Article

The Heavy Mineral Map of Australia: Vision and Pilot Project

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Abstract: We describe a vision for a national-scale heavy mineral (HM) map generated through automated mineralogical identification and quantification of HMs contained in floodplain sediments from large catchments covering most of Australia. The composition of the sediments reflects the dominant rock types in each catchment, with the generally resistant HMs largely preserving the mineralogical fingerprint of their host protoliths through the weathering-transport-deposition cycle. Heavy mineral presence/absence, absolute and relative abundance, and co-occurrence are metrics useful to map, discover and interpret catchment lithotype(s), geodynamic setting, magmatism, metamorphic grade, alteration or mineralization. Underpinning this vision is a pilot project, focusing on a subset of the national sediment sample archive, which is used to demonstrate the feasibility of the larger, national-scale project. We preview a bespoke, cloud-based mineral network analysis (MNA) tool to visualize, explore and discover relationships between HMs as well as between them and geological setting or mineral deposits. We envisage that the Heavy Mineral Map of Australia and MNA tool will contribute significantly to mineral prospectivity analysis and modeling here, particularly for technology critical elements and their host minerals, which are central to the global economy transitioning to a more sustainable, decarbonized paradigm.

Keywords: heavy minerals atlas; heavy mineral maps; National Geochemical Survey of Australia; mineral network analysis; geological setting; mineral system; mineral prospectivity; critical minerals; critical elements

1. Introduction

Heavy minerals (HMs), i.e., those with a specific gravity greater than 2.9 g/cm^3 (e.g., zircon, rutile, phosphates, spinels and oxides; see Table S1 in Supplementary Material), occur in low abundance in primary igneous and metamorphic rocks [1]. Due to their relative resistance to physical and chemical weathering, HMs can persist in the sedimentary rock record, where they can be used to determine sedimentary provenance [2]. Similarly, HMs that occur in unconsolidated sediments collected from modern catchments (watersheds) may be the only proxies available for subsurface geology where regolith cover is widespread. The presence or absence of particular HMs, and the relative makeup of the HM assemblages or their concentrations and distributions, can be indicative of geological processes including volcanism, metamorphism, alteration, weathering and mineralization [1]. For example, co-occurring augite, chrome-spinel, and olivine may indicate a mafic igneous origin; co-occurring garnet, staurolite, and kyanite may indicate a metamorphic source; and presence of gahnite may indicate high-grade metamorphism of zinc mineralization [3]. Thus, particular HMs can be termed *indicator minerals*. Moreover, HMs are common hosts for *technology critical elements*, e.g., pegmatite and carbonatite minerals hosting rare earth elements (REEs) [4]. These particular HMs, termed *technology critical minerals*, essential for a clean (decarbonized) energy future, are used in, e.g., photovoltaic panels, batteries and wind turbines [5-7]. Where HMs incorporate elements with stable

and radiogenic isotopes into their crystal lattice, they can be analysed using in-situ geo-chemistry/geochronology techniques in order to aid interpretation of the temporal and petrogenetic evolution of the continental crust.

Heavy minerals are used widely by the minerals and petroleum industry in upstream exploration. In the petroleum industry, HM suites are used to correlate continental strati-graphic successions where there can be a lack of biostratigraphic control [8]. Heavy minerals also are used widely in mineral exploration targeting due to their ability to indicate the original formation environments and changes in rock chemistry induced by mantle metasomatism, magmatic crystallization, hydrothermal alteration and mineralization. Published studies of successful mineral exploration-oriented applications of indicator mineral techniques apply to gold (Au), diamonds, mineral sands, nickel-copper, platinum group elements, volcanogenic massive sulfides, non-sulfide zinc, porphyry copper-mo-lybdenum, uranium, tin-tungsten, and REE mineralization (e.g., [9-18]. A recent summary of successes using indicator minerals with soil (till) geochemistry in the Canadian Cordil-lera is given by Mao et al. (2017) [18] and references therein.

