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Heavy mineral exploration on the continental scale

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INTRODUCTION

Heavy minerals (HMs) (i.e. minerals with a density greater than ~2.9 g/cm^3) are widely used by mineral explorers and researchers in upstream exploration and geological provenance studies (e.g. Averill 2001; McClenaghan et al. 2016; Salama et al. 2016). Some HMs, referred to as 'indicator' minerals, can be indicative of specific environments of formation or processes such as hydrothermal alteration and mineralisation (e.g. Nowicki et al. 2007; McClenaghan et al. 2014; Mao et al. 2017). The use of HMs in mineral exploration typically involves the systematic sampling and analysis (geochemical and mineralogical) of drainage sediments, however the applicability of these methods in Australia is poorly understood due to the variable and, in places, protracted 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 (Pillans 2007; Pain et al. 2012).

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 1315 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 National Geochemical Survey of Australia (NGSA) samples determined that the largest volumetric component of the sediments was quartz and feldspar group 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 found to contain mineral assemblages of potential utility in defining protolith sources and geological processes related to magmatism, metamorphism, metasomatism/alteration, and mineralization. The Caritat et al. (2022) study determined that it was feasible to generate heavy mineral maps of Australia (HMMA) as a new pre-competitive asset of potential interest to industry, government, and academic researchers. 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.

MATERIALS AND METHODS

The samples analyzed in the HMMA were collected as part of Geoscience Australia's National Geochemical Survey of Australia (NGSA) using the sampling methodology of Lech et al. (2007). The NGSA sample collection comprises a total of 1315 samples (including field duplicates) of catchment outlet sediments collected from 1186 catchments across Australia, with a sampling density of 1 sample per approximately 5200 km^2. Catchment outlet sediments are deposited outside riverbanks as floodwaters recede and may be modified by aeolian processes following deposition (Caritat 2022). The HMMA utilizes splits of the bottom outlet sediments (BOS) collected at each sampling site; BOS samples were taken at an average of ~60–80 cm depth in floodplain landforms, and are well-mixed, fine-grained composites of major soil and rock types present in the upstream catchment(s), unaffected by post-depositional anthropogenic inputs (Caritat 2022).

The 1315 BOS samples were processed and analyzed at the John de Laeter Centre at Curtin University following the processing and analytical methods described in Walker et al. (in prep.; Fig. 1). The samples, ranging in mass from approximately 17–1000 g, were dried and sieved to extract the 75–425 µm grain size fraction, from which a novel heavy mineral extraction process featuring liquid nitrogen and centrifugation was used to extract contained heavy minerals (density ~>2.9 g/cm^3) (Walker et al. in prep; Caritat et al. 2023). The resulting heavy mineral concentrates (HMC) were fixed in cylindrical 25 mm epoxy mounts with embedded 3-sided plastic templates for sample navigation purposes and a label featuring sample identity details plus a scannable QR code. Where an HMC produced for a sample exceeded ~0.5 g, the HMC was riffle split into HMC1 and HMC2, with the former archived; where the mass of HMC2 still exceeded that necessary for mounting, the 'cone and quarter' method was used to generate a representative subsample with the remainder archived. All of the mounts were polished and carbon coated prior to analysis by electron microscopy.

Automated mineralogical analysis of each mounted sample was completed using the TESCAN Integrated Mineral Analyzer (TIMA) in the John de Laeter Centre at Curtin University. The TIMA comprises four fully integrated silicon drift Energy Dispersive Spectroscopy (EDS) X-ray detectors linked to a TESCAN MIRA field emission gun (FEG) platform. It is optimized for high data throughput and utilizes combined backscattered electron (BSE) and energy dispersive spectrometry (EDS) inputs to rapidly identify sample mineralogy.

