THE USE OF ELECTRON PARAMAGNETIC RESONANCE SPECTRA AND GEOCHEMICAL ANALYSIS OF ACID INSOLUBLE RESIDUES FOR RECOGNISING PRIMARY ALTERATION HALOES OF GOLD MINERALISATION IN THE REGOLITH

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For the past fifteen years, an integrated paramagnetic/lithogeochemical technique has been developed for exploration for gold and massive sulphide deposits. The method is based on the interpretation of electron paramagnetic resonance (EPR) powder spectra and the trace element composition of the insoluble residue left after acid digestion of rock pulp samples. The residues consist dominantly of quartz, with minor feldspar and sericite. Quartz associated with mineralisation exhibits EPR spectra typical of lattice imperfections. The intensity of the spectra correlates well with the distributions of certain trace elements, such as As, Ge, K, Li, Rb and W associated with many gold deposits and Ba, Mn and Zn with massive sulphide deposits. Wall rock alteration patterns are commonly expressed by strong $[AlO_4]^\circ$ centres in the EPR spectra, accompanied by increased K and Rb concentrations, high Rb/K and Rb/Al ratios related to sericitic alteration, and Na, Ca and Sr depletion due to plagioclase destruction.

The use of this method has now been extended to deeply weathered terrain. Treatment of regolith samples with hot hydrochloric, nitric and sulphuric acids dissolves secondary minerals such as Fe, Mn and Al oxides and hydroxides, carbonates, sulphates and clays. The acid insoluble residue consists essentially of quartz and chalcedony, with some resistate minerals, and can be used to delineate primary mineralisation and wall rock alteration, in the same manner as quartz concentrates from fresh rock. Case studies have been carried out over gold deposits at Jim's Find, Tanami Desert (NT), Reedy, near Meekatharra (WA), Mt Percy, Kalgoorlie (WA) and McKinnons, Cobar (NSW). Pronounced EPR signals can be observed at the surface above the mineralised areas, in Au depletion zones and in the wall rock alteration haloes. High Rb/K ratios in surface material above mineralisation, and high Rb/Al ratios in wall rocks may indicate remnants of original sericitic alteration; at some sites there are surface anomalies of As, Cu and Pb.

Key words: weathering, regolith, gold exploration, EPR, PIXE/PIGME, acid insoluble residue, Jim's Find, Reedy Mine, Mt Percy, McKinnons

INTRODUCTION

The trace element content of specific minerals such as mica, feldspar, magnetite, tourmaline, apatite and pyrite has long been used in exploration (Levinson, 1974). Rutile has recently been added to that list (Scott et al., 1993). The present study uses a similar concept by determining the chemical composition and paramagnetism of easily produced insoluble residue, mainly quartz, left after acid digestion of rocks and regolith materials. Residues from quartz veins, rocks and soils have been investigated by the Geology Department of the University of Tasmania since 1983. The basis of the method is that quartz has a specific chemical composition with a very limited capacity for substitutional impurities and acceptance of inclusions. This results in paramagnetic and geochemical signatures with little background noise. Electron paramagnetic resonance (EPR) is a physical method that describes lattice imperfections.

Acid digestion is more intense than the effects of weathering, hence little difference should be expected between the chemical composition of the acid insoluble residue of unweathered rocks and their weathered equivalents, although the residue of the latter is somewhat higher in some resistate minerals (van Moort et al. 1995; Stott et al. 1997). This paper describes a study of the acid insoluble residue of regoliths and rocks for four deeply weathered Australian gold occurrences. A specific aim was to investigate whether persistent and uninterrupted paramagnetic and chemical expression of the primary mineralisation and its alteration halo persists through the regolith, unaffected by the leaching that has commonly resulted in subsurface Au depletion. The study involved 775 samples and only the major results are presented here

ELECTRON PARAMAGNETIC RESONANCE (EPR)

PRINCIPLES OF EPR

Electron paramagnetic resonance (EPR) spectroscopy has been defined as the form of spectroscopy concerned with microwave-induced transitions between magnetic energy levels of electrons having a net spin orbital momentum (IUPAC, 1989) The techniques of EPR and nuclear magnetic resonance (NMR) are thus basically the same: the alignments of magnetic moments by externally applied magnetic fields and their reorientation by the absorption of incoming electromagnetic radiation. The essential difference between the two techniques is that, in EPR it is the electronic magnetic moments that are being reorientated, whereas in NMR it is the nuclear magnetic moments.

