540 ppm).

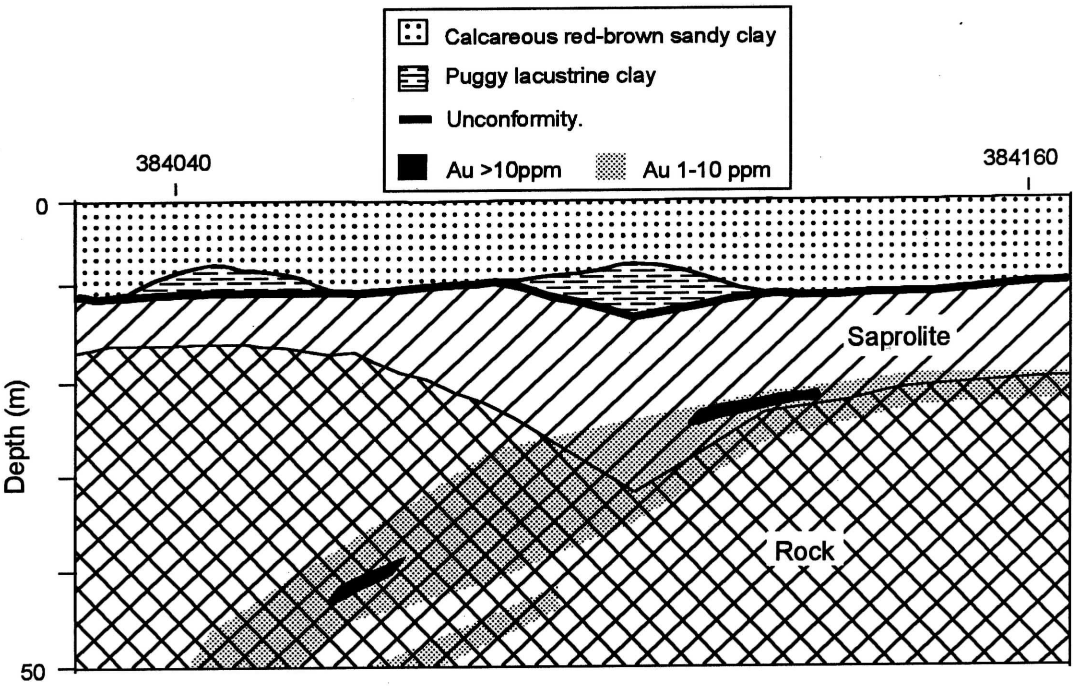

Figure 8: Soil traverse location, regolith and mineralization at Apollo line 526080N (modified from Lintern, 1996).

Groundwaters in this area are acid and highly saline; salinity and pH both increase with depth (about 5-8% TDS, pH 3.5-4.0 for shallow samples, and 19-26% TDS, pH 4.5-5.5 for deep samples). Major element abundances suggest the waters have been evaporated within a salt lake environment. Dissolved trace element compositions are very similar to Steinway (Section 2.6). The only element enrichments that appear associated with mineralization are Mo, which has relatively high concentration for an acid groundwater, and Co, Ni and Au. Halides (chloride and/or iodide), are expected to be an important mechanism for the dissolution of Au in such groundwaters.

A cross-section of the regolith for the traverse used for the extraction tests is shown in Figure 8.

3. Methods

3.1. Sample collection and preparation

Samples from each site were taken on traverses across buried Au mineralization (Section 2). Samples from Safari, Apollo and Curara were collected in calico bags, air dried and then stored in plastic. Samples from Fender, Bronzewing, Baxter and Steinway were collected into plastic bags and air dried (Table 1). Samples were sieved to < 2 mm and then riffle split into four aliquots for analysis by MMI, enzyme leach, HCl extraction and sequential partial extraction.

Table 1: Summarized sample treatments

Site	Sample	Treatment	Storage
Baxter	5 - 20 cm (spade)	plastic bag air dry	sealed plastic bags
Fender	0 - 1 m (drilled)	plastic bag air dry	sealed plastic bags
Bronzewing	30 - 50 cm (spade)	plastic bag air dry	sealed plastic bags
Curara	2 - 20 cm (spade)	calico bag air dry	sealed plastic jars
Safari	2 - 50 cm (drilled)	calico bag air dry	sealed plastic bags
Steinway	0 -1 m (power auger)	plastic bag air dry	sealed plastic bags
Apollo	0 -1 m (drilled)	calico bag air dry	sealed plastic bags

3.2. Sequential selective extractions

The three methods, as described below, were performed at the CSIRO laboratories in Perth, and are observed to be commonly highly selective for particular mineral phases in soils (Chao, 1984). Five grams of sample were weighed into a centrifuge tube and then sequentially extracted by the methods described below:

3.2.1. pH 5 acetate (carbonates and surface adsorbed metals)

The sample was shaken with 95 mL 1 mole/litre (M) ammonium acetate at pH 5 for 6 hours. The mixture was then centrifuged (4000 rpm, 15 minutes) and the supernatant decanted. The extraction was repeated. The solid was then mixed with 10 mL 0.1 M ammonium chloride and centrifuged. The aliquots were combined for analysis by Inductively Coupled Plasma – Mass Spectroscopy (ICPMS) for Ag, As, Au, Be, Ba, Bi, Ca, Cd, Ce, Co, Cr, Cu, Fe, Hg, Li, Mn, Mo, Ni, Pb, Pt, Sb, Se, Sn, Te, Th, Tl, U, W, Zn and Zr.

3.2.2. 0.1M hydroxylamine (Mn oxides)

The residual solid from the extraction was then mixed with 90.0 mL 0.1 M hydroxylamine hydrochloride in 0.01 M HNO_3 for at least 30 minutes. The mixture was centrifuged and the supernatant decanted and analysed by ICPMS for the same suite of elements as the pH 5 extraction (Section 3.2.1).

3.2.3. 0.25M hydroxylamine (amorphous Fe oxides)

The residual solid from the extraction was then mixed with 90.0 mL 0.25 M hydroxylamine hydrochloride in 0.25 M HCl at 50°C for at least 30 minutes. The mixture was centrifuged and the supernatant decanted and analysed by ICPMS for the same suite of elements as the pH 5 extraction (Section 3.2.1).

3.3. HCl extractions

HCl extractions were performed by Ultra Trace Pty Ltd. Four grams of sample was digested in 8 mL 4 M hydrochloric acid (HCl) at 15°C for 4 hours. The solution was then analysed by ICPMS for the same suite of elements as the pH 5 extraction (Section 3.2.1), less Cr. There was also a separate extraction using concentrated (10 M) HCl. In addition, extra extractions were performed with an added oxidizing agent, giving an "enhanced" Au digest.

3.4. Mobile metal ion analysis

The Mobile Metal Ion (MMI; ® Wamtech Pty Ltd) process uses two leachant solutions to dissolve target metals (Mann *et al.*, 1995). The technique involves acid solution analysis by ICPMS for Cd, Cu, Pb and Zn and alkaline solution analysis by ICPMS for Ag, Au, Co, Ni and Pd. The extractions and analyses were performed by Analabs Pty Ltd, using approximately 100 g for each of the two extractions.

3.5. Enzyme Leach analysis

Enzyme Leach, done by Activation Laboratories Ltd, utilizes a reaction between glucose oxidase and dextrose to produce low concentrations of hydrogen peroxide to partially leach amorphous Mn oxides (Clark, 1993) from soils. Extracts were analysed by ICPMS for Ag, As, Au, Ba, Bi, Br, Cd, Ce, Cl, Co, Cs, Cu, Dy, Er, Eu, Ga, Gd, Ge, Hf, Hg, Ho, I, In, Ir, La, Li, Mn, Mo, Nb, Nd, Ni, Os, Pb, Pd, Pr, Pt, Rb, Re, Ru, Sb, Sc, Sm, Sn, Sr, Ta, Tb, Te, Th, Ti, Tl, Tm, U, W, Y, Yb, Zn and Zr.

3.6. Iodide extraction analysis

Iodide extraction, done at the CSIRO laboratories in Perth, targets highly soluble Au, which is most probably in chemical form (Gray *et al.*, 1998). The extraction solution is 1 $\underline{M}$ sodium bicarbonate / 0.1 $\underline{M}$ potassium iodide, saturated with CO_2 and adjusted to pH 7.4 with hydrochloric acid. A soil:solution ratio of 1:2 g:mL is used and the mixture gently rolled for 7 days. Activated carbon is added to the mixture to absorb all dissolved Au and the carbon analysed at the end of the extraction, thus determining all Au dissolved during the extraction (and removing any readsorption problems).

4. Comparisons between methods

4.1. Sequential selective extractions

The selective extractions are generally successful at specifically dissolving certain minerals or phases. The pH 5 reagent extracts ALL of the Ca from the carbonate-rich Kalgoorlie sites (*i.e.*, Steinway and Apollo) and the low soil carbonate Safari and Curara sites, though less Ca is extracted in the Northern sites, where some to all of the Ca is as non-carbonate minerals. Other elements partially {bracketed} or mostly to wholly extracted by this reagent are As (Kalgoorlie sites) Ba, {Be}, Cd (Kalgoorlie), {REE}, {Cr}, {Cu} (Kalgoorlie), {Li} (Kalgoorlie), {Mn}, {Ni} (Apollo), {Pb}, Th, U and Zn (Apollo). For a number of these elements, particularly As, REE, Th and U, only a small proportion were extractable by any reagent, so this comment relates to that proportion of the extractable component dissolved by pH 5 acetate. Manganese dissolved by the pH 5 acetate reagent may represent Mn within carbonates, separate-phase $MnCO_3$, or very soluble Mn oxides (as represented in Figure 9).

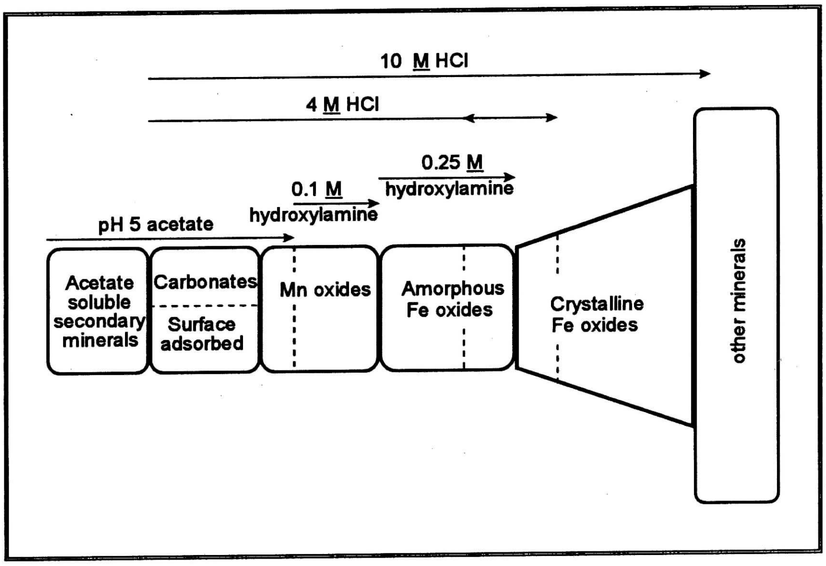

Figure 9: Diagrammatic representation of the phases dissolved by selective and acid extractions.

The second extraction, 0.1 M hydroxylamine, dissolves separate phase Mn oxides. Plotting extractable (sum of all 3 sequential extractions) vs. total Mn (Figure 10) indicates an approximately linear relationship at each individual site, with a residual of unextractable Mn, that varies from approximately 100 ppm at Apollo to 500 ppm at Baxter. Other elements partially {bracketed} or mostly to wholly extracted are {Au} (Steinway), {Ba}, Co, {Ni}, {Pb} (Bronzewing and Baxter) and {Tl} (Bronzewing). The low number of elements substantially dissolved by this reagent is surprising, given the accepted capacity of separate phase Mn oxides to be major sinks for metals. The extractable Mn broadly correlates with total extractable Fe (Figure 11), even though these two elements are dissolved by different reagents, suggesting a secondary cause for these two phases, such as presence of a drainage channel, or particular biological effects. Thus, a number of extractable metals can correlate with total and extractable Mn, even though amorphous Fe oxides host most of these elements, but show no correlation with TOTAL Fe.

The 0.25 M hydroxylamine reagent dissolves 'amorphous' Fe oxides. Although only a very minor proportion of the total Fe is dissolved, there is good agreement between Fe dissolved by the selective extractions and 4 M HCl, suggesting dissolution of specific Fe-rich components, be they separate phase minerals or disordered surfaces. Other elements partially {bracketed} or mostly to wholly extracted with amorphous Fe oxides are Ag, {Ba}, Be, {Cd}, {Co}, Cr (Safari and Kalgoorlie), Cu, Li (Kalgoorlie), {Mn}, Ni, Pb, REE, {U} and {Zn}.

