Heavy mineral exploration on a continental scale: The Geoscience Australia – Curtin University Heavy Mineral Map of Australia project

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SUMMARY

Heavy mineral techniques have been successfully used as exploration vectors to ore deposits around the world. However, heavy mineral exploration case studies and pre-competitive datasets relevant to Australian conditions are relatively limited. The Heavy Mineral Map of Australia (HMMA) project, part of Geoscience Australia's Exploring for the Future program, is addressing this gap by determining the abundance and distribution of heavy minerals (specific gravity >2.9 g/cm^3) in 1,315 floodplain sediment samples obtained from Geoscience Australia's National Geochemical Survey of Australia (NGSA) project. Archived NGSA samples from floodplain landforms were sub-sampled and subjected to dense media separation and automated mineralogy assay using SEM-EDS analysis.

A stage 1 data package released in July 2022 contained mineralogical assay data for 234 samples from the Darling–Curnamona–Delamerian (DCD) region of south-eastern Australia. A stage 2 data package for 188 samples within the Barkly-Isa-Georgetown (BIG) region of north-eastern Australia was released in December 2022.

The massive number of mineral observations generated during the project (150 million mineral observations anticipated; 166 unique mineral species identified to date) required development of a novel Mineral Network Analysis (MNA) tool to allow end users to discover, visualise and interpret mineral co-occurrence relationships. The mapping function of the MNA tool can also be used to rapidly search the heavy mineral database for the purpose of exploration targeting. Stage 1 results revealed the co-occurrence of multiple Zn-minerals in drainages surrounding the Broken Hill Pb-Zn deposit. These Zn-minerals (e.g., gahnite (Zn-spinel) and ecandrewsite (Zn-ilmenite)) are interpreted to reflect high-grade metamorphism of base metal mineralisation. Zn-mineral co-occurrences were also observed in locations not associated with known mineralisation, and may represent new exploration opportunities.

Demonstrating the heavy mineral data from both stage 1 and 2 releases using MNA will be the focus of this presentation. Mineral assay data from all 1,315 samples will be publicly released by the end of 2023.

Key words: exploration, indicator minerals, automated mineralogy, network analysis

INTRODUCTION

In young geomorphic terrains (e.g., Cenozoic mountain belts), the heavy mineral budget of drainage sediments is representative of the source protoliths within the catchment area. Exploration for mineral deposits in these areas typically involves the systematic sampling and analysis (geochemical and mineralogical) of drainage sediments. The applicability of these methods in Australia is less well understood due to the variable history of physical and chemical weathering across the continent, as well as the possibility that geomorphic drainage patterns and erosion cycles have evolved significantly over geological time.

The Heavy Mineral Map of Australia (HMMA) project is a joint Geoscience Australia-Curtin University initiative designed to define a heavy mineral baseline for the Australian continent. The starting materials utilized were 1,315 floodplain sediment samples collected from drainage catchments covering ~81% of the Australian continent (Caritat, 2022). A pilot study (Caritat et al., 2022) carried out on a subset of NGSA samples determined that a large volume of the sediments was comprised of quartz and feldspar, minerals which are of minimal diagnostic value in mineral exploration or determining basement geology. The heavy mineral fraction, separated from the bulk sediments using gravity separation techniques, was however found to contain mineral assemblages of potential utility in defining protolith sources and geological processes related to magmatism, metamorphism, metasomatism/alteration and mineralization. The study determined that it was feasible to provide heavy mineral maps of Australia as a new pre-competitive asset of potential interest to industry, government and academic scientists. The derived mineralogy from the HMMA project will provide explorers with a better understanding of background mineral abundances and geoscientists with new insights into the composition and evolution of the Australian crust.

