# LATERITE GEOCHEMICAL DATABASE FOR THE SOUTHWEST YILGARN CRATON, WESTERN AUSTRALIA

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## ABSTRACT

This is the first release of a 53-element dataset for approximately 2000 laterite samples from the SW quadrant of the Yilgarn Craton. The samples were taken on a nominal equilateral triangular grid with a 9 km edge with each sample comprising about 1 kg of ferruginous nodules and pisoliths from lateritic residuum, lag formed from lateritic residuum, or of ferruginous gravel contained in locally derived colluvium. Some authigenic gravel may, inadvertently, have been included.

The laterite geochemical atlas is designed to provide a regional geochemical framework at spacing close enough to recognize regional geochemical trends, major lithological differences and dispersion halos around significant bedrock mineralization. The sample spacing is wide enough to cover a substantial part of the Yilgarn Craton and still provide useful data for exploration and environmental purposes.

Significant results of the first stage of sampling, completed in the SW quadrant of the Yilgarn Craton, are presented. These include increased Au abundances in the NE part of the sampling area that cluster around known gold deposits; their extent may mean more widespread mineralization in these areas. The chalcophile element index (CHI6*) illustrates potential for Au and base metal mineralization in the westernmost part of the Yilgarn Craton; the pegmatophile PEG4* index shows a regional NW trend north of the Saddleback greenstone belt. Chromium concentrations in granitic terrain may indicate mafic-ultramafic remnants outside the known greenstone belts. A regional Hg anomaly trends NW over more than 500 km.

This interim report, together with the release of the analytical data, provides information about the sampling strategy, preparation methods, analysis, and some new element distribution patterns with significance to exploration.

## INTRODUCTION

### Background

This report accompanies the preliminary release of 'laterite'[1] geochemical data from the SW quadrant of the Yilgarn Craton. A more comprehensive data set for the western Yilgarn Craton, contoured maps for all analytes, a discussion of the analytical results, summary statistics and geostatistical procedures will be published in early 2007 as a GSWA record/MERIWA Final Report M371.

The main objective of the laterite geochemical atlas is to stimulate mineral exploration in the Yilgarn Craton. Data for the western Yilgarn Craton are intended to demonstrate the feasibility and value of low-density geochemical maps of the whole Yilgarn Craton and adjacent terrains.

Laterite geochemistry data from the CSIRO-AGE database (Smith *et al*., 1992; Geological Survey of Western Australia, 1998), covering the SW Yilgarn Craton, demonstrated that low-density sampling (nominal equilateral triangular grid with a 9 km edge equivalent to one sample per 70 $km^2$) can outline regional geochemical trends (Cornelius *et al*., 2001) that are of value to the mineral exploration industry. This is significant because most of the western Yilgarn Craton can be sampled at this spacing as remnants of lateritic residuum may be present even in largely eroded terrains. In colluvial-depositional terrains, lateritic nodules and pisoliths may be part of colluvium or may form lenses within it. This material, although no longer residual, has regional geochemical relevance.

The SW Yilgarn Craton was selected as the starting point as there is much existing data and access is easy. Apart from the world-class bauxite deposits, the Boddington Au mine and the Greenbushes rare metal pegmatite, the SW Yilgarn Craton has an apparent lesser mineral endowment than its eastern counterpart. This may, in part, reflect less intense exploration.

The geochemical atlas will provide baseline data for comparison with both existing and new datasets. In essence, the sampling was at a scale broad enough to be affordable, yet at a sufficient density to identify prospective areas for detailed exploration. The dataset may also prove useful for environmental purposes, *e.g*., the regional distribution of Se for agriculture and geomedical studies.

The choice of analytes and their respective analytical methods were based on the expected concentrations and likely mineral hosts in this ferruginous sample medium. For a few elements, compromise was needed between the most suitable method and budget constraints. However, sample material and pulps are stored with the Geological Survey of Western Australia for possible future re-investigation.

### Climate

Inland, the SW quadrant of the Yilgarn Craton is semi-arid; closer to the coast and in the SW corner, the climate is typically Mediterranean with dry summers and cool winters. Rainfall ranges from >1000 mm near the coast and in the SW, to 200 mm inland.

### Geology of the SW Yilgarn Craton

The geological framework of the Yilgarn Craton has recently been revised by Cassidy *et al*. (in press), and much of the following is extracted from this. They identified six terranes from W to E, comprising the South West Terrane, Narryer Terrane, Youanmi Terrane, and Eastern Goldfields Superterrane (which contains three terranes). A small part of the current dataset (25%) is from samples located in the Youanmi Terrane; the majority (75%) is from the South West Terrane, which

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[1]The term 'laterite', as used in this report, refers to lateritic residuum (ferruginous duricrust, nodules and pisoliths), lag formed from lateritic residuum, and nodules and pisoliths that have become part of colluvium, in the context of laterite geochemistry. Some of the materials classified here as lateritic residuum may have experienced local transport of about 100-200 m, or may have formed in a sediment.

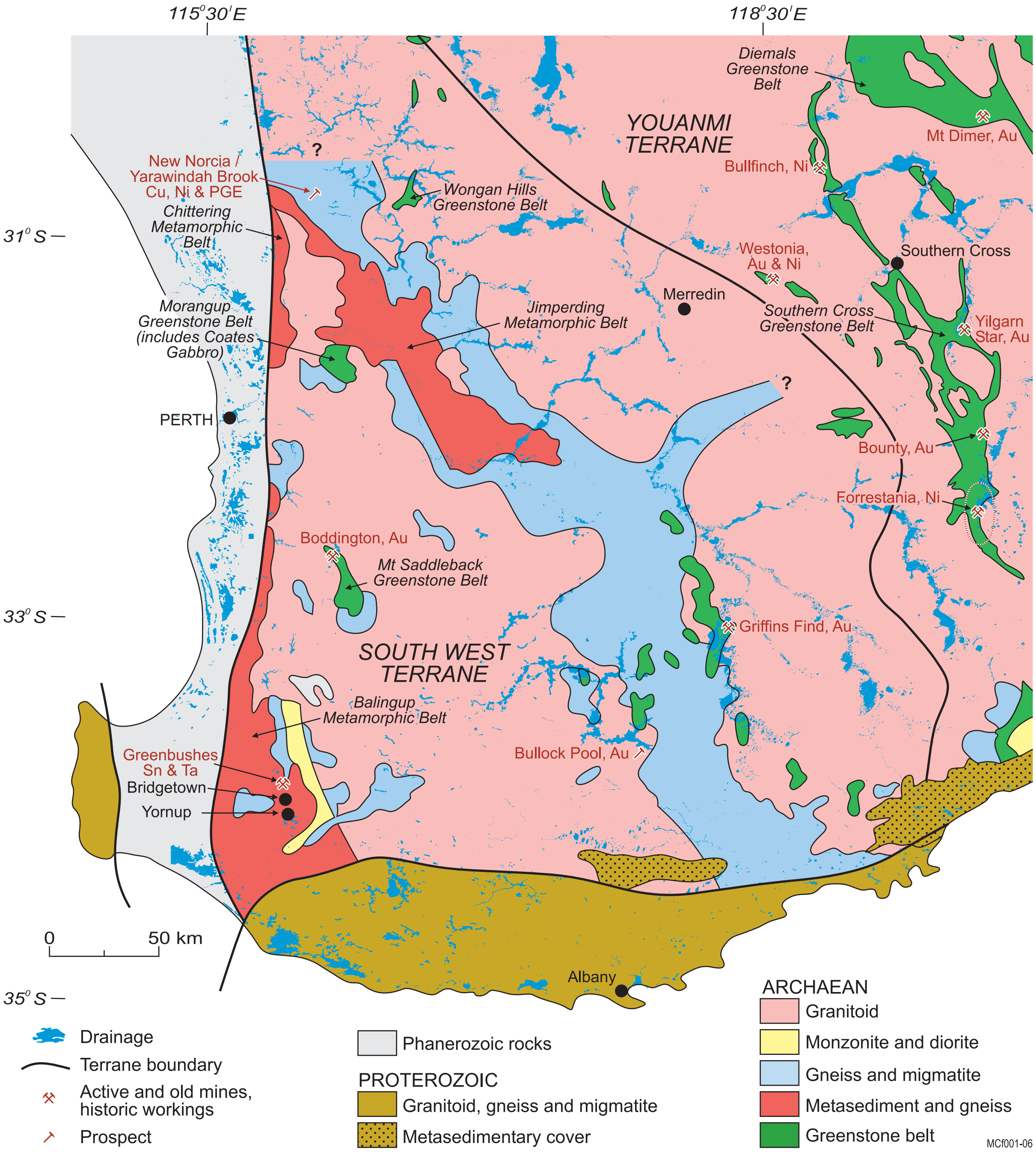


Figure 1. Geology and tectonic/structural provinces in the SW quadrant, after Wilde et al. (1996), GSWA 1:2.500000 generalised geology of Western Australia 1999 (www.doir.wa.gov.au/aboutus/geoview), and Cassidy, in press.

consists of multiply deformed granitic gneiss, and metamorphosed sedimentary and igneous rocks, with deformation and intrusion of granitic rocks and pegmatites in the Late Archaean (Myers, 1993; Wilde *et al.*, 1996; Cassidy *et al.*, in press). Supracrustal successions in the South West Terrane (Figure 1) comprise volcanic, siliciclastic and chemically-precipitated sedimentary rocks (*e.g.*, Wongan Hills greenstone belt) which show a variety of ages, including 3.2-2.8 Ga for the Chittering, Jimperding and Balingup metamorphic belts (quartzofeldspathic gneisses) to Late Archaean ages of c. 2.7 Ga for the Saddleback greenstone belt (Wilde *et al.*, 1996; Cassidy *et al.*, in press). Late Archaean ages have been recorded for granitic rocks of the South West Terrane (summarized in Nemchin and Pidgeon, 1997). A major zone of migmatite and gneiss extends SE from the Jimperding Metamorphic Belt to the southern edge of the Yilgarn Craton (Wilde *et al.*, 1996). Mafic-ultramafic rocks occur in the Jimperding Metamorphic Belt (Wilde and Low, 1978), *e.g.*, at Yarawindah Brook, SE of New Norcia, where discrete platinum group minerals were identified

(Harrison, 1984; Cornelius *et al*., 1987), and to the south in the Army Reserve Area and the Morangup Greenstone Belt (Wilde and Pidgeon, 1990) that hosts a body of gabbro at Coates Siding (Coates Gabbro) (Baxter, 1978). Other small occurrences of mafic–ultramafic rocks include variably altered and weathered peridotitic and pyroxenitic rocks near Yornup, S of Bridgetown (Wilde and Walker, 1984; Cornelius *et al*., 1987).

