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ABSTRACT

Understanding the character of Australia's extensive regolith cover is crucial to the continuing success of mineral exploration. We hypothesise that the regolith contains geochemical fingerprints of processes related to the development and preservation of mineral systems at a range of scales. We test this hypothesis by analysing the composition of surface sediments within greenfield regional-scale (southern Thomson Orogen) and continental-scale (Australia) study areas. In the southern Thomson Orogen area, the first principal component (PC1) derived in our study [Ca, Sr, Cu, Mg, Au and Mo at one end; rare earth elements (REEs) and Th at the other] is very similar to the empirical vector used by a local company (enrichment in Sr, Ca and Au concomitant with depletion in REEs) to successfully site exploration drill holes for Cu–Au mineralisation. Mapping of the spatial distribution of PC1 in the region reveals several areas of elevated values and possible mineralisation potential. One of the strongest targets in the PC1 map is located between Brewarrina and Bourke in northern New South Wales. Here, exploration drilling has intersected porphyry Cu–Au mineralisation with up to 1 wt% Cu, 0.1 g/t Au, and 717 ppm Zn. The analysis of a comparable geochemical dataset at the continental scale yields a compositionally similar PC1 (Ca, Sr, Mg, Cu, Au and Mo at one end; REEs and Th at the other) to that of the regional study. Mapping PC1 at the continental scale shows patterns that (1) are spatially compatible with the regional study and (2) reveal several geological regions of elevated values, possibly suggesting an enhanced potential for porphyry Cu–Au mineralisation. These include well-endowed mineral provinces such as the Curnamona and Capricorn regions, but also some greenfield regions such as the Albany-Fraser/western Eucla, western Murray and Eromanga geological regions. We conclude that the geochemical composition of Australia's regolith may hold critical information pertaining to mineralisation within/beneath it.

Introduction

Two of the great challenges to mineral exploration, particularly in Australia, are (1) gaining a better understanding of the almost ubiquitous regolith cover and (2) making better use of this knowledge to unearth new mineral wealth within or beneath this cover. These challenges arise from the fact that the efficiency of most traditional geophysical and geochemical exploration methods, initially developed for areas of bedrock outcrop and shallow subcrop, is blunted by the thickness of the intervening weathered and/or transported material.

We hypothesise here that one way of characterising the cover and studying distal footprints of mineral systems, both national priorities of the UNCOVER Initiative (http://www.uncoverminerals.org.au/), is through surface (regolith) geochemical surveys. We test the above hypothesis by analysing the composition of surface sediments within greenfield regional-scale (southern Thomson Orogen) and continental-scale (National Geochemical Survey of Australia or NGSA) study areas. The

present study is to our knowledge the first attempt at investigating the upscaling of a regional Australian geochemical survey to the continental scale, and drawing implications from this for mineral exploration.

Background

CRC LEME Thomson region geochemical survey

During 2005–2006, 'the Cooperative Research Centre for Landscape Environments and Mineral Exploration (CRC LEME)' carried out surface regolith sampling over about ten 1:250 000 scale map sheets in northwestern New South Wales, in collaboration with Geoscience Australia (GA) and the Geological Survey of New South Wales (GSNSW) (Caritat & Lech, 2007; Lech & Caritat, 2007). This survey was one of a number of pilot projects aimed at defining fit-for-purpose methodologies for a potential future national survey. A few sampling media were targeted; most pertinent here are the shallow catchment

outlet sediment samples (10–25 cm depth), which were collected at 79 sites for Mobile Metal Ion® (MMI) analysis. Quality control data are reported in Caritat and Lech (2007).

Southern Thomson Orogen regional geochemical survey

The Southern Thomson Project (http://www.ga.gov.au/scientific-topics/minerals/unlocking-resource-potential/southern-thomson) is a collaboration between GA, GSNSW and the Geological Survey of Queensland (GSQ). It is aimed at better understanding the mineral systems potential of this region within the southern Thomson Orogen straddling the New South Wales–Queensland border. As part of this project, a surface regolith geochemical survey was conducted over the Eulo and Toompine 1:250 000 scale map sheets in Queensland, with the aims of (1) characterising the geochemical composition of the regolith over the area, and (2) identifying any surface expression of basement lithologies and/or mineral systems detectable from the surface (Main & Caritat, 2016). Fieldwork for this phase of the project took place during October–November 2013 and included the collection of 41 Top Outlet Sediment (TOS; 0–10 cm depth) samples for MMI analysis. Quality control data are reported in Main and Caritat (2016).

Combined southern Thomson regional geochemical survey

In the following, the combined CRC LEME and GA-GSNSW-GSQ surface geochemistry projects are collectively referred to as the southern Thomson (geochemical) survey for brevity. In total 120 (79 CRC LEME + 41 GA-GSNSW-GSQ) near-surface samples were taken over the combined area of ~185 000 km^2, yielding an average sample density of ~1/1540 km^2. A list of 30 elements common to both datasets and with comparable analytical ranges and distributions was collated (see Methods). A simplified geological map of the area also showing relevant mines and mineral occurrences is available in the Supplementary Papers (Figure SP1).

National Geochemical Survey of Australia

The NGSA was an ultra-low-density geochemical survey of the surface regolith of Australia, aimed at bridging a gap in the documentation and understanding of the multi-element composition of Australia's surface regolith to match its well-known and utilised continental-scale geophysical datasets (e.g. magnetic, radiometric and gravity datasets). Samples of transported sediment were collected from near the outlets of ~1200 large river catchments at depths of 0–10 cm (TOS) and ~60–80 cm (Bottom Outlet Sediments; BOS). The NGSA covered over 80% of Australia (>6 million km^2) at an average sample density of ~1/5200 km^2 (Caritat & Cooper, 2011a, 2016; Lech, Caritat, & McPherson, 2007). The TOS samples analysed by MMI at 1191 sites are discussed herein. The same 30 elements common to the southern Thomson regional dataset were selected (see Methods). A simplified geological map of the area also showing relevant mines, mineral

deposits and mineral occurrences is available in the Supplementary Papers (Figure SP2).