HEAVY MINERAL DATASETS

At the time of submission of this paper, the HMMA project had publicly released heavy mineral baseline data for two areas of central and eastern Australia (Figure 1):

(1) Darling-Curnamona-Delamerian (DCD) area comprises the Darling Basin, the Curnamona Province, and the Delamerian Orogen from 234 NGSA samples collected from Tasmania, Victoria, New South Wales, South Australia and Queensland.
(2) Barkly-Isa-Georgetown (BIG) dataset contains mineralogy information for 188 NGSA samples in Queensland, the Northern Territory and South Australia.

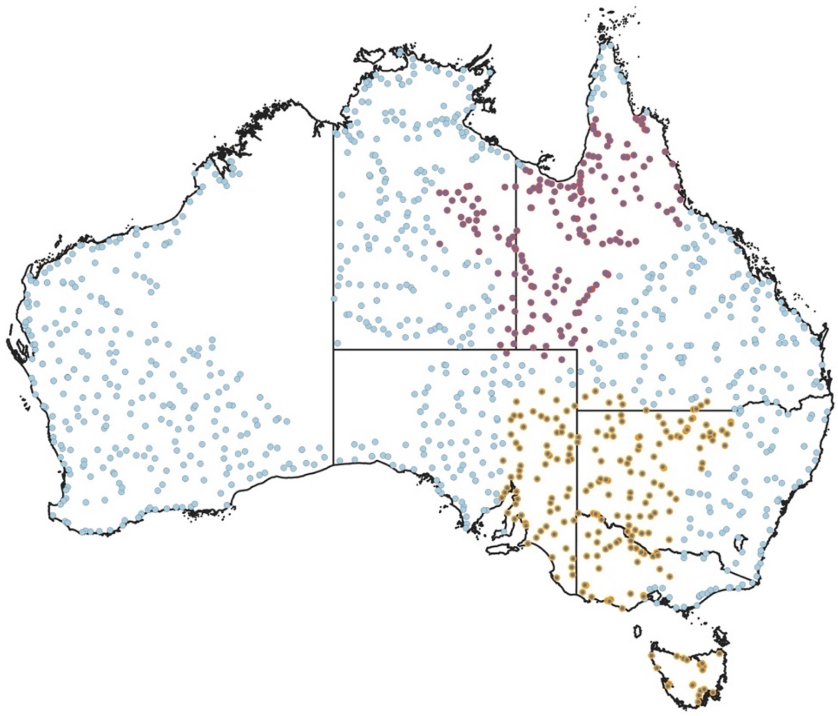

Figure 1: Location of the 1,315 NGSA samples analysed in the Heavy Mineral Map of Australia project. Highlighted in the diagram are samples reported in this study, including the Darling-Curnamona-Delamerian (yellow) and Barkly-Isa-Georgetown (red) areas.

MATERIALS AND METHODS

Samples

Materials selected for HMMA analysis were obtained from splits of the Bottom Outlet Sediment (BOS) samples in the NGSA collection stored at Geoscience Australia in Canberra. The BOS samples were taken, on average, from ~60 to ~80 cm depth in floodplain landforms, and are considered to be materials least likely to have been affected by modern land use practices (e.g., physical disturbances) and anthropogenic inputs (e.g., fertilizers).

Sample preparation and analysis methods

The BOS samples were dried and sieved to a 75-430 µm size fraction before the contained heavy minerals (i.e. those with a specific gravity >2.9 g/cm^3) were extracted using dense media separation and mounted on cylindrical epoxy mounts (Figures 2 and 3). The mounts were then polished, carbon-coated and analysed using automated mineralogy techniques using a TESCAN Integrated Mineral Analysis (TIMA) instrument in the John de Laeter Centre at Curtin University. Analytical outputs include chemical X-ray maps, mineralogical assays and grain maps to enable future detailed microanalysis.