There are many practical applications of EPR in the fields of biology, life and medical sciences, chemistry, earth and environmental sciences, physics and material science (Rudowicz, 1998) Instrumentation consists of a resonance cavity with a standing microwave of constant frequency between two strong electromagnets If the magnetic field is swept, the microwave energy is absorbed at specific magnetic flux densities because of resonance of unpaired electrons between the parallel and antiparallel state The EPR spectra in this study have been recorded as analogue X-band (9 15 GHz) powder spectra The intensities have been measured as peak heights on first derivative absorption spectra obtained under standard instrument conditions, as reported by van Moort and Russell (1987) These intensities are relative values only They are, however, entirely reproducible and have been found to be constant over fifteen years on the JEOL FEX3X ESR spectrometer of the Central Science Laboratory of the University of Tasmania

Since EPR requires the presence of unpaired electrons in the sample being studied, its range of applications is restricted to paramagnetic substances. Near ore-bodies, quartz and other minerals contain numerous out-of-place atoms and various substitutional and interstitial impurities (including ore constituents) These cause a considerable amount of lattice defects that result in paramagnetism. It is necessary to use the acid insoluble residue for EPR studies, rather than untreated rocks pulps, because the spectra of untreated material contain strong and unidentifiable interfering signals derived from other minerals However, as the EPR of quartz is very specific, minor contamination by feldspar, sericite and other phases in the acid insoluble residue has no significant effect (Nand and van Moort, 1995)

RELATIONSHIP BETWEEN EPR AND GOLD MINERALISATION

The relationship between EPR signals and gold mineralisation in quartz and rocks has been investigated by various authors (Scherbakova et al 1976; Matyash et al 1982; van Moort and Russell; 1987, van Moort and Brathwaite; 1988, Nand 1989; Russell and van Moort 1997). Recently, it was found that auriferous jasperoids from Carlin, Nevada, USA, are more paramagnetic than barren ones (van Moort et al 1995) Subsequently, a comprehensive study of the EPR spectra of wall rock alteration products of acid and intermediate volcaniclastic rocks in the Mt Read volcanics of western Tasmania has enabled the distinction between wall rock alteration in general and wall rock alteration associated with VHMS deposits (Aung Pwa, 1995; Aung Pwa and van Moort, 1998c) The present study extends this use of the acid insoluble residue of finely ground fresh rock powders to the characterisation by EPR of the acid insoluble residue from highly weathered regolith as a sample medium in gold exploration

STUDY AREAS

The study sites were the Jim's Find South gold deposit in the Tanami-Granites area in the Northern Territory (Stott, 1994), the Rand Pit, Reedy Mine near Meekatharra, WA (Robertson et al 1990), the Mystery Zone at Mt Percy, Kalgoorlie WA (Butt, 1991; 1993) and the McKinnons gold deposit near Cobar NSW (Bywater et al 1996; Rugless and Elliott, 1995; Aung Pwa and van Moort 1998a)

Each site is characterised by regoliths 70-90 m deep overlying primary gold mineralisation in different host rocks and of different genesis Each has some supergene enrichment of Au and, other than at Reedy, has a sub-surface zone of Au depletion

The primary style of mineralisation in the four occurrences varies considerably At Jim's Find, Au is associated with quartz carbonate veining and envelopes of sericite-pyrite alteration, hosted by interbedded graywackes, phyllites and basalts At Reedy, mineralisation is in quartz veins and shears within altered mafic/ultramafic rocks intruded by porphyries At Mt. Percy, mineralisation is associated with finely disseminated pyrite and quartz veining in quartz albite porphyries and fuchsite-carbonate alteration zones in talc-chlorite ultramafic rocks. In the McKinnons deposit, primary epithermal Au-Ag mineralisation occurs associated with pyrite-illite wall rock alteration and extensive silicification All areas have been affected by deep chemical weathering under humid climatic conditions, probably during the late Cretaceous to early Tertiary Subsequently, the regolith profiles have been modified (and partly eroded) under arid conditions that persist to the present.