Mineral systems concept

Although ore bodies themselves can be less than a few metres or tens of metres in width, the processes leading to their formation and preservation, summarised by the 'mineral systems' concept of Wyborn, Heinrich, and Jaques (1994) (Figure 1a), commonly affect a much larger area. Thus, relatively small, high-value end products, the economically defined ore zones, can derive from processes operating at large scales potentially leaving extensive footprints, for instance when mineralising fluids permeate a suitable lithology leaving behind a tell-tale legacy of hydrothermally altered rock indicating the mineralisation corridor. In a more recent version of the mineral systems model, the temporal dimension and the critical spatio-temporal window for ore deposition are introduced (Huston et al., 2016; Figure 1b). When sampling surface sediments at low density, such as outlet sediments in large catchments, the objective is more to test if large-scale elements of the mineral system were intersected rather than to detect the precise location of ore bodies. The latter must be the objective of follow-up work. It is worth noting that parts of a mineral system may be under-sampled by geochemical surveys, especially those applying an ultra-low-density approach. The mineral systems approach is gaining in popularity as a useful concept (e.g. Blewett, 2014; Huston et al., 2016; Jaques, Jaireth, & Walshe, 2002; McCuaig, Beresford, & Hronsky, 2010; Murphy et al., 2011) and is a practical link for the application of (low-density) surface geochemical mapping to mineral exploration (Reimann, Ladenberger, Birke, & Caritat, 2016).

Geochemical footprints of mineral systems in the regolith

Mineral systems processes such as mineralisation and alteration modify the mineralogical and geochemical composition of rock. Through weathering over large timespans, distinct geochemical characteristics can be imparted to the regolith either directly by in situ weathering of modified (e.g. mineralised/altered) rock, or via transport of this modified geochemical signature in the bedrock through the overlying regolith (e.g. Anand, Aspandiar, & Noble, 2016). The existence of such geochemical haloes at or near the surface is well established in a variety of environments, although the exact formation mechanisms are still debated and most likely specific to individual conditions (e.g. Cameron, Hamilton, Leybourne, Hall, & McClenaghan, 2004; Kelley, Kelley, Coker, Caughlin, & Doherty, 2006). It is clear that geochemical anomalies can propagate through (even transported) regolith cover via pore water (e.g. seismic pumping), bubbles, plant roots, capillary pressure, animals (e.g. termitaria), nanoparticles, or electro-chemical cells (op. cit.; Anand et al., 2016; Hamilton, 1998). Once at or near the surface, lateral mechanical transport, including colluvial, alluvial and eolian, can further disseminate the
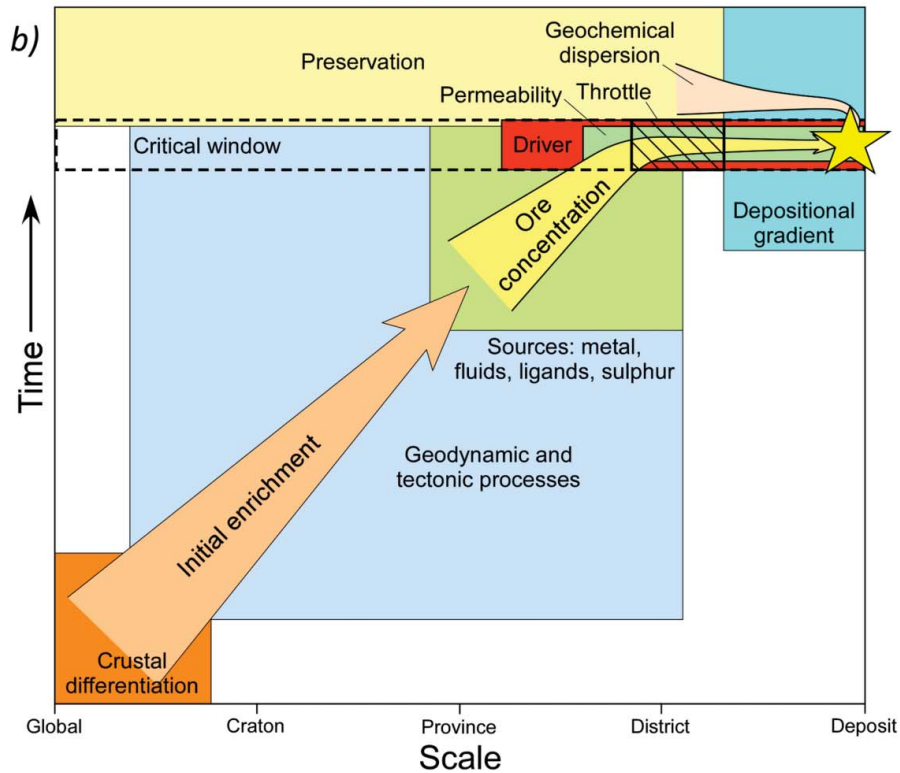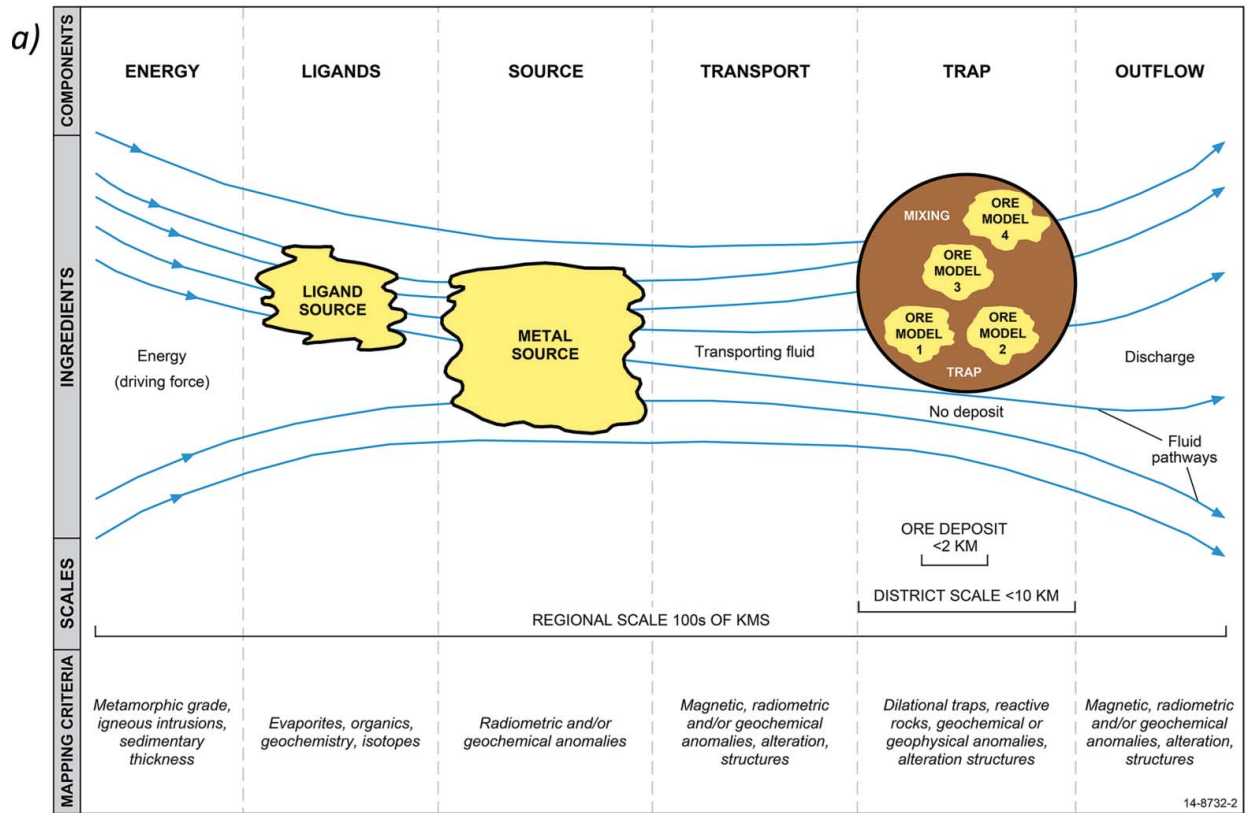
Figure 1. (a) Schematic representation of the original mineral systems concept showing the range of spatial scales involved and mapping criteria (modified after Knox-Robinson and Wyborn, 1997); and (b) casting of the conceptual model in a time–space context (Huston et al., 2016).

