REGIONAL-SCALE REGOLITH GEOCHEMISTRY: IDENTIFICATION OF METALLOID ANOMALIES AND THE EXTENT OF BEDROCK IN THE ARCHAEAN AND PROTEROZOIC OF WESTERN AUSTRALIA.

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Base metal, PGE, and ferroalloy metal anomalies, and the extent of covered bedrock can be identified using the chemistry of regolith sampled at low density (one sample per 16km^2) over Archaean and Proterozoic rocks of the Nabberu area of central Western Australia A variety of transported regolith media have been sampled, as in-situ regolith comprises about 15% by area At the regional scale, results are not biased according to most sample media, but meaningful interpretation of regolith chemistry requires knowledge of the nature and distribution of regolith, and integration of regolith chemistry with other data such as airborne geophysics

In conjunction with airborne magnetics and gravity, a variety of trace elements at a range of concentrations in regolith (eg from Sc at a maximum of 32 ppm, to In at a maximum of 1 35 ppm) show that mafic igneous rocks are more extensively developed at the southerly junction of the Nabberu and Peak Hill 1:250 000 map sheets, where Archaean granite and subordinate greenstone were previously mapped These mafic rocks represent Proterozoic sills and extrusives which have anomalous regolith concentrations of Pt and Pd on Peak Hill Elevated concentrations of some base metals and ferroalloy elements in regolith near the contact of two groups of Proterozoic sedimentary rocks in the central northern part of Nabberu coincide with (a) a gravity high marking the northern extent of the Yilgarn Craton, and (b) an area of structural complexity including reverse faulting and shearing

Key words: regolith, Nabberu, additive index

INTRODUCTION

Since 1994, the Geological Survey of Western Australia (GSWA) has been carrying out mapping and chemical analysis of regolith on various 1:250 000 scale map sheets in the Yilgarn Craton and adjacent Proterozoic marginal basins in Western Australia To date, twelve sets of maps and explanatory notes have been published, and current production is between three and four sets of maps and explanatory notes per year The primary aim of the program is to provide regional-scale information on the distribution and composition of regolith as a stimulus to mineral exploration However, as discussed in this paper, this regional regolith and geochemical mapping program has wider implications in terms of understanding the distribution of bedrock, and helping to understand regional geological relations Although other agencies have produced regolith maps at similar scales (eg Craig, 1995), apart from the Ebagoola sheet in Queensland (Pain et al , 1994; Cruikshank and Butrovski, 1994), the GSWA regolith program is the only systematic approach to both mapping the regolith and determining its composition on a broad scale in Australia

As large and contiguous areas of Western Australia are covered in regolith, an understanding of the composition and distribution of regolith is necessary in order to identify the nature and distribution of bedrock in that (a) the regolith can retain some features of the bedrock parent, and (b) dispersion haloes from mineralised bedrock are often preserved in the overlying regolith. The importance of these concepts has been underlined by the discovery of the significant gold deposits in areas of virtually zero outcrop, where only regolith-based exploration methods could be applied (eg Kanowna Belle (2 6 million oz gold: Ridley and Groves, 1993); Bronzewing (38 3 Mt at 2 9 g/t gold; Dugdale, 1997).

The composition and distribution of regolith has been addressed in several mine- or prospect-scale studies, such as the relationship of calcrete and gold mineralisation (Lintern and Butt, 1997), laterite geochemistry (Smith and Perdrix, 1983), and the geochemistry of lag (Robertson, 1997) In contrast to these studies, the GSWA program approaches regolith distribution and composition at (a) a lower nominal sample density of one sample per sixteen square kilometres (equating to approximately 1000 samples per 1:250 000 scale map sheet), and (b) utilises various sample media: although the preferred sampling medium is first- or second-order stream sediments, in areas where drainages are lacking or poorly defined, sheetwash, soil, laterite or lake sediment is sampled. At each sample site, a sample of the regolith is collected for subsequent multi-element analysis, and characteristics of the regolith, the regolith sample and the surrounding geology are recorded on a standard form These site data have proven invaluable in evaluating regolith chemistry, and as an adjunct to Landsat TM, aerial photography, geophysical and other remotely-sensed data in construction of a regolith distribution map The GSWA program has shown that understanding the chemistry of regolith is difficult if the distribution of different regolith types is unknown, so a regolith distribution map is an integral part of the GSWA program In order to illustrate facets of the program and its applications, examples are discussed in the following from the Nabberu 1:250 000 sheet (Morris et al , 1997) This contribution discusses the sampling strategy, regolith-landform map compilation, chemical analysis of regolith, and a statistical comparison of regolith over different bedrock types and regolith units