SAMPLE PREPARATION

Because it is so important to obtain as pure a quartz concentrate as possible, preparation of the acid insoluble residue of the regolith samples needs special care The conventional methods removing of carbonates and Fe and Mn oxides from soils and sediments with hydrochloric acid (Milner, 1962; Russell and van Moort, 1987), treatment with nitric acid (van Moort et al , 1995) or even sequential treatment with hot hydrochloric and nitric acid are inadequate for lateritic material In order to remove the Fe and Mn oxide grains, coatings and cement, hot aqua regia (Stott et al , 1997) or sequential treatment with hot hydrochloric and hot nitric acid is required Such treatment also removes Al oxides and hydroxides, phosphates, residual sulphides and most sulphates The remaining clays and some other minerals such as alunite can be removed by hot sulphuric acid digestion and subsequent thorough rinsing Remaining magnetic minerals may be extracted by use of a hand held magnet. Constant vigilance remains required because, for example, talc is completely acid insoluble, whereas gibbsite and, to a minor degree boehmite and many resistate minerals such as spinels and garnets are acid soluble. Valuable references to the response of individual mineral species to acid treatment can be found in Dana and Ford (1966) and Duda and Rejl (1990), and a discussion of the poor efficiency of extraction techniques to determine so-called "total compositions" of regolith materials can be found in Gedeon et al. (1977)

PURITY OF CONCENTRATES

The acid insoluble residue of the rock and regolith pulps consists essentially of silicates, especially quartz, minor sericite and talc, traces of alkali feldspar and resistate minerals such as zircon and titania polymorphs. It is rare to encounter more than traces of other silicates as they have either already been destroyed by weathering (Loughnan 1968) or degraded or removed by the acid treatment (Nand and van Moort, 1995)

XRD analysis of the acid insoluble residue from Jim's Find indicates quartz, minor sericite and traces of kaolinite and rutile only (Stott et al 1997). Microscopic inspection, however, indicates that there is a substantial amount of microcrystalline chalcedony, possibly the result of hydrolysis during weathering of the silicates Residues from the Rand Pit contain quartz, minor sericite and traces of kaolinite and feldspar, and those from Mt Percy have quartz and minor sericite, with talc and feldspar from the ultramafic rocks The residues at McKinnons are mainly composed of quartz (probably >90%) and a minor amount of mica. Surface soil samples consist partly of microcrystalline chalcedony aggregates with inclusions of Fe oxides, and the deeper samples consist of quartz with only a few inclusions.

CHEMICAL ANALYSES

All samples were chemically analysed for their bulk composition by simultaneous PIXE/PIGME at the 3 MV van de Graaff accelerator at ANSTO, Lucas Heights (Bird and Williams 1989) The method uses a defocused proton beam hitting a 3 mm diameter target of finely crushed material that has been homogenised and pelletised with spectrographic graphite. The instrumental conditions of these analyses have been reported by van Moort et al (1995), and their precision and accuracy by Russell et al (1996) The minimum detection limits for the material studied are comparable to, or better than, XRF (Stott et al. 1997) The data for McKinnons were complemented by some ICP-MS analyses The elements consistently present in concentrations above the detection limit are listed in Table 1 Note that the detection limit of Au by PIXE is rather high The presence of even small amounts of other minerals, such as sericite and feldspar greatly affects the chemical composition of the acid insoluble residues

THE DISTRIBUTION OF AU AND EPR SIGNALS

The Au values in all cases are those determined by INAA on the bulk samples prior to their acid treatment and are presented in the references cited for the individual deposits The EPR intensities have been determined on the acid insoluble residue of the same samples used for Au determinations

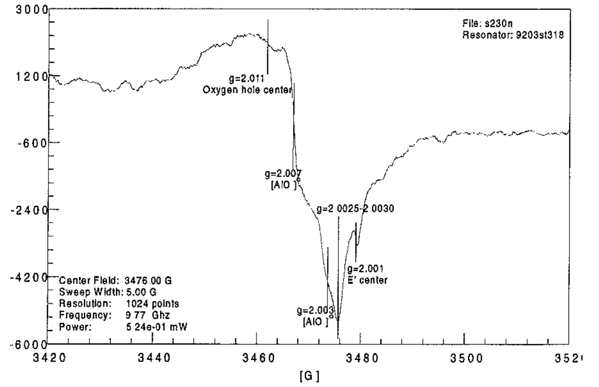

Figure 1: *First derivative EPR X-band spectrum at room temperature of powdered quartz with identified g values Sample 13200 from Jim's find South, Tanami, N T*