geochemical signature. Tailored geochemical protocols and methods, including hydrogeochemistry, biogeochemistry, soil gas and soil hydrocarbon chemistry, and weak and/or selective geochemical extractions, such as MMI (Mann, 2010), have been developed over recent decades to enhance the detection of these subtle elemental or isotopic fingerprints, which have to be detected against the background of the natural geochemical signature of the regional weathering rocks at the site or within the catchment.

Methods

In this contribution, we focus on the surface sediment samples and the MMI method of extraction. The MMI method was designed to extract only weakly bound elements adsorbed on the surfaces of soil particles (e.g. Fe-oxyhydroxides, clay minerals, organic matter), based on the idea that these elements could have migrated up through a regolith profile (including potentially sedimentary basin sequences) that developed post-mineralisation (e.g. Mann, 2010; Mann, Birrell, Mann, Humphreys, & Perdrix, 1998). In both the regional (southern Thomson) and national (NGSA) studies, comparable sample collection, preparation and analysis methods were applied, allowing for a comparison of results at the regional and continental scales, a first for Australia. Briefly, topsoil samples were collected at the outlets of large catchments targeting floodplain or overbank landforms (with an inevitable and variable contribution of eolian material being recognised locally). The samples were air-dried, homogenised and sieved to a coarse (<2 mm) fraction (approximating 'whole rock' composition) before being digested with the multi-element MMI reagent and analysed by inductively coupled plasma-mass spectrometry at the ALS/SGS Laboratories in Perth, Western Australia. A comprehensive quality control and assessment program was integral to each study from inception to reporting. Data and analysis quality between the two datasets were deemed comparable; for more detail, please refer to the original reports from the CRC LEME (Caritat & Lech, 2007), southern Thomson project (Main & Caritat, 2016) and NGSA (Caritat & Cooper, 2011b; Caritat, Cooper, Lech, McPherson, & Thun, 2009; Caritat, Cooper, Pappas, Thun, & Webber, 2010; Lech, Caritat, & McPherson, 2007) projects.

The resulting MMI compositional data from the regional southern Thomson and continental NGSA geochemical surveys were analysed statistically and geospatially to produce maps of element associations, some of which we interpret as being indicative of components of mineral systems (Wyborn et al., 1994). The following data analysis methodology was applied:

1. A list of elements common to both the regional and national datasets was established, from which elements with an excessive proportion (>∼30%) of censored values (i.e. below the lower level of detection, LLD), or those deemed not fit for purpose (i.e. with poor precision or accuracy), were removed. This resulted in 30 elements (Ag, Au, Ba, Ca, Cd, Ce, Co, Cu, Er, Gd, La, Li, Mg,

Mn, Mo, Nd, Ni, Pb, Pr, Rb, Sc, Sm, Sr, Tb, Th, Ti, U, Y, Yb, Zn) being retained in both datasets.

2. A statistical approximation of the censored or missing values was performed in a step called imputation. This was achieved using the nearest-neighbour methodology of the 'impRZilr' function of the 'robCompositions' package (Hron, Templ, & Filzmoser, 2010) in the R statistical language and environment (CRAN, 2016). The method replaced censored values with robust estimates of concentrations, generally below the LLD for the element, but occasionally by values slightly above the LLD. This was considered acceptable given the lower precision of element determination at concentrations near the LLD.

3. In accordance with the contemporary practice known as compositional data analysis (CoDA), the raw concentration values (in parts per million, or ppm) were transformed in order to circumvent compositional data limitations of closure, relativity and non-normality (Aitchison, 1999; Reyment, 1989); here the centred logratio (clr) method was applied. Without such transformation, classic statistical methods may not be applicable to compositional data without a risk of distortion and misinterpretation of results (McKinley et al., 2016).

4. The multivariate statistics method of principal component analysis (PCA; e.g. Jolliffe, 1986) was applied to the clr-transformed data in order to (1) reduce dimensionality from 30 non-independent variables (elements) to a more manageable set of orthogonal (independent) principal components (PCs) that are linear combinations of the elements and account for the bulk of the data variability, and (2) reveal the element associations that are statistically the most significant. The dominant PCs generally represent 'structure' in the data, which is controlled by mineral stoichiometry and reflects dominant geological processes. Thus, PCA has been deemed a useful 'process discovery' tool (Caritat & Grunsky, 2013).