4.2. HCl extractions

There are two separate (not sequential) reagents. The first, 4 M HCl, dissolves similar elemental concentrations to that of the sum of the sequential extractions. Minor exceptions were observed for Co, Ce, Ba, and Fe for Fender and Safari, possibly due to granite-derived material at surface. In Figure 9, the variation in Fe dissolved by 4 M HCl (relative to the sequential extractions) is represented by the double-headed arrow: *i.e.*, incomplete dissolution of the amorphous Fe by 4 M HCl in some cases, and partial dissolution of crystalline Fe for other samples.

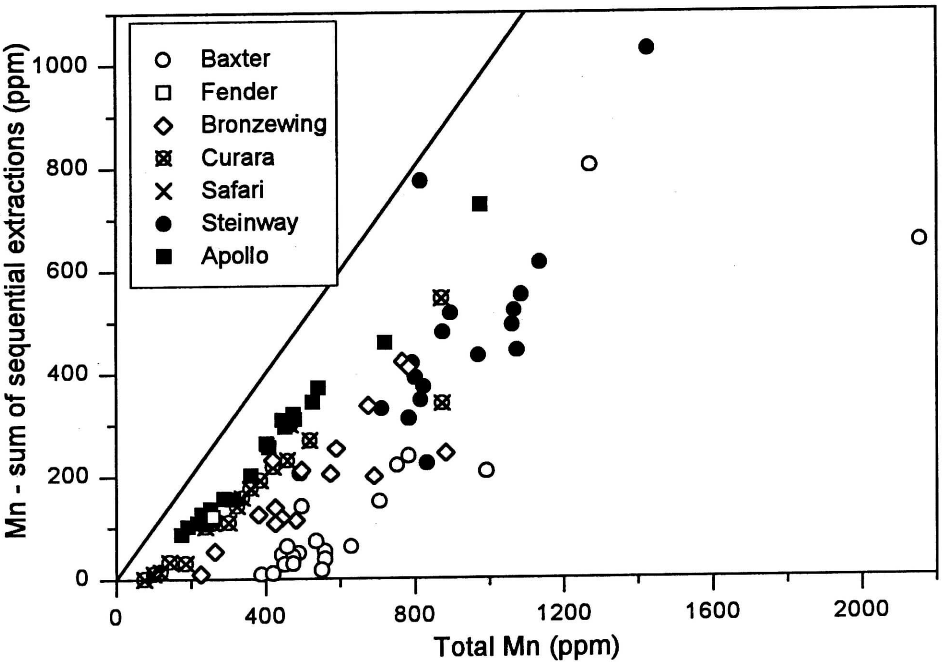

Figure 10: Sequentially extracted Mn vs. total Mn for all sites

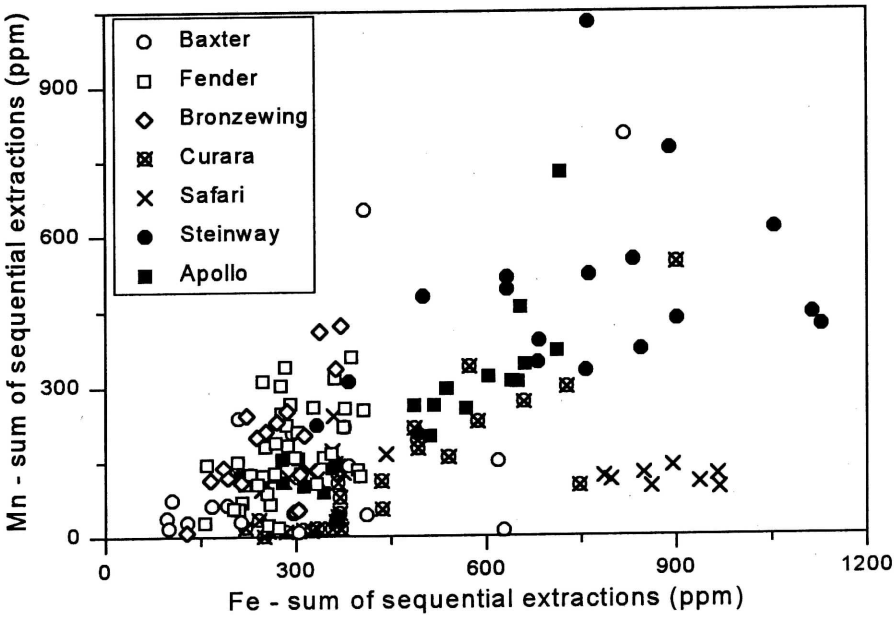

Figure 11: Correlation between Mn and Fe extracted by the three sequential extractions.

The 10 M HCl reagent extracts 10 - 50 times more Fe than 4 M HCl and commonly dissolves 5 - 30% of the total Fe. Other elements for which moderately {bracketed} or significantly more was extracted by 10 M HCl than for 4 M HCl are {Ag} (Fender and Apollo), As, {Ba} (Baxter and Bronzewing), {Ca} (Safari), {Cd}, {Co} (Fender), {Cu} (Northern and Central), Hf (though still

≤ 0.1% of total), Mn (Northern), Mo, Nb, {Ni} (Central and Northern), Pb, {REE}, Sb, Se (Baxter, Fender, Bronzewing and Safari), Sn, Th, Tl, {U} (Northern and Central), W and Zn.

4.3. Mobile metal ions

MMI is two separate techniques. The first, an acid extraction for Cd, Cu, Pb and Zn, gives results that are similar, in terms of comparison between samples at each site, to HCl and selective extraction. In general, the carbonate-rich Kalgoorlie sites give much lower MMI responses, relative to other reagents, possibly due to carbonate neutralizing the acid MMI reagent and reducing metal solubility.

The second method is an alkaline extraction for Ag, Au, Co, Ni and Pd, which gives virtually identical Au results to the Iodide and enhanced HCl extractions. In soils containing significant carbonate (Safari, Steinway and Apollo), these extractants dissolve 70 - 80% of the total Au (Figure 12), whereas the proportion of Au extracted in the northern sites is significantly lower, probably because of occlusion of Au. MMI is also very effective at dissolving Ag, as expected for a method optimized for Au. Thus, the MMI extraction is not giving any additional information for Au or Ag that can not be obtained using total or standard (*e.g.*, cyanide or *aqua regia*) analyses. Probably because this MMI extraction is done under alkaline conditions, the Co data are unlike those observed for other techniques. For all elements except Co and Ni, MMI gives much greater (generally by at least 5 times) extraction than Enzyme Leach.

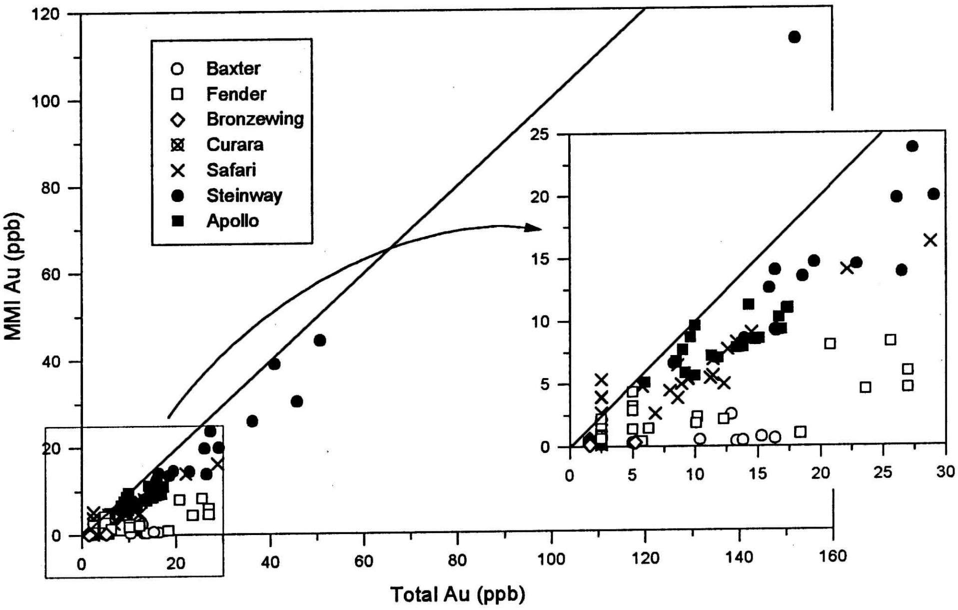

Figure 12: MMI Au vs. total Au for all sites

4.4. Enzyme Leach

The Enzyme Leach reagent is targeted at an 'amorphous' Mn phase, although the proportion of Enzyme Leach Mn varies dramatically between sites (Figure 13) from about 20% at Bronzewing to < 0.5% at Steinway. Except for Enzyme Leach Co, no other element shows any clear correlation with Mn. In general, Enzyme Leach element results are not correlated with other methods, and a much larger range of elements is determined than for MMI. However, a number of Enzyme Leach elements, namely Cs, Fe, Ga, Hf, La, Nb, Pb, REE, Sc, Sn, Th, Ti and Zr, show very close linear correlations. Most of these elements tend to be high-charge, with only low concentrations (except for Fe). This suggests either a highly specific interaction between these elements and Fe within the soil phase(s) dissolved by Enzyme Leach or an analytical interference from Fe. This effect should be understood before these elements are routinely used.

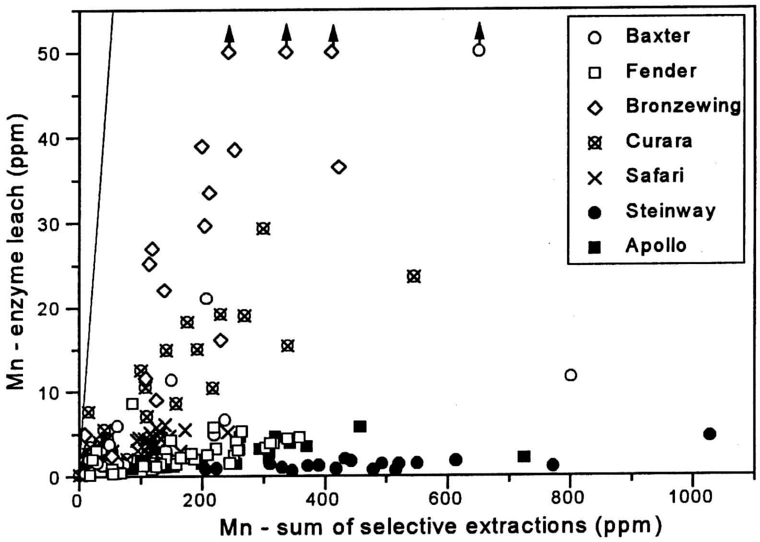

Figure 13: Enzyme Leach vs. selective extractions for Mn.

4.5. Iodide extraction

As indicated above, the Iodide extraction for Au gave similar results to both HCl and MMI extractions, with particularly high proportional Au solubility (70+%) for carbonate-rich soils. This indicates that reworking of Au in these soils is creating a substantial pool of highly soluble Au that is extracted by a wide range of solutions. Therefore, these extractions are giving little, if any, extra exploration information than total, *aqua regia* or BLEG Au.

5. Comparison of sites

5.1. Baxter

Two traverses were used at this site. With the exception of Au, no elements appear to give useful exploration data. The Harmony deposit has 0.5 - 3 m of colluvium over mineralized ferruginous saprolite, and there has been sufficient mechanical or biological mixing to bring some Au to the surface. There is up to 15 ppb Au in soils over mineralization, and MMI and HCl digests both give useful results (Figure 14). However, these reagents dissolve most of the accessible Au, and presumably, total Au, *aqua regia* or CN digests would give equivalent results.

There is a higher concentration of Mn oxides for the most easterly sample on both traverses, although the multi-element responses differ: one of these anomalous samples is enriched in a number of elements using various extractants, namely Ag, Cd, Ce, Co, Cu, Fe, Mn, Ni and Zn; whereas the other sample is anomalous in Ce, Cu and Mn only. The reason for the differences is not known, but the critical observation is that they appear to represent FALSE positives: *i.e.*, a positive soil response that is unrelated to any mineralization. Enzyme Leach I and Cu and MMI Ni weakly correlate with mineralization (Figure 15) on one of the two traverses. However, the poor repeatability, the lack of any clear reason for I, Cu and Ni correlating with mineralization, and the strong false positives, suggest these correlations are accidental.