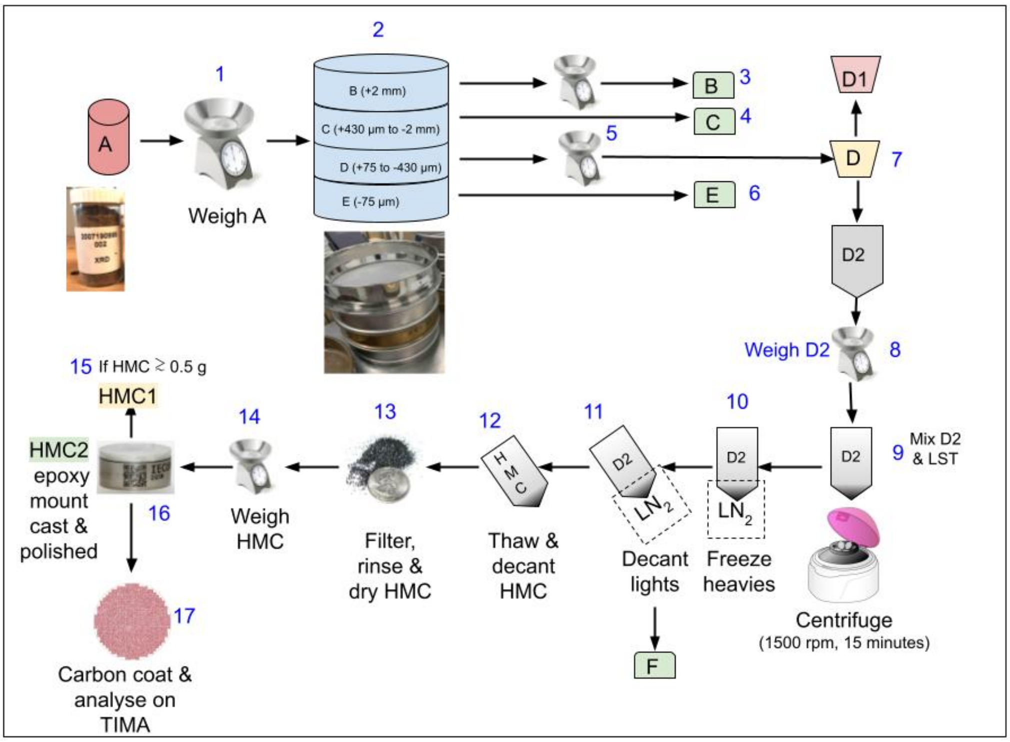

Figure 2. Laboratory method developed for the HMMA project. Initial BOS split is sieved to isolate the +75 to -430 µm diameter fraction (D). A split sample (D2) is mixed with a solution of lithium heteropolytungstate (LST). Mineral grains with specific gravity greater than 2.9 g/cm^3 sink to the bottom of the tube during centrifugation. The heavy mineral concentrate (HMC) located at the bottom of the centrifuge tube is frozen in liquid nitrogen, and the light media portion is decanted. The HMC portion is then thawed, decanted, filtered, rinsed and dried. Dry HMC is poured into the base of a 25 mm diameter circular reservoir containing a U-shaped reference marker. Liquid epoxy is added to the cast and cured to hardness. The HMC-rich surface of the epoxy mount is polished, carbon-coated and then analysed using SEM-EDS techniques on a TIMA automated mineralogy instrument.

