A continental-scale geochemical atlas for resource exploration and environmental management: the National Geochemical Survey of Australia

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Abstract: The National Geochemical Survey of Australia (NGSA) was carried out to bridge a vast knowledge gap about the concentration and distribution of chemical elements at the Earth’s surface in Australia and consequent poor understanding of processes controlling their distribution here. The aim of the project was to contribute to improving exploration for energy and mineral resources through the pre-competitive delivery of a new spatial layer of compositional data and information.

Surface (0–10 cm depth) and shallow (c. 60–80 cm) samples of catchment outlet sediments were collected from 1315 sites located near the outlet of 1186 catchments (c. 10% of which were sampled in duplicate) from across Australia. The total area covered by the survey was 6.174 million km², or c. 81% of Australia, at an average sampling density of 1 site per c. 5200 km². A number of field parameters (e.g. soil colour, pH), bulk parameters (e.g. electrical conductivity, particle size distribution) and geochemical parameters (i.e. multi-element composition of dry sieved <2mm and <75 μm grain-size fractions) were determined. The grain-size fractions were analysed to determine (1) total, (2) aqua regia soluble, and (3) Mobile Metal Ion (MMI®) extractable element contents.

These data were collated into a spreadsheet and graphically represented as a series of 529 geochemical maps (http://www.ga.gov.au/ngsa). These constitute the first continental-scale series of geochemical maps for Australia based on internally consistent, state-of-the-art data pertaining to the same sampling medium collected, prepared and analysed in a uniform and thoroughly documented manner and over a short time period. They are being used to better understand the accumulation, mobility and significance of chemical elements in the near-surface environment. Applications to date and ongoing and future directions are discussed.

Supplementary material: Appendices 1-4 of summary statistics are available at http://www.geolsoc.org.uk/SUP18853

Keywords: geochemical survey; geochemical atlas; regolith; Australia; composition; processes; resources

Received 17 October 2014; revised 11 December 2014; accepted 4 January 2015

Modern geochemical surveys were developed in the twentieth century (see review of Garrett et al. 2008) primarily as a means of finding ore deposits (geochemical prospecting). Since then they have been carried out in many regions (e.g. Webb et al. 1978), countries (e.g. Cohen et al. 2012), multinational regions (e.g. Reimann et al. 2000) and, more recently, continents (e.g. Smith et al. 2012; this study), at various scales, ranging from ultra-high density (>1 sample/km²) to ultra-low density (c. 1 sample/10000 km²). At the same time, their application has expanded to also encompass environmental monitoring, land-use decision support, natural resource management, and medical geology. A variety of sampling media, including rock, sediment, soil, soil gas, ground water, surface water, rain, snow, vegetation and even animals, have been targeted by geochemical surveys over time. A few recent surveys have even targeted several media to better understand the mobility, residence and biogeochemical cycles of elements in the environment. Different designs and strategies led to different applications, but overall geochemical surveys are seen as providing fundamental information to support various government and industry activities (Garrett et al. 2008; Thornton 2012).

A five-year Onshore Energy Security Program (OESP) was announced in 2006 to enable Geoscience Australia to deliver high quality pre-competitive (government-funded, publically available) geoscience information relating to onshore energy prospectivity (Johnson 2006). The National Geochemical Survey of Australia (NGSA), which was part of this programme (Baldwin 2007), collected transported regolith (sediment) samples from across the Australian continent and determined their inorganic chemical composition. The NGSA provided the only nation-wide, internally consistent geochemical dataset with state-of-the-art detection limits. It aimed to:

a) help calibrate and ground-truth the airborne radiometrics coverage of Australia (including addressing mother-daughter disequilibrium in the U decay chain);

b) fill gaps in the existing airborne radiometric and geochemical coverages of Australia with quality data;

c) permit multi-element characterization and ranking of radiometric anomalies (e.g. differentiation of U signatures from ‘hot’ granites, black shales or palaeochannels); and

d) provide fundamental data to enable first-order characterization of geothermal hot-spots.

As such, the NGSA project (http://www.ga.gov.au/about/what-we-do/projects/minerals/concluded/national-geochemical-survey) supported and added value to a number of other OESP projects, particularly the Australia-Wide Airborne Geophysical Survey project (http://www.ga.gov.au/about/what-we-do/projects/minerals/concluded/awags; Minty et al. 2009a) and the Uranium Systems project (http://www.ga.gov.au/about/what-we-do/projects/minerals/concluded/uranium-systems). Additionally, the NGSA has and is expected to continue to have wider applications in mineral exploration for various commodities as well as in natural resource management.