In addition to relative and absolute abundances of indicator minerals in the HM frac-tion, the trace element chemistry of particular indicator minerals can be useful for dis-criminating between barren and mineralized rocks, and vectoring towards mineralization using rapid analytical methods such as in-situ electron, proton and laser microprobe tech-niques. For example, arsenic (As) in pyrite is a proxy for Au in many deposits [19], and REE patterns in apatite can record the hydrothermal evolution of iron-oxide copper gold deposits [20]. Sophisticated statistical methods have been applied to suites of trace ele-ments in indicator minerals data to distinguish fertile (mineralized) from barren (unmin-eralized) formation environments (e.g., [21-25]. Furthermore, in-situ age dating of HMs containing radiogenic isotopes using, e.g., sensitive high-resolution ion microprobe (SHRIMP) or laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) can lead to establishing precise geochronological and petrogenetic frameworks in detailed investigations, e.g., dating of detrital cassiterite formation relative to adjacent granite, see McInnes (2019) [26].

The provision of occurrence maps and chemistry data for HMs from sediment catch-ments and mineral districts in Canada is viewed by industry as a valuable pre-competitive geoscience dataset, and indicator minerals have contributed to the discovery of new min-eral deposits [27-29]. The exploration industry in Australia carries out proprietary HM surveys at both tenement and regional scales, with a focus on specific commodities (e.g., DeBeers collected 830,000 HM samples across Australia during a 1990's diamond explo-ration campaign), however there has been limited release of HM datasets by publicly funded research agencies or universities [30].

No country, let alone continent, has, to our knowledge, maps and datasets of the dis-tribution of HMs available at the regional scale (over tens of thousands to millions of square km) to enhance geoscience insight and guide mineral exploration. For instance HM (and other mineralogy) datasets can be used in the creation of mineral prospectivity mod-els in addition to the traditional geochemistry, geophysics, and geology datasets (e.g., [31]. The present communication articulates a vision for a HM map of Australia and explores the feasibility of providing such as a pre-competitive asset for promoting new exploration investment in Australia. It does this by quantifying the modal abundances of HMs in a limited number of samples obtained from the National Geochemical Survey of Australia (NGSA; www.ga.gov.au/ngsa; Caritat & Cooper [32]), a unique archive of catchment sed-iments collected on a continental scale (Figure 1). Thus the opportunity identified here, as exploration in areas under cover intensifies, is to analyze the HMs from the sedimentary cover as a novel 'window' to bedrock geology and events/processes such as metamor-phism, magmatism, alteration and mineralization.

This papers accordingly aims to test the following:
1. Are the NGSA samples appropriate for HM identification and quantification using automated mineralogy technologies?
2. Can the bulk samples be used or must the HM fraction be physically separated first?

3. Is there sufficient mineralogical diversity in the HM assemblages of a few random samples to predict the discovery of varied and informative HM patterns at the national scale?
4. Are those preliminary observations on HM extracted from alluvial sediments broadly compatible with the geology of their respective catchment areas?
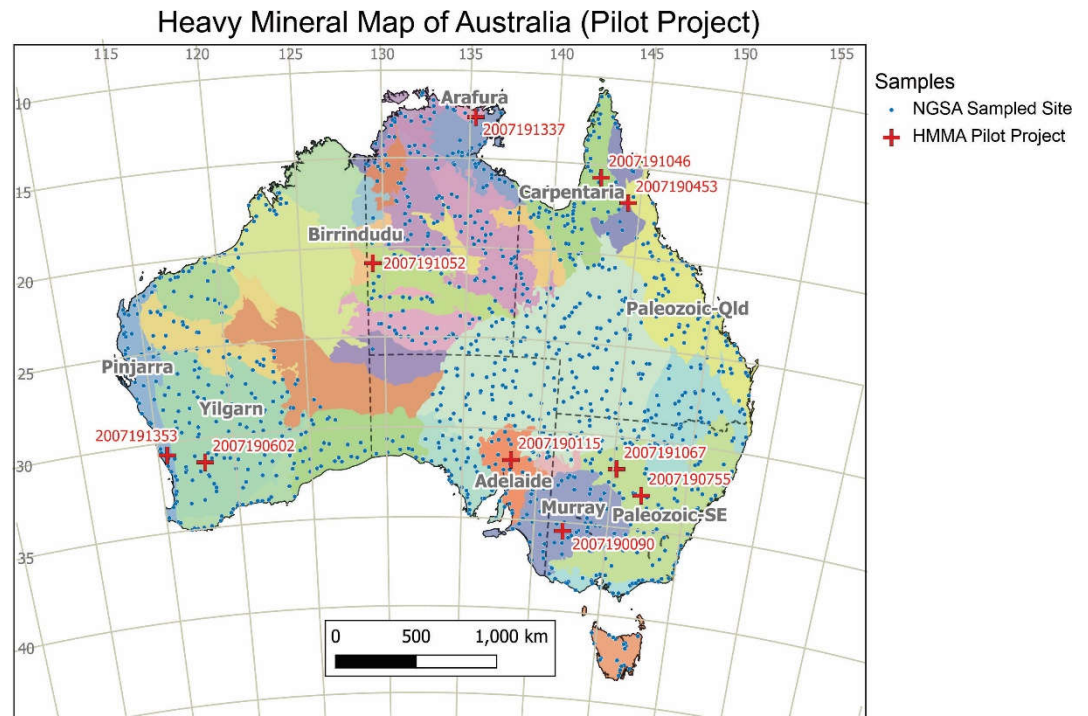
Figure 1. Distribution of NGSA sample sites (blue), including the 10 pilot project sites discussed herein and identified by sample ID (red), overlain on Australia's geological regions (variable colors; [33]). Relevant geological regions are labelled. Map projection: Albers equal area.