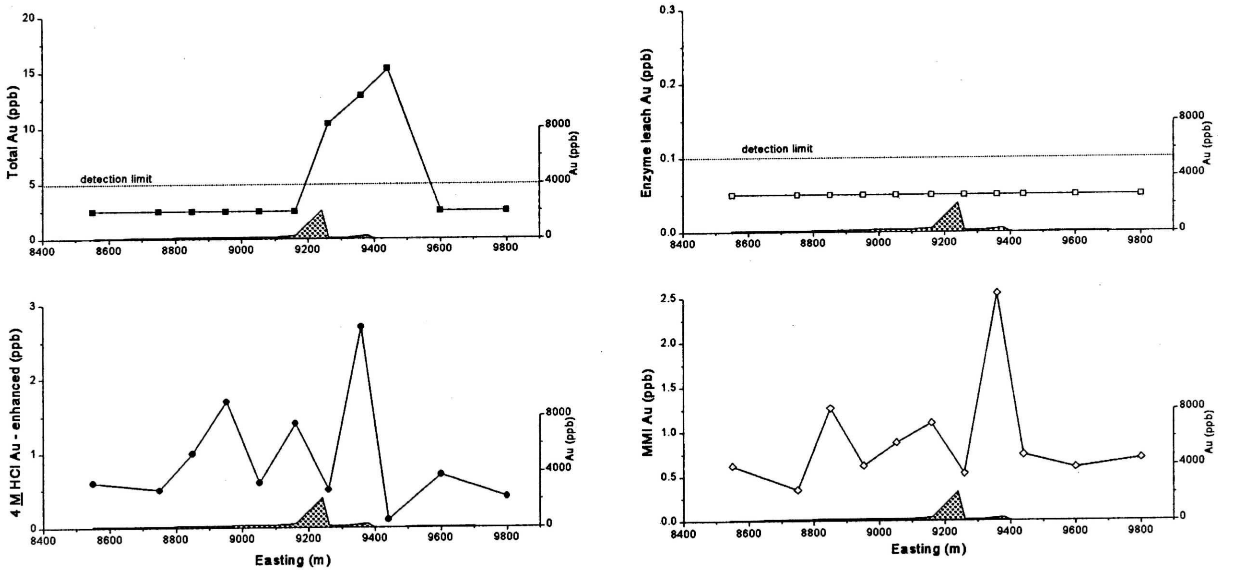

Figure 14: Total, 4 M HCl, Enzyme Leach and MMI extractable Au for Baxter 12600N traverse. (Shaded area represents Au content in overburden-saprolite unconformity).

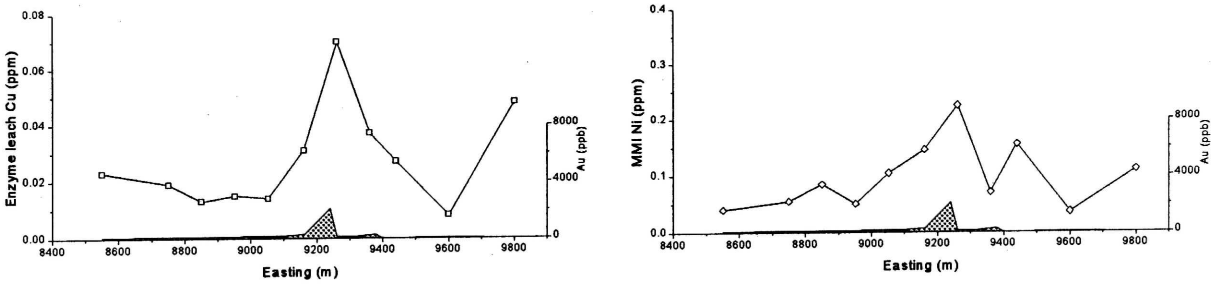

Figure 15: Enzyme Leach Cu and MMI Ni for Baxter 12600N traverse. (Shaded area represents Au content in overburden-saprolite unconformity).

5.2. Fender

This site has 2 - 8 m of sand and silty clay over mineralization (in saprolite or lateritic residuum). Primary mineralization contains Au, Ag, As, Sb, Cu, W, Hg and Mo. Three traverses were used, including one in which the saprolite is depleted in Au. The total and extractable (not Enzyme Leach) Au in the soils peak over mineralization for the Au-rich traverse (240N; Figure 16), which (as at Baxter) is probably due to the thin cover. Total, 4 M HCl, 10 M HCl and MMI Au all give virtually identical distribution patterns for the soil traverses. No other elements (total or extractable) are correlated with mineralization. Concentrations are comparable for all 3 traverses, despite the major variation in the magnitude of mineralization at the unconformity for the three traverses. This poor success includes extractions possibly successful at other sites (*e.g.*, Enzyme Leach Cu and I, MMI Ni).

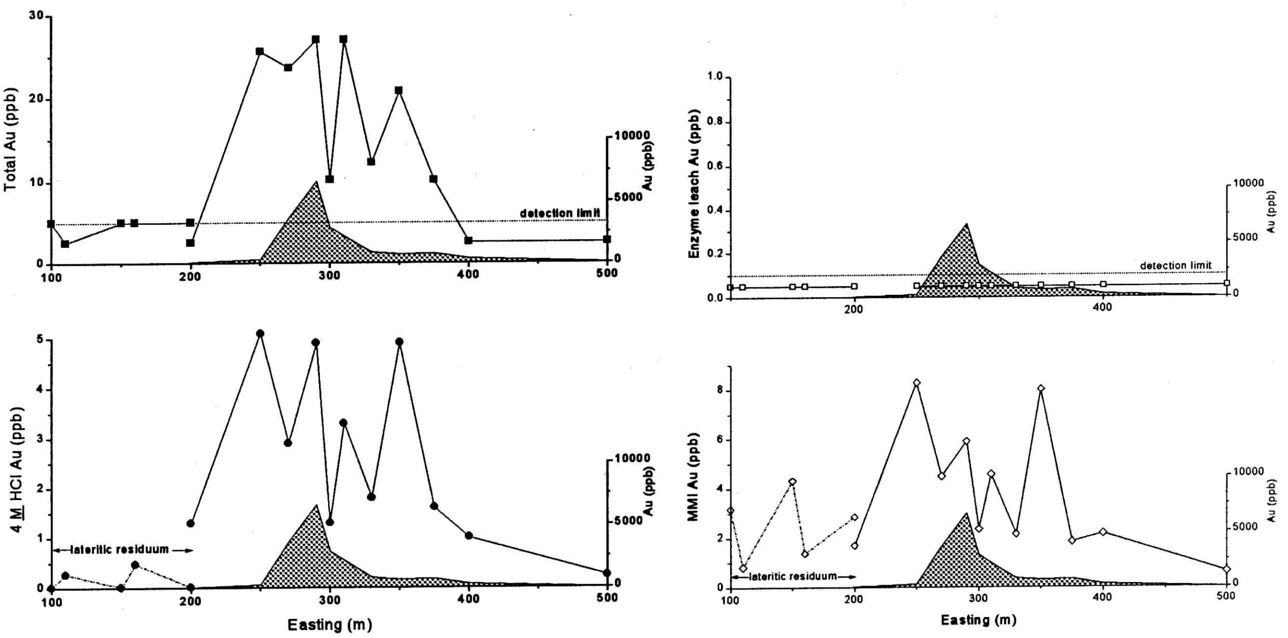

Figure 16: Total, 4 M HCl, Enzyme Leach and MMI extractable Au for Fender 240N traverse. (Shaded area represents highest determined Au content in top 8 m).

A strong soil anomaly is observed for the eastern-most sample of the Au-poor traverse, which shows high concentrations of Ag (up to 480 ppb, background < 40 ppb), Cd (180 ppb), Cu (12 ppm), Pb (45 ppm), Zn (7 ppm) and, to a lesser extent, W (5 ppm), generally observed for all of the extraction methods. For this sample the MMI reagent dissolves a highly significant proportion of the base metals: MMI to 10 M HCl (the most extreme extractant used) ratios are Ag (38%), Cd (42%), Cu (16%), Pb (5%) and Zn (55%). This sample appears to be a FALSE positive anomaly.

5.3. Bronzewing

Mineralization at Bronzewing is covered by 5 - 25 m of colluvium and alluvium derived from distal sources, with no significant Au anomaly at surface. Enzyme Leach Cu correlates (weakly) with mineralization (Figure 17), though this could be coincidental as Cu is not associated with mineralization at depth. Enzyme Leach Co and Mn are higher than elsewhere, and Co is correlated with Mn for most of the extraction methods. At this site, there is an active major drainage that is not coincident with the mineralization (compare with Curara; Section 5.4) and the geochemical signal is stronger in the channel than over mineralization (*i.e.*, a FALSE positive). This is possibly related to Mn in hardpan precipitated within the drainage channel.

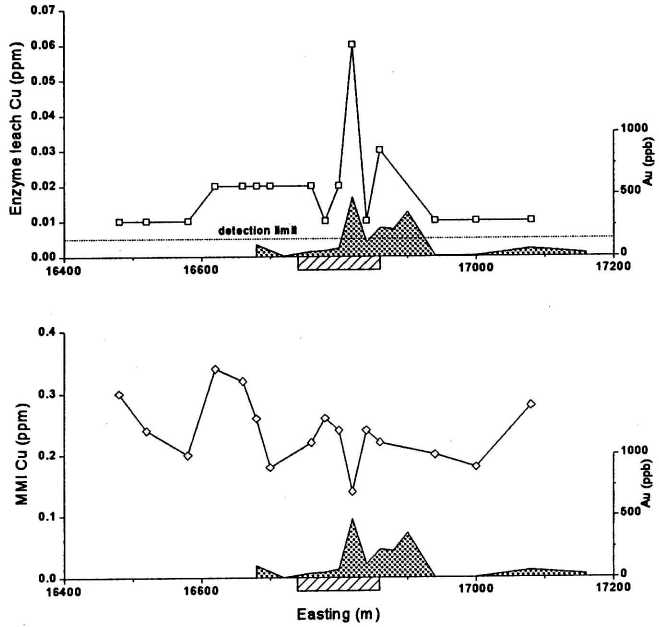

Figure 17: Enzyme Leach and MMI Cu from Bronzewing line 9800N. (Shaded area is lateritic Au concentration and hatched area is position of mineralization at 100 m depth).

5.4. Curara

At Curara an active drainage system overlies the buried mineralization. Soils in the drainage have high concentrations of separate phase Mn oxides (up to 500 ppm Mn; Figure 18) and amorphous Fe (up to 600 ppm Fe). All methods, including total analysis, give anomalous responses directly overlying mineralization (Figure 18). No method shows particular superiority in terms of anomaly to background: the worst methods being pH 5 acetate (high detection limits), 10 M HCl (high backgrounds) and totals. Other elements that are high over mineralization, for various extractions, are As, Au, Ba, Be, Cd, Ce, Co, Cs, Cu, Ga, Hg, Mo, Nb, Ni, Pb, Pd, Pt, REE, Sb, Sn, Te, Th, Tl, U, W, Zn and Zr.

However, these multi-element anomalies show critical control from Mn and/or amorphous Fe oxides, and appear to be ultimately controlled by the position of surface drainages. Other drainages in unmineralized areas also show a clear spatial correlation between extractable Mn and the various drainages in the study area. Multi-element HCl, MMI and Enzyme Leach anomalies are observed for these barren traverses, which can be directly correlated to Mn content. Plotting extractable elements vs. controlling elements (*e.g.*, extractable Mn or Fe) did not indicate any relative enrichment for the mineralized traverse for any of the extraction methods (example for MMI Cd given in Figure 19).

Thus, accumulation of amorphous Fe oxides and Mn oxides is the main control over metal solubilities, and any correlation of element concentration with buried mineralization for a single traverse is coincidental. These results can be compared with those for Baxter (Section 5.1) and Bronzewing (Section 5.3), for which the Mn drainage anomalies are not over mineralization.

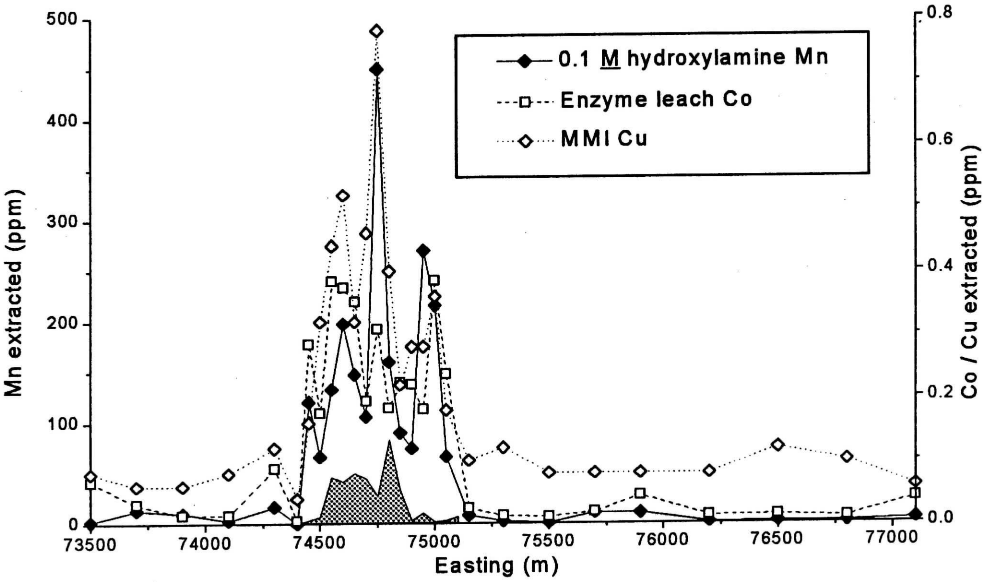

Figure 18: Selected extraction results across the Curara traverse (Shaded area represents Au in buried laterite).