The large V shaped EPR signal with a width of about 2 mT and an effective spectroscopic splitting factor of $g \approx 2$ is typically associated with gold mineralisation (Russell and van Moort 1997) The centre shows details reminiscent of the $[AlO_4]^{\circ}$ centre in quartz identified by Petrov et al (1990) and what Scherbakova et al (1976) and Matyash et al (1982) called the "Al-O" centre Other centres are not of practical value (van Moort and Barth, 1994) Figure 1 shows a typical EPR signal in auriferous quartz All spectra observed in this study are comparable, but for their intensities

Jim's Find South, Tanami, NT

In order to compare the trends of the distributions of the EPR intensity and the Au mineralisation, 144 samples from the surface down to depths of 90 m were selected from three regolith sections (Stott, 1995) Where the complete regolith profile is preserved, Au determined by INAA is present as laterally extensive sub-horizontal zones of secondary Au enrichment (0 01-3 g/t) in lateritic gravels and within the saprolite above the primary ore zone; there is also a zone of subsurface Au depletion (Figure 2)

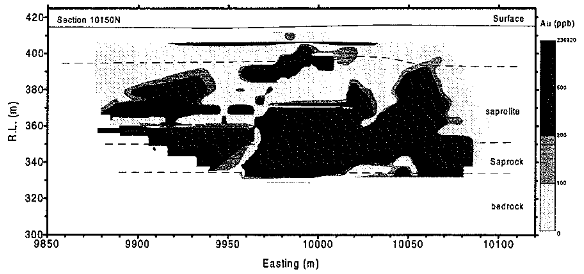

Figure 2: *Distribution of Au (determined by INAA) at Jim's Find South, Tanami, N T, Section 10150N, Note secondary surface enrichment and subsurface leaching*

The acid insoluble residue from the primary mineralisation shows two separate EPR haloes over and above the Au anomalies (Figure 3) The intensities are approximately three times stronger than those from near the surface and the barren zone There is no EPR expression of the near surface secondary gold enrichment and the EPR anomaly does not reach the surface (Xu Li and van Moort, 1997)

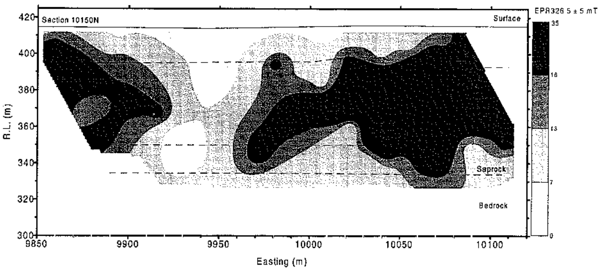

Figure 3: *Relative EPR326 5±5 mT signal distribution at Jim's Find South The paramagnetic halo is larger than the extent of the primary Au mineralisation*

Rand Pit, Reedy mine, near Meekatharra, WA

Gold is present in and around two sub-economic ore shoots on the south face of the Rand Pit, conforming approximately to two mica schist zones within mafic schists (Figure 4) The profile is truncated and saprolite occurs close to the surface Accordingly, there is no surface enrichment and lateral dispersion is weak(<50 ppb) extending for less than 20 m

One hundred and ten samples were selected for the EPR study The EPR values of the acid insoluble residue change in proportion to log Au content of the bulk rock (Figure 4) There are high EPR values near the surface, especially above the mica schist, and close to the mica schists at depth (Figure 5) The barren ultramafic rocks have low EPR values

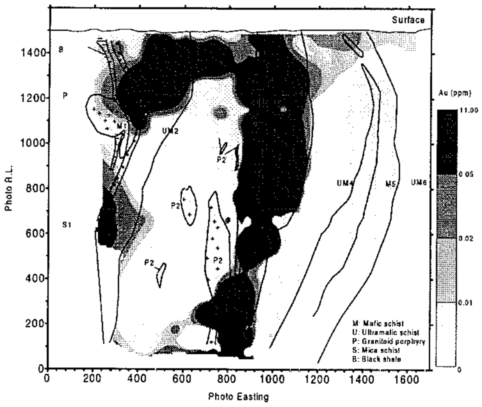

Figure 4: *Distribution of Au (determined by INAA) at Rand Pit, Reedy Mine, near Meekatharra, W A*