2. Materials and Methods

The selection, preparation and analysis of NGSA samples for the present study are detailed in the Supplementary Material. Briefly, 10 NGSA top outlet sediment (TOS) samples (depth 0-10 cm) were selected across the country, dried sieved to the fraction 75-430 μm, and either mounted 'as is' (whole rock or 'WR' samples) or after heavy mineral separation by dense fluids (heavy mineral concentrates or 'H' samples) on resin mounts. These mounts were then polished, carbon coated, and subjected to automated mineralogy identification and quantification using a TESCAN® Integrated Mineral Analyzer (TIMA) scanning electron microscope-energy dispersive spectrometer (SEM-EDS) at the John de Laeter Centre (JdLC) at Curtin University. Please refer to the Supplementary Material for more information.

3. Results and Discussion

3.1. Pilot project

The pilot project on 10 NGSA samples across the country delivered both whole rock (prefix WR) and HM concentrate (prefix H) data for over 50 different minerals (Figure 2 and Tables S2 and S3 in Supplementary Material). The WR samples are dominated by quartz (50 to 97 vol%) and matrix silicates (feldspars, clay minerals), rendering them unsuitable to precise and sensitive HM quantification. The HM concentrates, conversely, are generally dominated by dense minerals, including ilmenite (median concentration across all samples = 25.3 vol%), rutile (14.2), zircon (12.7), schorl-dravite (Fe-Mg sodium tourmaline; 1.59), hematite/magnetite (1.18), pyrite (1.06), pseudorutile/leucoxene (0.61), uvite-feruvite (Mg-Fe calcium tourmaline; 0.70), pumpellyite (0.70), monazite (0.53), followed
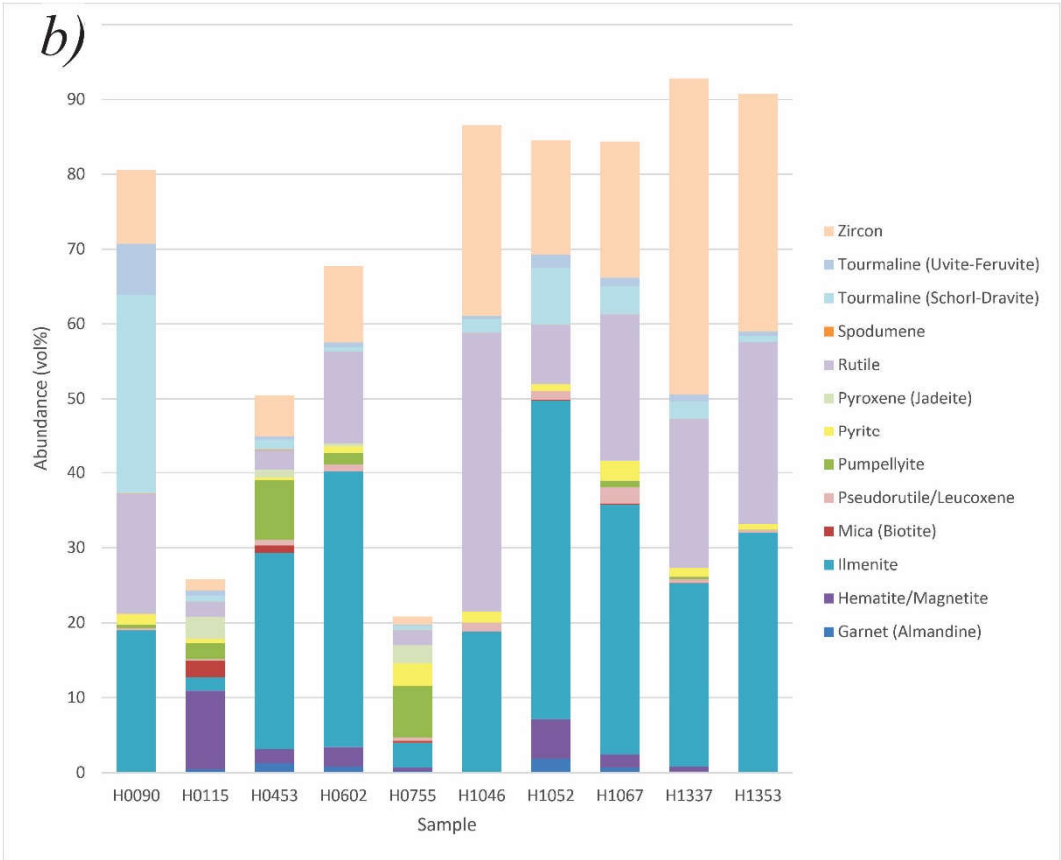
by minor (<0.5 vol%) punkaruaivite, garnet, micas, xenotime, chromite, spodumene, etc., and traces (<0.01 vol%) of various other HMs. Thus, we recommend that HMs be separated and concentrated prior to meaningful and useful identification and quantification. The HMs identified in this pilot project indicate that a diversity of HMs are present, and a variety of HM association are observed across the continent. A national HM map (or, more appropriately, atlas of maps), once generated and made available through a data portal and analyzed with a geographical information systems and/or through mineral network analysis, could reveal a rich, diverse and informative HM ecosystem across the continent. Already, the analyzed samples' HMs show a range of spatial distributions across the continent (Figure 3). Selected individual HM maps are shown in the Supplementary Material.

Figure 2. Stacked bar diagrams of heavy mineral concentrations in whole rock (prefix WR) (a), and heavy mineral fractions (H) (b) of the 10 NGSA samples (identified by last four-digit code). Note that non-dense minerals such as quartz and feldspars are not shown.
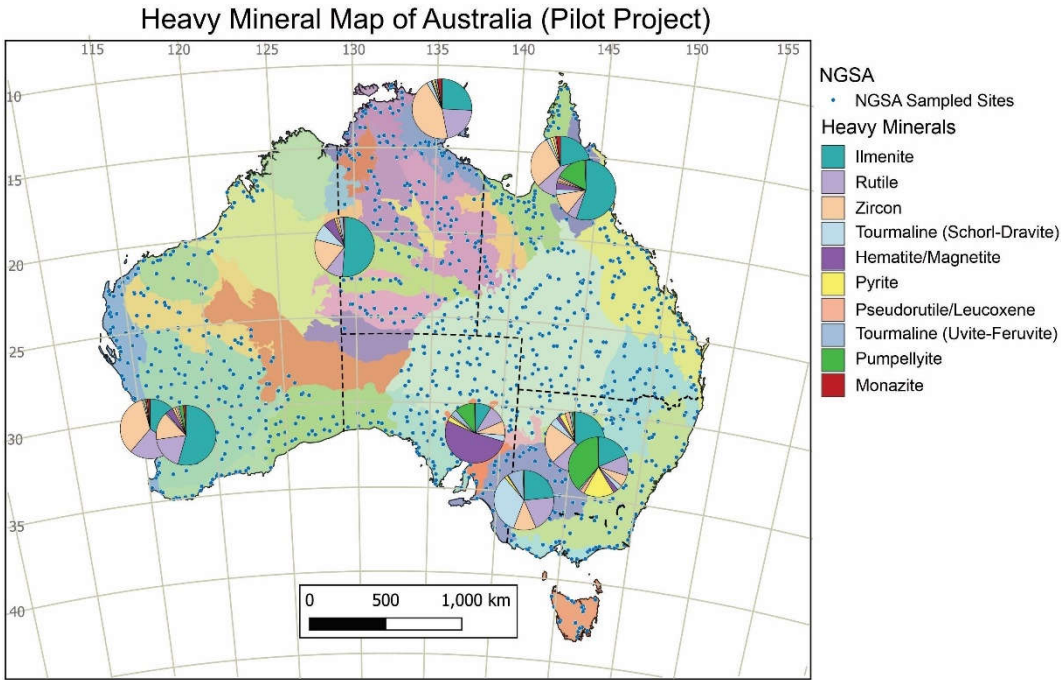