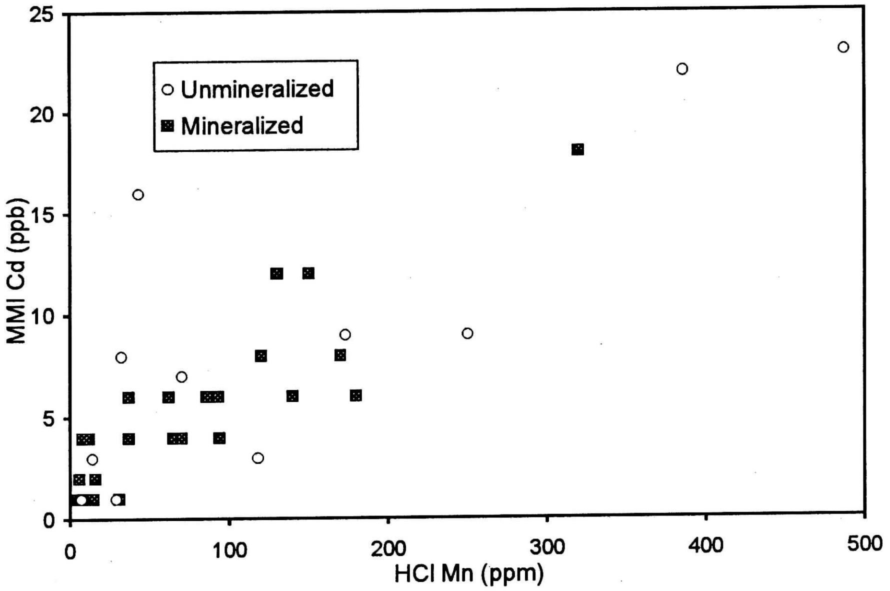

Figure 19: MMI extractable Cd vs. HCl extractable Mn for unmineralized and mineralized traverses in the Curara district.

5.5. Safari

The Safari traverse has 4 - 6 m sandy calcareous cover over Au-rich saprolite. Total and extractable Au in the soils (by most methods) peak over mineralization, probably as a function of the thin cover. Tungsten (4 M HCl and Enzyme Leach) also appeared correlated with mineralization, though not as closely as Au. No other elements correlate with the position of mineralization. Distributions of Ce, Co, Cu, Ni, Pb and Zn appear to be weakly correlated with that of extractable Mn or Fe, for some extractions.

5.6. Steinway

Mineralization at Steinway is overlain by 5 m of leached saprolite and 25 m of palaeochannel sediments. Despite this, total Au peaks at 155 ppb, approximately 100 m E of mineralization, and other extraction methods confirm this result (Figure 20). MMI, Iodide and the enhanced HCl reagents extracted similar proportions of the Au from all samples, except the one with the highest Au content. This sample shows relative solubility differences in the order MMI > Iodide > Conc. HCl (enhanced) > 4 M HCl (enhanced). Thus, for example, the 4 M HCl (enhanced) reagent dissolved only 11% of the total Au in this soil sample, but 73±18% of the total Au for other samples in the traverse. This indicates that Au in this sample is less soluble, and suggests that it is primary and physically transported.

Total and extractable Ag also show a well-defined peak over mineralization, though 80 m to the west of the main Au peak. Total and HCl extractable (but not Enzyme Leach) W also overlie mineralization. Other elements that appear to correlate with the position of buried mineralization are Co (selective extractions only) and Zn (HCl and selective extractions). In contrast, Ni and Pb correlate with the Mn high 200 m E of the position of buried mineralization and do not appear to define mineralization. Cobalt and, possibly, Cd appear to have two peaks: one above mineralization and the other associated with the Mn high.

Several aspects of the Steinway soil anomaly suggest that the signal is probably due to physical transport of Au-bearing detritus, namely:

(i) the very high Au concentration;
(ii) the poor solubility of the Au-rich sample
(iii) the single point Ag anomaly, 80 m west of the Au anomaly;
(iv) a total W (which is generally highly insoluble) anomaly.

This is possibly from outcropping mineralization approximately 1 km south of Steinway. Transported lateritic gravels containing Au grains occur at 2 – 5 m depth, beneath the calcareous topsoils (Lintern and Gray, 1995a).

5.7. Apollo

This site has 5 - 10 m transported cover over 10 - 30 m variably leached saprolite and saprock. Gold concentrations show no correlation with buried mineralization. In contrast, there is a major Zn anomaly (550 ppm; Figure 21) directly overlying mineralization. Approximately 85% of the Zn is extracted by pH 5 acetate, suggesting an association with carbonates. Both Enzyme Leach and MMI gave good Zn responses, as did the other methods. Thus, this is not a subtle anomaly only observed by the partial extractions, but a zone with a major enrichment of Zn. MMI Co and (weakly) pH 5 acetate Co and Mn appear to correlate with this anomaly

A second multi-element anomaly was observed for the western-most soil, which was anomalous in Ag (450 ppb), Cd (170 ppb), Cu (15 ppm), pH 5 acetate Fe (27 ppm) and 4 M HCl W (26 ppb). The Ag was dissolved by 0.25 M hydroxylamine, suggesting incorporation in amorphous Fe oxides, whereas the Cd and Cu are pH 5 acetate soluble. It is possible that this anomaly could increase to the west. Thus soils at this site showed two separate anomalies, each with distinct multi-element signatures, in which the anomalous elements were highly extractable, even by the weak reagents. Further work would probably define the source(s) of these anomalies. One possibility is elements dispersing from weathering sulphides north of the traverse, precipitating in the soils either as separate phase carbonates, or within the pervasive soil calcite.

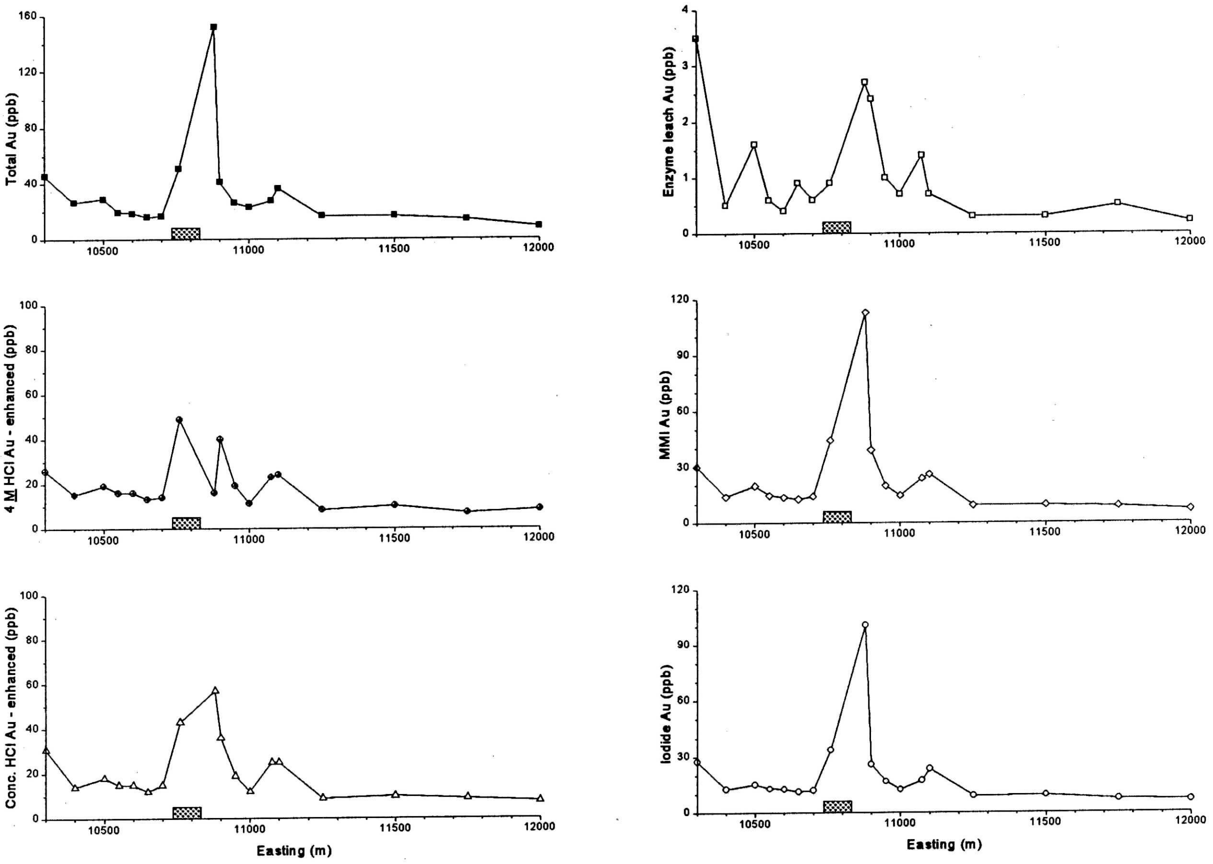

Figure 20: Total, 4 M HCl, 10 M HCl, Enzyme Leach, MMI and Iodide extractable Au from Steinway soil traverse. (Shaded area represents Au mineralization in Archaean).

Cerium, Co, Cu, Ni and Pb have distributions and solubilities indicating association with Mn oxides and/or amorphous Fe, which have greatest concentrations to the east of the traverse. Thus, this site shows a number of soil anomalies that appear unrelated to the buried Au mineralization.

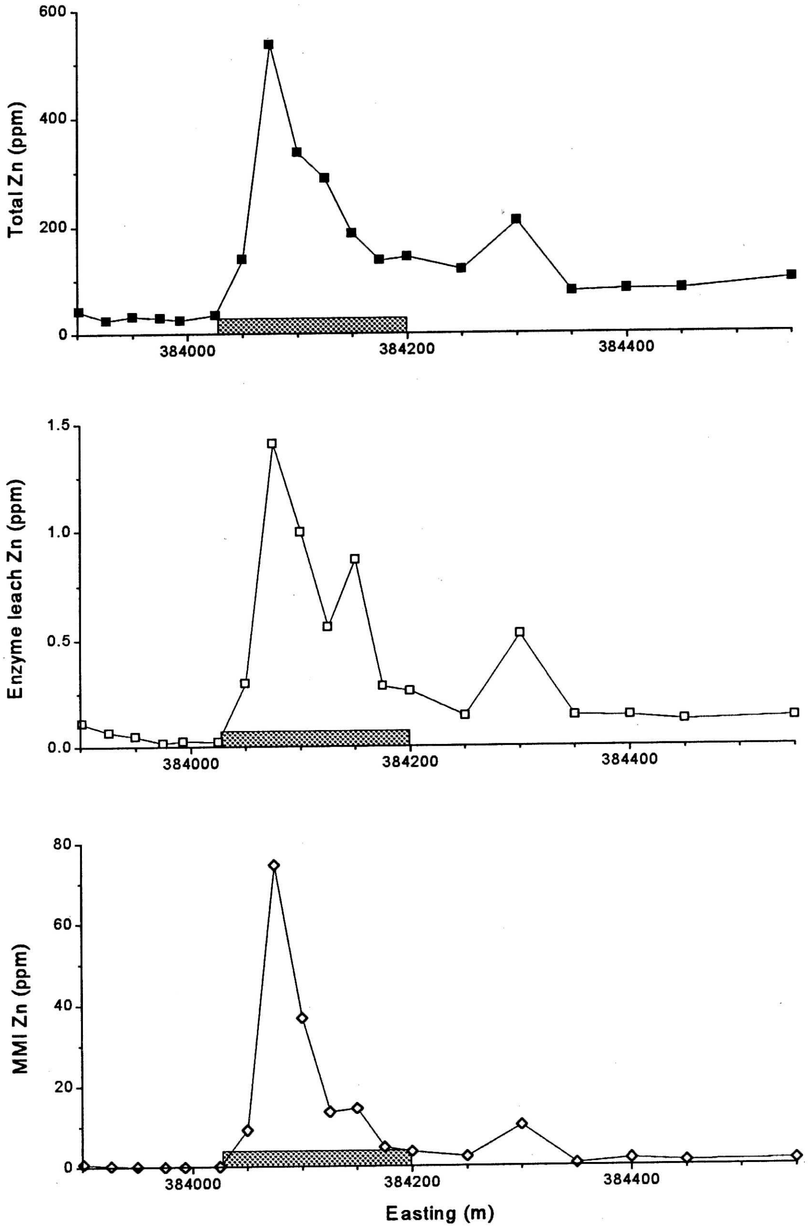

Figure 21: Total, Enzyme Leach and MMI Zn from Apollo traverse. (Shaded area represents Au mineralization in Archaean)

6. DISCUSSION AND CONCLUSIONS

The results discussed here are highly site-specific. This might be due to effects of the soil matrix, such as the presence or absence of carbonates, Mn oxides and/or less crystalline Fe oxides. Landscape position, and present-day drainage channels might also have a significant effect. The groundwater conditions vary considerably from fresh and neutral to the north, to highly saline and acid in the Kalgoorlie area, which have major consequences for the transport of a number of elements. Another factor that can vary significantly in arid environments is the amount of organic material, which will be affected by the ephemeral nature and/or scattered distribution of the vegetation.