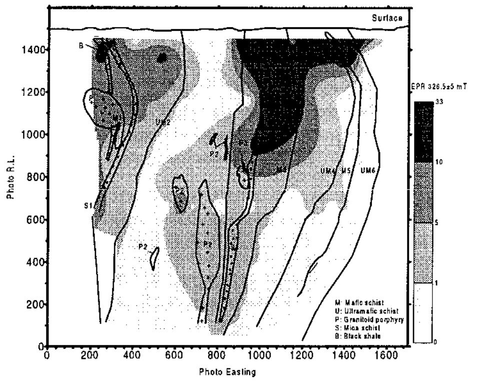

Figure 5: *Relative EPR 326 5±5 mT distribution at Rand Pit, Reedy Mine, W A The EPR halo is larger than the primary Au occurrence*

Mystery Zone, Mt. Percy, near Kalgoorlie

One hundred and eighty seven regolith samples from section 15850N were selected The geology, regolith subdivisions and Au concentrations determined by INAA on bulk samples prior to acid treatment are shown on Figure 6 An additional 197 samples were analysed from a background area, about 1 km north

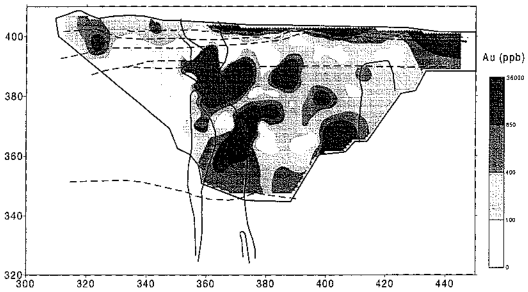

Figure 6: *Distribution of Au (determind by INAA) in the Mystery zone, Mt Percy W A Note the secondary surface enrichyment and subsurface leaching*

Primary Au mineralisation is associated with the porphyries and adjacent fuchsite-carbonate-altered ultramafic rocks In the regolith, there is a widespread zone of high Au concentrations (>100 ppb) in calcareous soils, lateritic residuum and mottled clays in the upper 3-5 m Below this there is a 5-10 m zone of Au depletion (from the upward projection of primary mineralization) approximately corresponding to the upper clay-rich horizons, overlying a zone of supergene enrichment The gold mineralisation at depth occurs in alteration zones

Unfortunately, the samples from the very surface were not available for EPR measurements But just below the lateritic gravels, the EPR values are high, whereas Au is depleted This indicates that the EPR of the acid insoluble residue is not affected by weathering At depth, the high EPR values are found in the mineralised porphyries and fuchsite-carbonate rocks, where they occur (Figure 7) The background area has flat EPR spectra (Aung Pwa and van Moort, 1998b).

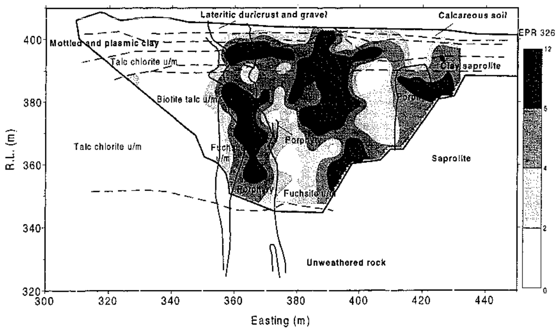

Figure 7: *Relative EPR 326 5+5 mT signal distribution in the Mystery Zone, Mt Percy, W A The EPR halo is undiminished in the subsurface Zone*

McKinnons, near Cobar, NSW

This study involves 101 drill core regolith samples from the 155150N mine section through the open pit and 39 surface soil samples from a line 400 m to the north The McKinnons open pit averaged 1 9 g/t Au; the outline of the supergene enrichment zone (Au>0 3 g/t) is shown in Figure 8

The distribution map of EPR intensities in the drill core samples of the mine section reveals a significant EPR halo outlining the Au mineralisation The halo is open to the west, which is confirmed to be an area of weak mineralisation, and at depth (Figure 9) The EPR response of the surface line 400 m north of the McKinnons open pit is very weak (Aung Pwa and van Moort, 1998b)