GEOLOGY OF THE NABBERU 1:250 000 MAPSHEET

The Nabberu 1:250 000 map sheet spans Archaean granite-greenstones of the Yilgarn Craton and Marymia Inliers, and unconformably overlying Proterozoic sedimentary and less common igneous rocks of the Capricorn Orogen (Gee, 1979; Tyler and Thorne, 1990) as shown in Figure 1 Geological mapping of the Nabberu map sheet at 1:250 000 scale was carried out by Bunting et al (1982), and the Nabberu area has figured in more regionally-based publications dealing with Proterozoic sedimentary rocks of the then Glengarry Basin (Bunting, 1986; Gee and Grey, 1993), and the Savory and Bangemall Basins (Williams, 1990, 1992) Liu (1997) has presented a solid geology map of the Nabberu 1:250 000 scale mapsheet, largely based on recently-acquired Australian Geological Survey Organisation (AGSO) geophysical data

ARCHAEAN GRANITE-GREENSTONE

Archaean granitic rocks in the southern part of Nabberu and the Marymia Inlier are variably foliated and porphyritic adamellite, granodiorite, or monzogranite and include syenite dated at 2648 ± 8 Ma (Nelson, 1997) of the Shoemaker Impact Structure (Shoemaker and Shoemaker, 1996; Pirajno and Glikson, 1998) Greenstones are largely mafic volcanic rocks, with subordinate felsic volcanic rocks and banded iron-formation (BIF) The Bridle Face Greenstone Belt (Griffin, 1990; Fig 1), informally referred to as the Nabberu Greenstone Belt by Liu (1997), hosts the only known mineralisation on the Nabberu mapsheet, the structurally-hosted Horse Well gold deposit, with inferred resources of 0 24 Mt at 4 3 g/t Subparallel to this greenstone belt to the west is the Cunyu Greenstone Belt, which is in close proximity to a regional-scale fault informally referred to as the Merrie Range Fault by Liu (1997).

PROTEROZOIC SEDIMENTARY ROCKS

Recent mapping by the GSWA has resulted in a reassessment of the stratigraphy of sedimentary rocks of the Capricorn Orogen to the north of the Yilgarn Craton (Pirajno et al , 1996) Three sub-basins are now recognised, two of which are represented on Nabberu Rocks of the Juderina Formation and Troy Creek beds (Fig 1) belong to the Yerrida Group, which is unconformably overlain by sedimentary rocks of the Earaheedy Group These are in turn unconformably overlain by sedimentary rocks of the Bangemall (Williams, 1990) and Savory Groups (Williams, 1992) respectively.

The Yerrida Group rocks in the southwest of the Nabberu mapsheet (Juderina Formation) consists of shale and sandstone, with some dolerite sills of the Killara Formation (Pirajno et al., 1996) In the northeast, the Troy Creek beds are in unconformable contact with the Earaheedy Group, and in fault contact with the Bangemall Group (Fig 1) The Troy Creek beds comprise a range of rock types from shale, through carbonate, sandstone and BIF.

The Earaheedy Group rocks form a broad synclinal sequence, and are unconformably overlain by Bangemall Group rocks in the north of Nabberu Earaheedy Group rocks show a range of lithologies from arenite, chert, conglomerate and carbonate (Yelma Formation), through BIF and ferruginous clastic rocks (Frere Formation), quartz-rich sandstone of the Wandiwarra and Windidda Formations, and mature sandstone of the Princes Ranges Quartzite

The Bangemall and Savory Groups are dominated by quartz-rich sandstones with subordinate lenses of shale and conglomerate, but include clastic rocks and carbonates of the Scorpion Subgroup of the Bangemall Group.