The depth of transported cover appears to be significant. With the possible exception of Steinway, for which the anomaly appears to be due to physical transport from upslope (Section 5.6), sites with greater than 10 m transported material do not appear to show any anomaly at surface.

The partial extraction methods have particular characteristics that are important for interpretation. The MMI analysis is two separate techniques. The first, an acid extraction for Cd, Cu, Pb and Zn, give results that are similar, in terms of comparison between samples, to HCl and the selective extraction reagents. However, the absence of Fe and Mn data for this extraction make inference on the effects of surface conditions difficult. As these are the primary metal scavengers, inclusion of analyses for these elements is judged to be an important requirement for the correct interpretation of the data obtained by this method.

The second MMI method is an alkaline extraction for Ag, Au, Co, Ni and Pd, which appears to be optimized for Au and Ag. In soils containing significant carbonate, 70 - 80% of the total Au is dissolved, whereas the proportion of Au extracted is significantly lower in the northern sites. These results closely match the CSIRO Iodide method and the enhanced HCl digests. None of these extractants appear to be giving any additional exploration information for Au or Ag than cannot be obtained using standard analyses. In comparison, probably because the extraction is alkaline, Co data are unlike those observed for other techniques. In only one case (MMI Ni for one of two traverses at Baxter) do MMI results appear to show any correlation (albeit weak) with buried mineralization, that could not be observed using other methods.

The Enzyme Leach method also appears to give unique results, quite dissimilar to those from other methods, although the strong correlation between Fe and Cs, Ga, Hf, La, Nb, Pb, REE, Sc, Sn, Th, Ti and Zr is a significant issue for interpretation. With a few minor exceptions (I, Cu and Ni for one of two traverses at Baxter, and a weak Cu correlation at Bronzewing), Enzyme Leach does not appear to give data that correspond to the location of buried mineralization.

The apparent (weak) relationships between mineralization and one or two elements using partial extractions are noted above. However, there is commonly no obvious relationship between such observations, or any reason why there should be any correlation.

Use of partial extractions, as summarized here, showed either strong false positives (or in the case of Curara, possibly a 'false positive' coincidentally over mineralization), or very poor ability for the extraction methods to show buried mineralization, except where totals would work anyway. At several sites (*e.g.*, Baxter, Fender and Safari), Au (using a number of methods) successfully delineates mineralization, but partial extraction methods using the other elements are unsuccessful. It is concluded that, at the sites investigated, partial extractions only successfully locate buried mineralization where this can also be done using conventional methods. Although the partial extraction methods may still have value in giving better signal-to-noise ratios, or making subtle anomalies more obvious, they do not appear to offer any advantages for Au exploration in areas of transported overburden in the Yilgarn.

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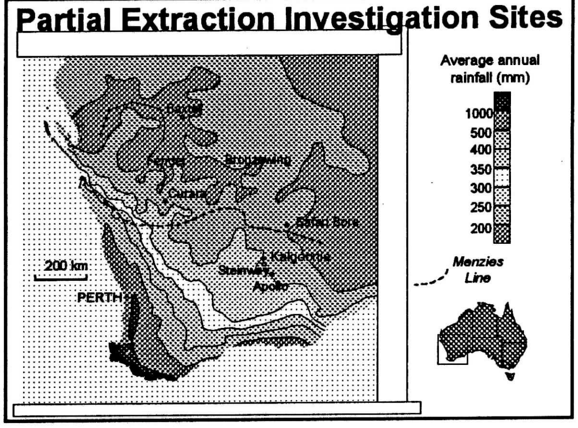
Selective Extraction for Au in areas of transported overburden, Yilgarn Craton, Western Australia

D.J. Gray, J.E. Wildman and G.D. Longman

Partial Extraction Investigation Sites



Partial Extraction Sites

- Baxter: 0.5 - 3 m colluvium over min. ferruginous saprolite
- Fender: 2 - 8 m sand and silty clay over min. (saprolite or lateritic residuum)
- Bronzewing: 5 - 25 m co-alluvium over min. ferruginous saprolite
- Curara: 5 - 10 m co-alluvium over enriched mottled zone
- Safari: 4 - 6 m sandy calcareous cover over Au-rich saprolite
- Steinway: 25 m transported, up to 5 m leached saprolite over mineralization
- Apollo: 5 - 10 m transported over 10 - 30 m variably leached saprolite and saprock

Selective Extraction Methods

- CSIRO Iodide
- Three step Selective Extraction
  - pH 5 Acetate (carbonates)
  - 0.1 M hydroxylamine (Mn oxides)
  - 0.25 M hydroxylamine (amorphous Fe oxides)
- Enzyme Leach
- MMI
- Cold 4 M HCl and Concentrated HCl

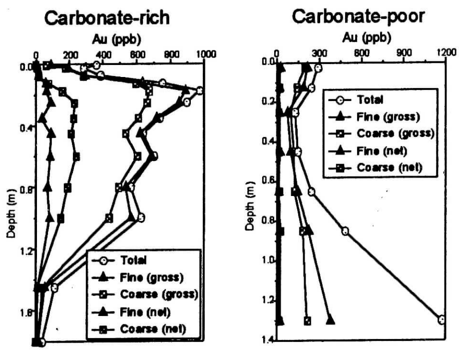
Iodide Extraction

- A WEAK Au extractant is used.
- 0.1 M KI / 1 M $NaHCO_3$ - pH 7.4
- Coarse (< 10 mm) and fine samples (< 75 μm)

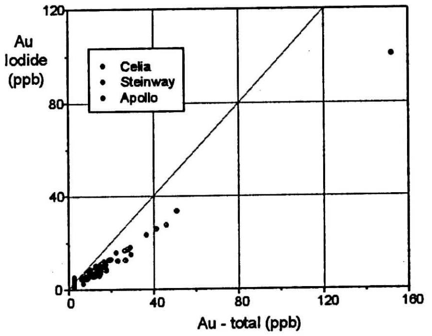
- Solubilities:

  Rock/saprolite - commonly low (some exceptions)
  Laterite - moderate
  Mn oxide - very high when pulverized
  Pedogenic carbonate - high (even when unpulverized)
  Organic - low, due to readsorption
  Hardpan - high when pulverized
  Colloidal Au - 16% iodide soluble

Mt Hope Profiles

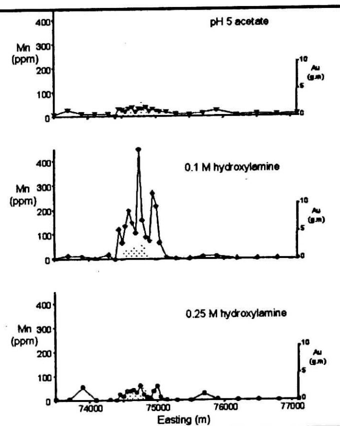


Au - Iodide Extraction

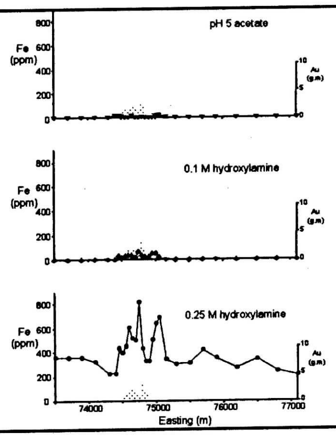


Selective Extractants

- Standard Reagents, with sequential treatment of sample
- pH 5 Acetate:
  Will dissolve carbonates and weakly bound metals
- 0.1 M Hydroxylamine
  Dissolves Mn oxides
- 0.25 M Hydroxylamine
  Dissolves amorphous Fe oxides



Curara - Mn (selective exts.)



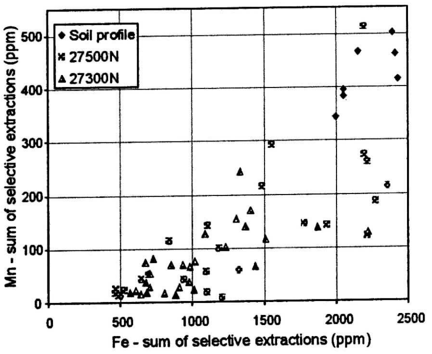
Curara - Fe (selective exts.)

Sequential Selective Extractions

Elements dissolved in each extractions [() - partial]

- pH 5 Acetate (carbonates and weakly bound)
  Ba, (Be), Ca, (REE), (Cu), (Mn), Th, U and (Zn)
- 0.1 M Hydroxylamine (Mn oxides)
  Mn, Ba, Co, Ni, and (Pb)
- 0.25 M Hydroxylamine (amorphous Fe oxides)
  Fe, Be, (Co), Cu, Li, (Mn), Ni, Pb, REE, (U) and (Zn)
- Correlation between extractable Fe and Mn
  ∴ many extractable metals correlate with Mn, even if only dissolved by 0.25 M hydroxylamine

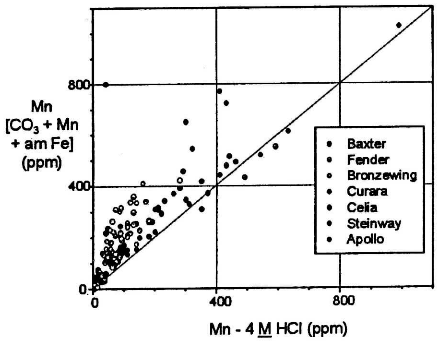
Extracted Mn vs. Fe



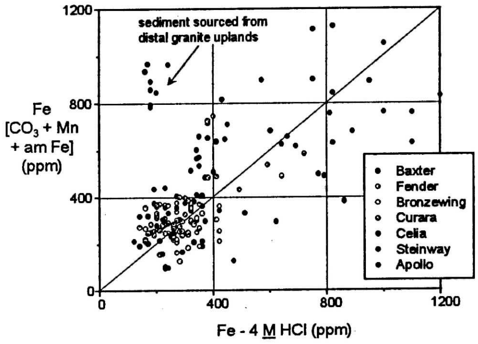
HCl Extractants

- 4 M Cold HCl:
  Similar to sum of sequential extractions, though does not distinguish between phases.
  Incomplete extraction for high carbonate samples (> 30%).
- Concentrated HCl:
  Quantitatively dissolves several mineral phases, including Fe oxides.
  Will extract W.
- Also use an enhanced reagent to optimise Au dissolution

Mn Extraction



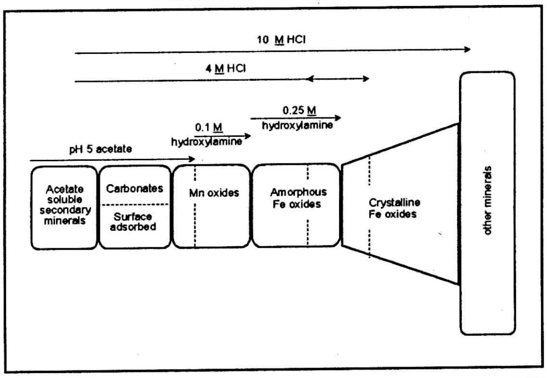
Fe Extraction



Extraction Characteristics of Mn and Fe

- Most Fe not extracted, with most extractable Fe dissolved in 0.25 M hydroxylamine and/or 4 M HCl
- Most Mn extracted with 0.1 M hydroxylamine
- < 10% Mn is dissolved by the pH 5 acetate - highly soluble Mn, either within carbonates, separate-phase MnCO3, or particularly soluble Mn oxides
- < 10% Mn dissolved only with 0.25 M hydroxylamine is presumably Mn within amorphous Fe oxides.
- Extractable vs. total Mn gives a linear relationship, with unextractable residual of approximately 100 ppm.
- Agreement between Fe and Mn, although extracted by different reagents, suggesting deposition by similar processes