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In 2008, Caritat et al. (2008b) gave an account in this journal of the status of geochemical surveys in Australia, including an overview of pilot projects that led to the development of NGSA, and laid out the strategy for the NGSA. The present report reviews the recently completed NGSA project, including the main application outcomes and research efforts that derived from it, and can be considered a sequel paper to Caritat et al. (2008b).

At its completion in June 2011, the NGSA delivered:

a) a geochemical dataset that was national in scope, internally consistent and acquired through the application of state-of-the-art methods and instrumentation;

b) a web-delivered geochemical atlas of Australia for 68 elements showing for the first time what their concentrations in surface materials are and how they vary spatially;

c) reports, including a hard copy geochemical atlas (Caritat & Cooper 2011a), and papers documenting the project in detail and drawing implications on energy resource prospectivity and other applications; and

d) an archive of samples covering almost the entire continent for future investigations.

Background to the project

The NGSA project aimed to provide pre-competitive data and knowledge to support exploration for energy resources in Australia. In particular, it improved existing knowledge of the concentrations and distributions of energy-related elements such as U and Th at the national scale. The project was underpinned by a series of pilot geochemical surveys carried out in the previous four years by Geoscience Australia and the Cooperative Research Centre for Landscape Environments and Mineral Exploration (CRC LEME) to test robust and cost-effective protocols for sample collection, preparation and analysis. Examples of these are the Riverina (Caritat et al. 2005; Caritat et al. 2008a) and the Thomson (Caritat & Lech 2007; Lech & Caritat 2007) pilot geochemical surveys. Selected results from these pilot projects were summarized in Caritat et al. (2008b).

The NGSA project, briefly described below, was conducted in collaboration with all the State and the Northern Territory (NT) geoscience agencies. It was initiated because of the absence of a comprehensive geochemical coverage for Australia and because such a data layer is an important complement to national-scale geological and geophysical datasets (Caritat et al. 2008c).

The distribution of geochemical data available at the commencement of the survey through the national repository (OZCHEM database; Champion et al. 2007) is shown in Figure 1. The map shows that there were vast areas of the country (>60%) that lacked any geochemical information. Where geochemical data were available in the public domain, they may often not have been internally comparable as a result of:

a) inconsistent sampling material (e.g. rocks of various types and/or degree of alteration, mineralization or weathering);

b) inconsistent sample preparation methods (e.g. total analyses v. partial digests/extracts with strong to weak acids or other solutions);

c) differences in instrumentation used and between laboratories, leading to variable lower limits of detection (LLD) between datasets (e.g. older versus state-of-the-art instruments);

d) lack of metadata on data quality (e.g. instrument calibration, bias, precision, sample type description, replicates, etc.); and

e) variable suites of elements determined (e.g. sometimes a very limited suite such as Au only or Au+Cu).

Although a significantly improved nation-wide, levelled coverage of airborne gamma-ray spectrometric (radiometric) data (Minty et al. 2009a,b) became available (Fig. 2) during the course of the

Fig. 1. Distribution of whole rock geochemical data in Australia (plus signs) extracted from the OZCHEM national database as at June 2006, overlain on bedrock and regolith coverage.
NGSA project, field calibration of radiogenic elements K, U or Th was perhaps not as systematic as desirable and the question of disequilibrium in the radiogenic decay chain of U was poorly constrained as a result. It was hoped that the NGSA data, in combination with the new radiometric coverage, would yield insights into this problem.

Some regional geochemical surveys had been carried out in parts of Australia (e.g. Morris et al. 1998; Cohen et al. 1999; Cornelius et al. 2008; the pilot geochemical surveys mentioned above), but no national coverage existed. The modern concept of regional geochemical surveys was first developed last century, and has since proven to be a reliable tool for mineral exploration at various scales (Garrett et al. 2008; Smith & Reimann 2008).