As is typical of many parts of central Western Australia, there is little outcrop of many basement rock types on the Nabberu mapsheet, although BIF and ferruginised sedimentary rocks of the Frere Formation form prominent hills in the central part of the map sheet, and low hills composed of quartz-rich sandstone of the Bangemall Group are found north of Blue Hill (Fig 1) Granite-greenstones in particular are poorly exposed, with an estimated maximum of 5% outcrop area With such poor exposure, indirect means of inferring the extent and composition of bedrock (eg airborne geophysics, Landsat TM imagery, aerial photography, regolith chemistry) become more important

REGOLITH-LANDFORM MAPPING

An integral part of understanding the composition of regolith is understanding regolith distribution As contract geologists and GSWA staff have collected regolith samples and recorded site information data, a regolith classification scheme that is both simple to use and applicable to a variety of geological associations and topographies is necessary The GSWA has adopted a regolith-landform approach (based on that of Craig and Anand, 1993), where regolith is classified according to its composition, and position in an idealised landform profile A full description of this scheme as used on the Nabberu mapsheet (and used in this paper) is given in Morris et al (1997), whereas the current version (modified from the initial scheme) is summarised in Morris et al (1998) On the Nabberu 1:250 000 sheet, regolith is divided according to its landform position into that which formed in place on top of parent bedrock (relict regime regolith; no net loss or gain of material), regolith that is actively eroding off areas of outcrop or subcrop (erosional regime regolith; net loss of material), and depositional regime regolith (divided into colluvial regime regolith, alluvial regime regolith, and sandplain; net gain of material) Within these regimes, regolith on the Nabberu 1:250 000 mapsheet was further subdivided according to its parent rock (where possible) using a range of qualifiers The more recently-adopted scheme (Morris et al , 1998) retains and expands the landform classifications, and simplifies the compositional qualifiers into more broad categories not restricted to identification of rock type

Regolith map compilation relies largely on delineation of regolith polygons using Landsat TM data and aerial photography, but also employs other data sets, such as digital elevation modelling and geophysics However, in many cases these data are insufficient to resolve the nature of individual polygon types, and in these situations, individual site information is invaluable A review of the approach to regolith map compilation has been presented by Sanders and Coker (1997)

An idea of the amount of outcrop on the Nabberu mapsheet (and conversely, the importance of the regolith) is given by the small amount of relict (< 1%) and erosional (16%) regime regolith, which essentially equates to outcrop area Of the remaining 83%, depositional colluvial regime regolith accounts for 43% (principally areas of sheetwash), whereas depositional alluvial regime regolith (eg active alluvial channels, areas of overbank deposits, lakes) accounts for 17% by area, and sandplain accounts for 23% of the regolith cover It is clear from these data, that only 17% of regolith on the Nabberu mapsheet gives any direct clue as to the underlying bedrock

DELINEATION OF BEDROCK EXTENT USING REGOLITH CHEMISTRY

We illustrate the use of chemistry of samples collected at a low sample density in the delineation of bedrock by examining the distribution of three trace elements, which show a range in levels of concentration These are indium (maximum concentration in regolith of 1 35 ppm), selenium (9 1 ppm), and vanadium (895 ppm) Amongst the Earaheedy Group rocks, these three elements effectively pick out the iron-rich lithologies of the Frere Formation, even though elements like In and Se are at low concentrations (Fig s 1, 2, 3) Selenium in particular also shows higher concentration in regolith over the western part of the Wandiwarra Formation (adjacent to the Frere Formation), relative to the remainder of this formation Regolith-landform mapping of the Nabberu 1:250 000 mapsheet (Morris et al , 1997) has shown that in this western part of the Wandiwarra Formation, elevated regolith In, Se, and V concentrations adjacent to the Frere Formation correspond to depositional colluvial-regime regolith derived from the Frere Formation, deposited on the Wandiwarra Formation The remainder of the Wandiwarra Formation consists of regolith largely derived from the underlying bedrock; elevated concentrations of some trace elements over the Wandiwarra Formation in the vicinity of Blue Hill are discussed below

The distribution of Sc in regolith also illustrates the importance of regolith-landform mapping in interpreting regolith chemistry Over most of the Wandiwarra Formation, Sc levels are relatively uniform, apart from near the contact with the overlying Bangemall Group in the vicinity of Blue Hill, where concentrations are lower (Fig. 4). On the regolith-landform map, this area of lower regolith Sc corresponds to sandplain which is widely distributed over the Bangemall and Savory Groups to the north, and has been transported south over the Wandiwarra Formation west of Blue Hill area, effectively suppressing the underlying bedrock signature.