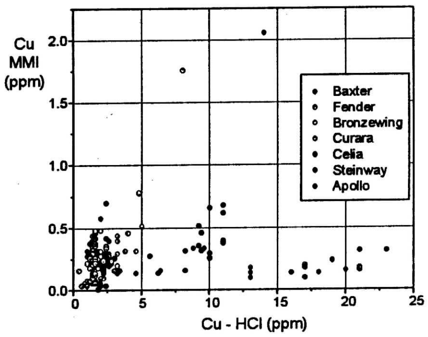
Extraction Model



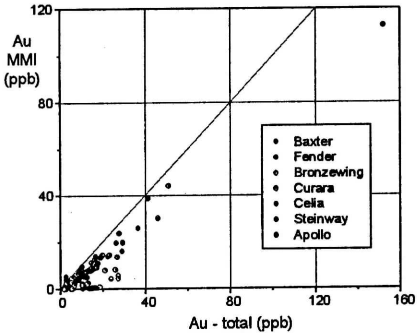
Mobile Metal Ions (MMI)

- Two different extractions:
- A (Cu, Zn, Pb, Cd):
  Weakly acid, will attack Mn oxides and amorphous Fe oxides
  For each individual site MMI results weakly correlate with HCl extractions, no overall pattern.
  Sometimes gives better contrast than HCl or selective extractions
- B (Au, Ag, Pd, Co, Ni):
  Alkaline, dissolves most Au, Ag (and Pd ?).
  Weakly dissolves Co and Ni, no understood relationship with other methods

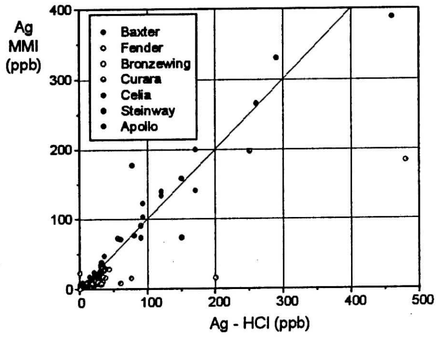
Cu - MMI Extraction



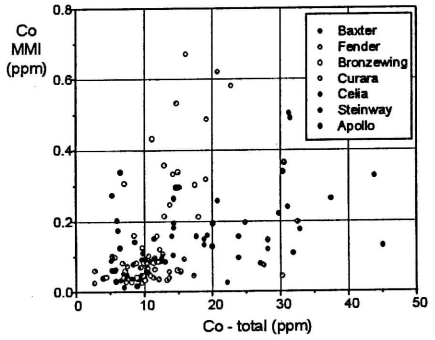
Au - MMI Extraction

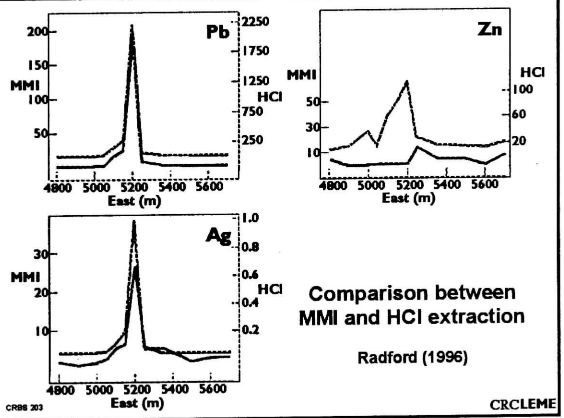


Ag - MMI Extraction



Co - MMI Extraction





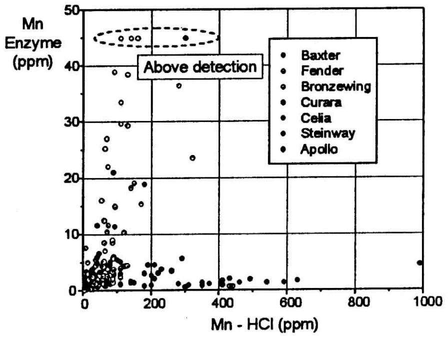
Comparison between MMI and HCl extraction

Radford (1996)

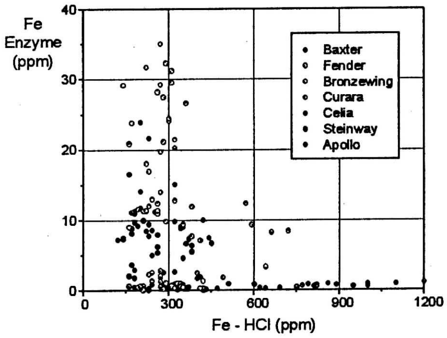
Enzyme Leach

- Designed to dissolve amorphous Mn oxides
- Analyse a large suite of elements:
  Ag, As, Au, Ba, Be, Bi, Br, Cd, Ce, Cl, Co, Cs, Cu, Dy, Er, Eu, Fe, Ga, Gd, Ge, Hf, Hg, Ho, I, In, Ir, La, Li, Lu, Mn, Mo, Nb, Nd, Ni, Os, Pb, Pd, Pr, Pt, Re, Rb, Rh, Ru, Sb, Sc, Se, Sm, Sn, Sr, Ta, Tb, Te, Th, Ti, Tl, Tm, U, V, W, Y, Yb, Zn, Zr
- Less than ½ these elements give values routinely above detection in these samples
- Cs, Ga, Hf, La, Nb, REE, Pb, Sc, Sn, Th, Ti and Zr - highly correlated with Fe (analytical problem ?)
- No clear relationship with other extractions

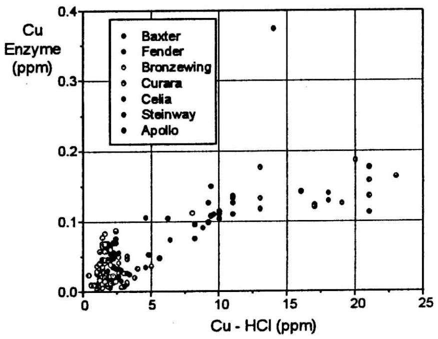
Mn - Enzyme Leach



Fe - Enzyme Leach



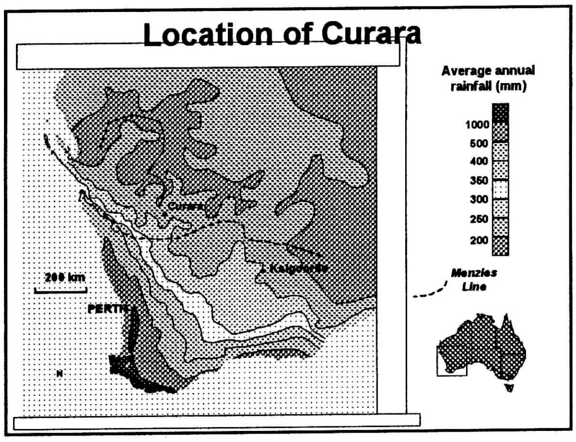
Cu - Enzyme Leach



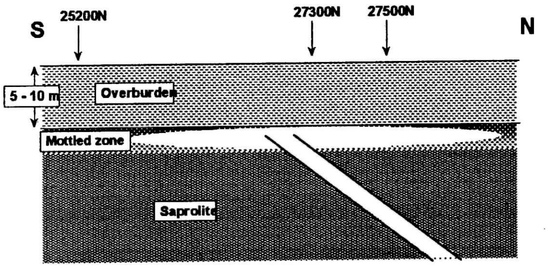
Curara - Site Characteristics

- 100 km N of the Menzies Line
- Semi-arid to arid, average annual rainfall ~ 230 mm.
- The vegetation is dominated by mulga and by various types of poverty bush and turpentine
- Total resource of 520,000 oz (1995), sulphide < 3%
- The present day drainage system over the mineralized zone also follows mineralized fault splay
- Laterite mineralization well defines the primary mineralization. Hosted by nodular mottled zone, with deeper supergene Au enrichment. Laterite outcrop in the south west corner of the anomaly

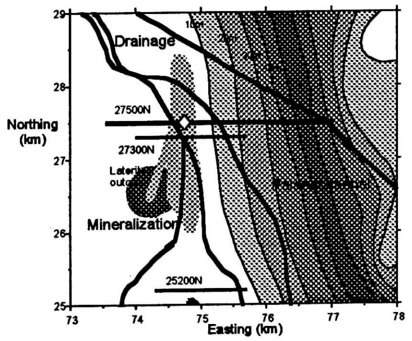
Location of Curara



Curara - cross section



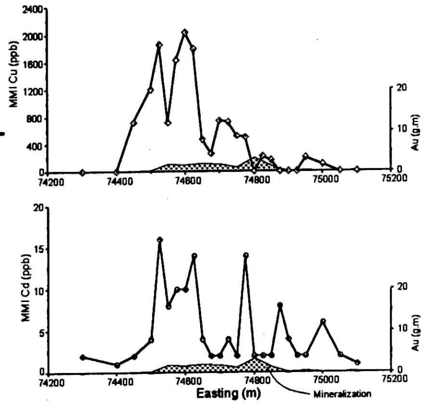
Curara - Initial Soil Traverses



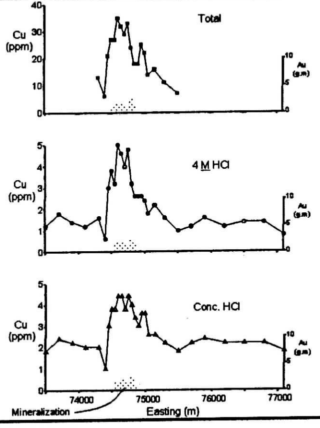
Anomalous elements for initial traverses

- Ba, Be, Cd, Co, Cu, Ni, Pb, REE, U and Zn for most to all of the extractions
- As, Au, Cs, Ga, Hg, Mo, Nb, Sn, Te, Th and Tl for one or some of the extractions.
- Different techniques optimal for various elements (e.g., MMI gave the highest contrast for Cu over mineralization, with no enhancement for Co and Ni)
- All methods worked for particular elements. Worst anomaly-to-background pH 5 acetate & total
- Mn (all; up to 500 ppm), Fe (all; up to 600 ppm). The greater amorphous Fe oxides and Mn oxides over mineralization may be controlling solubilities

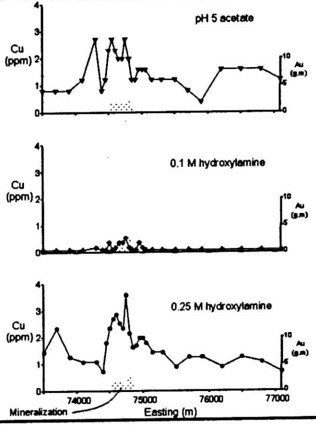
Curara - Initial MMI Results

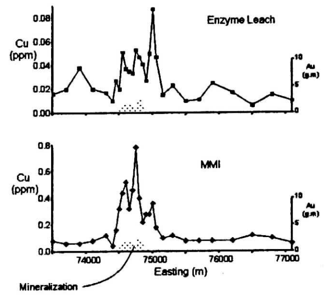


Curara - Cu (total & acid)



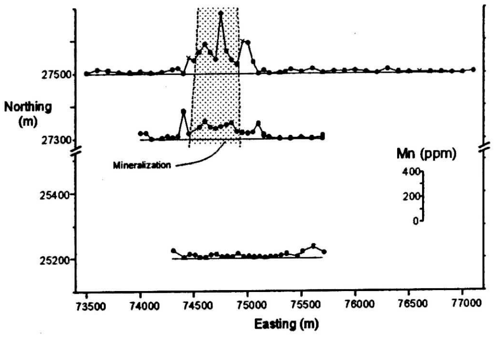
Curara - Cu (selective exts.)



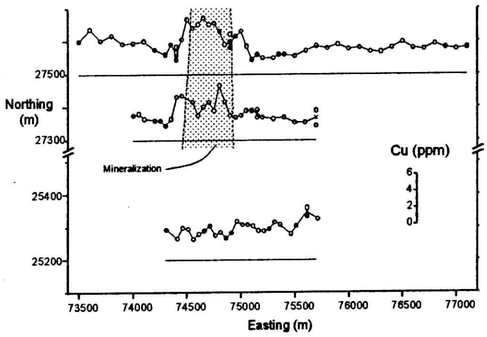


Curara - Cu (partial exts.)