5. The PCs accounting for the most variability in the data, generally the first four to six PCs, were mapped and geospatially interpolated using ordinary kriging (spherical semi-variogram models, variable searching radius, 12 nearest input sample points, using ArcGIS v.10.2) to produce continuous, coloured raster maps of PC values. These maps were then interpreted in the context of potential mineralisation footprints. Here we focus on the results for the first principal component (PC1), while other PCs, some of which pertain to lithology, weathering, mineralisation, etc., are discussed elsewhere (e.g. Caritat & Grunsky, 2013; Main & Caritat, 2016).

Results and discussion

Multivariate statistical analysis

Table 1 presents the summary statistics for the above 30 elements analysed after MMI extraction in both the regional (southern Thomson) and continental (NGSA) studies. As

Table 1. Summary statistics for 30 elements analysed after MMI extraction in the regional (southern Thomson) and continental (NGSA) studies.

Element	Southern Thomson (N = 120)					NGSA (N = 1191)				
	LLD	Min	Median	Mean	Max	LLD	Min	Median	Mean	Max
Ag	0.001	0.0004	0.004	0.007	0.070	0.001	0.0001	0.005	0.011	0.302
Au	0.0001	0.00004	0.0004	0.0004	0.0014	0.0001	0.00001	0.0002	0.0004	0.020
Ba	0.01	0.19	2.51	3.14	12.5	0.01	0.01	0.87	1.41	15.3
Ca	10	176	638	634	1470	10	7.7	390	423	3680
Cd	0.001	0.0006	0.004	0.005	0.023	0.001	0.0002	0.005	0.01	1.75
Ce	0.005	0.002	0.091	0.162	1.23	0.005	0.001	0.101	0.39	12.1
Co	0.005	0.004	0.232	0.289	1.14	0.005	0.002	0.178	0.26	2.58
Cu	0.01	0.29	1.03	1.18	4.29	0.01	0.01	0.96	1.16	30.5
Er	0.0005	0.0006	0.021	0.028	0.131	0.0005	0.0004	0.0112	0.038	2.23
Gd	0.001	0.002	0.060	0.073	0.364	0.0005	0.0006	0.029	0.07	1.61
La	0.001	0.0001	0.015	0.039	0.273	0.001	0.0002	0.027	0.12	3.31
Li	0.005	0.002	0.010	0.014	0.118	0.005	0.0003	0.008	0.019	0.788
Mg	1	45	240	260	2000	1	2	140	193	2920
Mn	0.01	0.16	6.8	9.2	72.5	0.005	0.079	3.99	6.83	59.7
Mo	0.005	0.002	0.009	0.011	0.036	0.005	0.0003	0.007	0.011	0.276
Nd	0.001	0.0004	0.085	0.143	0.961	0.001	0.0008	0.092	0.27	6.87
Ni	0.005	0.071	0.450	0.543	2.70	0.005	0.006	0.411	0.723	16.1
Pb	0.01	0.002	0.05	0.07	0.28	0.01	0.002	0.04	0.19	5.9
Pr	0.001	0.0001	0.012	0.021	0.158	0.001	0.0002	0.016	0.054	1.25
Rb	0.005	0.022	0.071	0.082	0.259	0.00025	0.003	0.107	0.146	2.63
Sc	0.005	0.002	0.009	0.014	0.136	0.005	0.0007	0.008	0.051	6.84
Sm	0.001	0.0002	0.030	0.045	0.288	0.001	0.0004	0.025	0.063	1.34
Sr	0.01	0.95	6.24	6.82	23.8	0.01	0.05	2.40	3.52	35.6
Tb	0.001	0.0002	0.008	0.010	0.051	0.001	0.0002	0.004	0.011	0.247
Th	0.0005	0.0005	0.015	0.026	0.166	0.0005	0.0002	0.021	0.101	3.52
Ti	0.003	0.002	0.030	0.088	2.16	0.003	0.002	0.019	0.09	26.5
U	0.001	0.001	0.036	0.045	0.315	0.001	0.001	0.063	0.121	3.49
Y	0.005	0.004	0.172	0.219	1.00	0.005	0.003	0.098	0.29	4.16
Yb	0.001	0.0006	0.014	0.018	0.081	0.001	0.0003	0.007	0.027	1.56
Zn	0.02	0.02	0.07	0.13	0.80	0.02	0.01	0.12	0.48	19.5

LLD: lower level of detection; Min: minimum (after imputation; see text); Max: maximum.

expected the range (max−min) of most elements is larger (commonly by a factor of two or more) for the NGSA than for the southern Thomson datasets. This occurs because the larger an area of investigation, the more likely one is to sample significantly different lithologies, regolith materials and environmental conditions in general. The only exception noted to this trend is for Mn, which has a ∼20% larger range, and indeed a maximum value also, in the southern Thomson than in the NGSA datasets. The medians (robust estimators of the central values) from both studies are within a factor of two of each other for most elements, with greater discrepancies noted only for Ba and Sr (median southern Thomson/median NGSA of 2.6 and 2.9, respectively). This characteristic is believed to reflect the fact that the majority of the southern Thomson samples are from the Eromanga geological region, which has been noted previously to be highly enriched in MMI Ba and Sr (Caritat, Cooper, Mann, & Prince, 2011), consistent with a dominantly sedimentary environment.

The results of the PCA conducted (separately) on both datasets are presented in Table 2 for PC1, with the scaled and ordered loadings (e.g. Joliffe, 1986) also illustrated in Figure 2. For the southern Thomson dataset (Figure 2a), PC1 has the most negative scores for Sm (lowest), Nd, Pr, Th, La and Ce and the most positive scores for Mo, Au, Mg, Cu, Sr and Ca (highest). The total variance explained by PC1 here is 49.3%. For the NGSA dataset (Figure 2b), PC1 has the most negative scores for Sm (lowest), Pr, Nd, Gd, Tb, Ce, La and Th and the

Table 2. Loadings resulting from the PCA conducted for 30 elements analysed after MMI extraction in the regional (southern Thomson) and continental (NGSA) studies.