THE EXTENT OF MAFIC ROCKS IN THE SOUTHWEST OF NABBERU

Airborne geophysical data (ie. aeromagnetics, radiometrics, gravity) have recently been released for the Nabberu area by AGSO. These data have largely formed the basis for a solid geological interpretation of the Nabberu 1:250 000 mapsheet by Liu (1997). He suggested that the Cunyu Greenstone Belt in the southwest of the Nabberu mapsheet (Fig. 1) is of greater extent than previously mapped, extending east to the Merrie Range Fault, and northwest along the fault trace. The concentrations of V (range 6 - 895 ppm; Fig 3) and Sc (maximum 32 ppm; Fig. 4) in regolith over Nabberu show a sharp increase in concentration broadly west of a line corresponding approximately with this fault trace. The high regolith Sc concentrations extend beyond the area of greenstone mapped by Bunting et al. (1982), to include large parts of the overlying Juderina Formation, but drop sharply at the northern boundary with the overlying Yelma Formation. Reconnaissance mapping in the southwest of the Nabberu 1:250 000 mapsheet and on the neighbouring Peak Hill mapsheet has not only confirmed a wider extent of mafic volcanic and intrusive rocks in this area than previously thought, but also shown that these rocks are not Archaean greenstones, but mafic extrusive and high-level intrusive rocks of the Proterozoic Killara Formation. Furthermore, Subramanya et al. (1995) recorded low but anomalous platinum group element (PGE) abundances in regolith over the Killara Formation regolith in the southeast corner of the adjacent Peak Hill mapsheet, with levels of Pt up to 3 ppb and Pd up to 11 ppb. These may be related to the presence of pyrrhotite blebs in hydrothermally altered dolerite of the Killara Formation. Higher than normal levels of PGE in regolith are recorded in contiguous areas on the Nabberu mapsheet (Fig. 5), which are coincident with areas of mafic igneous rocks.

We conclude that although the geophysical data does indicate a greater extent of mafic lithologies than previously mapped, (a) regolith chemistry and mapping do not support the extension of mafic rocks to the north and east as suggested by Liu (1997), and (b) these mafic rocks represent Proterozoic extrusive and intrusive rocks, and not Archaean greenstones.

CONTOURED ELEMENT INDEX MAPS

In regolith studies dealing with the chemistry of ferruginised duricrust (or laterite) in the mineralised parts of the Yilgarn Craton, Smith et al. (1989) and Smith and Perdrix (1983) showed that pathfinder elements and additive indices can be used to highlight potential areas of mineralisation in arid terrains. The additive index approach has been successfully applied to identification of known and potential areas of gold mineralisation on the Sir Samuel 1:250 000 mapsheet (Kojan et al., 1996a, b) using a greenstone chalcophile index. These indices involve combining elements in an additive fashion (ie. element a + element b + element c etc), although some account must first be taken of the relative concentration of elements. This involves calculation of standard scores. Initial log-transformation of the data reduces the impact of extremely high and low values. Following this, data are standardised, which involves expressing each value in terms of its standard deviation relative to the overall distribution. These derived standard scores allow direct comparison of element concentrations (both within and between element suites) regardless of absolute concentration. These standard scores are then summed to produce the additive index value. Two contoured additive index plots for regolith chemical data from the Nabberu 1:250 000 mapsheet (Fig.s 6A and 6B) show a chalcophile element association (summed standard scores for As, Sb, Bi, Mo, Ag, Sn, W and Se), and a pegmatite association (As, Sb, Sn, Ga, W, Nb and Ta, analogous to the PEG-4 plot of Smith et al. (1989)).