The Youanmi terrane, combining the Murchison and Southern Cross Granite-Greenstone Terranes of Tyler and Hocking (2001), contains a series of c. 3.0 Ga greenstone belts. These are dominated by mafic and ultramafic rocks, a basal quartzite unit, with less common BIF and are overlain locally by an upper greenstone succession of felsic volcanic or siliciclastic sedimentary rocks (c. 2.73 Ga) in some areas. The accompanying granitic rocks are mainly monzogranite and granite gneiss emplaced at c. 2.76–2.68 Ga and 2.66–2.62 Ga (Cassidy *et al*., 2002, Geological Survey of Western Australia, 2005).

A summary of the main lithological constituents of 51 greenstone belts in the former Southern Cross Granite-Greenstone Terrane has been provided by Griffin (1990), and those of the former Murchison Province have been discussed by Watkins (1990). Results of more detailed mapping (*e.g*., Riganti and Chen, 2002) and detailed SHRIMP U-Pb geochronology (*e.g*., Geological Survey of Western Australia, 2005) have shown that volcanism or sedimentation occurred at 3.05–2.93, 2.81, and 2.76–2.72 Ga (Cassidy *et al*., in press and references therein).

Based on style of volcanism, geochemistry and chronology, three tectonostratigraphic terranes have been identified in the easternmost Eastern Goldfields Superterrane. There is much detailed knowledge of this superterrane, due to its extensive metal endowment, predominantly gold and nickel. In contrast to the adjacent terranes, its volcanism ranges from >2.81-2.66 Ga (Cassidy *et al*., in press). Greenstones consist of mafic and ultramafic volcanic rocks, with felsic volcanic rocks in the upper parts of the succession of some areas. Late-stage, syn-orogenic basin successions are found in several of the component terranes. Unlike the adjacent terranes, the Eastern Goldfields Superterrane has abundant ultramafic rocks and less BIF.

Some accompanying granitic rocks have volcanic correlatives, whereas others (*e.g*., Low-Ca granitic rocks) lack volcanic equivalents. Granite was emplaced largely between 2.72-2.63 Ga.

**Mineral deposits**

In the area covered by this data release (south of 30°S and west of 120°E) there are several world-class mineral deposits, including the Boddington Au Mine and the Greenbushes Sn-Ta deposit, both located near the western margin of the Yilgarn Craton (Figure 1). Hassan (1998) has summarized the type and distribution of mineral occurrences in the SW of Western Australia, noting that this area also contains world-class bauxite deposits and produces coal, mineral sands and silica sand. The eastern part of the SW quadrant, the Youanmi Terrane, hosts Ni deposits in the Forrestania greenstone belt (Forrestania) and Au deposits further north at Marvel Loch, Southern Cross (historic) and Westonia (Cooper and Flint, 2006). Economic iron ore is found at Windarling Range, Mt Jackson, and Koolyanobbing, associated with greenstone belts N of Southern Cross.

**Regolith of the SW Yilgarn Craton**

Weathering, mainly during the Tertiary, produced a thick regolith that typically comprises weakly weathered bedrock or saprock, saprolite, commonly bleached in its upper part, and a clay-rich zone, in places mottled, that gives way to a ferruginous, siliceous or bauxitic upper zone. In the inland, particularly over granite-gneiss terrain, sandplain covers the residual profile; sands and silts forming the sandplain were derived from the residual profile and vary in thickness from <1m to tens of metres. In many parts of the craton, the regolith is more complex due to erosion and deposition; however, the current sampling program generally targets residual settings with a preserved or partly preserved profile. A discussion of the regolith geology of the Yilgarn Craton is given by Anand and Paine (2002).

For this type of geochemical sampling, the most important part of the regolith is its ferruginous upper part, the lateritic residuum. This comprises lateritic duricrust and loose lateritic gravel composed of ferruginous nodules and pisoliths. The lateritic residuum forms a useful sample medium for detecting dispersion haloes in the regolith emanating from Au, base metal and rare metal deposits (Smith *et al*., 1992; Anand *et al*., 1993; Anand, 2001). The target and associated pathfinder elements are closely associated with the secondary Fe oxides that are the main components of the ferruginous materials. Ferruginous pisoliths and nodules are not only found on lateritic residuum, but can also form a lag on eroded, saprolite-dominated areas (Anand, 1998a) or become a part of colluvium and alluvium in depositional terrains. In these non-residual environments, the relationship between the ferruginous materials and the underlying bedrock and weathering profile is less clear than in a residual setting in which the regolith profile and the lateritic residuum are preserved. However, on the broad spacing and scale of this geochemical survey, some lateral movement of the nodules and pisoliths, *e.g.*, up to 1 km, is acceptable if not desirable. In contrast, lateritic duricrust may be more representative of the local lithology and is generally more suitable for follow-up sampling.

Pisoliths and nodules may also have formed in sediment and this gravel may be difficult to distinguish from lateritic residuum in the field. A gravel of authigenic pisoliths will have little or no genetic relationship with the underlying bedrock (Anand and Paine, 2002) and therefore is not deliberately targeted as a sample medium.

## LATERITE SAMPLING

### Terminology and classification of sample materials

The preferred sample medium for the laterite geochemical atlas is lateritic gravel, which consists of nodules and pisoliths that form the upper part of the lateritic residuum. These contributed 81% of samples in the SW quadrant. Where this material is too scarce or absent, lag formed from this gravel is the next best option (13% of samples). In the absence of gravel, duricrust was collected (2% of lateritic residuum); these samples generally comprise nodules released from the duricrust and fragments of duricrust. In all cases, sample material was composited from various locations over a reasonably large area (*e.g*., 50 x 50 m). In depositional terrain, particularly colluvium (Figures 21 and 22), pisoliths and nodules are retrieved from around roots (Figure 19), at the base of trees (Figure 20) or from the surface. These samples are marked as 'Colluvium' in the database and comprise 5% of all samples. Samples of uncertain provenance are designated ' unknown substrate' (1%).

The gravel generally comprises pisoliths and nodules varying in size from approximately 5-30 mm (Figures 17 and 18). The gravel shows a wide variation in colour from light brown through yellow and dark red to black. Its composition ranges from maghemite, hematite to goethite rich. Some samples have very low Fe and Al contents, and are mainly comprised of quartz grains and kaolinite (Figures 15 and 16). These are incipient nodules that are common in the central part of the south west terrane and were described in more detail by Li Shu *et al*. (2005). Other samples have very high Fe contents (99th percentile: 62% $Fe_2O_3$) (Figures 11 and 12) and may have formed from Fe-rich bedrock, *e.g.*, a mafic dyke, or may be of authigenic origin. The majority of samples, however, show $Fe_2O_3$ concentrations between 11-39% (10th-90th percentiles) (Figures 13-16). Alumina concentrations range from 14-36% (10th-90th percentiles) and there is a strong positive correlation between the annual rainfall and the Al content in the ferruginous gravel in the western part of the Yilgarn Craton. The relationship between major elements, mineralogical composition, and trace and minor elements will be investigated in the final release (GSWA record/MERIWA Final Report M371).

For interpretation of the geochemical data and assessing the significance of subtle signatures, it is important to take into account the setting of the sample (from lateritic residuum, from lag or from colluvium). At 9 km sample spacing (*i.e.*, an area of approximately 70 $km^2$) it is critical to collect a representative sample. Lag derived from lateritic residuum generally has been dispersed and mixed, and is more suitable than residual lateritic duricrust and its gravel.

There are many other types of ferruginous materials on the Yilgarn Craton (Anand, 1998a; Anand and Paine, 2002) which have different chemical characteristics to those of lateritic residuum and gravel formed from it. Iron-cemented gravel (ferricrete) formed on or within sediments would be expected to show no genetic relationship with the underlying mottled and saprolitic clays (Anand and Paine, 2002). Care was taken to avoid ferricrete and Fe-segregation by considering the regolith materials in their local landform setting and the regolith. However, authigenic, or partly authigenic pisoliths may have been sampled inadvertently. A few samples in this dataset have high Ti and V concentrations and possibly are derived from ferricrete rather than from lateritic residuum (Anand and Paine, 2002). However, for the purpose of this interim release, the analyses have been retained and the sample medium marked accordingly as 'unknown substrate', or LQ100 or LQ200. Care was taken to ensure that uniform and compatible sample media were collected, and appropriately coded, following the terminology and classification of Anand and Paine (2002), and Anand *et al.* (2002). However, more than 10 samplers have been involved in the collection of this dataset, including the CSIRO-AGE and Astro Yilgarn Regolith collections, and some inconsistencies in the selection and classification of the sample materials are to be expected.

**Sample collection**

Available and verifiable collections of lateritic residuum from the Yilgarn Craton (the CSIRO-AGE and the CRC LEME - Astro Yilgarn Regolith collections) were re-analyzed in preference to collecting new samples. Reanalysis of existing sample material reduced the cost of field sampling,