Extractable Mn for Initial Traverses



Extractable Cu for Initial Traverses

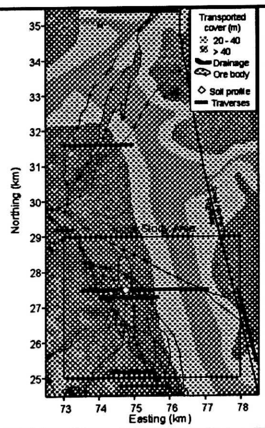


Curara - Initial Conclusions

- Anomaly in all methods over mineralization
- Marked accumulation of amorphous Fe oxides and Mn oxides in a shallow drainage at the same point on the transect
- Geochemistry successful by any method. However, soil landscape and mineralization coincide. The area is flat and well vegetated - a stable environment with the slow accumulation of clays and hydromorphic minerals at the low point which is depositional rather than erosional. This system accumulates locally sourced anomalous materials
- Is anomaly due to mineralization or drainage ?

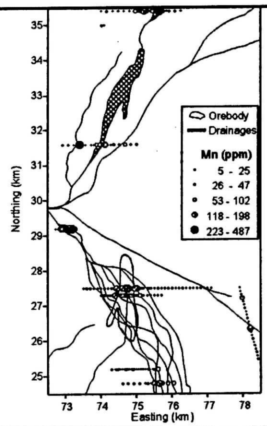
Further Traverses

- Results for the initial traverses could not distinguish the effects of buried mineralization and surface drainage
- Further traverses across drainages in poorly mineralized areas
- 41 samples for HCl extractions
- 11 samples chosen for MMI and Enzyme Leach

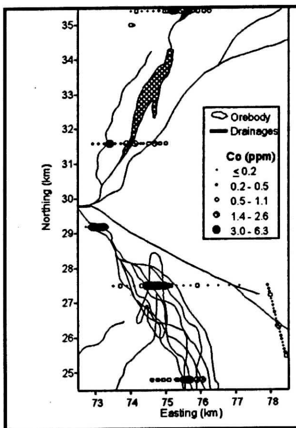


Curara Study Area

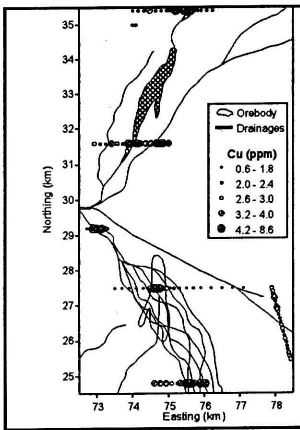
Curara - HCl extractable Mn



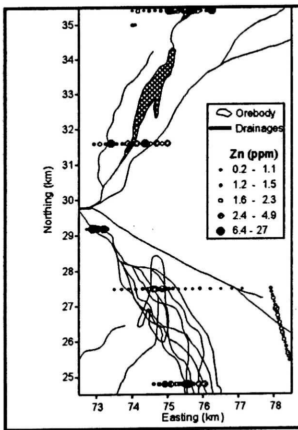
Curara - HCl extractable Co



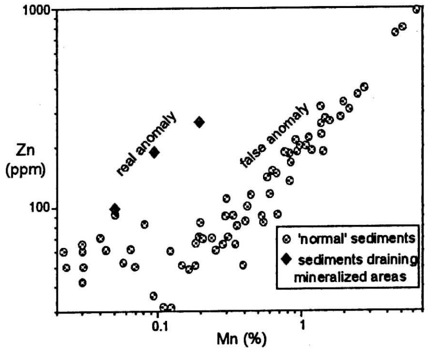
Curara - HCl extractable Cu



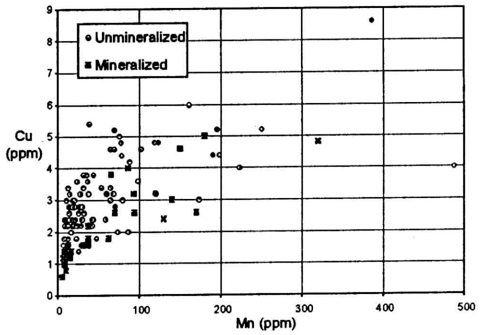
Curara - HCl extractable Zn



Stream Sediments - Northern Ireland



HCl Cu vs. HCl Mn



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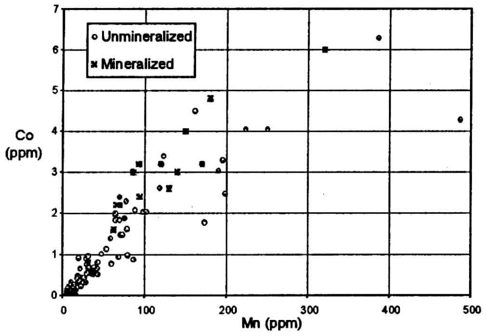
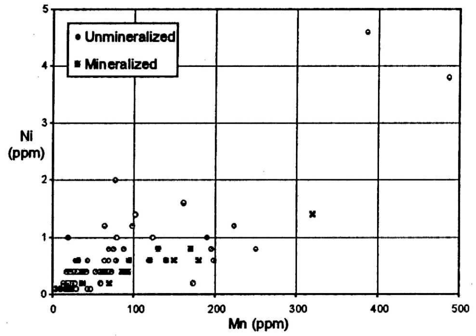
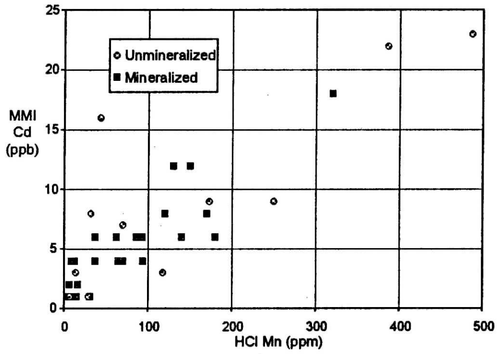
HCl Co vs. HCl Mn



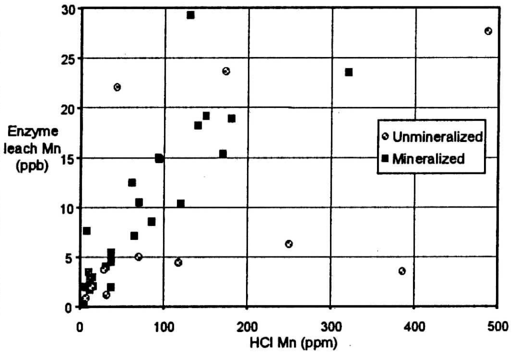
HCl Ni vs. HCl Mn



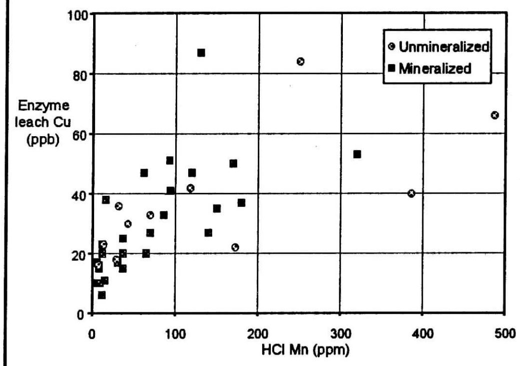
MMI Cd vs. HCl Mn



Enzyme leach Mn vs. HCl Mn



Enzyme leach Cu vs. HCl Mn



Further Traverses - Results

- Clear enhancement of extractable Mn with drainage
- For all techniques, other elements (Ca, Cd Ce, Co, Cu, Ni, Pb, Zn and Ba) appear to follow Mn, less strongly correlated with drainage
- Poorest correlation for Fe (batch effects)
- No enhancement over mineralization for any elements, nor for element/Mn or element/Fe ratios for any extractions

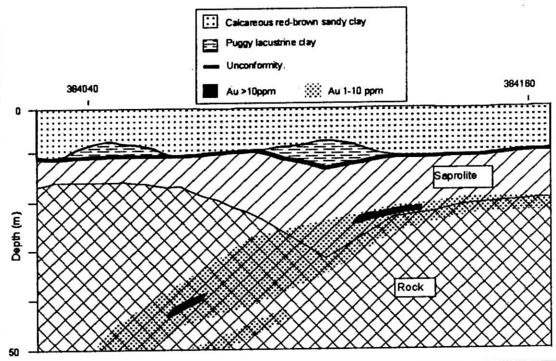
Curara - Conclusions

- Primary controlling phases are Mn oxides and amorphous Fe oxides
- Anomalies observed for other elements for ALL extractions appear primarily related to Mn and Fe
- MMI and enzyme leach can sometimes give better anomaly-to background than other methods, but are more expensive and less defined. Selective extraction gives more data, though with higher detection limits. HCl best for normal exploration
- However, at Curara element anomalies appear primarily related to surface drainage. Where drainage follows a shear, there can be local correlations with buried mineralization

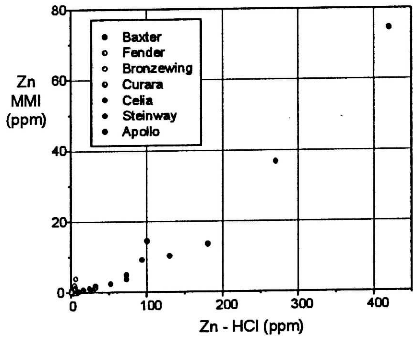
Apollo

- 5 - 10 m transported over 10 - 30 m variably leached saprolite and saprock
- Base metals, particularly Zn, have high soil concentrations
- Zn anomaly directly overlies mineralization. Quantitatively extracted by HCl or selective extractants (85% by pH 5 acetate), suggesting association with carbonates
- No observed soil Au correlation with mineralization

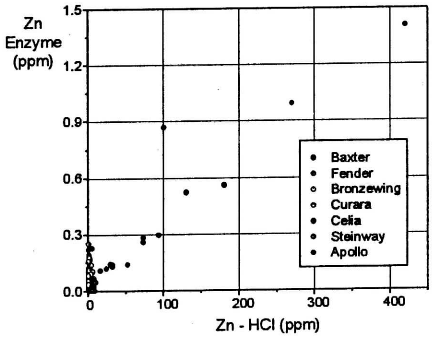
Apollo 526080N

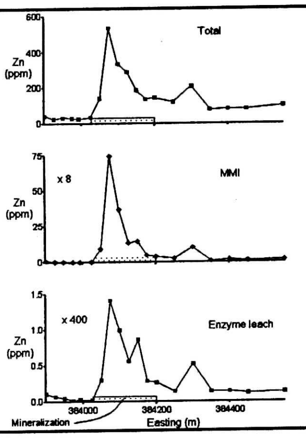


Zn - MMI Extraction

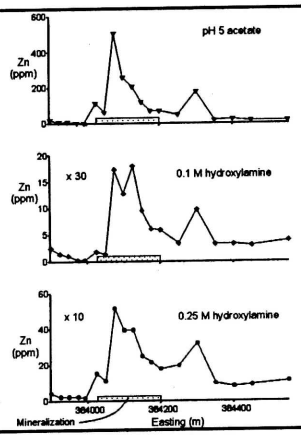


Zn - Enzyme Leach





Apollo - Zn (total and partial exts.)

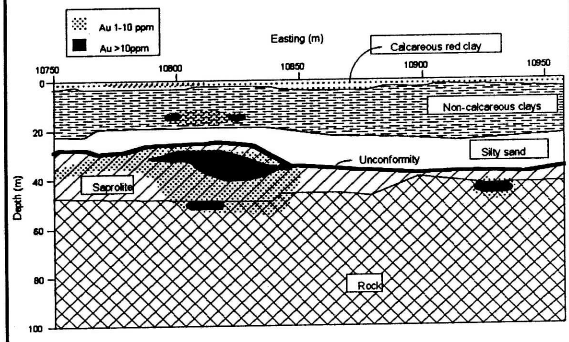


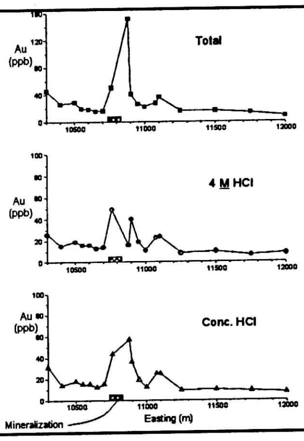
Apollo - Zn (selective exts.)