The objectives of the NGSA project were to:

- collect transported regolith samples at the outlet of large catchments covering >90% of Australia using an ultra-low sampling density approach, and preserve an archive of these samples for future investigations;
- prepare and analyse the samples to extract the maximum amount of geochemical information (60+ elements/parameters) using internally consistent, state-of-the-art techniques;
- populate the national geochemical database with the resulting new data; and
- compile an atlas of geochemical maps for use by the mineral exploration industry to identify areas of interest in terms of energy-related resources and other mineral commodities, which can then be the focus of targeted exploration investment.

**Materials and methods**

Samples were collected from 1186 catchments (or 1315 sites, including duplicates), which together cover over 6.174 million km² or c. 81% of Australia at the average sample density of 1 site per 5200 km² (statistics based on equal area projection). Approximately 200 catchments in South Australia and Western Australia could not be sampled during this project due to access limitations. Collaboration with State and NT geoscience agencies was critical for the completion of the project, particularly regarding the sampling phase.

Sampling procedures were reported in Lech et al. (2007) and field data were compiled in Cooper et al. (2010). Sample preparation protocols were documented in Caritat et al. (2009) and sample analysis methods were detailed in Caritat et al. (2010). A data quality assessment is presented in Caritat & Cooper (2011b). The geochemical atlas (Caritat & Cooper 2011a), which should be used in the context of the above mentioned reports, presented 529 maps illustrating the geographical distribution of the concentration of chemical elements and properties as acquired by the NGSA project.

The sampling method was adapted to Australian landscape and climate conditions (e.g. importance of aeolian landforms in some areas, climate ranging from tropical to arid). It was fine-tuned and field-tested during the Riverina, Gawler and Thomson pilot projects (e.g. see Caritat et al. 2008b). The cost of a national survey was minimized by applying an ultra-low sampling density approach (generally accepted to mean between 1 site per 1000 km² and 1 site per 10000 km²). The strategy adopted for the national geochemical survey is briefly described below.

**Sampling medium**

Catchment outlet sediments (similar to overbank/floodplain sediments in most cases) were sampled at two depths (from 0 to 10 cm below the surface as well as at a depth of between c. 60 and 80 cm on average). Overbank or floodplain sediments are a common sampling medium in geochemical surveys (e.g. Ottesen et al. 1989; Volden et al. 1997; Xie & Cheng 1997; Bølviken et al. 2004). Those sediments can reasonably be assumed to best represent well-mixed, fine-grained composite samples of major rock and soil types present in the upstream catchments. The term
‘catchment outlet sediment’ was deliberately chosen because it was more general than ‘floodplain sediment’ to allow for those cases where aeolian influence was important in the regolith formation process. To the extent that the sampled catchment outlet sediments were supporting biological activity, they also can be defined as soils (SSSA 2008); thus the terms ‘sediment’ and ‘soil’ have been used interchangeably to refer to the sampling medium in various publications on NGSA data (see below).

**Sampling sites**

Initially 1385 catchments covering 91% (or c. 7 million km²) of Australia across all States and Territories were targeted for sampling (Fig. 3). Five catchments were assigned a second sampling site (i.e. target site) due to their size and topography so in total, it was expected that 1529 samples (1390 catchments + 10% of which to be sampled in duplicate) would be collected. Most catchments were sampled near their outlet, while those exhibiting internal or poorly defined drainage were sampled at, or as close as possible to, their lowest point. Lech et al. (2007) gave details of the method for determining sampling sites. Catchments smaller than 1000 km² (mostly coastal) and small islands were not included in the survey. The resulting distribution of catchment outlet sites targeted for sampling is shown in Figure 4 and translated to an average sampling density of c. 1 site per 5500 km².

**Sample collection**

A detailed Field Manual was compiled (Lech et al. 2007) and all sampling equipment and consumables were centrally purchased. Despite best efforts to access all target sites, only 1186 catchments could be sampled before the deadline for field work was reached. Of these 1186 catchments, 123 were sampled in duplicate (on average c. 200 m away from the original site) for quality control purposes, and six of the largest catchments were sampled at two widely separated locations (on average 69 km apart), yielding a total of 1315 sampled sites (Fig. 5). At each site, a Top Outlet Sediment (TOS) sample was collected from 0 to 10 cm depth (below the root zone, if applicable), and a Bottom Outlet Sediment (BOS) sample was collected from a depth of (on average) between 60 and 80 cm. To reduce natural soil heterogeneity, every sample collected was a composite either from a shallow soil pit (TOS) or from at least three auger holes or, rarely, a deeper pit (BOS) at a given site (see Lech et al. 2007, for more information). On average, 9 kg of sediment were collected per sample.