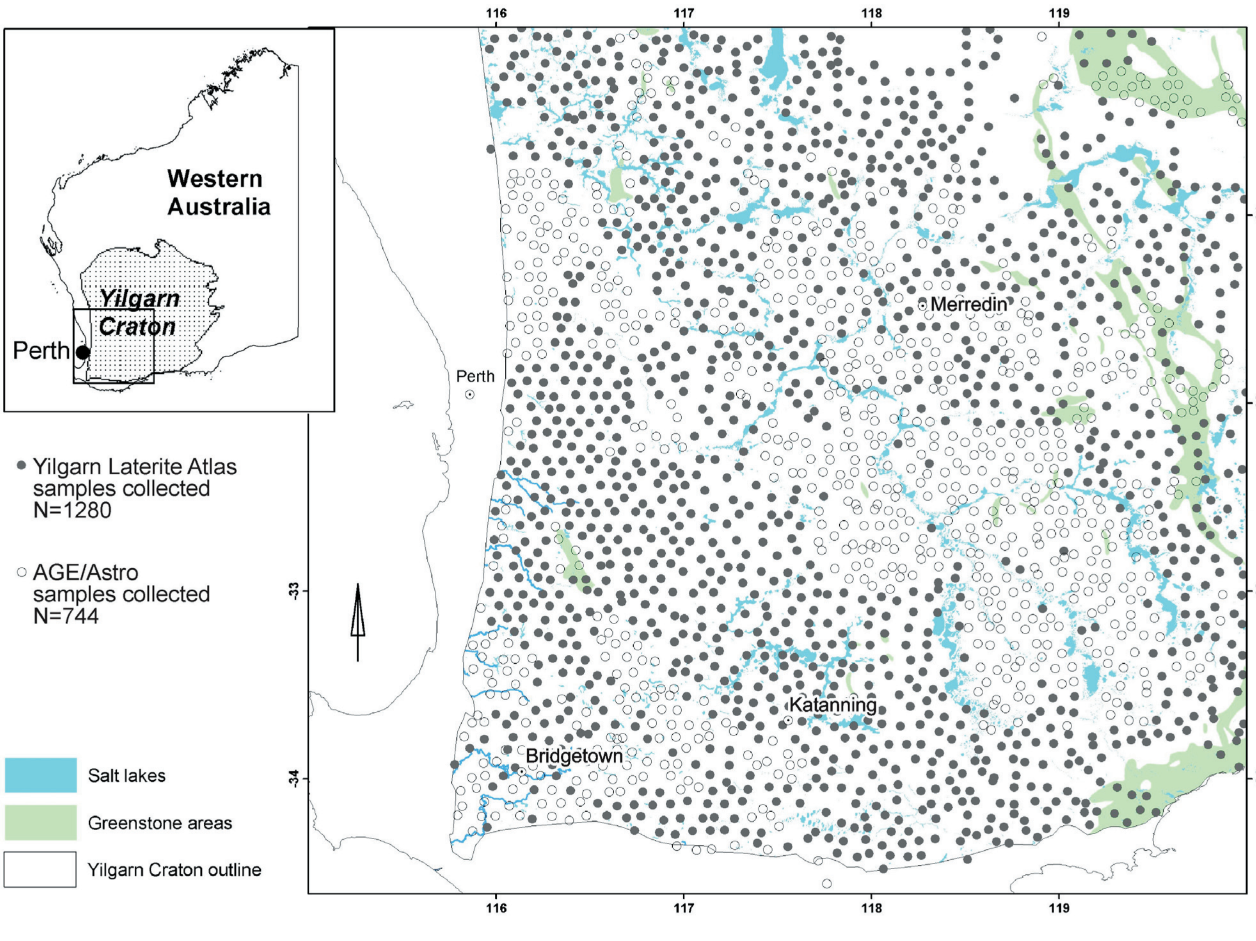


Figure 2. Location of field sample sites and samples from existing sample collections.

and some sample sites were either difficult or impossible to access (mine sites, disease risk areas, private land). The sample locations were checked against a nominal equilateral triangular grid with a 9 km edge and those samples within a radius of up to 4 km around the grid nodes were selected for analysis provided that the minimum weight of the available sample was >400 g of unprepared sample or >100 g of pulp. Where total sample and pulp were available, a small sample of the original material was taken as a reference and approximately 100 g of the pulp was taken for geochemical analysis. Four hundred and eighty nine samples from the CSIRO-AGE collection and 255 samples from the Astro Yilgarn Regolith collection were analysed. A total of 1280 new samples were collected for this project (Figure 2). Standardized sample and landform descriptions are available for all new samples, but not for some from the CSIRO-AGE and Astro collections.

All proposed new sample locations were plotted on GSWA 1:250 000 geological maps, with sites preferentially located in areas of Czl (lateritic residuum) or Czs (sandplain). Sample locations in areas with extensive overburden or erosion were moved to the nearest suitable site within a radius of approximately 4 km. Sample teams were given the discretion to move the sample site from areas of largely transported cover (generally in areas of broad drainage), to maintain the sample spacing, however, in about 5% of all cases, no suitable sample was found.

At all sites, two samples (each about 1 kg) were collected, one as a reference and the other for geochemical analysis. A third sample was collected as a field duplicate at a rate of about 1 in 40. Sampling strategies for regional laterite sampling were discussed in Cornelius *et al*. (2001).

In agricultural areas, sampling was mainly along reserves for public roads and tracks, to avoid delays brought about by contacting landowners. Care was taken to avoid areas of disturbance and contamination. Access to private land was sought in circumstances were no other sample sites were available. On pastoral or crown land, samples were collected along tracks and grid lines. Permits to access all CALM-controlled land in the SW Yilgarn were obtained, and permission was sought from the local CALM officer to enter specific nature reserves.

In the field, regolith-landform information was gathered at each sample site, together with representative digital photographs. Recording of sample information was on an A4 template. This information was entered into an Access database and linked to the analytical data. Extracts of this information will be given in the final release of the database as a GSWA Record/MERIWA Final Report M371.

Parts of the N and NE of the SW quadrant are covered with dense native bush and scrub, mainly N and NE of the agricultural zone. Here, sampling could not be completed during the first stage of this project due to access difficulties. It is planned to complete this with helicopter sampling in 2006. Approximately 100 sample sites are required to complete this area.

## SAMPLE PREPARATION AND ANALYSIS

### Introduction

Sample preparation and analysis were by Ultra Trace Analytical Laboratories Pty. Ltd. (Ultra Trace), Canning Vale, Western Australia following public tender. The analyte suite, digestions, methods and detection limits are listed in Table 1. The details of the digestions are given below from www.ultratrace.com.au/services/index.php (D. Ruane, Ultra Trace, personal communication 2006).

### Sample preparation

For all new samples, approximately 1 kg of reference material was kept untreated; for most samples from the Astro Yilgarn Regolith and CSIRO-AGE collections, a small reference sample (0.1-0.4 kg) was kept, however, approximately 260 samples from the Astro Yilgarn Regolith collection were only available as pulps. For analysis, a 1-1.5 kg sample was milled to <75 µm in a robotic low-Cr ring mill. Some samples required crushing to reduce the particle size prior to milling. Crushing

## Table 1.
## Analytes, digestion and analytical methods, and lower limits of detection

| Analyte | Unit | Digest | Method | Lower limit of detection |
|---|---|---|---|---|
| SiO2 | % | fusion disc | XRF | 0.01 |
| TiO2 | % | fusion disc | XRF | 0.001 |
| Al2O3 | % | fusion disc | XRF | 0.01 |
| Fe2O3 | % | fusion disc | XRF | 0.01 |
| MnO | % | fusion disc | XRF | 0.01 |
| MgO | % | fusion disc | XRF | 0.01 |
| CaO | % | fusion disc | XRF | 0.01 |
| Na2O | % | fusion disc | XRF | 0.01 |
| K2O | % | fusion disc | XRF | 0.01 |
| P2O5 | % | fusion disc | XRF | 0.001 |
| Ag | ppm | 4 acid | ICP-MS | 0.5 |
| As | ppm | 4 acid | ICP-MS | 0.5 |
| Au | ppb | Aqua regia | ICP-MS | 0.2 |
| Ba | ppm | Sodium peroxide fusion | ICP-MS | 10 |
| Be | ppm | 4 acid | ICP-MS | 0.1 |
| Bi | ppm | 4 acid | ICP-MS | 0.1 |
| Cd | ppm | Aqua regia | ICP-MS | 0.1 |
| Ce | ppm | 4 acid | ICP-MS | 0.05 |
| Cl | ppm | fusion disc | XRF | 20 |
| Co | ppm | 4 acid | ICP-MS+AES | 1+2 |
| Cr | ppm | fusion disc | XRF | 10 |
| Cs | ppm | 4 acid | ICP-MS | 0.1 |
| Cu | ppm | 4 acid | ICP-AES | 1 |
| Eu | ppm | 4 acid | ICP-MS | 0.02 |
| Ga | ppm | 4 acid | ICP-MS | 0.2 |
| Hg | ppb | Aqua regia | ICP-MS | 10 |
| In | ppm | 4 acid | ICP-MS | 0.02 |
| La | ppm | 4 acid | ICP-MS | 0.05 |
| Lu | ppm | 4 acid | ICP-MS | 0.02 |
| Mo | ppm | 4 acid | ICP-MS | 0.2 |
| Nb | ppm | Sodium peroxide fusion | ICP-MS | 1 |
| Ni | ppm | 4 acid | ICP-AES | 1 |
| Pb | ppm | 4 acid | ICP-MS | 1 |
| Rb | ppm | Sodium peroxide fusion | ICP-MS | 0.2 |
| S | ppm | fusion disc | XRF | 10 |
| Sb | ppm | 4 acid | ICP-MS | 0.1 |
| Sc | ppm | 4 acid | ICP-AES | 1 |
| Se | ppm | 4 acid | ICP-MS | 1 |
| Sm | ppm | 4 acid | ICP-MS | 0.05 |
| Sn | ppm | 4 acid | ICP-MS | 1 |
| Sn_fus | ppm | Sodium peroxide fusion | ICP-MS | 10 |
| Sr | ppm | 4 acid | ICP-MS | 0.1 |
| Ta | ppm | 4 acid | ICP-MS | 0.05 |
| Ta_fus | ppm | Sodium peroxide fusion | ICP-MS | 0.5 |
| Te | ppm | 4 acid | ICP-MS | 0.2 |
| Th | ppm | Sodium peroxide fusion | ICP-MS | 0.5 |
| Tl | ppm | 4 acid | ICP-MS | 0.1 |
| Tm | ppm | 4 acid | ICP-MS | 0.02 |
| U | ppm | 4 acid | ICP-MS | 0.05 |
| V | ppm | fusion disc | XRF | 10 |
| W | ppm | Sodium peroxide fusion | ICP-MS | 5 |
| Y | ppm | Sodium peroxide fusion | ICP-MS | 0.1 |
| Yb | ppm | 4 acid | ICP-MS | 0.05 |
| Zn | ppm | 4 acid | ICP-AES | 1 |
| Zr | ppm | fusion disc | XRF | 5 |

equipment and ring mill were cleaned with compressed air and a barren quartz wash between each sample.

Samples previously analyzed for the CSIRO-AGE and Astro Yilgarn Regolith projects were prepared at CSIRO using a low-Cr (K1045) ring mill with a barren quartz wash between samples (Robertson *et al*., 1996). Ignition loss was not determined for any sample.

**Dissolutions**

*Sodium peroxide fusion.* A 0.25 g aliquot of the sample was fused at 700ºC in alumina crucibles with sodium peroxide. The fused material was dissolved in concentrated hydrochloric acid, diluted to 500 ml with water and analyzed by ICP-OES or ICP-MS.

*Four acid.* A 0.3 g aliquot of the sample was taken up in nitric, perchloric, hydrochloric and hydrofluoric acids. The digest temperature was raised steadily to dryness. The remaining solids were dissolved to a final volume of 50 ml in 10% hydrochloric acid.

*Aqua regia.* A 40 g sample was digested in mixed nitric and hydrochloric acids in plastic bottles. The digest was diluted and mixed. The plastic bottles were discarded after use, ensuring no cross contamination

*Fusion disc.* Fused discs for X-ray fluorescence analysis were made on a Labtec Essa robotic fused bead system using 1.5 g sample and 10.5 g of Li borate flux (12 parts lithium metaborate and 22 parts lithium tetraborate) that were fused at 1050˚C. Analysis was by Philips PW2404/2440 X-ray spectrometer using a 4 KW end window Rh X-ray tube.