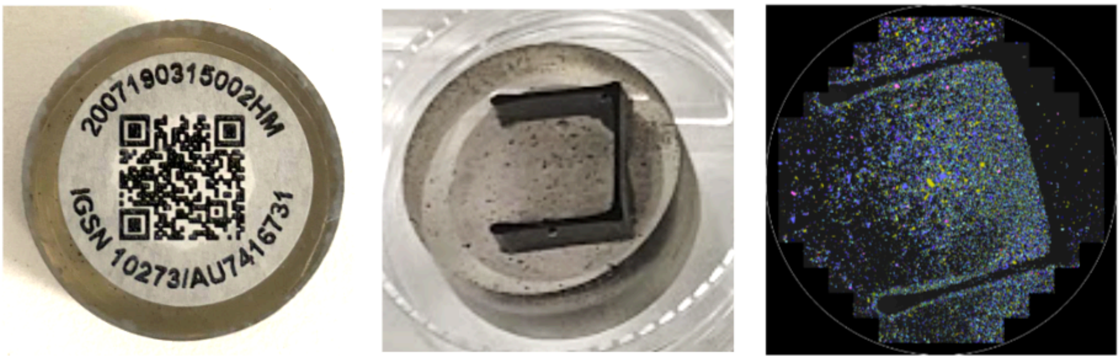

Figure 3. An example of a 25 mm diameter round mount from the HMMA project. (Left) The backing on each round mount contains a QR code linking the sample to the Geoscience Australia data portal where sample location and metadata can be found. (Centre) The obverse side contains a polished surface where naked mineral grains are carbon coated for SEM-EDS analysis. The black U-shaped object within the epoxy is a polymer reference marker. (Right) Coloured mineral map generated using the TIMA automated mineralogy instrument.

Automated Mineralogy Results

The total number of mineral observations in the DCD dataset is ~30.1 million from 234 samples, while the BIG dataset consists of ~18.1 million grains from 188 samples. On average, each 25 mm round mount contains ~115,000 grains (range 6,000-525,000), and therefore the expectation is that the final HMMA dataset will contain more than 150 million mineral observations. There are currently 166 unique minerals identified in the HMMA mineral library.

Mineral Network Analysis

The automated mineralogy methodology used in this project generates large amounts of geospatial mineral chemistry and mineralogy data, the analysis of which requires the application of novel visualization techniques. Mineral network analysis (MNA) has been shown by Morrison et al (2017) to be a dynamic and quantitative tool capable of revealing and visualizing complex patterns of abundance, diversity and distribution in large mineralogical data sets. The HMMA project has its own MNA tool - the *Mineral Network Analysis for Heavy Minerals (MNA for HM)*, which can be found at: https://geoscienceaustralia.shinyapps.io/mna4hm/.

Mineral network graphs take the form of "ball and spoke" shaped models (Figure 4), where the layout of the model provides key information on the relationships between heavy minerals observed in the DCD-BIG dataset (422 samples):

(1) *Mineral abundance:* every mineral present in a sample is represented by a node (represented as balls or circles in Figure 4), with the size of each node proportional to the abundance of the mineral within the sample population, and the colour representing mineral groups (e.g., sulfides in blue). In Figure 4, the most to least abundant sulfide minerals observed are pyrrhotite (276 samples), pyrite (213 samples), chalcopyrite (123 samples), galena (41 samples) and finally bornite (27 samples).

(2) *Mineral co-occurrence:* minerals that co-occur in a single sample are linked by connectors (represented as straight lines in Figure 4), whose line thickness is proportional to the number of samples where the minerals are found to co-occur. In Figure 4, the pyrite-pyrrhotite pair co-occurs in 168 samples, whereas the pyrite-galena pair only co-occurs in 27 samples.

(3) *Mineral exclusivity:* node proximity and connectiveness is a reflection of the exclusivity of a mineral co-occurrence. An example of an exclusive mineral relationship in Figure 4 is the bornite-pyrrhotite pairing. Bornite does not co-exist with any other sulfide mineral in the network. Another observation that can be made is that no sample contains both galena and chalcopyrite because of the lack of a connector between them.

The *MNA for HM* tool also allows the user to locate on a map where samples with specific mineral (co-)occurrences are located. For example, Figure 4 displays the locations of 80 samples containing the chalcopyrite-pyrite-pyrrhotite assemblage, along with a breakdown on relative mineral abundances in each sample.