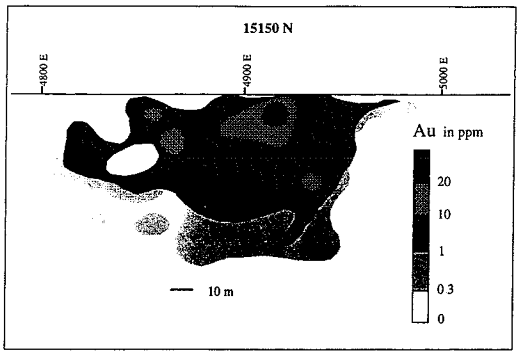

Figure 8: *Distribution of gold in the McKinnons deposit, Cobar (Marshall et al., 1996)*

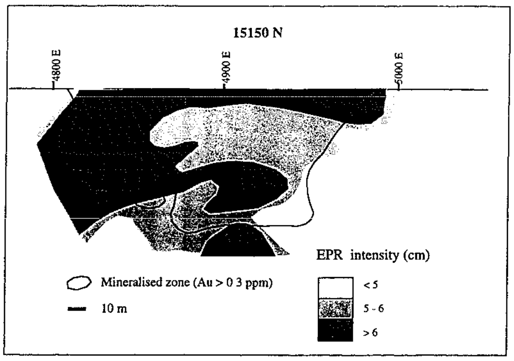

Figure 9: *Distribution of EPR signal intensities measured at magnetic flux density sweeps 326 5+5mT in acid insoluble residues of regolith samples from 15150 N section, McKinnons gold deposit*

GEOCHEMICAL SIGNATURES RELATED TO GOLD MINERALISATION

The multi-elemental data permit a more structured discussion of the relationship with mineralisation than the EPR data alone Space allows only a summary of the results here

The Au concentrations discussed below are those determined on the whole samples, not the acid insoluble residues The Au concentrations in the residues never show zones of supergene enrichment, as secondary Au is dissolved by the acid digestion Primary dispersion patterns in the untreated and acid treated material are comparable

Jim's Find South, Tanami, NT

There is a spatial relationship between the occurrence of Au and acid insoluble F, Al, K, V, Mn, Fe, Ga, Rb and W that is essentially related to sericitic wall rock alteration The distribution of K expresses the relationship between sericite and the primary occurrence of Au (Figure 10) The data presented by Stott et al , (1997) with respect to the concentration of Al are superseded, as the material still contained residual kaolinite Sodium, Ca and Sr depletion at depth is related to wall rock alteration and, near the surface, to weathering.

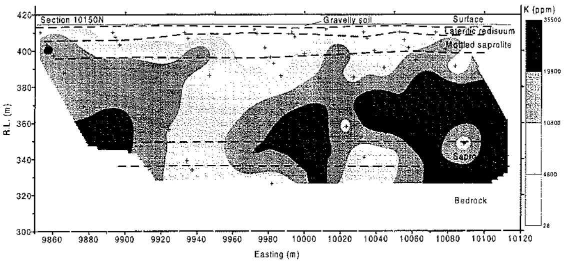

Figure 10: *Distribution of K in the acid insoluble residue at Jim's Find South, Tanami, N T*

A high Rb/K ratio and of elevated As, Cu, Ni, Pb and Zn contents give a good surface expression of the mineralisation The association between As and primary mineralisation is preserved throughout the regolith

Rand Pit, Reedy Mine, Meekatharra, WA

Potassium, Rb, V and, in particular, Ga and W show a spatial relation with the occurrence of Au that appears to be related to the sericitic alteration The K distribution is shown in Figure 11 Copper and Pb show surface enrichment over the mineralisation, best expressed as (Cu(Pb) Sodium, Ca and Sr are not systematically depleted in the ore zones

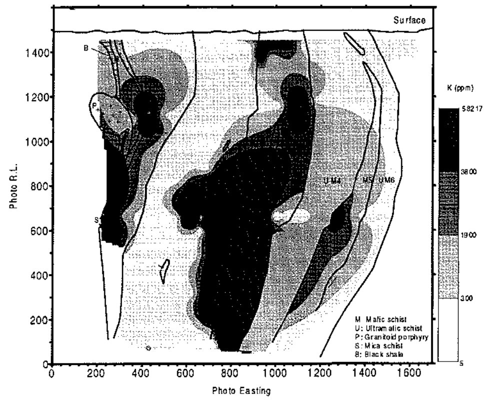

Figure 11: *Distribution of K in the acid insoluble residue at Rand Pit, Reedy Mine, W A (Xu Li, 1998)*