A suite of 53 elements, including Au, was analyzed variously by XRF, ICP-OES and ICP-MS. For cost reasons, INAA was not used in this project, although approximately 300 samples had been previously analyzed by INAA (Becquerel Laboratories) and XRF (CSIRO) for the Astro Yilgarn Regolith project. These INAA analyses (Cornelius *et al*., 2005a) can be used for comparison.

**Quality Control**

Quality control was maintained throughout the program by analyzing recognized standards (5% of total analyses), duplicates (5% of total analyses) and blanks (5% of total analyses) provided by the analytical laboratory. Thus, in any batch of forty analyses, 34 samples were unknowns, two were a recognized standard, two were duplicates of unknowns, and two were blanks. In addition to field and sample duplicates, two specifically-prepared laterite standards were submitted with each batch as unknowns. Approximately 300 samples that were previously analyzed for the Astro Yilgarn Regolith program by INAA and XRF (Cornelius *et al*., 2005a) are available for comparison with ICP-MS and XRF (Ultra Trace) analyses. A preliminary assessment shows a systematic discrepancy between Zr results by XRF (CSIRO) compared with Zr by XRF (Ultra Trace) and this is being investigated. There were no significant differences for other analytes.

Approximately 150 samples from the CSIRO-AGE collection were analyzed by Ultra Trace as part of a preliminary study in early 2002, prior to the commencement of the main sampling and analytical program for this project. In order to integrate these analyses into the main data set, approximately 10% of the analyses were repeated as part of this analytical program, and deemed acceptable.

**Accuracy**

Independent verification of the data was provided by repeat analyses of two specially prepared samples and six international standards. Two 100 kg standards comprising lateritic nodules and pisoliths from the western Yilgarn Craton were pulped to <75µm and homogenized by Gannett Holdings, Perth. One has anomalous PGE and base metal concentrations; the other has the composition of lateritic residuum on granite-gneiss of the Darling Range. Analyses for all analytes were obtained from six international and national laboratories and consensus values calculated. In

**Table 2.**
**Summary statistics for 2024 analyses.**

| Analyte | Min. | Percentile | | | | | | | | | Max. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 5th | 10th | 25th | 50th | 75th | 90th | 95th | 98th | 99th | |
| **SiO2** | 1.92 | 12.60 | 18.44 | 34.40 | 47.60 | 55.00 | 61.30 | 64.54 | 69.40 | 72.15 | 85.10 |
| **TiO2** | 0.01 | 0.38 | 0.42 | 0.52 | 0.71 | 1.09 | 1.60 | 2.01 | 2.49 | 2.90 | 12.94 |
| **Al2O3** | 0.43 | 11.80 | 14.30 | 18.00 | 21.40 | 26.20 | 35.96 | 42.98 | 50.50 | 52.98 | 62.60 |
| **Fe2O3** | 2.42 | 8.89 | 10.60 | 14.10 | 18.50 | 27.60 | 39.32 | 46.86 | 57.26 | 62.33 | 92.70 |
| **MnO** | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | 0.01 | 0.02 | 0.03 | 0.05 | 0.07 | 1.30 |
| **MgO** | <0.01 | 0.02 | 0.03 | 0.04 | 0.06 | 0.09 | 0.12 | 0.15 | 0.18 | 0.21 | 1.44 |
| **CaO** | <0.01 | <0.01 | <0.01 | 0.02 | 0.03 | 0.04 | 0.06 | 0.08 | 0.12 | 0.21 | 2.48 |
| **Na2O** | <0.05 | <0.01 | <0.01 | <0.01 | 0.02 | 0.04 | 0.08 | 0.12 | 0.19 | 0.26 | 1.26 |
| **K2O** | <0.01 | 0.01 | 0.02 | 0.03 | 0.07 | 0.15 | 0.35 | 0.53 | 0.95 | 1.97 | 5.55 |
| **P2O5** | 0.004 | 0.011 | 0.013 | 0.016 | 0.023 | 0.032 | 0.044 | 0.054 | 0.072 | 0.087 | 0.282 |
| **Ag** | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | 1 |
| **As** | 2 | 7 | 9 | 13 | 19 | 27 | 35 | 42 | 69 | 119 | 647 |
| **Au** | <0.2 | <0.2 | <0.2 | <0.2 | <0.2 | 0.4 | 0.8 | 1.2 | 2.2 | 3.7 | 41.2 |
| **Ba** | <10 | 20 | 20 | 30 | 40 | 70 | 130 | 190 | 395 | 570 | 1890 |
| **Be** | <0.1 | 0.4 | 0.5 | 0.6 | 0.9 | 1.2 | 1.6 | 1.8 | 2.2 | 2.6 | 9.6 |
| **Bi** | <0.1 | <0.1 | 0.1 | 0.2 | 0.3 | 0.4 | 0.6 | 0.9 | 1.6 | 2.8 | 19.1 |
| **Cd** | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | 0.55 |
| **Ce** | 2 | 8 | 11 | 18 | 31 | 54 | 91 | 128 | 179 | 235 | 829 |
| **Cl** | <20 | 20 | 40 | 60 | 80 | 140 | 240 | 360 | 520 | 740 | 2660 |
| **Co** | <1 | 1 | 2 | 3 | 5 | 7 | 11 | 14 | 20 | 25.76 | 277 |
| **Cr** | 20 | 90 | 110 | 150 | 220 | 320 | 520 | 748 | 1490 | 2796 | 14100 |
| **Cs** | <0.1 | <0.1 | 0.1 | 0.3 | 0.4 | 0.7 | 1 | 1.2 | 1.6 | 1.9 | 5.5 |
| **Cu** | 1 | 2 | 3 | 5 | 7 | 14 | 34 | 61 | 115 | 156 | 692 |
| **Eu** | 0.0 | 0.1 | 0.1 | 0.1 | 0.2 | 0.3 | 0.5 | 0.7 | 1.0 | 1.2 | 5.1 |
| **Ga** | 2 | 22 | 25 | 33 | 43 | 54 | 68 | 83 | 97 | 110 | 187 |
| **Hg** | <10 | <10 | <10 | <10 | 20 | 40 | 80 | 120 | 195 | 260 | 820 |
| **In** | 0.02 | 0.08 | 0.08 | 0.10 | 0.14 | 0.18 | 0.22 | 0.26 | 0.30 | 0.34 | 0.48 |
| **La** | 0.80 | 2.00 | 2.52 | 3.80 | 6.15 | 9.90 | 15.90 | 22.76 | 36.75 | 50.11 | 121.00 |
| **Lu** | <0.02 | 0.02 | 0.04 | 0.04 | 0.06 | 0.10 | 0.14 | 0.18 | 0.22 | 0.28 | 1.80 |
| **Mo** | 0.4 | 2.4 | 3.0 | 3.8 | 4.8 | 6.4 | 8.0 | 9.8 | 12.4 | 15.2 | 78.4 |
| **Nb** | <5 | 6 | 8 | 10 | 14 | 19 | 25 | 31 | 37 | 44 | 78 |
| **Ni** | 3 | 11 | 14 | 20 | 30 | 43 | 59 | 75 | 110 | 169 | 2130 |
| **Pb** | 2 | 17 | 21 | 29 | 39 | 51 | 68 | 80 | 99 | 118 | 167 |
| **Rb** | <0.2 | 1 | 2 | 3 | 6 | 11 | 19 | 26 | 46 | 67 | 273 |
| **S** | <10 | 80 | 120 | 180 | 280 | 396 | 520 | 640 | 810 | 898 | 2210 |
| **Sb** | <0.1 | 0.1 | 0.2 | 0.3 | 0.5 | 0.7 | 1.0 | 1.1 | 1.4 | 1.9 | 47.5 |
| **Sc** | <2 | 5 | 7 | 10 | 16 | 25 | 42 | 59 | 87 | 114 | 295 |
| **Se** | <1 | <1 | <1 | <1 | 1 | 3 | 5 | 6 | 7 | 8 | 12 |
| **Sm** | 0.15 | 0.40 | 0.50 | 0.70 | 1.10 | 1.70 | 2.58 | 3.45 | 5.03 | 6.45 | 18.10 |
| **Sn** | <1 | <1 | 1 | 2 | 2 | 3 | 4 | 5 | 6 | 7 | 25 |
| **Sr** | 1 | 3 | 3 | 4 | 6 | 10 | 17 | 25 | 42 | 57 | 349 |
| **Ta** | <0.05 | 0.4 | 0.5 | 0.6 | 0.8 | 1.2 | 1.7 | 2.0 | 2.5 | 2.9 | 21.1 |
| **Te** | <0.2 | <0.2 | <0.2 | <0.2 | <0.2 | <0.2 | 0.2 | 0.2 | 0.2 | 0.4 | 1.4 |
| **Th** | 1 | 19 | 25 | 44 | 80 | 133 | 198 | 242 | 335 | 393 | 854 |
| **Tl** | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | 0.1 | 0.2 | 0.3 | 0.4 | 1.5 |
| **Tm** | <0.02 | 0.02 | 0.04 | 0.04 | 0.06 | 0.10 | 0.14 | 0.18 | 0.26 | 0.30 | 1.88 |
| **U** | 0.2 | 1.9 | 2.4 | 3.5 | 5.2 | 8.0 | 11.4 | 14.3 | 19.0 | 23.7 | 47.8 |
| **V** | 40 | 160 | 190 | 250 | 350 | 510 | 740 | 920 | 1150 | 1360 | 2720 |
| **W** | <5 | <5 | <5 | <5 | <5 | <5 | <5 | <5 | 5 | 10 | 135 |
| **Y** | <0.1 | 2.8 | 3.2 | 4.5 | 6.4 | 9.3 | 13.5 | 17.8 | 25.4 | 31.6 | 141.0 |
| **Yb** | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.7 | 1.0 | 1.3 | 1.7 | 2.1 | 12.0 |
| **Zn** | 1 | 4 | 5 | 7 | 10 | 14 | 21 | 27 | 42 | 55 | 615 |
| **Zr** | 30 | 208 | 240 | 290 | 360 | 485 | 615 | 705 | 878 | 1045 | 3790 |
| **CHI6*** | 42 | 102 | 118 | 146 | 177 | 218 | 268 | 318 | 459 | 569 | 2771 |
| **PEG4*** | 5 | 12 | 14 | 17 | 20 | 25 | 33 | 38 | 46 | 53 | 109 |

general, analyses of recognised standards provided by Ultra Trace and of the two CSIRO standards were accepted if the analyzed value and the consensus value agreed to within 20%, providing the analyte concentration is greater than ten times the lower limit of detection.

Insufficient accuracy was recorded for the measurement of Nb in fusion discs by XRF and these measurements were repeated using a sodium peroxide fusion digest and ICP-MS finish.