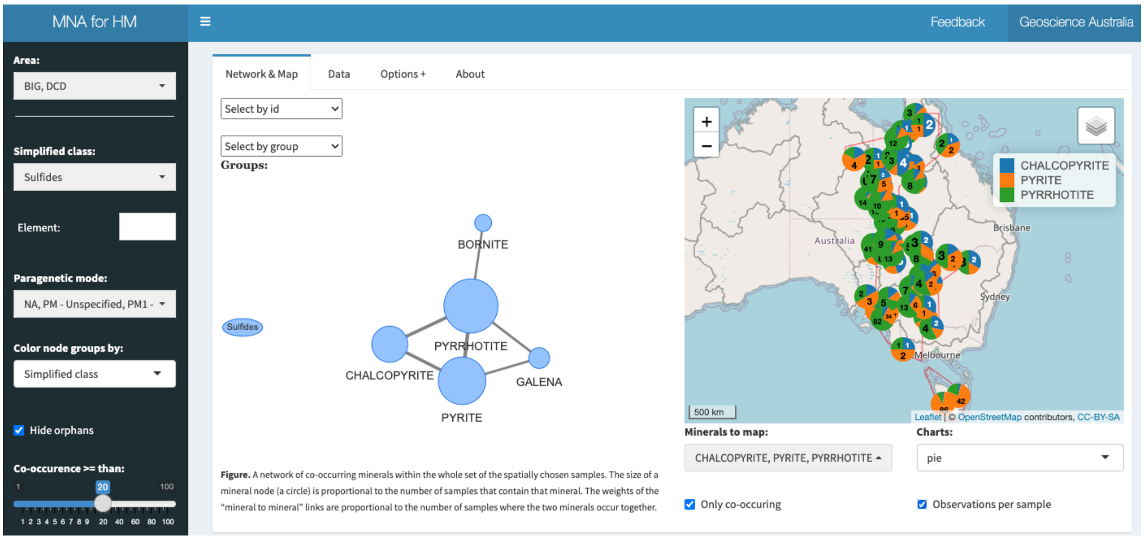

Figure 4. An example of how the *Mineral Network Analysis for Heavy Minerals* tool can be used to interrogate the 48.2 million minerals observed in the BIG-DCD datasets. The ball and spoke image at centre left shows the mineral network for all sulfide minerals that co-occur in more than 20 samples. The most abundant sulfide minerals present are pyrrhotite>pyrite>chalcopyrite>galena>bornite. The map image at right shows the location of the 80 samples where chalcopyrite, pyrrhotite and pyrite co-occur. The mineral abundance data can be displayed in pie-chart form, with the numbers within the pie slice indicating the number of times a mineral is observed in each sample.

IMPLICATIONS FOR MINERAL EXPLORATION

HMMA mineral data is available to the exploration geosciences community as pre-competitive data:

(1) DCD HMMA data release: http://dx.doi.org/10.11636/Record.2022.031
(2) BIG HMMA data release: http://dx.doi.org/10.11636/Record.2022.043

Although not an exhaustive list at this stage of the project, the detrital minerals observed in the released HMMA data that may have been derived originally from hard rock base and precious metal mineralisation include:

- *Sulfides*: arsenopyrite, bornite, chalcocite, chalcopyrite, covellite, galena, molybdenite, pentlandite, pyrite, pyrrhotite and sphalerite.
- *Oxides*: cuprite, ecandrewsite, ferrohogbomite, gahnite, lewisite, sweetite, zincochromite and zincohogbomite.
- *Carbonates*: aurichalcite, rosasite
- *Halides*: simonkolleite
- *Phosphates*: plumbogummite
- *Silicates*: willemite, zincostaurolite
- *Alloys*: tongxinite

Zinc mineral networks

The Curnamona Province and the Delamerian Orogen host significant Zn-Pb deposits within metamorphic sedimentary rocks (O'Brien et al., 2015; Tott et al. 2019). The *MNA for HM* tool was configured to search for the network of minerals containing Zn in the BIG-DCD dataset (Figure 5). Gahnite was the most commonly observed Zn mineral, found in 312 of the 422 samples, an unexpectedly high rate of occurrence (74%). Ecandrewsite was found in only 21 samples (5%), with almost half of these occurrences in the vicinity of the Broken Hill (Figure 5), the type locality for ecandrewsite (Birch et al., 1988). Similar co-relationships are observed for gahnite-zincochromite, gahnite-zincostaurolite and gahnite-tongxinite pairs in the Broken Hill area.