Figure 3. Distribution map of 10 selected HMs in the HM concentrates of the 10 NGSA samples used in the present pilot project (pie charts), overlain on Australia's geological regions (variable colors; [33]). Map projection: Albers equal area.

The ten pilot NGSA locations display a wide range of minerals indicative of diverse geological environments (www.mindat.org): H0090 has the highest spinel concentration (0.46 vol%), a mineral typically indicative of mafic igneous rocks, kimberlite, or pegmatite; H0115 is highest in harkerite (0.22), chlorite (0.28) and hematite/magnetite (10.5), minerals suggesting high-temperature contact metamorphism, low-grade metamorphic rocks, or iron-rich sedimentary or igneous rocks, respectively (thus representing a mixed terrane signature); H0453 is highest in cassiterite (0.16), indicative of medium- to high-temperature hydrothermal veins or alluvial placers; H0602 and H1052 are second highest and highest samples in ilmenite (36.7 and 42.6, respectively), suggestive of igneous rocks or placer deposits; H1046 and H1337 are second highest and highest samples in monazite (1.90 and 2.16, respectively), a mineral typically associated with REEs enrichment; H1337 is also highest in zircon (42.2) whilst H1353 is second highest in zircon (31.8), a mineral suggesting an igneous or metamorphic rock affinity.

Cassiterite is present in only three of the 10 samples (H0453, H0602, H1046), whilst harkerite is present in only five (H0115, H0453, H0602, H0755, H1353), making these two of the most 'specific' indicator minerals of the project. Minerals such as zircon, monazite and ilmenite, conversely, are some of the most 'common' minerals, being found in all 10 samples. Ilmenite is the 'dominant' HM (most abundant of all the recorded HMs) in five of the 10 samples (H453, H602, H1052, H1067, H1353); schorl-dravite is the 'dominant' HM in H0090; hematite/magnetite in H0115; pumpellyite in H0755; rutile in H1046; and zircon in H1337. These observations augur well for a highly diverse and complex mineralogical 'ecosystem' in the Australian regolith, the study of which aims to understand patterns of mineral occurrence and coexistence in the context of their environments [34].