**Precision**

For all analytes, the precision should be better than 20% [(2*standard deviation/mean) x 100] at 10x the lower limit of detection. Duplicate analyses were acceptable if the half relative difference (HRD) — ((assay #1-assay#2)/(assay #1 + assay#2)) x 100 is <10, provided the analyte concentration is greater than 10 times the lower limit of detection. Blank values were acceptable if they were less than three times the lower limit of detection.

Nickel and Zn showed insufficient precision in two batches and these were reanalyzed for these elements by the same method with a satisfactory result.

## ANALYTICAL RESULTS

**Data presentation**

All analytical results are listed in Appendix 1 (see attached CD) in tab-delimited .txt and in .xls file formats. The file also contains information on the sample type and material. Standard analyses and original reports from the analytical laboratory are not included here but will be part of the final GSWA record/MERIWA Final Report M371.

Summary statistics for all analytes are listed in Table 2. Results for Au, Cu, two cumulative indices, the CHI6* (Smith *et al*., 1989) and the PEG4* index (Smith *et al.,* 1987), Ni, Cr and Hg are shown as bubble plots with the size of the bubbles proportional to the element concentration, superimposed onto contoured images. The normalized element concentrations were imaged using a spherical kriging process in ArcGIS8.2 to highlight regional trends ranging from red-orange indicating high abundances, to blue indicating low abundances. Single point anomalies are downgraded by kriging but can be identified on the bubble plot. This presentation combines visualization of regional trends with objectivity of raw data. A typicality index shows samples with an affinity towards alkaline ultramafic rocks.

**Gold**

The Au distribution across the SW Yilgarn Craton (Figure 3) shows several multi-sample clusters and single point anomalies against a background of 1.2 ppb Au (95$^{th}$ percentile). Most of the anomalous clusters correspond, on a broad scale, with areas of known Au mineralization (Figure 1) around Westonia, Southern Cross, the Mount Dimer greenstone belt, Bullock Pool and Griffins Find (36 ppb approximately 20 km NW of Griffins Find). In the Jimperding metamorphic belt, a cluster with a maximum concentration of 17 ppb Au is located approximately 30 km north of the Wundowie Au deposit. Boddington Au mine, the largest Au producer in the SW Yilgarn Craton, only shows a very weak gold signature (4.4 ppb), due to the intensive leaching of Au from the nodular-pisolitic gravel at surface, sampled as part of this project, but not from the subsurface fragmental duricrust (Anand, 1998b) by high rainfall along the western part of the Yilgarn Craton. In the high rainfall areas, it is therefore imperative to include chalcophile elements as well as Au in regional Au exploration using lateritic nodules and pisoliths (Anand, 1998b; Anand, 2001).

The significance of several single-point anomalies throughout the SW Yilgarn Craton can only be established by closer spaced follow-up sampling of lateritic residuum and other sample media.

**Copper**

On a regional scale, high Cu concentrations (>61 ppm; 95$^{th}$ percentile) are more common in the Southern Cross and Marda-Diemals greenstone belts than in the granite-gneiss terrains (Figure 4).

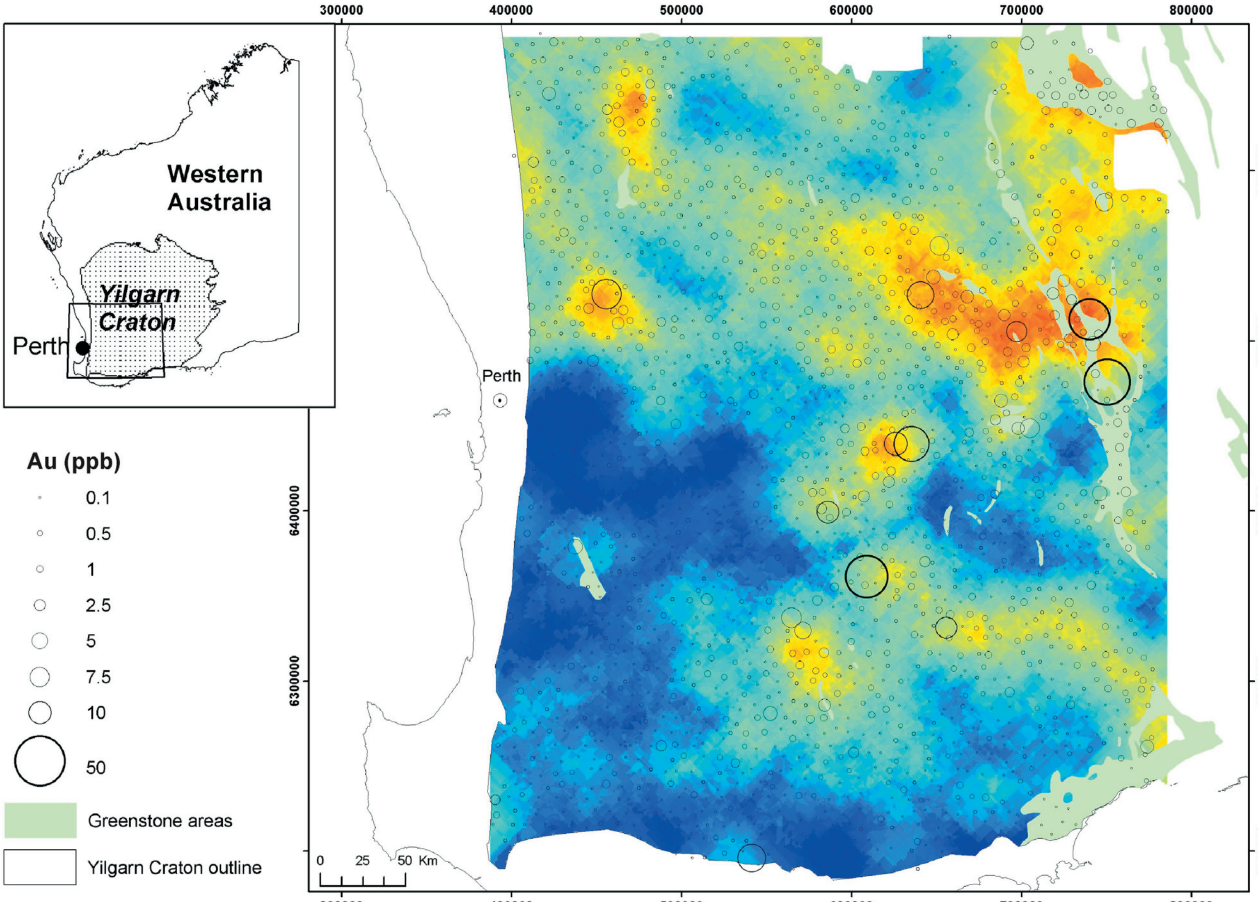


Figure 3. Kriged image and bubble plots of Au concentrations.

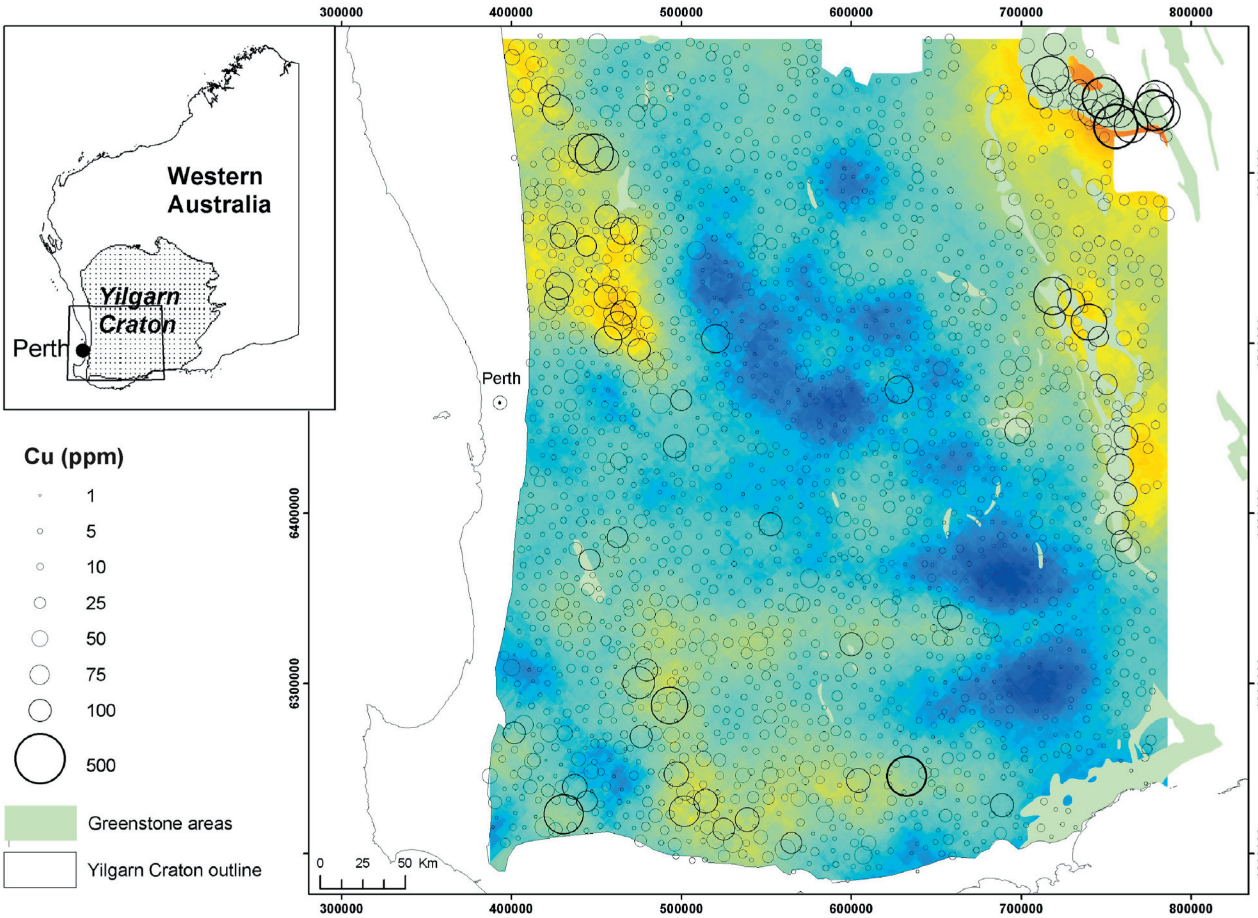


Figure 4. Kriged image and bubble plots of Cu concentrations.