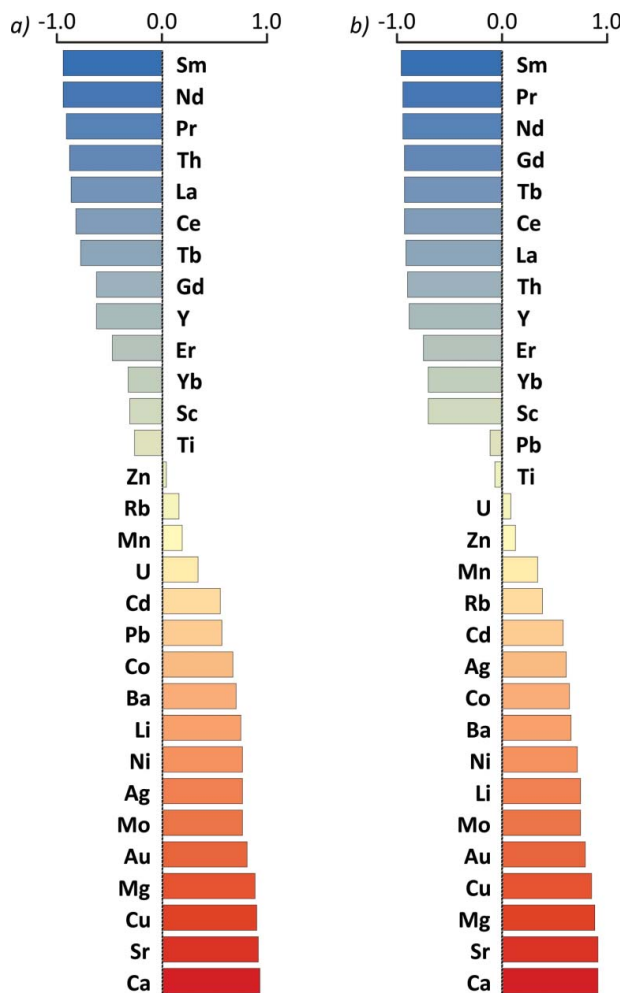| Element	Southern Thomson	NGSA
Ag	0.199	0.151
Au	0.209	0.193
Ba	0.181	0.160
Ca	0.244	0.227
Cd	0.144	0.143
Ce	−0.213	−0.229
Co	0.177	0.157
Cu	0.233	0.208
Er	−0.123	−0.185
Gd	−0.164	−0.230
La	−0.225	−0.226
Li	0.194	0.183
Mg	0.231	0.216
Mn	0.046	0.081
Mo	0.200	0.184
Nd	−0.248	−0.232
Ni	0.197	0.175
Pb	0.148	−0.027
Pr	−0.239	−0.234
Rb	0.040	0.093
Sc	−0.080	−0.171
Sm	−0.249	−0.237
Sr	0.240	0.227
Tb	−0.202	−0.229
Th	−0.229	−0.220
Ti	−0.068	−0.015
U	0.088	0.019
Y	−0.163	−0.217
Yb	−0.082	−0.171
Zn	0.010	0.031

Figure 2. Graphical representation of the scaled and ordered loadings of PC1 for 30 elements analysed after MMI extraction in both (a) the regional (southern Thomson) and (b) continental (NGSA) studies.

most positive scores for Mo, Au, Cu, Mg, Sr and Ca (highest). The total variance explained by PC1 here is 53.3%.

The associations found at the negative ends of the PC1 scores of both datasets are mainly light lanthanides or rare earth elements (REEs), with the exceptions of Tb, which is a heavy REE, and Th, which is an actinide. REEs commonly behave in a very similar way in geological environments due to their comparable physico-chemical characteristics (Henderson, 1984), and thus this clustering of REEs is not surprising. Light REEs typically are more abundant in granitoid rocks and shales than in other rock types; they are typically hosted in heavy minerals/resistates (e.g. monazite, xenotime, and allanite) or in lesser concentrations but in more ubiquitous minerals such as feldspars, biotite and pyroxenes (e.g. Reimann & Caritat, 1998). During weathering, the relative abundance of REEs in the parent rock can be preserved in the soil profile, or alternatively a slight enrichment in the less mobile light REEs can be observed, and the mobile fraction of REEs (i.e. that not locked into primary silicates or resistates) can be washed down the profile by (acidic) precipitation (e.g. Ling et al., 2015; Minařik, Žigová, Bendl, Skřivan, & Šťastný, 1998; Nesbitt,

1979). REEs have been found to adsorb readily on clay minerals, organic matter and metal oxyhydroxides in soil profiles (e.g. Öhlander, Land, Ingri, & Widerlund, 1996; Prudêncio, Figueiredo, & Cabral, 1989).

The associations found at the positive ends of the PC1 scores of both datasets are mainly reminiscent of carbonate-related alkaline earth metals (Ca, Sr and Mg) and ore-related precious/transition metals (Au, Cu and Mo). The alkaline earth metals association is consistent with the geochemical signature expected from sedimentary rocks (Caritat et al., 2011) and/or soil carbonate/calcrete. Note that the formation of carbonate in the regolith occurs under oxidising and alkaline conditions and can be biomediated (McQueen, Hill, & Foster, 1999; Reith et al., 2011; Schmidt Mumm, & Reith, 2004). The precious/transition metals association is likely a signature of ore-related elements having moved through the alluvial/colluvial sediments post-deposition (Anand et al., 2016; Mann, Birrell, Fedikow, & Souza, 2005) and is generally consistent with the regolith signature of mineralisation including porphyry-associated deposits such as Cadia-Ridgeway and Northparkes (McQueen, 2005). In conclusion, it appears that PC1 dominantly reflects weathering (both dissolution/bleaching as revealed by the REEs, and neoformation of regolith carbonate), with an intriguing addition of metals possibly reflecting mineralisation.

Recognition of mineral systems footprints in the southern Thomson region

A local mineral exploration company also using MMI geochemistry in the southern Thomson region (at higher spatial resolution) has developed an empirical geochemical vector of enrichment in Sr, Ca and Au concomitant with depletion in REEs (without multivariate compositional statistical analysis) to successfully site drill holes targeting Cu–Au mineralisation in the region (J. Macauley, personal communication, 2013). This empirical vector coincidentally is very similar to PC1 developed above using multivariate compositional statistics. Based on this, the map of the spatial distribution of PC1 across the southern Thomson study area (Figure 3a) is hypothesised to have the potential to show enhanced prospectivity for Cu–Au mineralisation (warm colours). In a mineral systems context, this map potentially shows areas of metal deposition or enrichment, with a particular emphasis on the potential for porphyry Cu and/or Au mineralisation.