Sample collection was carried out by the State and NT geoscience agencies following a hands-on, in-field training period with the Geoscience Australia NGSA team. At each locality a detailed site description, field pH, and dry (if possible) and moist Munsell® soil colours were recorded and several digital photographs were taken (Cooper et al. 2010). All information was recorded digitally to facilitate subsequent uploading into databases.

**Sample preparation**

All samples were sent to Geoscience Australia for processing, where they were air-dried and homogenized. A bulk split (c. 50%) of each sample was archived for future investigations. The remainder was riffle split and dry sieved to ≤2 mm (‘coarse’) and ≤75 μm (‘fine’) fractions. The ≤2 mm fraction was mechanically ground for some analyses, while the finer fraction was not. The sample preparation protocols were discussed in detail in the NGSA Sample Preparation Manual (Caritat et al. 2009).

**Sample analysis**

The analysis philosophy from the outset was to apply a multi-element approach to two grain-size fractions prepared by at least two digestion methods, in order to maximise the amount of geochemical information extracted from the samples. Sample analysis was carried out for 68 elements (total element content) using X-Ray Fluorescence (XRF) and (Reaction Cell) Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) at Geoscience Australia. The ICP-MS analyses were carried out on a total digest (HF + HNO₃) of fragments of the XRF fused beads (Pyke 2000). Additional parameters recorded at Geoscience Australia were pH 1:5 (soil:water), electrical conductivity 1:5 (soil:water), and laser particle size analysis. Analyses for selected elements not available at Geoscience Australia (e.g. Au, F, Se, and Pt group elements) were undertaken externally using specialized methods. Additional digests/analyses (e.g. after aqua regia digestion, ligand-based extraction, near visible-infrared spectroscopy) were also carried out.
out externally. The Mobile Metal Ion (MMI®) analysis, which is a weak ligand-based extraction designed to primarily solubilise loosely bound species at the surface of soil particles (see Mann 2010), of the <2 mm TOS samples was made possible through collaboration with SGS Minerals Services. Thus, with two depths (TOS, BOS) sampled and two grain-size fractions (<2 mm, <75 μm) analysed by two (total, aqua regia) or three (total, aqua regia, MMI®) analytical methods, up to nine concentrations per element were obtained per sampled site (see below). Bulk properties such as pH (by saturated paste in the field, and by potentiometry on 1:5 soil:water slurries in the lab), electrical conductivity (by potentiometry on 1:5 soil:water slurries in the lab), and sand-silt-clay proportions (by laser particle size analysis; cut-offs at 2000-20-2 μm used) were also determined on bulk (unsieved) samples of the TOS and BOS. Details of the sample analysis protocols are discussed in the NGSA Analytical Methods Manual (Caritat et al. 2010).

**Quality assessment/quality control**

Sample numbers were randomized to minimize regional bias, help separate false from true anomalies and obtain meaningful estimates of the variance of duplicates. Field duplicates, analytical duplicates, internal standards and certified reference materials were introduced at regular intervals in the analytical streams. Care was also taken throughout the project to minimise contamination, cross-contamination and mislabelling risks. Details were discussed in the NGSA Data Quality Assessment report (Caritat & Cooper
Data analysis & products

Non-parametric statistics and exploratory data analysis principles (e.g. Tukey 1977) were used to analyse the NGSA dataset, as geochemical data is commonly skewed and containing potential outliers. Censored data (<LLD) were replaced by ½ LLD. National-scale geochemical maps were produced and released as a Geochemical Atlas (Caritat & Cooper 2011a) and a web-based map collection (http://www.ga.gov.au/ngsa). Reports providing preliminary interpretations and including graphical and statistical analysis of the NGSA data were prepared separately and published (see below).

Timeline

Following planning in the first half of 2007, fieldwork, including initial training, began in mid-2007 and concluded in late 2009. Figure 5 shows the final distribution of catchments actually sampled for NGSA at the end of the fieldwork campaign (December 2009). Sample preparation started in early 2008 and concluded in December 2009. Sample analysis started late 2008 and finished in late 2010. Data analysis and reporting took place in 2010 and early 2011. The project concluded on time in late June 2011, with an official dataset and product release at the Association of Mining and Exploration Companies (AMEC) convention in Perth, 28–30 June 2011.