Mystery Zone, Mt. Percy, Kalgoorlie, WA

Primary mineralisation at Mt. Percy is associated with felsic porphyries and the fuchsite-carbonate alteration of the ultramafic rocks they intrude. The alteration zone is typically pyritic and, in addition to Au, is characterised by high abundances of K, Rb, W and Ga in the acid insoluble residue. There is also a good correlation between Ge and Au.

The mineralisation is characterised by high Rb/K and Rb/Al ratios at the surface. This is consistent with the presence of the sericitic (fuchsite) alteration. The K distribution is shown in Figure 12.

Tungsten is consistently enriched throughout the primary mineralisation with concentrations of 10-40 ppm over the porphyries and between 5-27 ppm in the fuchsite bearing ultramafic rocks compared to < 2 ppm in the barren talc chlorite rocks. Tungsten is the best indicator element for Au in the Mystery zone.

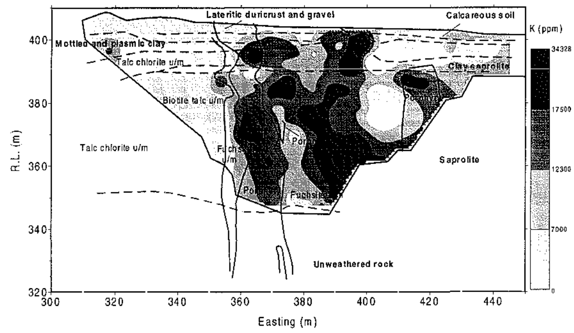

Figure 12: *Distribution of K in the acid insoluble residue at Mystery Zone, Mt. Percy WA (Xu Li, 1998).*

McKinnons, near Cobar, NSW

The geochemical halo associated with the McKinnons gold mineralisation is characterised by enrichment in Cu, Zn, Pb, Ag, As, Sb, Ba and Bi and depletion of K, Al, Fe, Mg, Ca, Na, Ti, Cl, F, Ga, Rb, Zr, Y, V, and Tl. Most of these depleted elements, except possibly Ti and V, are considered indicators of wall rock alteration involving sericite destruction during the emplacement of Au mineralisation along zones of intense fracture. Some of these elements exhibit geochemical zonality in the regolith. The zonality is characterised by enrichment in Cu, Pb, Ag, As, Sb, Ba, Bi, Mo and W, and depletion in Zn and Ni in the upper level of the deposit and at the surface. These geochemical features are considered to be primary geochemical signatures associated with Au and base metal mineralisation.

Copper, Zn, Pb, Ag, As, Sb, Ba, Bi and Mo have potential as surface indicators of concealed mineralisation.

DISCUSSION

The relationship between substitutional electron donors (Al, Ga), electron acceptors (Fe, Ti, Ge) and compensating interstitial ions (H, Li, Na, K, Ca, Mg) in natural and cultured quartz is well documented (Bambauer, 1961; Flörke et al. 1982; Russell et al. 1996; Weil, 1984). Substitutional and interstitial impurities in quartz correlate positively with the intensity of the EPR signal. Russell and van Moort (1998) described the positive correlation between the intensity of the EPR signal in auriferous vein quartz at Beaconsfield and the concentrations of K, Ti, Fe, Al, Ge Li and, surprisingly, Au and As. Nand (1989) observed a positive correlation between the EPR signal and K, Ti, Al, Li, Mg and, again, Au contents in quartz at Fosterville, Victoria. EPR analysis was used to characterise Rb- and V-rich sericitic wall rock alteration in Carlin, Nevada (van Moort et al., 1995). Aung Pwa (1995) used EPR analysis to describe intersecting alteration haloes at the Rosebery and Hercules Zn-Pb-Cu-Au deposits in western Tasmania. One of these halos is related to wall rock associated with metamorphism and deformation (strong EPR signals in Au mineralisation). The second halo is related to primary Cambrian mineralisation (EPR signal related to Mn substitutions in quartz) (Aung Pwa and van Moort, 1998c).