There are two noticeable exceptions: a NW Cu trend in the southwest of the craton, along strike of the Saddleback greenstone belt, extends from approximately 20 km south of the Saddleback greenstone belt to the southern edge of the craton, a distance of approximately 120 km. The significance of two weak E trends that branch off the SE trend is unclear. A prominent regional Cu anomaly south of the Wongan Hills greenstone belt in the Jimperding metamorphic belt, trends NW and extends approximately 150 km in that direction, possibly extending into the NW quadrant. This trend may reflect abundant mafic rocks in this part of the metamorphic belt with a small amount of associated base metal sulphide, such as at Yarawindah Brook, SE of New Norcia. A sample near the Yarawindah Brook mafic-ultramafic body has a Cu concentration of 140 ppm (>98$^{th}$ percentile).

**CHI6* index**

It is beyond the scope of this interim report to discuss all chalcophile elements and this will be part of the final GSWA record/MERIWA Final Report M371. However, the CHI6* index (As+3.56Sb+10Bi+3Mo+30Ag+30Sn+10W+3.5Se), first introduced by Smith and Perdrix (1983), provides a useful summary and highlights areas with anomalous concentrations of one or many of the eight chalcophile elements that make up the index. As with the PEG4* index below, very high concentrations of a single element can bias the index and some caution is required with interpretation.

The most significant feature of the kriged and contoured CHI6* (Figure 5) data is a cluster of anomalous scores in the Southern Cross greenstone belt, an area of known Au deposits. Most significant contributors to the high CHI6* scores are As and Sb, followed by Bi, Mo, Se, Sn and W.

Smaller, less anomalous clusters occur around Bridgetown-Yornup in the SW corner of the quadrant (As, Bi, Sb, Sn and W), in the Westonia region west of Southern Cross (As, Bi and Sb) and within

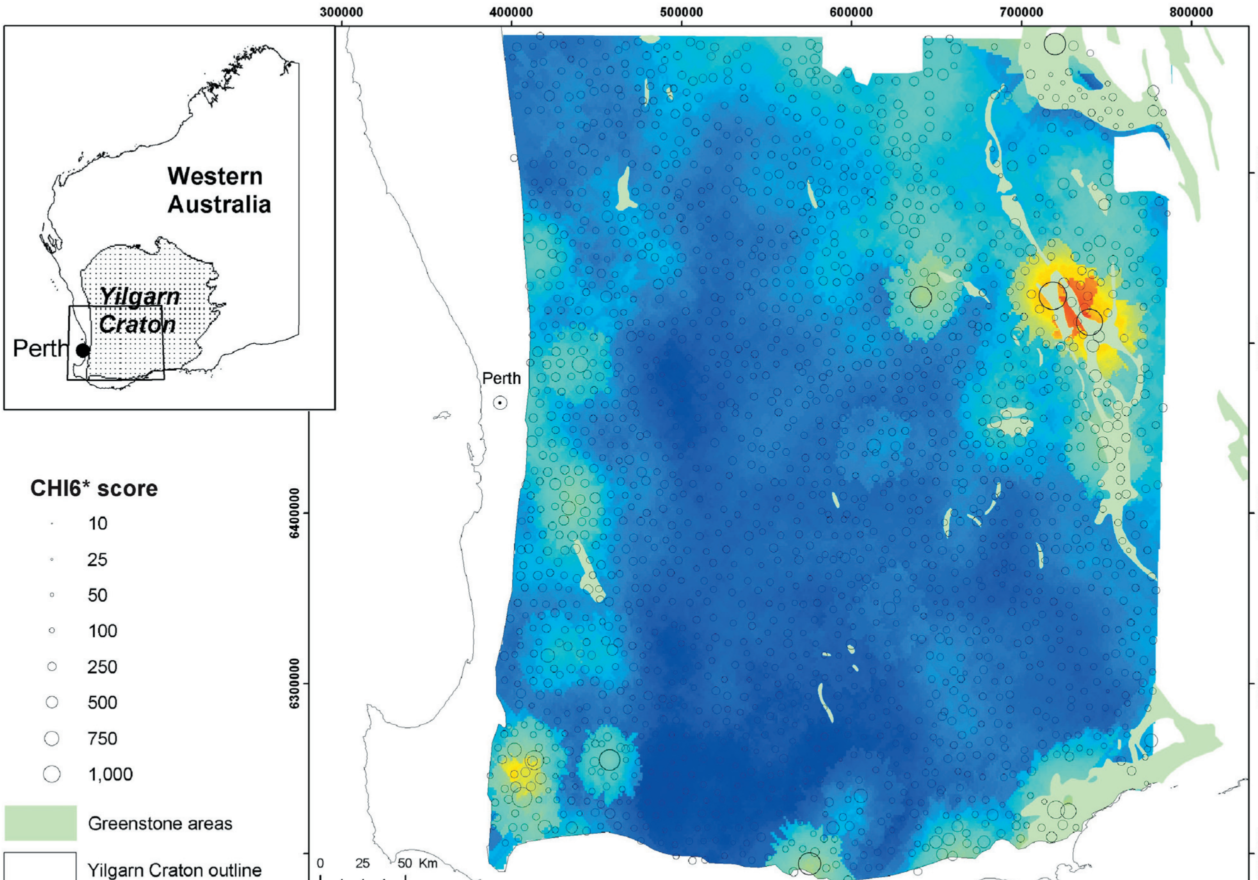


Figure 5. Kriged image and bubble plots of CHI6* scores.

and along strike of Proterozoic rocks overlying the southernmost part of the craton (As and Sb). The clusters in the southwest Yilgarn broadly correlate with the 'chalcophile corridors' of Smith *et al.* (1989), but the present study lacks resolution due to significantly wider sample spacing. However, the broader, regional cover of this survey shows a weak anomaly N of the Saddleback greenstone belt that had not been recognized previously. This geochemical signature (Sn, As, Mo and Bi) extends into the Chittering and Jimperding Metamorphic Belts. Because of the commonality of some elements in the CHI6* index with those in the PEG4* one (As, Sb and Sn), the patterns here are similar. Colour contouring at different levels can render the chalcophile trends more subtle in this part of the SW Yilgarn Craton.

**PEG4* index**

The rare metals are of particular interest, because of the world-class Sn-Ta ore body at Greenbushes in the SW Yilgarn Craton. The PEG4* index, a sum of element concentrations multiplied by empirical factors (0.09As+1.33Sb+Sn+0.6Nb+Ta) was first introduced by Smith *et al.* (1987) to identify multi-element anomalies associated with the Sn-Ta pegmatite systems at Greenbushes. The index is used here to highlight regional rare metal trends and to compare these to the earlier work mentioned above. Data by Smith *et al.* (1987) show PEG4* scores for lateritic gravel from the mineralized area at Greenbushes reach up to 4300 with the 200 contour outlining the immediate mine area; scores of >45 delineate the broad footprint of the pegmatite system.

The present data (Figure 6) show a cluster of PEG scores >46 (98$^{th}$ percentile) centred on the Bridgetown-Greenbushes area. However, two larger trends with similar PEG4* scores occur to the north, SW and NW of the Saddleback greenstone belt. These trends appear to have a SE-NW orientation and the most significant anomaly is located along strike of the Saddleback greenstone belt with concentrations of 19 ppm Sn, 6.6 ppm Ta and 32 ppm Nb. This may indicate Sn-Ta

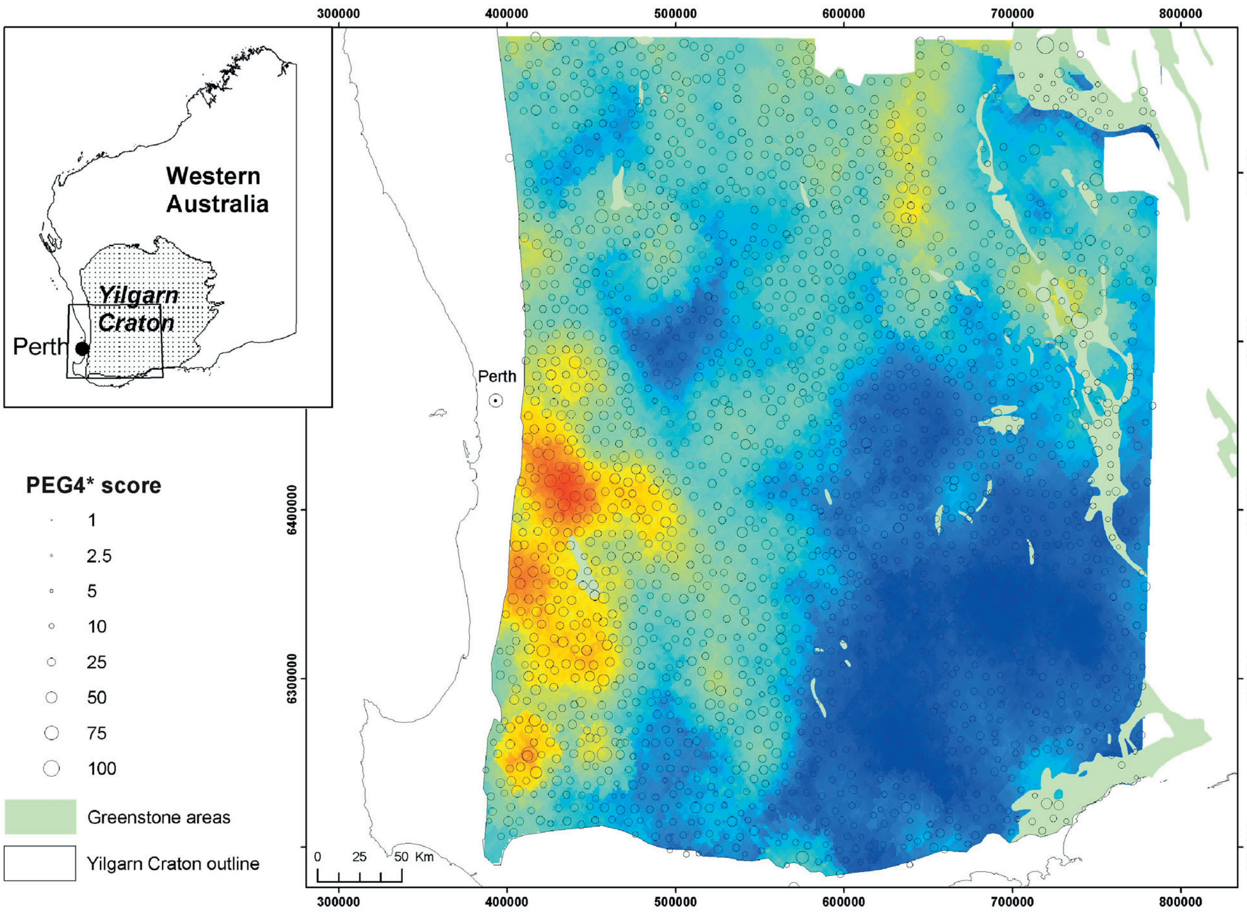


Figure 6. Kriged image and bubble plots of PEG4* scores.

pegmatites along strike of the Saddleback greenstone belt. Single anomalies and small clusters (2-3 scores >33) are common throughout the SW quadrant and possibly indicate small clusters of pegmatites.