Results

In the Geochemical Atlas of Australia (Caritat & Cooper 2011a), a series of 529 geochemical maps were presented. The maps were grouped here by analytical method, with the total content maps shown first, followed by aqua regia digestion, then Mobile Metal Ion (MMI®) maps. For enhanced flexibility, the digital Geochemical Atlas on the NGSA webpage (http://www.ga.gov.au/ngsa) allows the user to search and view individual maps in this or any order, or alternatively download all maps pertaining to any given element/parameter as a bundle. Summary statistics of all NGSA results are given in Appendices 1-4 in the Supplementary Material.

In creating the geochemical maps for the atlas, the following procedures were followed.

1. For catchments sampled in duplicate for the purposes of quality control (N=123), only one set of data was retained. The arbitrary decision was taken to keep the sample with the (randomly allocated) lowest sample identification number of the pair and set aside the one with the higher number.
2. Any data returned as <LLD were replaced by ½ LLD.
3. Similarly, any data returned as above the upper limit of detection (>ULD) were replaced by 2 ULD (only Al, Sr and W concentrations after aqua regia digestion are affected by >ULD issues).
4. Dot maps (e.g. Fig. 6) rather than interpolated raster maps were shown. Map symbology was based on exploratory data analysis principles (Tukey 1977). The data for each element were sorted in order of increasing value (ranked) and univariate isometric logratio (ilr) transforms (e.g. see Filzmoser et al. 2009) were calculated. The ilr transformation yields a correct representation of compositional data in Euclidean space where standard statistical methods can be applied. Minimum (0th percentile), first quartile (25th percentile), median (second quartile or 50th percentile), third quartile (75th percentile) and maximum (100th percentile) values were determined by identifying the appropriate rank in the sorted data. A small circle symbol (○) was assigned for data between the minimum and the first quartile, a small dot (.) for data between the first quartile and the median, a larger dot (•) for data between the median and the third quartile, and a plus sign (+) for data between the third quartile and the maximum.
5. For identifying the existence of outliers, lower and upper fences were calculated on the ilr-transformed data as follows:
   a. Lower fence = 25th percentile - (1.5 × IQR); and
   b. Upper fence = 75th percentile + (1.5 × IQR), where IQR is the Inter-Quartile Range (75th percentile–25th percentile). Where the lower fence was smaller than the minimum or the upper fence greater than the maximum, no lower or upper outliers existed. If, however, values in the dataset existed between the minimum and the lower fence they were assigned a large circle symbol (○). Similarly, if values in the dataset existed between the upper fence and the maximum they were assigned a large solid square symbol (■). Thus, the latter two symbols were not present in all maps, as the existence of lower and/or upper outliers depends on the structure (i.e. size of IQR relative to range, skewness) of the dataset at hand.

Discussion

The NGSA results, database and atlas were released just over three years ago (at the time of writing) and it is perhaps appropriate to review here what use has been made of it to date, what collaborations and projects have spun off it, and what research opportunities are being pursued.

The first application to be published using the NGSA data was a national map of soil field pH (Caritat et al. 2011a), one of the more fundamental soil properties governing or influencing many others, including compositional ones. This showed how Australian soil pH is strongly bimodal (with modes at pH 6–6.5 and 8–8.5) and, whilst topsoil pH is generally similar to subsoil pH (64% of cases), in 28% of cases it is more acidic and in 7% of cases more alkaline. Importantly, the NGSA data fill significant gaps in knowledge about the distribution of soil pH in various States/NT and provides a unifying or levelling dataset for the State/NT datasets, some of which are based on different methods and approaches.

A preliminary investigation of the mineral exploration potential of the NGSA data was also performed by Caritat et al. (2011b) for a selection of commodities (Au, Cu, Pb, Th, U, Zn and rare earth elements or REEs). The relatively simplistic approach of comparing the spatial coincidence between areas of elevated (total) concentration of these elements and the distribution of known deposits and occurrences was adopted. This was done at the national scale and, for U, also at the regional scale (Pine Creek area, NT). In the case of Zn, a more sophisticated concentration-area (CA) approach was also trialled. The conclusion was reached that the NGSA samples from many catchments with known deposits or occurrences had anomalously elevated (at or above 75th percentile level) concentrations of the relevant commodity element. Possible mechanisms for the existence of these anomalous values, including contamination from mining activities, were discussed. The potential for new areas on which to focus mineral exploration effort and investment was highlighted.