The chalcophile index plot highlights the extended areas of mafic rocks in the southwestern part of the Nabberu mapsheet, as well as the Frere Formation. However, an area of higher chalcophile index scores in the Blue Hill area does not correspond directly to any particular bedrock unit in that it spans parts of the Wandiwarra, Frere and Yelma Formations (Earaheedy Group) and encroaches on the Bangemall Group. The pegmatite index shows similar areas of high index values to the chalcophile index plot, largely picking out the Frere Formation, the extended area of mafic rocks in the southwest of the mapsheet, and the Blue Hill area, while also highlighting low values for Archaean granitoids and most of the Bangemall and Savory Groups.

The AGSO geophysical data shows a gravity high in the Blue Hill area, interpreted as an area where the acoustic basement is closer to the surface (ie. the cover of Proterozoic sedimentary rocks is thinner). One interpretation of these data is that this gravity high marks the northern extent of the Yilgarn Craton beneath the Capricorn Orogen. As an adjunct to this, recent geological mapping by the GSWA of Proterozoic sedimentary sequences in the northern part of the Nabberu 1:250 000 mapsheet has highlighted an area of relatively intense shearing and reverse faulting, coincident with the areas of anomalously high chalcophile and pegmatite index scores, and a gravity high in the Blue Hill area. We speculate that in this area, anomalous element concentrations in regolith, as shown by additive indices, do not solely represent bedrock control (in that the anomaly spans several bedrock units) but also in part correspond to perturbations in the basement and some structural control on mineralisation which is manifested in the regolith chemistry. Unlike the western part of the Wandiwarra Formation, the regolith-landform map does not support any particular depositional control on regolith chemistry in this case

DISCUSSION

We have presented examples of how regional regolith chemistry can be used as an adjunct to geological mapping, and to identify areas of potential mineralisation, in areas of limited bedrock outcrop. In all cases, regolith chemistry cannot be interpreted in isolation of other datasets, such as regional bedrock mapping, geophysics, Landsat imagery or regolith distribution. In the same vein, interpretation of one dataset in isolation from others can also produce spurious results. Furthermore, we have found that compilation of a reliable map showing the distribution of regolith (regolith-landform map) must be based on a combination of remotely sensed data (eg Landsat TM, aerial photography, airborne geophysics) and evenly-spaced ground observations recording the nature of both regolith and surrounding geology

On a regional scale, such as that employed by the GSWA regional regolith and geochemical mapping program, valid conclusions about variations in regolith chemistry can be drawn by comparing samples of various media types (excluding sandplain). From this, we conclude that although transported regolith accounts for more than 80% of regolith on the Nabberu mapsheet, at a sampling density of one per sixteen square kilometres, meaningful conclusions can be drawn about the distribution of bedrock and areas of potential mineralisation, as long as regolith chemistry is interpreted along with other data such as geophysics, regolith distribution, and regional mapping of bedrock. The implication here is that on the regional scale, regolith transport differences are sufficiently short that regional relationships are not obscured

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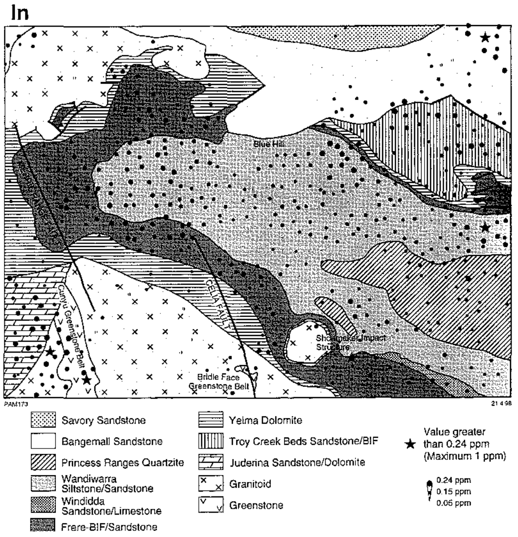

Figure 1: *Concentration of indium (In; ppm) in regolith on the Nabberu 1 250 000 scale map sheet (Morris et al , 1997), shown in relation to bedrock geology (after Bunting et al , 1982; Bunting, 1986; Pirajno et al , 1996) Concentrations up to 2 5 standard deviations above the mean shown as circles, with circle diameter proportional to concentration Concentrations above 2 5 standard deviations above the mean shown as stars*