The above hypothesis is further supported by the location of the Warraweena mineral occurrence (Figure 3b, tenements EL7252/7253) reported by another local mineral exploration company between Brewarrina and Bourke (http://www.thomsonresources.com.au/projects/porphyry-copper-gold), which falls within a region of high positive PC1 values as calculated above. Here a diamond drill hole spudded by Mid Eastern Oil Ltd in 1965 (Warraweena no.1; Figure 3b) intersected mineralisation with up to 1 wt% Cu within the basement; three follow-up diamond drill holes drilled by Newcrest Mining Ltd failed to produce economic intersections (op. cit.). The basement sequence, including the informally named Warraweena
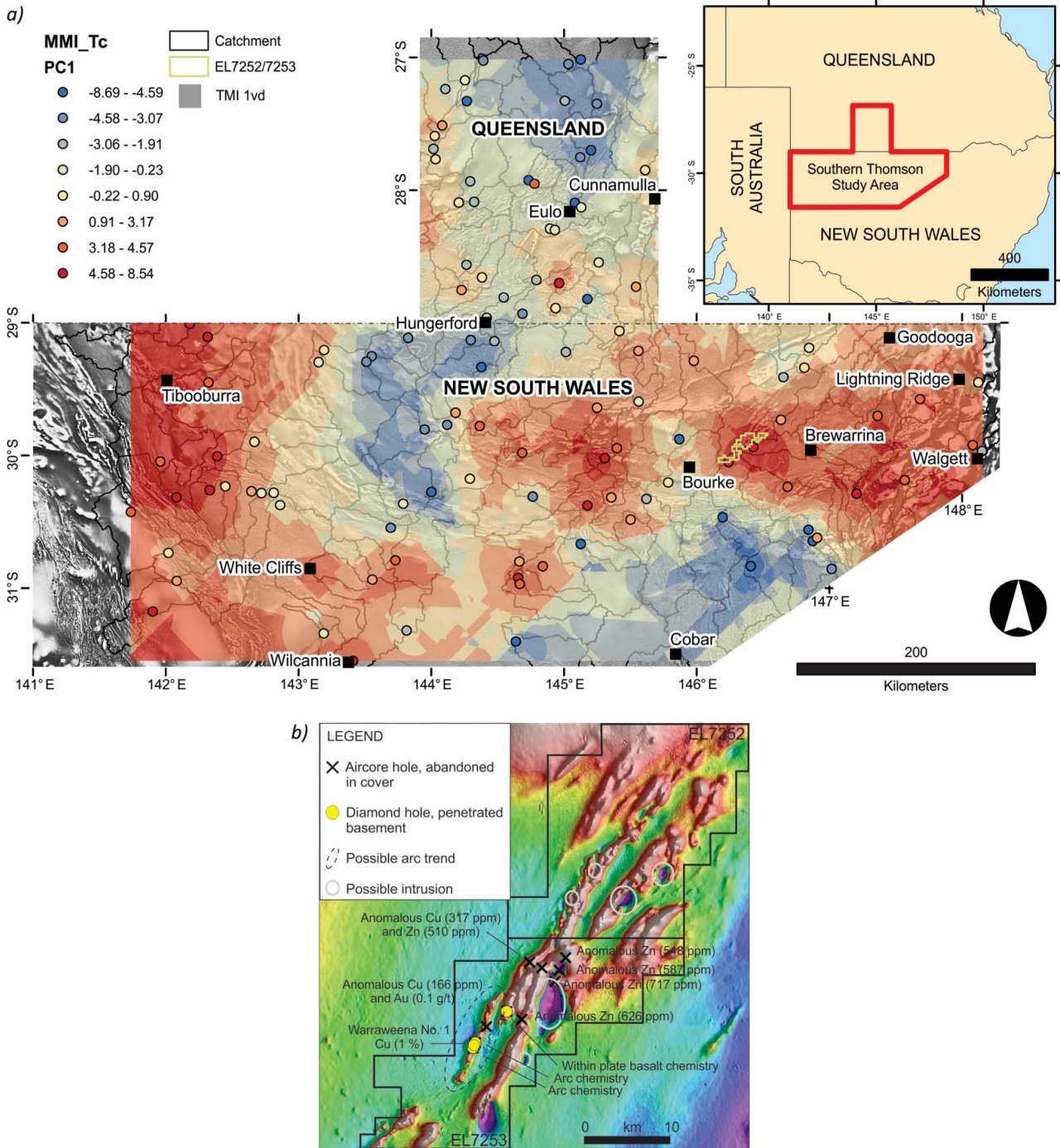
Figure 3. (a) Map of PC1 of the MMI extraction of coarse (<2 mm) surficial sediments from the southern Thomson survey study area. Values at sampling sites are shown by coloured circles; kriging interpolation is shown as a semi-transparent continuous raster based on the same colour scale (eight percentile-based classes). First vertical derivative of the total magnetic intensity (TMI 1vd) surface (Nakamura, 2015) is underlain (as shaded relief), as are catchment boundaries (as black/grey polygons). The green polygon shows the location of Thomson Resources Ltd tenements EL7252/7253, enlarged in (b), with the location of exploration drill holes over a TMI image (http://www.thomsonresources.com.au/projects/porphyry-copper-gold). Map (b) reproduced with permission from the Chief Executive Officer, Thomson Resources Ltd.

volcanics of unknown age, contains very fine-grained lavas and volcaniclastic units of calc-alkaline basaltic andesite composition with island arc affinities similar to Ordovician rocks of the Macquarie Arc (Burton, Dadd, & Vickery, 2008; Glen et al., 2010), which host world-class porphyry Cu–Au deposits such as Cadia/Ridgeway and Northparkes in the adjacent Lachlan

Fold Belt (http://www.thomsonresources.com.au/projects/porphyry-copper-gold). Burton et al. (2008) concluded that if the interpretation of a volcanic arc present in the Bourke area under approximately 100 m of cover were correct, the potential of the region for hosting porphyry, epithermal to mesothermal vein and skarn style Cu–Au $\pm$ Mo $\pm$ Ag

mineralisation could be enhanced. Thomson Resources Ltd followed this up with a detailed aeromagnetic survey leading to an aircore drilling campaign at Warraweena (Figure 3b), which resulted in further encouraging results, including intersections of up to 317 ppm Cu, 717 ppm Zn and 0.1 g/t Au (E. Rothery, personal communication, 2014; http://www.thomsonresources.com.au/projects/porphyry-copper-gold).