The association of Au at the Boddington mine with As, Sb and Sn (Anand, 1998b) suggests the pegmatophile signature NW of Boddington may also have significance as a possible indicator of further Au mineralization along strike of the Saddleback greenstone belt, with one sample (#103881) showing 2.4 ppm Sb, 14 ppm As and 40 ppm Mo.

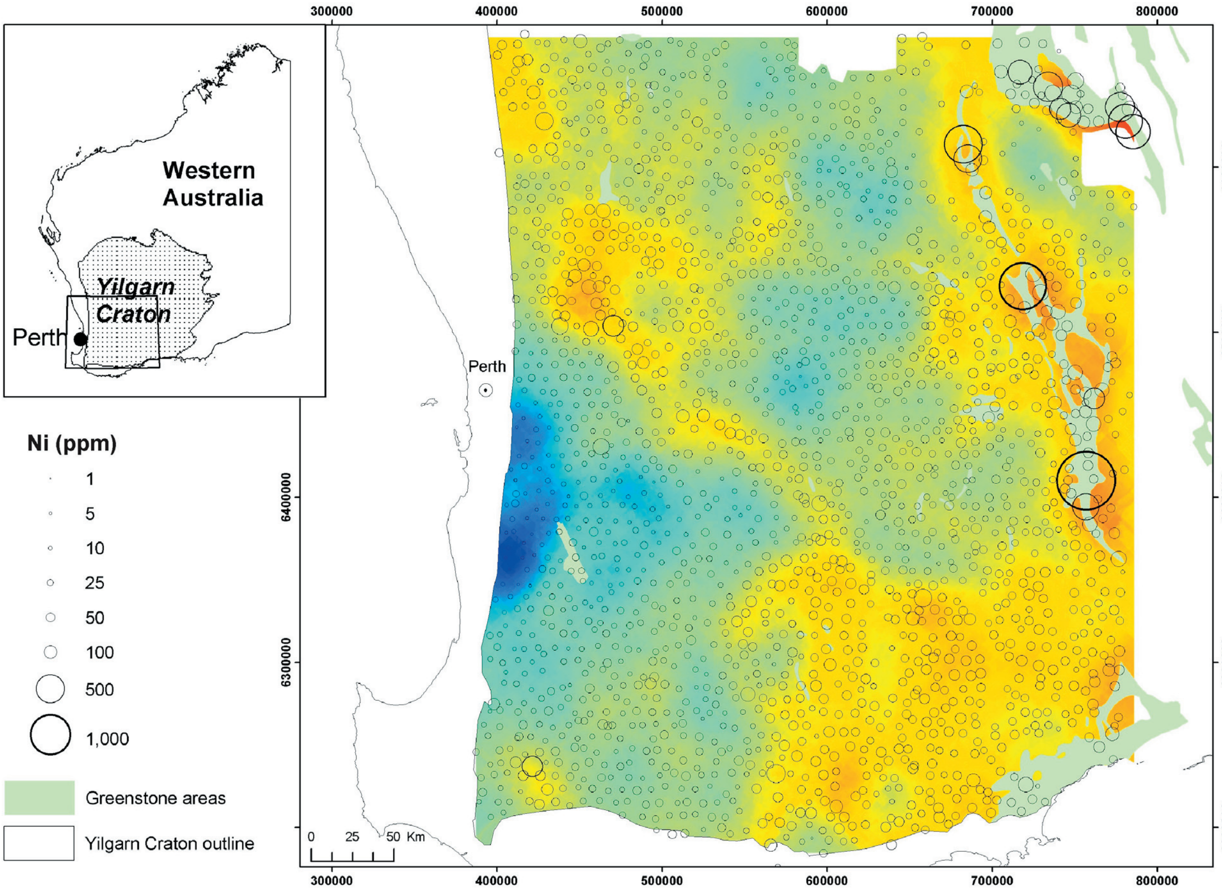


Figure 7. Kriged image and bubble plots of Ni concentrations.

## Nickel

Nickel concentrations generally reflect mafic-ultramafic rocks and accordingly are more abundant in the Southern Cross and Diemals greenstone belts than in felsic-dominated terrains such as the South West Terrane (Figure 7).

Nickel concentrations are clustered in the Jimperding Metamorphic Belt, south of Wongan Hills, with a maximum of 270 ppm Ni in sample #103191. The weakly anomalous Ni (and Cr) concentrations confirm some mafic and ultramafic rocks within the Jimperding metamorphic belt, such as the Coates Gabbro. There is a very large, but relatively weak Ni signature in the SE part of the quadrant, which is not yet understood.

## Chromium

Chromium is a reliable indicator of mafic-ultramafic rocks and can outline remnants of greenstone, sills and layered intrusions within areas of granite-gneiss. The Cr distribution (Figure 8) clearly outlines the main greenstone belts at Southern Cross and Diemals. High Cr also shows greenstone remnants near Lake Grace and scattered mafic-ultramafic bodies in the western Yilgarn, *i.e.*, near Bridgetown and in the Jimperding Metamorphic Belt, NE of Perth. Isolated anomalies in other parts of the South West Terrane coincide with small rafts of greenstone, sills and dykes of mafic-ultramafic composition.

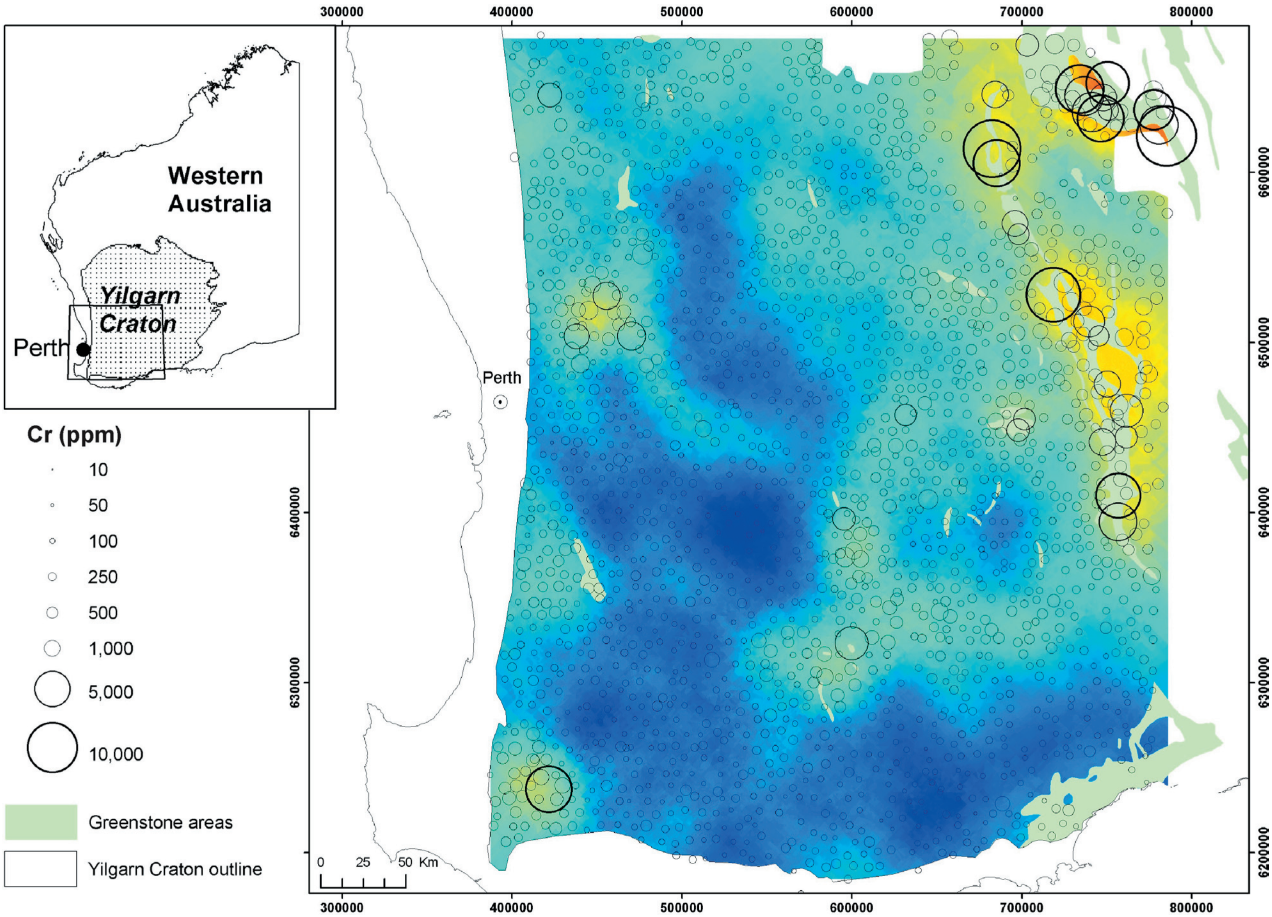


Figure 8. Kriged image and bubble plots of Cr concentrations.