The abundance of HM zircon (vol%) was compared to the concentration of chemical element zirconium (Zr, mg/kg) in the same NGSA samples, as determined by ICP-MS following fusion and nitric + hydrofluoric acid digestion [32]. There is a positive correlation between the two variables, both for WR and HM fraction zircon (Figure 4). Such correlations suggest an integrated mineralogical and geochemical approach to data interpretation may afford new knowledge insights hitherto unavailable due to the datasets not being considered in combination. Although the pilot project data are sparse, these preliminary observations suggest that information pertinent to bedrock can be derived from HM samples distributed across continental Australia. Additional knowledge of sediment transport directions and local geological features will aid in further understanding HM abundances and distributions.
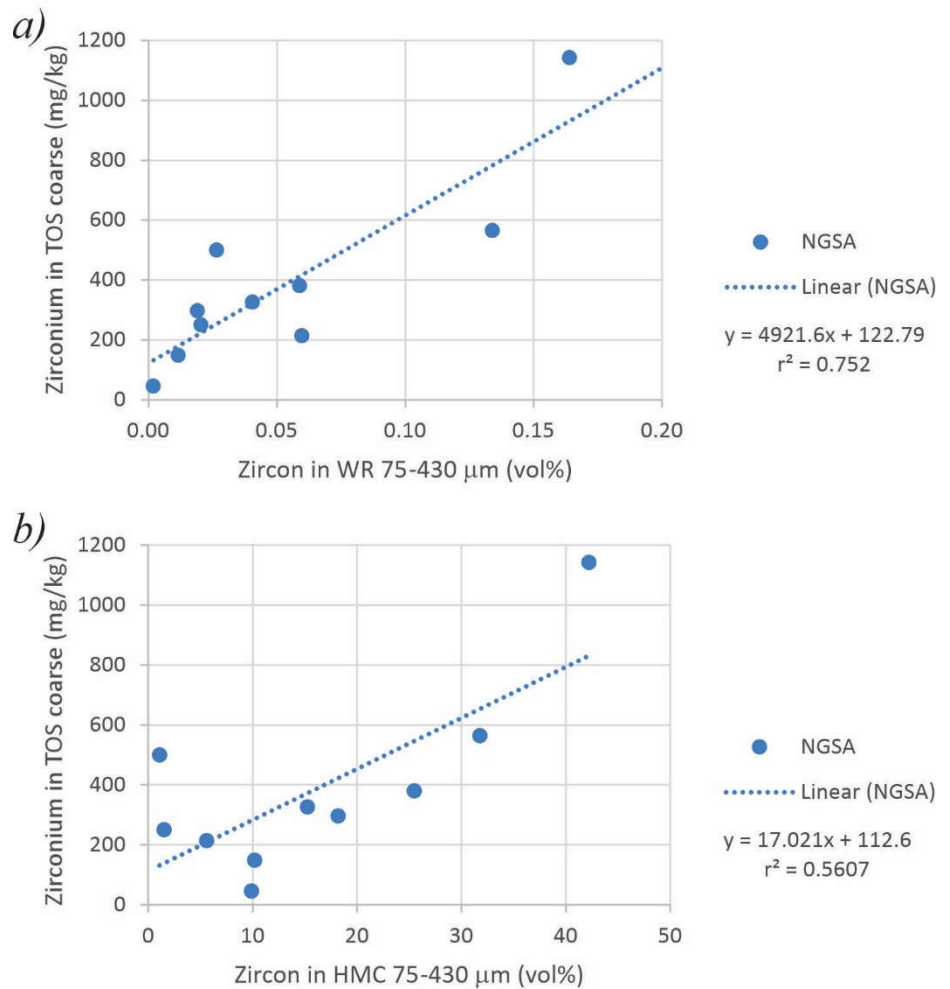
Figure 4. Scatterplots and least-square regressions of Zr in the 10 NGSA TOS coarse (<2 mm) fractions vs zircon concentration in the whole rock (WR) (a) and heavy mineral concentrates (HMC) (b) samples.

Cassiterite (SnO_2) was only recorded in sample #0453. This sample is from northern Queensland in the vicinity of the well-known Herberton/Mount Garnet tin mineralized districts [35]. The catchment it is derived from contains numerous tin mineral occurrences related to Carboniferous igneous rocks [36]. Looking at the geochemistry from the NGSA, this site has the highest total Sn concentration of the ten pilot samples (33.2 mg/kg total Sn vs 3.0 mg/kg or less for the other pilot sites), further supporting the correlation and consistency between mineral and geochemical datasets. In this case the simple presence/absence of a HM is of interest, rather than its abundance, namely that the presence of cassiterite indicates proximity to tin-granite. The local topography suggests erosion and transport of mineralized rocks located up-catchment, i.e., to the southeast of the sample location. As noted earlier, cassiterite is a HM amenable to in-situ U-Pb dating and follow-up geochronology can be used to test hypotheses around cassiterite temporal evolution and provenance [26].