In regard to the Delamerian, observations of elevated gahnite concentrations in drainages near Victor Harbour may have some affinity to the mineralisation styles at Pb-Zn-Ag deposits (e.g., Wheal Ellen, Angas, Strathalbyn and St. Ives) in the metamorphosed siliciclastic sediments of the Kanmantoo Group (Tott et al., 2019).

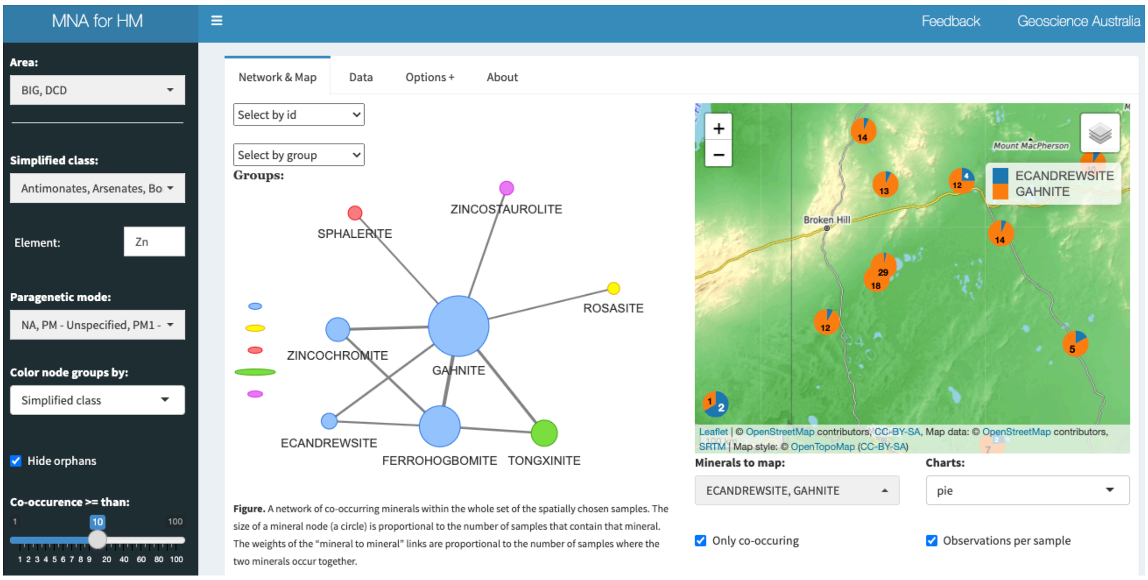

Figure 5. The world-class Broken Hill Pb-Zn-Ag deposit and numerous other base metal occurrences nearby are hosted in highly deformed and metamorphosed rocks. Gahnite ($ZnAl_2O_4$) and ecandrewsite ($ZnTiO_3$) are commonly found to co-occur in drainage networks surrounding Broken Hill, presumably reflecting relative proximity to original hard rock ores.

Tonxginite

An unexpected finding was the occurrence in ~14% of the samples of the base metal alloy tongxinite (Cu_2Zn), which co-occurs most often with cuprite (Cu_2O) in ~6% of samples (Figure 6). Concern was initially raised that the alloy phase may have been introduced as a contaminant during the sampling or sample processing stages, however no brass tools or fittings were used at any stage prior to analysis. Tongxinite has been reported in the Chinese literature to be found in base metal deposits in China since the 1990's (Mindat 2022 and references therein), along with one conference report as a heavy mineral found in sluicing operations in Finland (Tuiska and Pekka, 2010). From an exploration vectoring perspective, the presence of tongxinite in Australian drainages is significant because it has the highest implied density (8.29 g/cm^3; Webmineral 2022) of any of the 166 heavy minerals identified in the HMMA project.