If the patterns demonstrated by the MMI PC1 map of the regolith were indicative of areas with porphyry Cu–Au mineralisation potential in the basement (e.g. via hydromorphic dispersion and capillary rise during regolith carbonate formation), then several further regions of interest are revealed by the Thomson regional geochemical survey. These include the eastward continuation of the Warraweena area towards Walgett and spreading north and south; four regions in the centre of the study area (one ∼150 km northwest of Cobar, one ∼50–150 km west of Bourke, one ∼40 km northeast of Hungerford, and one ∼40 km northwest of Eulo); a region ∼80 km east of White Cliffs; around White Cliffs itself; around Wilcannia; and in the northwestern part of the area stretching from the Koonenberry Belt (∼80 km west of White Cliffs and Wilcannia) north to Tibooburra. Historic mining and/or known mineral occurrences have been reported at some of these sites, e.g. the Albert Goldfield, and the Mount Brown and Warratta inliers in the Tibooburra–Milparinka region (McQueen, 2007). Interestingly, the well-endowed Cobar area is not highlighted by positive PC1 values; we believe this is the result of (1) the relatively elevated concentrations of REEs (e.g. Sm, Nd, La, Ce) and Th in this part of the map driving PC1 to negative values, and (2) the different style of mineralisation at Cobar to that inferred at Warraweena. Please also note the particularly low sampling density in this part of the map, implying a greater degree of uncertainty about interpretation here compared with other parts of the regional map.

Upscaling to the continental scale

Switching to the national scale, PC1 from the NGSA's MMI dataset, described above, was mapped in the same way as the regional southern Thomson PC1 map (Figure 4). Spatially, the 'opposing' associations of carbonate + mineralisation, as one end-member, and REEs + Th, as the other end-member, define patterns of warm and cool colours, respectively, across the continent (Figure 4). These continental-scale geochemical patterns indicate where each association can be expected to predominate in surficial (transported) regolith. The Ca–Sr–Mg–Cu–Au–Mo association, which is very similar to that found in the Thomson regional survey described above, occurs in the following geological regions, as defined by Blake & Kilgour (1998) (from west to east): Pilbara–Capricorn–northern Yilgarn, Albany-Fraser, western Eucla, eastern Eucla, western Amadeus, Victoria, Adelaide, Eromanga, southern Georgina–Isa, Curnamona–western Murray and southern Surat. Given the vast differences in scale and sampling density between the two surveys compared here, it is surprising how closely the regional and continental patterns

(Figures 3a and 4) are consistent with one another (e.g. the national-scale map 'predicts' that the Thomson area will have 'highs' to the east, southwest and west and a northwest-trending 'low trough' coming up from the south through the middle of the study area; compare Figure 3a and Figure SP3 in Supplementary Papers). If this association were indeed indicative of Cu–Au mineral potential at the national scale, by extension of the regional case study from the southern Thomson region described above, then we suggest that some of these regions could be worthy of more detailed exploration effort and investment.

It is noted that several of the areas highlighted in Figure 4 by warm colours are in regions of thick sedimentary basin cover (e.g. Eromanga Basin, Eucla Basin). Thus, confirmation of mineral potential would need to be established by follow-up investigations, including where possible using drill holes, in order to screen out any false positive anomalies. Similarly, it appears that the MMI PC1 indicator developed here is quite reliant on weathering processes, including the formation or presence of carbonate in the (near-)surface regolith. There is, however, more to it than just the presence of calcrete, as indicated by the spatial patterns being in places quite different from published regolith carbonate distribution maps (e.g. Wilford, Caritat, & Bui, 2015, and references therein). Regions known to have Cu–Au mineralisation (cfr. Figure SP2 in the Supplementary Papers) are not all highlighted particularly strongly by the method (e.g. Macquarie Arc in New South Wales), and this should also be the subject of further work.

Conclusions

Multivariate statistical analysis of (appropriately transformed) compositional data obtained on surface regolith in the southern Thomson region (northern New South Wales/southern Queensland) and across the continent using the same chemical extraction method (Mobile Metal Ion®) has shown some interesting results.

The composition of the first principal component is almost identical for both datasets, from the regional to the continental scales (Ca–Sr–Mg–Cu–Au–Mo association as one end-member; light REEs–Th as the other). This principal component is interpreted to reflect weathering processes with potentially an overprint from mineralisation as shown by the presence of the precious/transition metals.

The spatial patterns of both studies are surprisingly comparable over the southern Thomson region, given the considerable differences in scale and data density.