3.2. Mineral network analysis

The automated mineralogy workflow generates large amounts of geospatial mineral mineralogy and chemistry data, the analysis of which requires the application of innovative statistical analysis and visualization techniques such as mineral network analysis (MNA). Network analysis is a subfield of graph theory that provides a dynamic, quantitative, and predictive visualization tool to uncover complex and otherwise hidden higher-

dimensional patterns of diversity and distribution in mineralogical 'big data' [37]. Key parameters that MNA provides for automated mineralogy datasets are:

1. Mineral abundance: every mineral present in a sample is represented by a node (e.g., a circle), the size of which is proportional to the abundance of the mineral within the sample population;
2. Mineral co-occurrence: minerals that co-occur in a sample are linked by edges (links), the length of which is inversely proportional to the number of samples where this pair of minerals co-occurs, and the weight (or thickness) of which is proportional to the number of samples where this pair of minerals co-occurs.

To integrate MNA in our workflow, we have built a bespoke MNA software tool using the 'Shiny' web application framework R package [38]. The Shiny MNA tool, 'MNA for HM', is accessible via the https://geoscienceaustralia.shinyapps.io/mna4hm link. The main purpose of the application is to interactively reveal persistent associations (co-occurrences) of heavy minerals, their spatial distribution, and relations to the first-order geological and geomorphological features such as geological provinces, mineral deposits, topography and hydrological catchments. Visualization of the mineral network, with the mineral dataset filtered or styled based on mineralogical classes (i.e., 'Types'), chemical elemental composition, and typical formation environment guides minimalistic but meaningful mapping of distribution of minerals typomorphic for particular geological environment or mineralization. By default, the mineral network is depicted as interactive force-directed graphs created with Fruchterman-Reingold's algorithm, which represent the distribution of nodes as a dynamic network with balanced spring-like interactions among nodes [39]. The underpinning R packages are 'visNetwork' [40] and 'igraph' [41].

The graphical user interface is illustrated in Figure 5. The top bar menu allows users to toggle between a Network & Map, Data, Options, and About tabs. Filters on the left hand side allow selection of samples by Area and of minerals by Environment, Type, and Element. The nodes can be colored by Mineral type or Mineral environment. A toggle box allows to Hide orphans (minerals not associated with any others, given the selection(s) made), and a slider allows setting of the Co-occurrence to a minimum (default = 1).
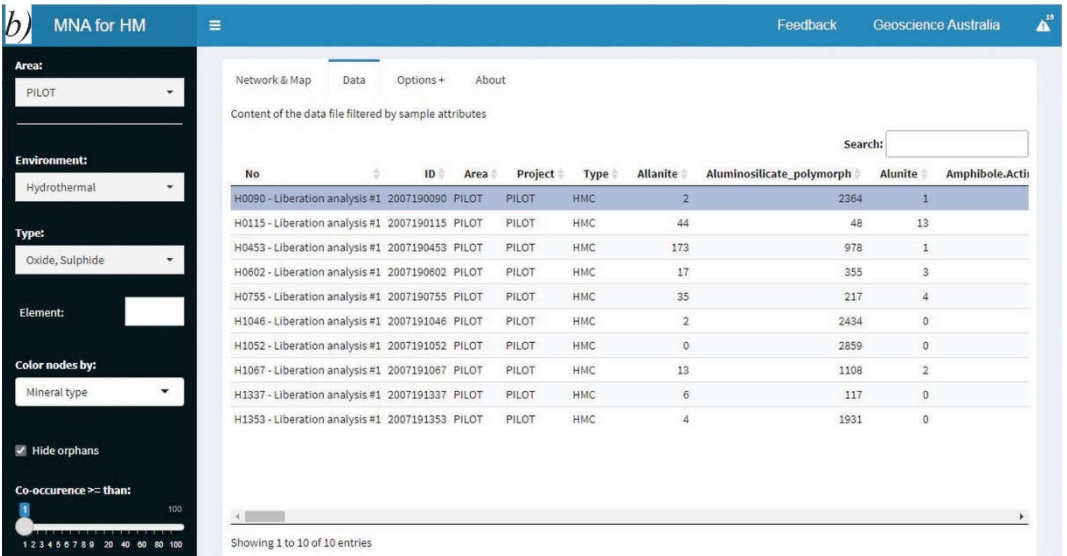
Figure 5. Graphical user interface for the Geoscience Australia MNA cloud-based visualization tool for the pilot project (https://geoscienceaustralia.shinyapps.io/mna4hm) showing the Network & Map (a), and the Data (b) screens.