The NGSA data for total K, U and Th in the <2 mm TOS samples were compared with airborne radiometric data by Wilford et al. (2011), because they afford a unique opportunity to ground-truth the geophysical measurements and calibrate them over a large part of Australia. Because the NGSA samples are thought to represent a large on-the-ground footprint (at least the sampled...
landform, at most the catchment) compared to the smaller ‘pixel’ size of the airborne radiometric data, a number of ways to average radiometric response over a larger area were tested. The best match between the two datasets was found when airborne radiometric data from a circle with a 300 m radius centred over the NGSA sampling site were selected, and the NGSA samples with excessive coarse material (which was removed from the analysed <2 mm grain-size fraction) were excluded. Coefficients of determination ($r^2$) significant at the $p<0.01$ level were obtained for K, Th and U (0.73, 0.58 and 0.33, respectively). The correlation for U is complicated by disequilibrium effects: volatile or soluble daughter products in the U decay chain (e.g. $^{222}$Rn and $^{226}$Ra) can be removed from some locations (because they are open, or intensely leached) and accumulate in others (because they are closed, or extremely dry), leaving the decay chain essentially out of secular equilibrium. Airborne radiometric responses for K and U were found to underestimate the ground-measured concentrations, whereas the opposite was true for Th. A preliminary correction for U derived from radiometric surveys was proposed, and a more sophisticated substitute to traditional soil maps.

A high level comparison of the NGSA TOS coarse results with the new European geochemical survey, GEMAS (Reimann et al. 2014), was conducted to address the question of how fundamentally different the surface soils are in Australia and Europe from the point of view of geochemical composition, at the continental scale (Reimann et al. 2012). It also addressed the issue of data comparability between disparate surveys and what lessons could be learned for global geochemical mapping. Twenty-six total elements and 14 aqua regia extractable elements, Loss On Ignition (LOI) and pH were found to be mutually consistent, through the cross-analysis of exchanged project standards during the two projects. Although the median concentrations for most elements were surprisingly similar, they were slightly but systematically more elevated in Europe than in Australia, except for Si and Zr. The median Chemical Index of Alteration (CIA; Nesbit & Young 1982) was found to be higher in Australia (72%) than in Europe (60%). Analytical quality control was seen as a key requirement for the integration of further continental datasets. A separate comparison with emerging data from Brazil showed that the CIA there is even higher (median CIA 95%; Schucknecht et al. 2012).

Still based upon the European and Australian continental datasets, new Predicted, Empirical Global Soil reference values (PEGS2) were proposed (Caritat et al. 2012) for the same 26 total, and 14 aqua regia soluble elements, plus LOI and pH. This was the first time such extensive, empirical geochemical datasets were used to provide these reference values, which have traditionally been calculated based on a small number of data points (or from

Fig. 6. Geochemical map of total Cr concentration in the coarse fraction of the Top Outlet Sediment (Caritat & Cooper 2011a). For a simplified lithological map, please refer to figure 1 in Caritat & Grunsky (2013).
smaller areas) coupled to models of the composition of the continental crust or world soils. Such values are commonly used in environmental studies to ‘determine’ if a soil may be contaminated or what the remediation target concentrations should be. Despite the fact that aqua regia digestion is a standard method in soil and environmental sciences, no soil reference values based on this partial digestion were available until then. It was shown that average upper continental crust is a poor estimator of the natural concentration of elements in soils. Moreover, substantial differences were found for many elements between published average soil values and the new empirical values. Geology, with the potent modifier of climate, and their direct and indirect consequences, are the dominant controls on soil and sediment composition at the continental scale.