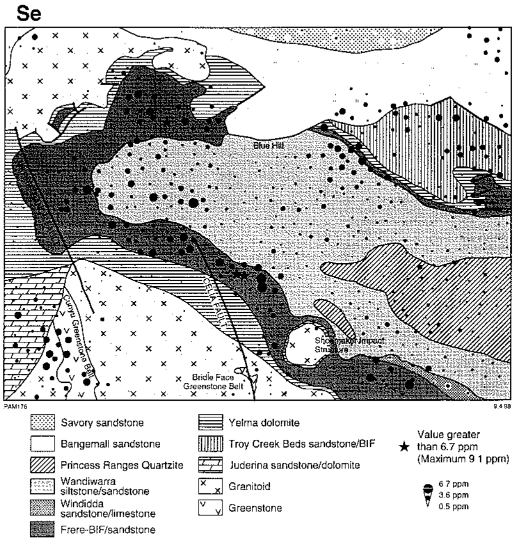

Figure 2: *Concentration of selenium (Se; ppm) in regolith on the Nabberu 1:250 000 scale map sheet (Morris et al., 1997). See Figure 1 for source of geology and description of symbols.*

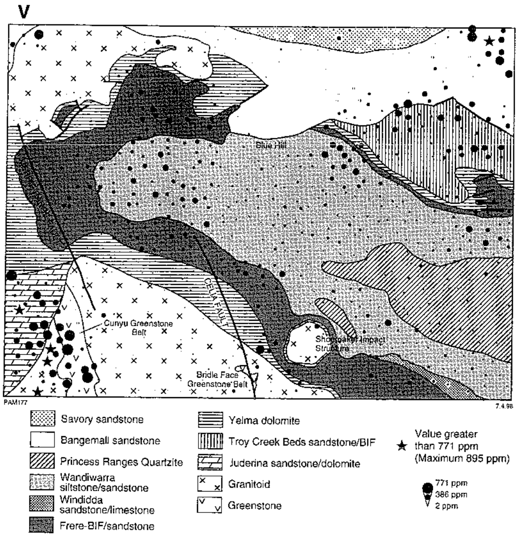

Figure 3: *Concentration of vanadium (V; ppm) in regolith on the Nabberu 1:250 000 scale map sheet (Morris et al., 1997). See Figure 1 for source of geology and description of symbols.*

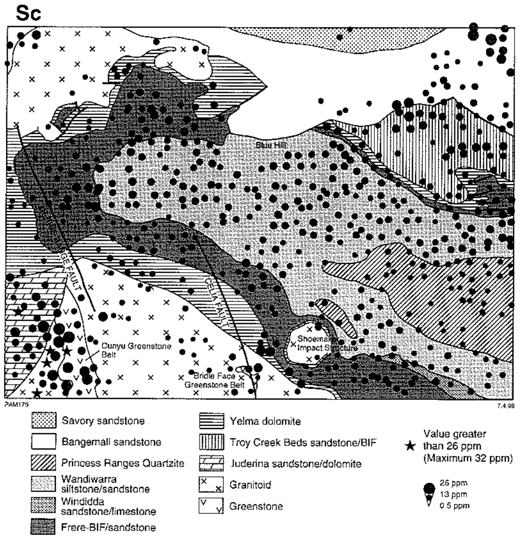

Figure 4: *Concentration of scandium (Sc; ppm) in regolith on the Nabberu 1:250 000 scale map sheet (Morris et al., 1997). See Figure 1 for source of geology and description of symbols. Concentrations less than approximately 3 ppm removed for clarity.*