Comparable positive correlations related to the intensities of the EPR signals and the occurrence of Au was observed at all four sites referred to in this study. However, EPR cannot replace Au assays. Only in the Mystery Zone, Mt Percy is there a quantitative correlation between the EPR intensity and Au content.

EPR of quartz is unaffected by the degree of weathering of the material in which the quartz is present (Hamdorf 1987; Nand, 1989). The present study indicates that EPR can detect surface indications of concealed Au deposits in highly weathered terrain and that it can be used to differentiate between barren and mineralised regolith at the surface, e.g., at Reedy, Mt Percy and McKinnons. The failure of this study to detect an EPR surface expression of underlying Au mineralisation at Jim's Find (Figure 3) may be attributed to admixtures of microcrystalline secondary chalcedony resulting from the hydrolysis of silicates during weathering. Such material does not show a strong EPR signal. Some of the surficial material may also have a transported component. It should be noted that the EPR signal is not necessarily related to the presence of sericite, as the McKinnons deposit is characterised by sericite destruction yet exhibits a very strong EPR signal.

The chemical composition of the acid insoluble residue reflects the type of wall rock alteration in all four areas associated with feldspar destruction and sericitisation, but sericite destruction in the McKinnons case. There is further evidence that the wall rock alteration is associated with the formation of a Rb- and V-rich sericite. Of further importance is the reliability of Rb/K ratios and Cu, Pb, Zn and As abundances in acid insoluble residues as indicators of mineralisation throughout the regolith to and including the surface soil. The haloes of these elements are larger than the associated Au mineralisation. In the case of the McKinnons deposit, Pb, Ag and Sb occur at the upper level of the mineralisation and Ni and Zn are enriched at the lower level. Similar distributions and relationships are also generally shown by total analyses of rock pulps.

CONCLUSION

Powder EPR spectra of the acid insoluble residue (quartz concentrate) of the regolith inclusive of the soil form a reliable indicator of wall rock alteration and are unaffected by the degree of weathering, unless dilution occurs. The EPR spectra are the result of substitutional and interstitial impurities in quartz and are associated with (gold) mineralisation.

The chemical expression in the acid insoluble residue of sericitic wall rock is K and Rb enrichment, increased Rb/K and Rb/Al ratios and, commonly, Al, Fe, Mg, F and V enrichment, except where wall rock alteration is characterised by sericite destruction. Sodium, Ca and Sr depletion invariably occurs as a result of plagioclase destruction. Arsenic, Ga, V and W in the acid insoluble residue may be good indicators of Au mineralisation through the regolith, and As, Cu, Pb and Zn may give a surface expression.

Similar results may be obtained for these and other potential pathfinder elements by total analysis of whole rock pulps. However, not all Au deposits have an associated suite of pathfinder elements, whereas research to date suggest that there is always an EPR signal.

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Table 1. *Typical detection limits for INAA, PIXE/PIGME and XRF for geological materials*

ELEMENT	INAA[A]	PIXE/PIGE[B]	XRF[C]
Ag	5	80	2
Au	5ppb	7	3
Al	—	400	0.01%
As	1	3	2
Ba	100	50	30
Ca	1%	45	0.01%
Cl	—	75	20
Co	1	3	20
Cr	5	13	10
Cu	—	2	4
Fe	200	5	1%
Ga	—	2	5
Ge	—	2	3
K	2000	35	0.01%
La	1	600	10
Mg	—	1500	0.01%
Mn	—	8	0.01%
Na	100	40	250
Nb	-	5	4
Ni	50	4	5
P	—	40	0.005%
Pb	—	4	5
Rb	30	3	5
S	—	140	0.005%
Sc	0.1	40	2
Si	—	1100	1%
Sn	0.01%	100	5
Sr	0.05%	3	10
Th	0.5	10	10
Ti	—	17	0.01%
V	2	13	5
Y	1	4	10
Zn	50	2	5
Zr	500	5	10

a: Bequerel Laboratories, Lucas Heights, NSW, Australia
b: This study conducted at Physics Division, Ansto, Lucas Heights, NSW, Australia
c: Xu, (1987) and CSIRO, Wembly, W.A., Australia