Collaborating State/NT Geological Surveys prepared their own reviews and interpretations of the NGSA data for their jurisdiction. The Queensland mineral prospectivity atlas presented a series of maps where catchments were coloured according to element (and, for the REEs, element group) concentrations (Tang & Brown 2012). Anomalous catchments were discussed in some detail in the context of known geology, mineral endowment and potential new areas of interest. The fine (<75 μm) fraction of the BOS sample was deemed the most effective in determining economic potential. The New South Wales assessment identified elevated Au, Pb, Sn and W levels in the north of the State (Flitcroft & Caritat 2011). In the NT, selected elements were discussed in terms of the local geology and known mineralization (Wygralak 2012). Maps were presented showing the catchments that were elevated in those elements a given number of times (e.g. three or five times) above background, the latter taken to be the geometric mean of the distribution. Scheib (2013) gave a detailed account of the distribution of elements in the Western Australian part of the NGSA project. Highest element contents were from the fine fraction of the BOS samples. The NGSA data highlighted several mostly undocumented geochemical anomalies for Pb, REEs and High Field Strength Elements (HFSEs; Hf, Nb, Ta, Zr). Some of these were attributed to local lithological sources, heavy mineral sand deposits, or tectonic elements (e.g. South West Terrane in the Yilgarn). The NGSA data were found to be able to highlight regional geochemical anomalies, the dominant causes of which were attributed to geology, regolith, grain size and stratigraphy.

The bioavailability of nutrients in Australian topsoils was examined using the MMI® analyses of the NGSA samples by Mann et al. (2012). Relative to total element content, the bioavailability of nutrients ranged from 0.1% to 31% for the 11 elements considered (Ca, Cu, Fe, K, Mg, Mn, Mo, Ni, P, Se and Zn). In a world first, continental maps of MMI® extractable element contents were produced and the resulting geochemical patterns were interpreted to reflect the dominance of lithology, mineralization, environmental processes and agricultural practices. In a comparison with Europe, where MMI® analyses were also obtained by the GEMAS project based on the success of NGSA, Mann et al. (2014) found that most elements showed slightly higher medians in European soils, with median_GEMAS/median_NGSA ratios generally ranging from 1 to 2. Exceptions to this were four elements (K, Mg, Rb and Sr) with higher median values in Australian soils. These elements are predominant in the arid and semi-arid interior and their accumulation is favoured by dry climatic conditions. Five elements (Al, Cd, Fe, Pb and Zn) had ratios greater than 5 and were considerably more concentrated in the mobile form in European soils.

A comprehensive statistical analysis of the NGSA data undertaken at the continental scale by Caritat & Grunsky (2013) established a number of element associations derived by PCA of the centred logratio (clr) transformed data (a transformation that circumvents data closure and skewness, similar to ilr discussed above). These associations and the spatial distributions of the principal component (PC) scores were used to interpret the dominant geological processes controlling regolith composition in Australia. Independent spatial information from geological maps, airborne radiometric and spaceborne spectroscopic datasets helped infer those processes, which were found to be lithological control (e.g. Se, Ti, Cr, V and Fe in PC3 corresponding to areas of known ultramafic and mafic rocks), weathering (e.g. REEs and HFSEs in PC1 corresponding to areas of intense weathering and leaching leaving an accumulation of resistate and/or heavy minerals), sediment transport (e.g. compositional differences between the fine and coarse fractions of the catchment outlet sediments), and secondary mineral precipitation (e.g. Mg, Ca, Sr in PC1, and Sr, Ca, LOI in PC4 corresponding to the accumulation of soil carbonate).

The NGSA data, among others, were also used in the first review of Australian salt lakes aimed at assessing their potential for strategic resources such as B, Li, valley, playa-type and calcrete-hosted U and potash (Mernagh 2013). A number of continental maps were produced to represent the mineral potential of salt lake systems, relying partly on NGSA results. On the basis of this report, industry took up exploration tenements (e.g. http://www.anbnswire.net/press/en/76404/; http://investorintel.com/potash-phosphate-intel/salt-lakes-potential-potash-supply-boost/).

Mueller et al. (2014) applied the spatial decorrelation method of Minimum/Maximum Autocorrelation Factors (MAF) to the clr-transformed NGSA data to assess its suitability for structure identification in the compositional setting. It was found that MAF was effective at delineating geochemically coherent regions. Structural analysis of the factors indicated slight differences in continuity across soil layers (TOS v. BOS) and grain-size fraction (fine v. coarse), leading to differences in the strength with which regional features appear on the interpolated maps.