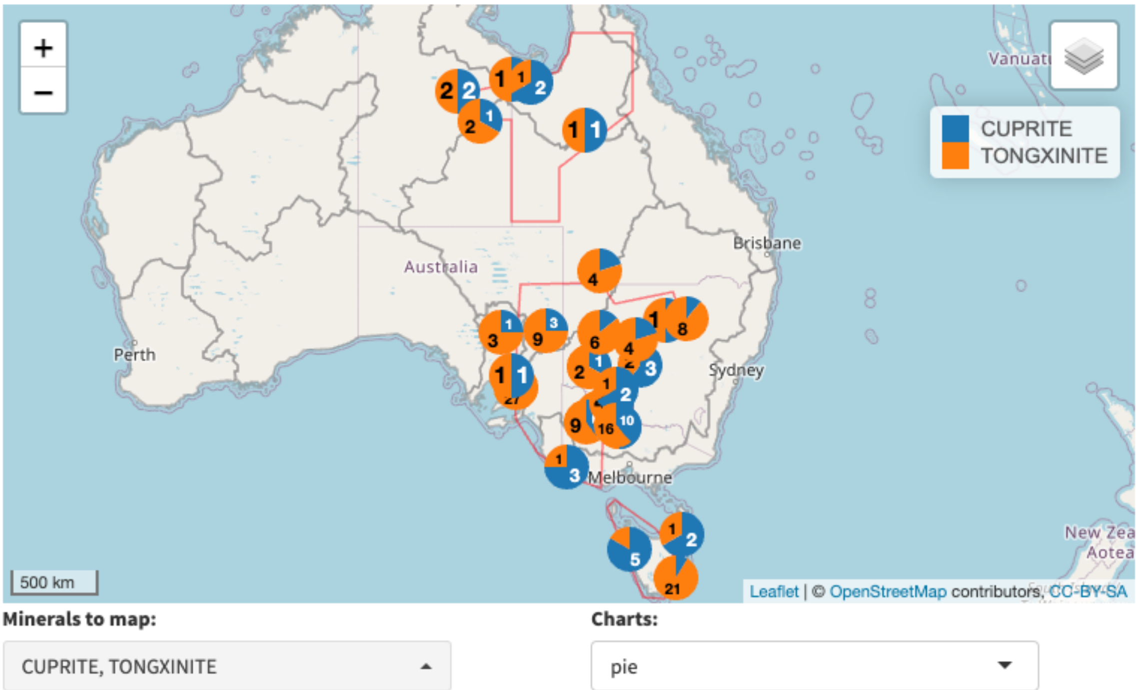

Figure 6. A map of co-occurring tongxinite (Cu_2Zn) and cuprite (CuO) in HMMA samples.

CONCLUSIONS

No country, let alone continent, has pre-competitive datasets that provide data about the baseline distribution of heavy minerals at a regional scale. The Heavy Mineral Map of Australia project is working to achieve this milestone by the end of 2023. The HMMA dataset, projected to reach 150 million mineral observations by the end of 2023, constitutes mineralogical "big data". The generated results include: presence/absence of HMs, absolute HM abundances (observations), and HM abundance relative to the mass of bulk sediment analysed (vol% or wt%). HM abundances can be displayed as maps using the Geoscience Australia portal or downloaded for detailed analysis and visualization using custom techniques.

The project is also demonstrating the utility of applying mineral network analysis (MNA) to the investigation of mineral co-occurrences, and how equilibrium mineral assemblages in metamorphosed base metal ores (e.g., gahnite-ecandrewsite-zincostaurolite) are reflected in adjacent catchments. The MNA for HM tool is freely available to the research community as an online resource.

The presence of detrital tongxinite is noted for the first time in Australia, although the significance of this observation in mineral exploration requires further study. It is hoped that the new quantitative HM mineralogy will be a useful input to exploration geoscience, and lead to more efficient mineral discovery in Australia.

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