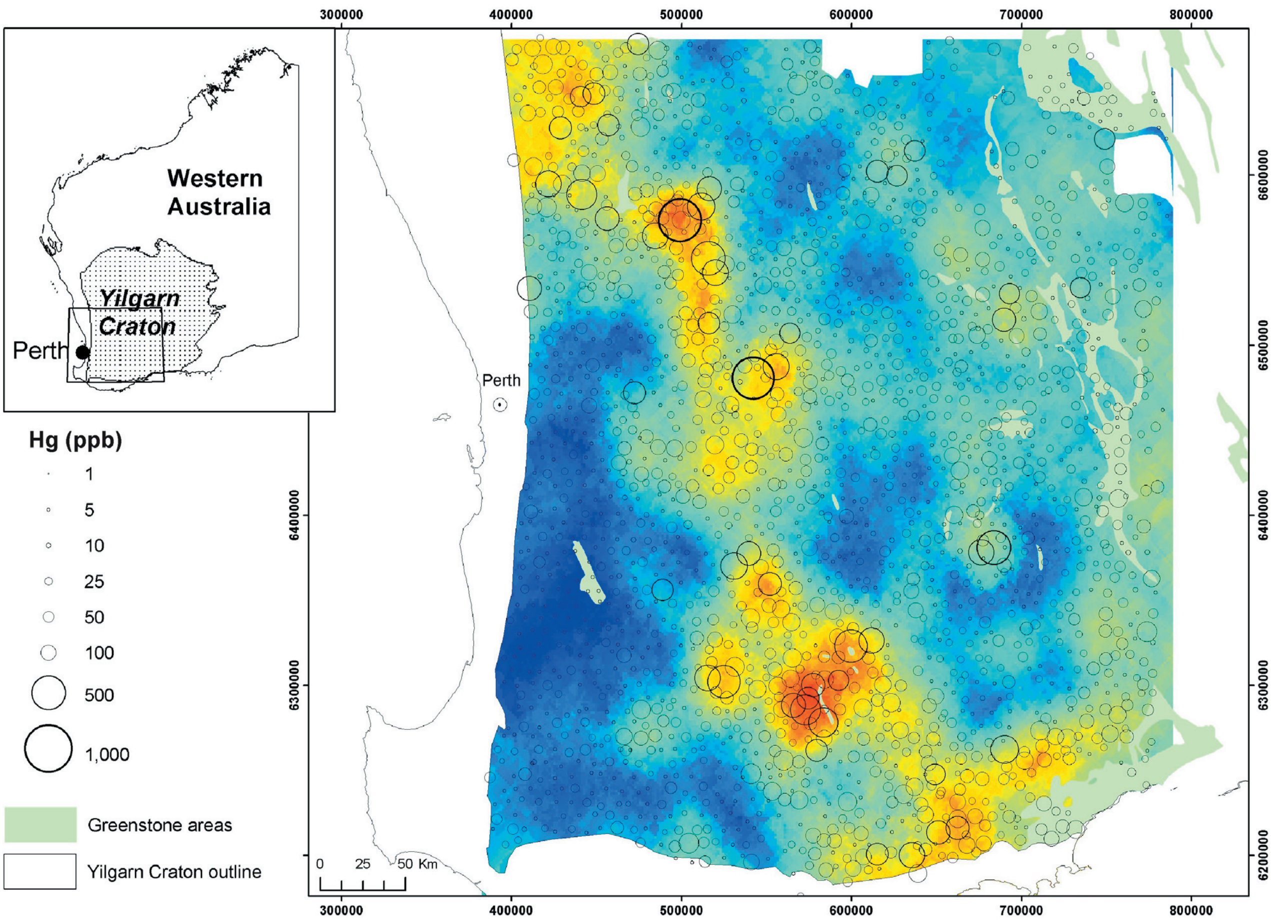


Figure 9. Kriged image and bubble plots of Hg concentrations.

**Mercury**
Mercury displays one of the most distinct regional trends unrelated to greenstone sequences (Figure 9). Anomalous Hg concentrations extend for over 500 km from NW of Wongan Hills to Jerramungup in the south. There, the trend changes direction and continues to the NE along the Archaean - Proterozoic boundary. Mercury concentrations range between 100-500 ppb with a maximum concentration of 820 ppb approximately 30 km E of Wongan Hills. The origin of the Hg trend is not clear, but it appears broadly aligned with the SE trend of the gneiss-migmatite zone along the eastern boundary of the South West Terrane. A spatial relationship also exists with sites of seismic activity as shown on the Western Australian Government website (www.ga.gov.au/urban/projects/nrap/perth_earthquake.jsp), broadly parallel to regional SE Faults in the SW Yilgarn Craton. To our knowledge, this is the first time this regional Hg trend has been revealed.

**Potential for alkaline ultramafic rocks (*e.g.*, kimberlite, lamproite, lamprophyre)**
The potential of the Astro Yilgarn Regolith data to show the geochemical signature of alkaline ultramafic rocks was evaluated using a typicality index (for explanation see Cornelius *et al.*, 2005b). The results of multivariate statistical analysis showed ferruginous gravel formed on or near small bodies of alkaline ultramafic rock at Nabberu, and near Errabiddy in the NE Yilgarn have typicality scores of 10-30%.

Data from the samples newly acquired in this survey have been evaluated by the same multivariate statistical treatment, using the same set of kimberlite target data and six elements (P, Nb, Co, Cr, La and Sm) but a different granite training data set. In the central part of the SW Yilgarn, the results (Figure 10) show five previously reported anomalies with the highest score (9.1%) at 46 Gate Road, NE of Mukinbudin, and a new anomaly (#104123) approximately 30 km WNW of Lake Grace, with a typicality score of 3.9%. The six low-order anomalies identified in the Astro Yilgarn Regolith dataset and the Yilgarn laterite Atlas dataset are distributed over an area of approximately 230 x

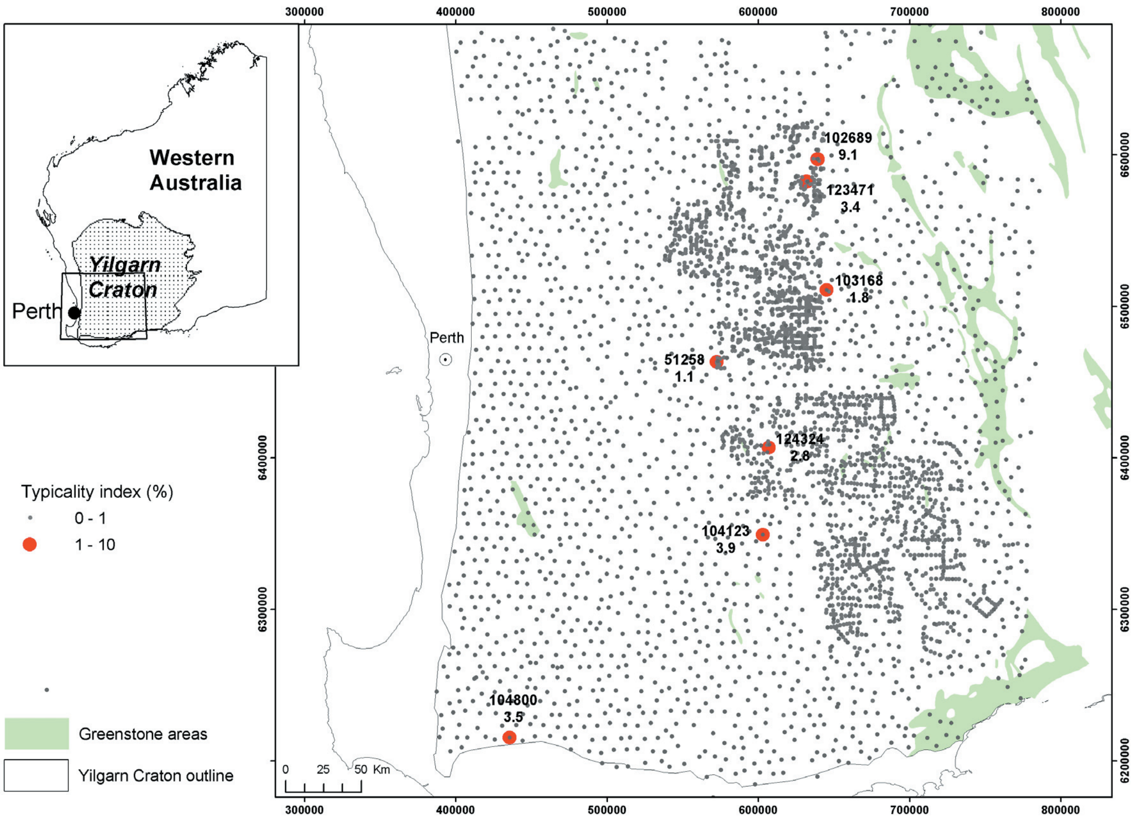


Figure 10. Map showing typicality (in per cent next to sample point) indices based on six element allocation procedure for the SW Yilgarn Craton.


Figure 11. Lateritic gravel on nodular duricrust. #103732. 63%Fe2O3.

Figure 12. Setting of sample #103732.


Figure 13. Lateritic gravel #104181 23%Fe2O3.

Figure 14. Setting of sample #104181 in gravel pit.


Figure 15. Lateritic gravel #102933 incipient nodules and lag. 10% Fe2O3.

Figure 16. Setting of # 102933 on low rise.

Figure 17.  Lateritic gravel in colluvium #104027 34%Fe2O3.

Figure 18.  Setting of #104027 on colluvial plain.


Figure 19.  Lateritic gravel in colluvium brought up by tree roots #104550.

Figure 20.  Lateritic lag around the base of a eucalypt #104726.


Figure 21.  Lateritic lag (bottom right) as part of #102695 polymict lag on colluvium.

Figure 22.  Setting of #102695 on a colluvial slope.

60 km with an approximate NNE orientation. With the exception of the 46 Gate Road locality, where the source of the anomaly appears to be lamprophyre as indicated by saprolite analyses, the source(s) of these low-priority anomalies remain unidentified. Another anomaly in this dataset with a typicality score of 3.6% is located 15 km ENE of Manjimup (sample #104800). The results show a small likelihood for further occurrences of alkaline ultramafic rocks in the SW Yilgarn Craton and, based on the results of previous work, the source of the anomalous scores (>1%) is likely to be lamprophyre.

## CONCLUSIONS

A preliminary evaluation of the laterite geochemical dataset for the SW Yilgarn Craton reveals the following regional patterns:

i. In the NE part of the SW Yilgarn Craton, the regional sampling shows clusters of Au anomalies around greenstones and known Au occurrences. The size of these clusters appears larger than would be expected from lateral dispersion of detrital material from these occurrences alone. Therefore, potential exists for additional Au mineralization ENE and SE of Merredin.

ii. The westernmost part of the Yilgarn Craton is an area of significant geochemical anomalies. In the northern part, corresponding to the Jimperding Metamorphic Belt, south of the Wongan Hills greenstone belt, a regional Cu anomaly is locally associated with anomalous As, Au, Bi, Hg, Mo and Sb. Elevated Cr and Ni concentrations indicate the presence of mafic-ultramafic rocks within this metamorphic belt.

iii. A cluster of anomalous CHI6* scores in the Bridgetown-Manjimup-Greenbushes area may be associated not only with Sn-Ta pegmatites at Greenbushes, but could also indicate massive sulphides due to anomalous As, In and Bi.

iv. Northwest of the Saddleback greenstone belt, anomalous Sb, Sn, Ta and Nb concentrations may indicate pegmatites along strike of the greenstone sequence and, potentially, further Au mineralization.

v. Chromium and Ni concentrations in the Bridgetown - Yornup area indicate mafic-ultramafic rocks.

vi. Anomalous As, Bi, Mo and Sb concentrations occur in Proterozoic rocks along the southern margin of the Yilgarn Craton indicating potential for Au mineralization.

vii. In the Katanning – Lake Grace area, clusters of weakly anomalous Cr concentrations indicate likely mafic remnants; some of which contain anomalous Au.

viii. A craton-scale SE-trending Hg anomaly, locally associated with anomalous Au, may indicate potential for Au mineralization at depth.

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