Further, exploration results (by a junior exploration company) and rigorous statistical analysis (this work) have independently yielded a remarkably similar geochemical indicator, one that is a proven empirical vector to mineralisation for that explorer on the ground and, additionally, that statistically accounts for the most variability in the data as shown by this study. Another mineral exploration company has reported encouraging drilling results from an area that this study shows to have high first principal component values.
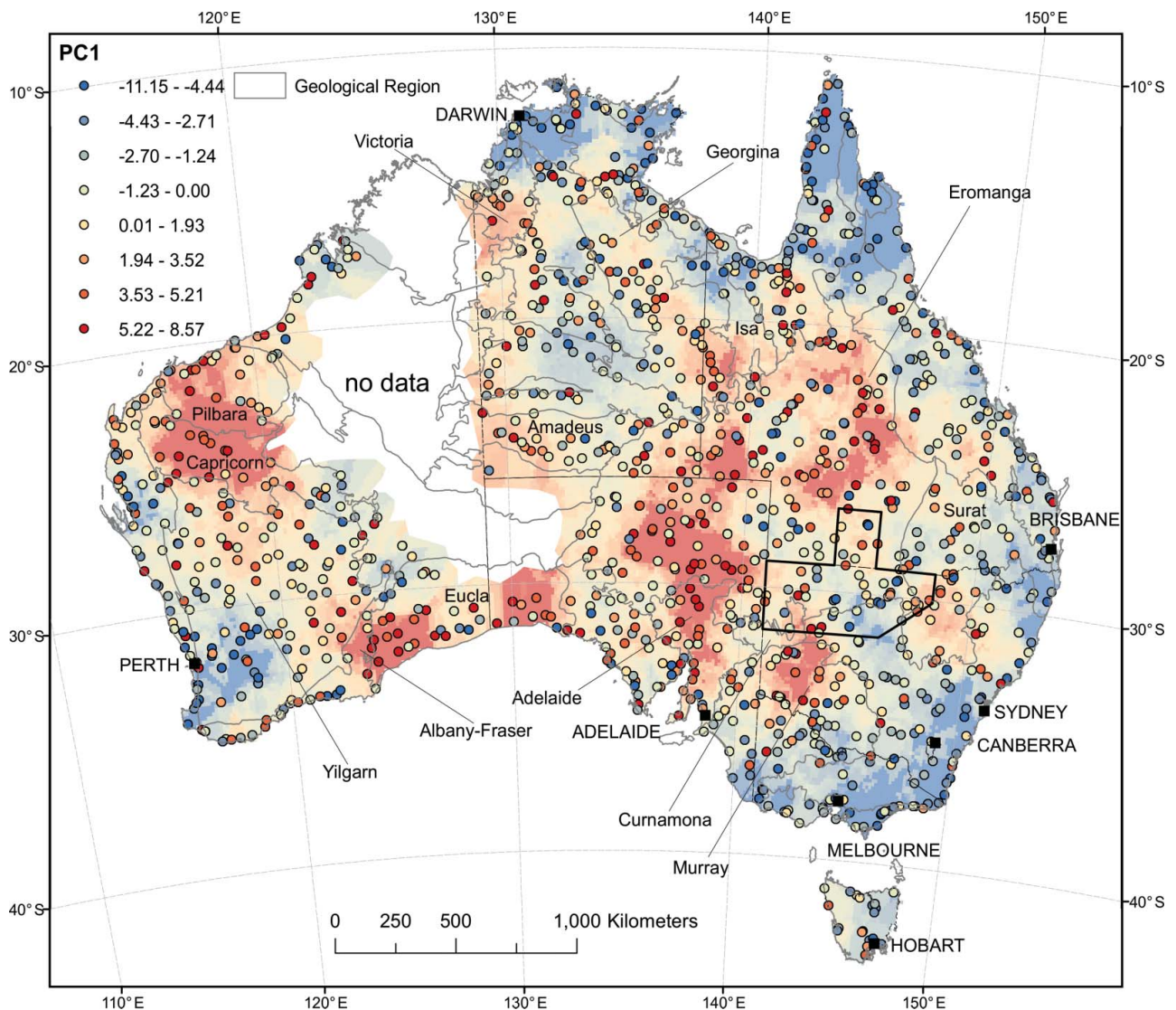
Figure 4. Map of PC1 of the MMI extraction of coarse (<2 mm) surficial sediments from the NGSA project study area. Values at sampling sites are shown by coloured circles; kriging interpolation is shown as a continuous raster based on the same colour scale (eight percentile-based classes). Geological regions (Blake & Kilgour, 1998) are overlain (as grey polygons); those discussed in the text are labelled. The southern Thomson project area (Figure 3) is shown by the black polygon.

If the Ca–Sr–Mg–Cu–Au–Mo association were indicative of the formation of soil carbonate with an overprint of elements dispersed from porphyry Cu–Au mineralisation in the Thomson region, as suggested by local exploration results, then a number of areas with this characteristic are highlighted and are potentially worthy of further investigations:

- At the regional scale: eastward continuation of the Warraweena area towards Walgett and spreading north and south; four regions in the centre of the study area (one ~150 km northwest of Cobar, one ~50–150 km west of Bourke, one ~40 km northeast of Hungerford, and one ~40 km northwest of Eulo); a region ~80 km east of White Cliffs; around White Cliffs itself; around Wilcannia; and in the northwestern part of the area stretching from the Koonenberry Belt to Tibooburra;

- At the national scale: Pilbara–Capricorn–northern Yilgarn, Albany-Fraser, western Eucla, eastern Eucla, western Amadeus, Victoria, Adelaide, Eromanga, southern Georgina–Isa, Curnamona–western Murray and southern Surat geological regions.

In terms of national exploration priorities, this study shows that potentially valuable information is held within the geochemical composition of surficial (transported) regolith, allowing discrimination between more and less prospective regions. This suggests that the geochemical characterisation of the cover in Australia (and the understanding of its evolution through time) is worthy of investment by industry, academia and government. Regolith geochemistry brings a value-adding complementary toolkit to consider in conjunction with geological, geophysical and geochronological datasets. The present study demonstrates a viable workflow to upscale

prospectivity analysis from regional studies to a continental perspective for porphyry Cu–Au mineralisation types; a similar methodology could be applicable to other mineralisation types from other regional greenfield case studies with (sub-) economic drilling intersections.

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Disclosure statement

No potential conflict of interest was reported by the authors.

Supplementary Papers

Figure SP1. Map of the surface geology (Raymond, 2012), geological regions (Blake & Kilgour, 1998), Cu–Au mines (Senior, 2014), Cu–Au mineral occurrences (Sexton, 2011) and sampled sites over the CRC LEME (Caritat & Lech, 2007) and GA-GSNSW-GSQ (Main & Caritat, 2016) southern Thomson project study area.

Figure SP2. Map of the surface geology (Raymond, 2012), geological regions (Blake & Kilgour, 1998), Cu–Au mines and mineral deposits (Senior, 2014), Cu–Au mineral occurrences (Sexton, 2011) and sampled sites over the NGSA (Caritat & Cooper, 2011) project study area.

Figure SP3. Map of PC1 of the MMI extraction of coarse (<2 mm) surficial sediments from the NGSA (Caritat & Cooper, 2011) project zoomed in to the southern Thomson project study area (inset). Values at the NGSA sampling sites are shown by coloured circles; kriging interpolation is shown as a continuous raster based on the same colour scale (eight percentile-based classes). First vertical derivative of the total magnetic intensity (TMI 1vd) surface (Nakamura, 2015) is underlain as shaded relief. The NGSA catchments (McPherson et al. 2011) are overlain as grey polygons. The green polygon between Brewarrina and Bourke shows the location of Thomson Resources Ltd tenements EL7252/7253 (cf. Figure 3 in main paper). Note that despite an apparent low shown here by the raster colours (controlled by longer wavelength interpolation), the three NGSA samples collected in the vicinity of these tenements all have positive PC1 values (0.4, 2.9, and 4.0 from southwest to northeast).

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