Steinway

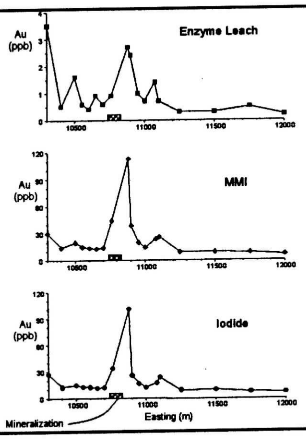
- 25 m transported, up to 5 m leached saprolite over mineralization
- Total Au peaks at 155 ppb over mineralization on the transect - other extraction methods correlate.
- Total and extractable Ag also shows a well defined peak over mineralization.
- Tungsten also defines mineralization and appears to have no relationship with Mn - highly insoluble.
- Cobalt, Cu and Zn correlate with the Mn high - do not appear to define mineralization.
- Au, Ag, W signal is probably due to physical transport

Steinway 4250N

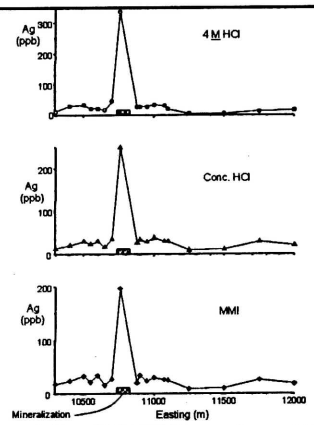




Steinway - Au (total & HCl)



Steinway - Au (partial extractions)

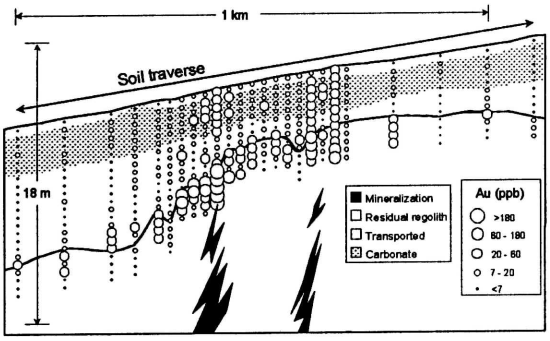


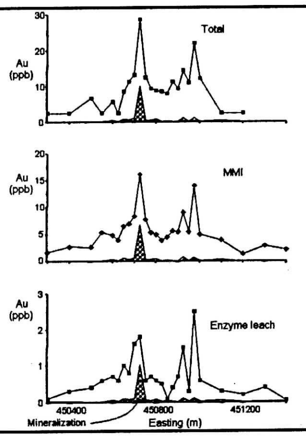
Steinway - Ag (acid & MMI)

Safari

- 4 - 6 m sandy calcareous cover over Au-rich saprolite
- Total and extractable (by most methods) Au in the soils peak over mineralization
- No other elements correlated with mineralization

Safari Bore Traverse

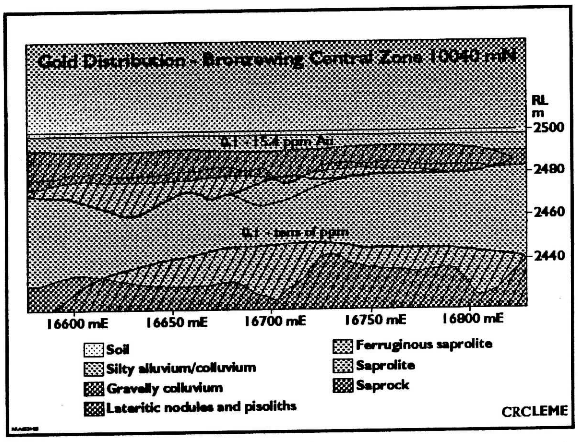




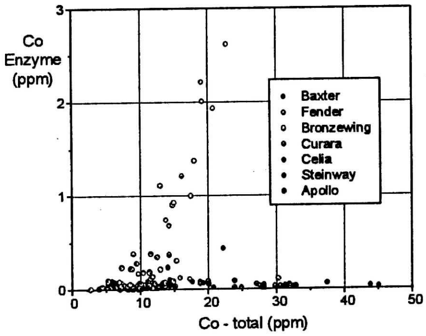
Safari - Au (total and partial exts.)

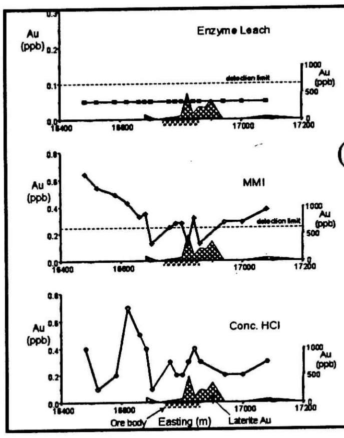
Bronzewing

- Mineralization is covered by 5 - 25 m co-alluvium from non-local sources. Fe-rich detritus enriched in Au, Cu, Ni, Zn, U
- Enzyme leach Co and Mn are higher than elsewhere
- Active major drainage is not coincident with the mineralization, and the geochemical signal is stronger in the channel than over mineralization.
- Gold anomaly at 16800 m E is 1.9 ppm at 10 m depth. This does not show an significant anomaly at surface. Dispersion into the colluvium is physical - Bronzewing has fresh groundwater not able to dissolve Au.
- Enzyme Cu correlates (weakly) with mineralization (co-incidence ?)



Co - Enzyme Leach

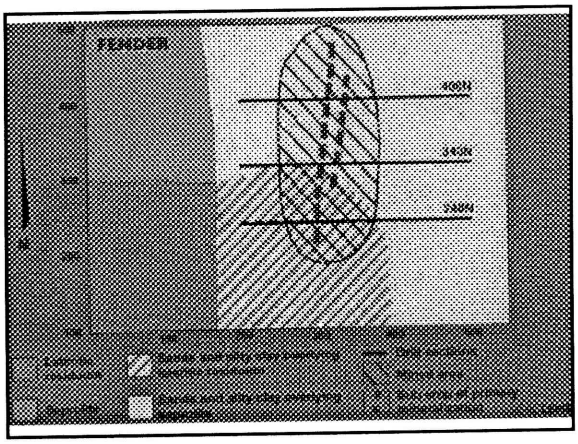


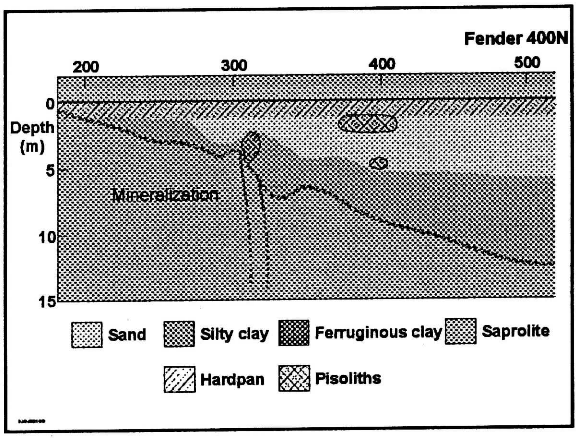


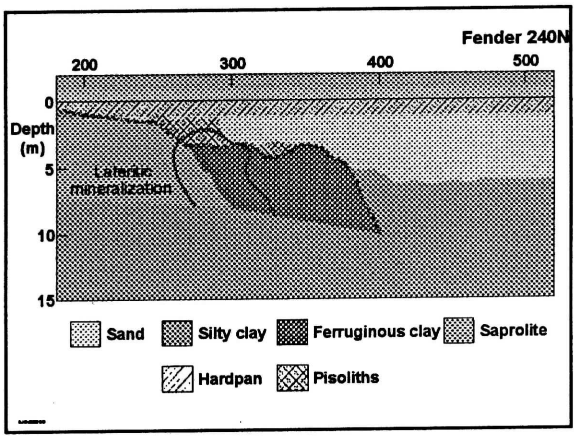
Bronzewing - Au (partial extractions)

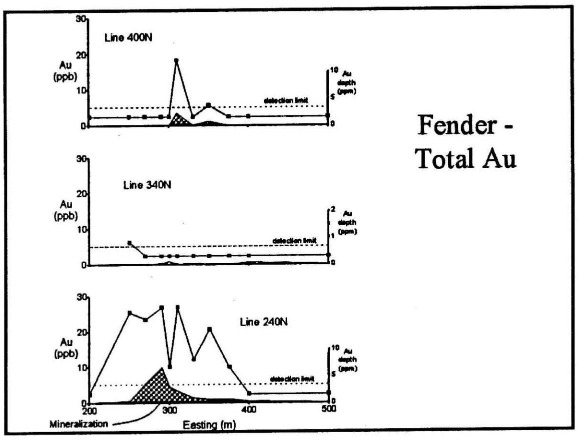
Fender

- 2 - 8 m sand and silty clay over mineralization. (saprolite or lateritic residuum)
- Three traverses (one Au-poor)
- Primary mineralization contains Au, Ag, As, Sb, Cu, W and Mo. 2 - 8 m cover
- Total and extractable (not Enzyme) Au in the soils peak over mineralization
- No other elements (total or extractable) are correlated with mineralization. Concentrations are comparable for all 3 traverses

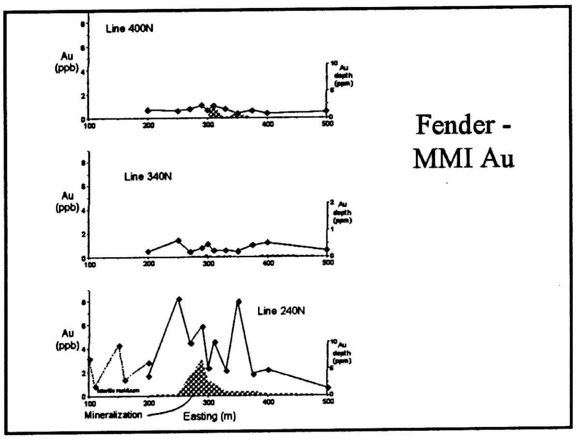








Fender - Total Au

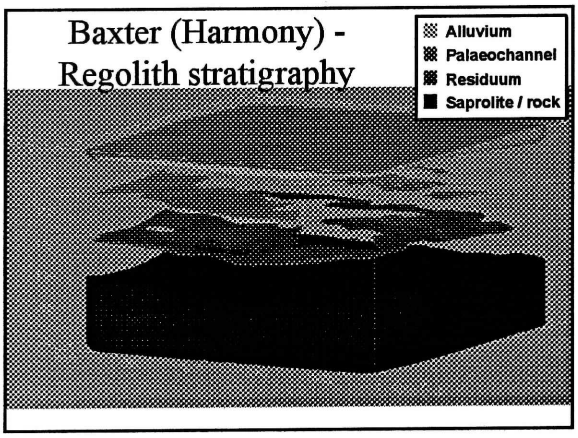


Fender - MMI Au

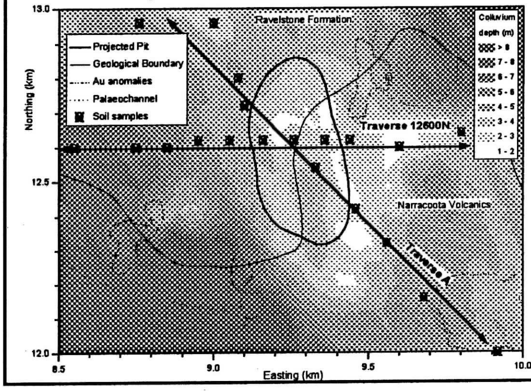
Baxter (Harmony)

- 0.5 - 3 m colluvium over mineralized ferruginous saprolite
- Two traverses
- Higher Mn oxides (500 ppm cf < 100 ppm background) to the east
- Higher Co, Ba, Be, Cu, Ga, Ni, REE, Se and Zn correlate with Mn effect
- Total Au up to 15 ppb in soils over mineralization, conc. HCl and MMI are similar.
- Enzyme I and Cu correlate with mineralization on one traverse.

Baxter (Harmony) - Regolith stratigraphy



Harmony Au deposit - Soil traverses



Comparisons between methods

- MMI offers a small suite of elements and does not normally include Fe and Mn;
- selective extractions give location of elements in soil phases - useful for initial investigations. Higher detection limits
- enzyme leach has detection limit problems, and possible problems with high-charge elements
- 4 M HCl gives results comparable with selective extractions, but with better detection limits, analytically simpler and cost effective

Results highly site-specific:

- Highly dependent on the soil matrix.
- They are not independent of the landscape position.
- Appear to depend on the availability and source of manganese.
- Elements in the mineralisation need to be effectively complexed by the extractant in a wide range of soil environments.

Partial Extraction - Summary

- No method has produced a clear signature over mineralization that cannot be seen by conventional analyses of the total sample
- MMI and Iodide Au very similar and generally dissolve 80 - 95% of the total Au in soils
- MMI Ag dissolves virtually all extractable Ag in all but two samples
- MMI Cu, Pb, Zn similar to acid extractable - related to the selective extraction results
- Enzyme Leach and MMI Co & Ni results give unique results