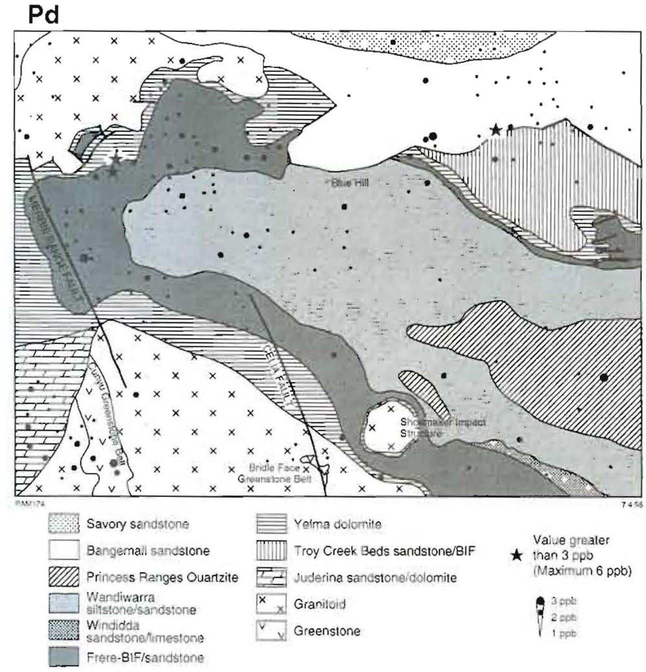

Figure 5: *Concentration of palladium (Pd; ppb)) in regolith on the Nabberu 1:250 000 scale map sheet (Morris et al., 1997). See Figure 1 for source of geology and description of symbols.*

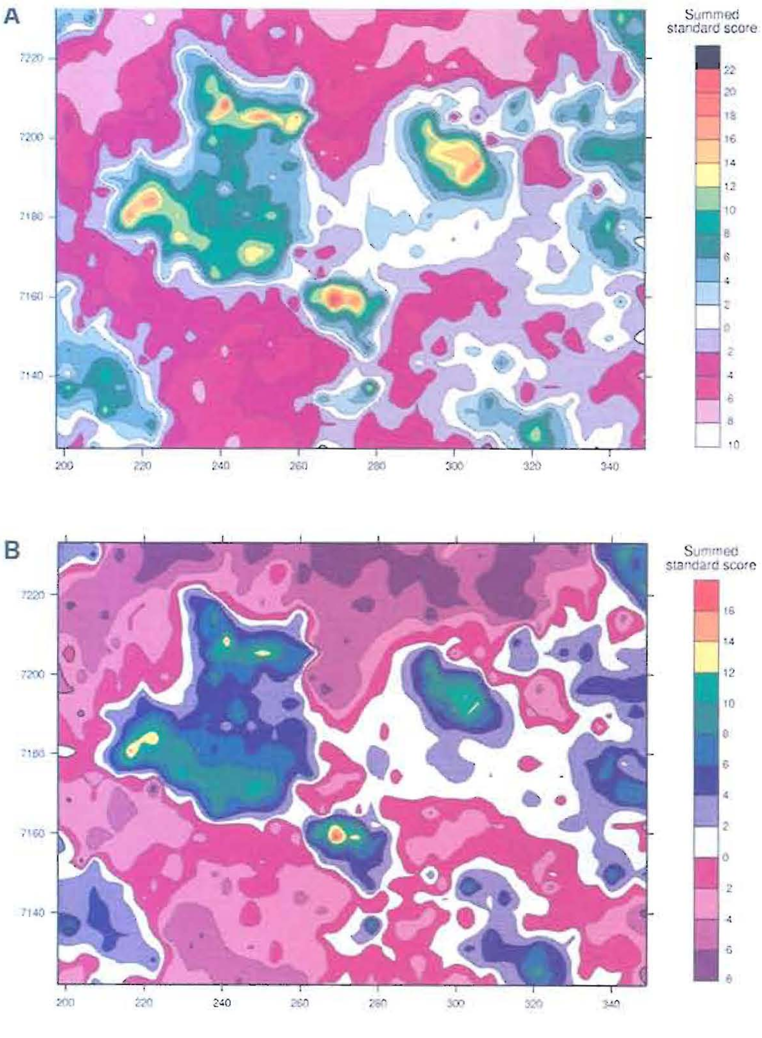

Figure 6: *Additive index maps for regolith on the Nabberu 1:250 000 scale map sheet (Morris et al., 1997). See text for discussion.*

A. Chalcophile element association (As + Sb + Bi + Mo + Ag + Sn + W + Se).

B. Pegmatite association (As + Sb + Ga + W + Nb + Ta).