On the main Network & Map tab (Figure 5a), a mineral network is shown to the left and map to the right. Minerals can be selected by ID and Group on the network, and the map has several layer, mineral selection and chart options. By hovering the cursor over a node, a dialog box appears showing the mineral's name, chemical formula, and count. By hovering the cursor over a vertex, a dialog box appears showing the number of co-occurrences the two linked minerals display in the database. The map on the right shows the location of the samples under consideration; these can include all the samples selected as per above, or a sub-selection by mineral name; the map can display several background layers and represent the points as growing dot/pie, radial by area/radius, or bar charts. A more detailed description of the MNA-HM tool will be provided separately at the end of the main project (see below).

The Data tab (partially displayed in Figure 5b) displays the filtered data underpinning the Network & Map plots. The data table presents the key sample metadata (including sample identifiers and geographical coordinates) and observations for the complete set of the identified minerals (e.g., the grains counts).

The aspiration is that down the track most of this functionality will be built in into Geoscience Australia's data delivery portal (https://portal.ga.gov.au).

4. The Heavy Mineral Map of Australia

The Heavy Mineral Map of Australia (HMMA) project is a collaboration between Geoscience Australia and Curtin University funded under the Australian Government's Exploring for the Future 2020-2024 initiative (https://www.ga.gov.au/eftf). Quantitative mineralogical data and metadata have to-date been acquired for over half of the NGSA sample set. A staged HMMA data release approach is planned with the dataset for a first priority area being launched publicly as early as by end 2022. Whether regionally or nationally, we envisage that 'background' HM maps would be used as a baseline datum from which HM anomalies potentially representing prospective mineral systems, or parts thereof, may be identifiable. By integrating HM maps and datasets into mineral prospectivity modeling, a methodology that leverages large and complex datasets (typically geochemistry, geophysics, and geology) to highlight areas of interest for mineral exploration (e.g., [31,42]), areas of Australia that were previously viewed as having little or no potential for hosting Tier 1-mineral deposits may be identified.

5. Conclusions

We introduce the innovative vision of a continental-scale map (or atlas of maps) of heavy minerals (HMs) in Australian floodplain sediments, the Heavy Mineral Map of Australia (HMMA). A pilot project was developed to test this vision on ten National Geochemical Survey of Australia (NGSA) samples spread around Australia. It has established that:

1. The NGSA samples contain sufficient HMs to allow their identification and quantification using automated mineralogy technologies.
2. The HM fraction must be physically separated from the bulk samples prior to automated mineralogical analysis to enhance detection and sensitivity.
3. The HM assemblages display high mineralogical diversity, foreshadowing the discovery of varied and informative HM patterns at the national scale.
4. The identification and quantification of HMs extracted from alluvial sediments are broadly consistent with the geology and geochemistry of their respective catchment areas.

The data, represented for instance by HM presence/absence (1/0), absolute HM abundance (counts), and HM abundance relative to the HM concentrates or to the bulk sediment samples (vol% or wt%), can be displayed as maps, e.g., using a geographic information system. In addition, the data, represented in terms of co-occurrences this time, can also be manipulated in hyperspace using a cloud-based mineral network analysis (MNA) tool, a prototype of which was developed for the HMMA project. Raw data, maps, and networks, together, provide a powerful environment to uncover mineralogical fingerprints of geodynamic setting, lithotype, magmatism, metamorphic grade, alteration, weathering, or mineralization.

The HMMA project is well underway, with a first data release planned for late 2022. After its full completion in 2024, it is hoped that the new quantitative HM mineralogy will be useful as an input to mineral prospectivity modeling, and that this will enhance mineral discovery, particularly of technology critical elements and minerals, so fundamental to the transition to a more environmentally sustainable, low-carbon economy.

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