Other collaborative investigations in progress include: predictive mapping of various geological entities defined between the surface and the Moho, such as GeoRegions and major crustal blocks using discriminant analysis (unpublished results); environmental covariate modelling of various regolith properties to better understand processes and their environmental (e.g. landscape) controls (e.g. Wilford et al. 2015); sediment provenance analysis using Nd isotopes and zircon U-Pb ages (unpublished data); a combination of NGSA geochemical and grain-size data and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) spectral data to map and monitor clay loss and other regolith processes (Cudahy et al., in press); a comparison of three continental datasets (Australia, China and Europe) with a view to providing guidance on dataset harmonization for establishing global geochemical baselines (Liu et al. 2015); and the development of a novel robust statistical method for high-dimensional compositional data (Scealy et al. 2015).

In addition, the NGSA has been the motivator for new data acquisition campaigns such as in the Cape York region by the Geological Survey of Queensland, and in the southern Thomson Orogen by the Geological Surveys of Queensland and of New South Wales and Geoscience Australia. Rather unexpected enquiries (i.e. outside of the target stakeholder group of resource explorers, academic researchers, government geoscientists, etc.) about the dataset also arose since its release, such as by infrastructure developers (soil pH), public health researchers (radioelements), veterinarians (various soil properties), and even local and international law enforcement agencies (potential forensic applications). If downloads from the project’s website http://www.ga.gov.au/ngsa are an indicator of uptake, the NGSA continues to be a popular source of information with cumulative downloads of the Atlas volumes and dataset reaching over 2000 three years after completion (Fig. 7). Evidence of recent independent uptake and use of the data includes works of Cohen et al. (2012), Garrett (2013), and Bui et al. (2014).
Potential future research directions for this dataset include: applications to mineral system science and mineral prospectivity; a better characterization of the Australian regolith (aligning with the UNCOVER initiative; Blewett 2014); integration with other isotopic systems (e.g. O, S, Sr, Pb) to better identify and trace geological processes; dating deposition of TOS and BOS samples to better grasp the temporal relationship between the two horizons and across the landscape. Other ideas and collaborative proposals are always welcome. The archive splits of all samples are potentially available for significant novel applications with potential for major breakthroughs (contact corresponding author for further details).

Conclusions

The National Geochemical Survey of Australia (NGSA) was conducted between 2007 and 2011 as part of the Australian Government’s energy security programme. It bridged a vast gap in our understanding of the composition of the Australian regolith by applying an ultra-low density sampling strategy making use of Nature’s mixing and deposition of weathering rock and soil materials in catchments (catchment outlet sediments, similar in most cases to overbank or floodplain sediments). Ultimately, the well-documented survey covered 6.174 million km$^2$ or c. 81% of Australia at the average density of 1 site per c. 5200 km$^2$ and applied a comprehensive analytical protocol including up to three different chemical digestion methods to four samples per site (two depths and two grain-size fractions per site). After a data quality assessment determined the fitness-for-purpose of the resulting analytical data, an extensive dataset and geochemical atlas comprised of 529 geochemical maps were released on time at the end of the project (http://www.ga.gov.au/ngsa).

The NGSA data have since been used in a number of geoscientific applications, reviewed briefly above, ultimately advancing our understanding of the composition of the regolith cover in Australia. This enhanced understanding of the surface and shallow regolith and its relationship to basement is especially critical in underexplored (‘greenfield’) areas of thick and/or transported cover, where some of Australia’s future resource wealth may be found. It is believed that the NGSA is well on track to achieving its aim of contributing to improving exploration for energy and mineral resources through the pre-competitive delivery of a new spatial layer of compositional data and information. The high-dimensional compositional dataset is proving extremely rich in information about the regolith and processes that control its composition, and is likely to deliver new knowledge for some time into the future.

Acknowledgements and Funding

The National Geochemical Survey of Australia was made possible through the Onshore Energy Security Program initiated and funded by the Australian Government. Collaborative arrangements were established with the geoscience agencies of all Australian States and the NT through National Geoscience Agreements. These agencies were instrumental in accessing all sampling sites and collecting the samples in a timely fashion. The authors would like to thank all land owners for granting access to the NGSA teams for the purpose of collecting samples. We are extremely grateful to the NGSA laboratory staff members at Geoscience Australia for their assistance in preparing and analysing all these samples. SGS Minerals Services are acknowledged for providing the MMI® analyses for the project as part of a collaborative arrangement with Geoscience Australia. Published with permission from the Chief Executive Officer, Geoscience Australia.

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