continued on page 6

Heavy mineral exploration on the continental scale

continued from page 1

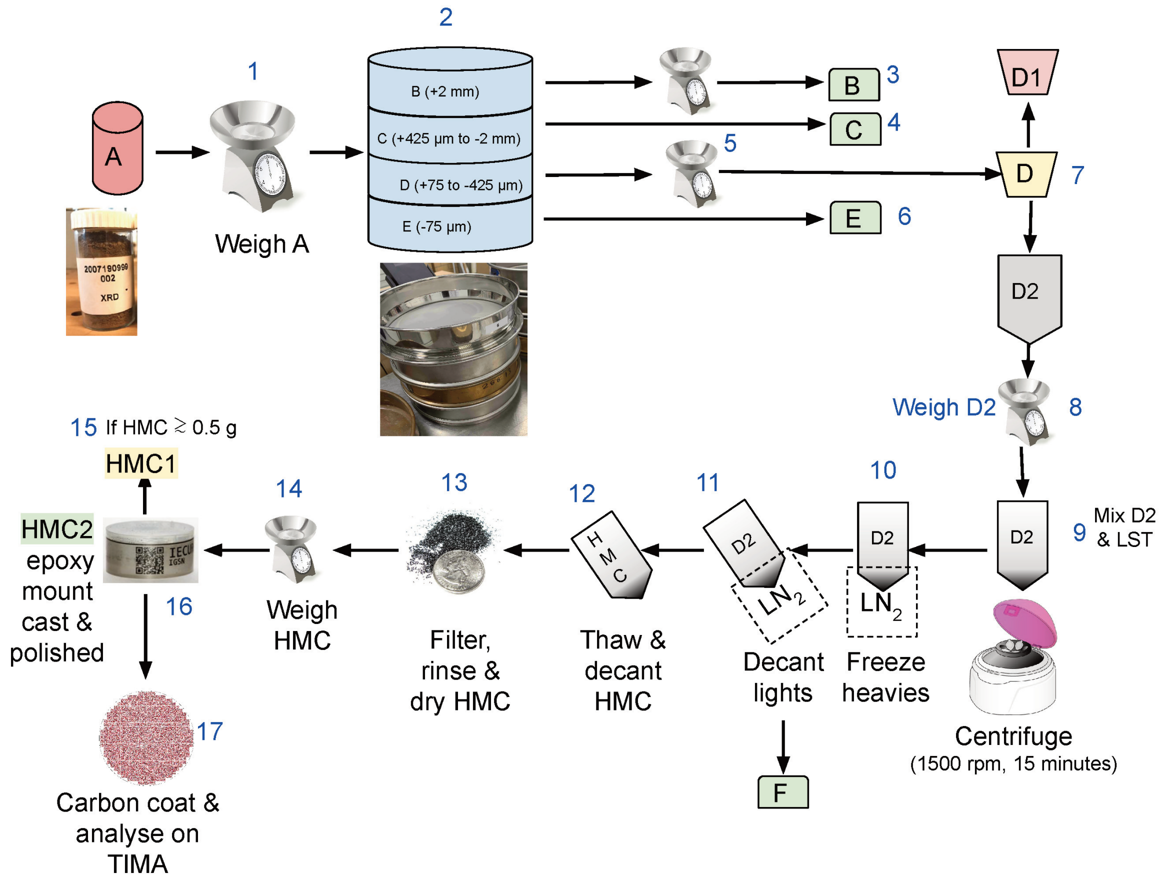

Fig 1. The sample preparation workflow for samples collected and processed for the Heavy Mineral Map of Australia (HMMA).

RESULTS

Automated mineralogical analysis of the HMMA sample set has identified approximately 160 unique mineral phases within Australian regolith and generated more than 140 million unique mineral observations. An 'observation' is defined as a monomineralic phase occurring either as a single liberated 'grain' by the TIMA, or a part of a polymineralic particle (e.g. an inclusion or a composite rock fragment) (Caritat et al. 2023). Most of these phases are unique Integrated Mineral Analyzer (IMA)-recognized minerals although several entries diverge from the IMA vocabulary. This divergence is typically due to factors such as the presence of mineral solid solutions or minerals with identical chemical compositions (e.g. the aluminosilicate polymorphs—kyanite, andalusite, and sillimanite).

Although not an exhaustive list, the detrital minerals observed in the released HMMA data that may have been derived originally from hard-rock base and precious metal mineralization include the following:

- Sulphides: arsenopyrite, bornite, chalcocite, chalcopyrite, covellite, galena, molybdenite, pentlandite, pyrite, pyrrhotite, and sphalerite;
- Oxides: cuprite, ecandrewsite, gahnite, sweetite, and zincohögbomite;
- Carbonates: aurichalcite/zincrosasite;
- Halides: simonkolleite;
- Phosphates: plumbogummite;
- Silicates: willemite, zincostaurolite;
- Alloys and Native Metals: tongxinite, gold, and platinum.

continued on page 8

***Note:** This EXPLORE article has been extracted from the original EXPLORE Newsletter. Therefore, page numbers may not be continuous and any advertisement has been masked.*

Heavy mineral exploration on the continental scale

continued from page 6

The heavy mineral (HM) dataset (various formats) and a comprehensive heavy mineral atlas of Australia are available and free to download as part of the HMMA final report (Caritat et al. 2023).

MINERAL NETWORK ANALYSIS

The large and multi-dimensional nature of the HMMA dataset encourages the application of novel analysis and 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 led to the development of its own bespoke MNA tool, the Mineral Network Analysis for Heavy Minerals (MNA for HM), which can be freely accessed at https://geoscienceaustralia.shinyapps.io/mna4hm/.

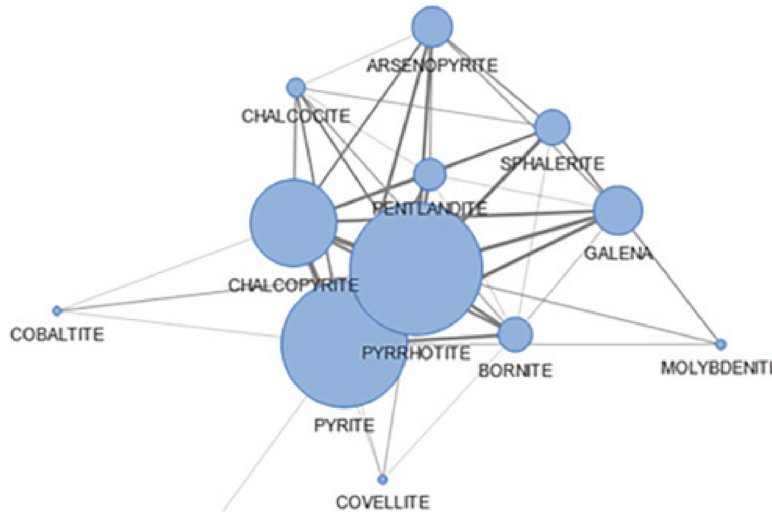

Fig. 2. Visualization of Heavy Mineral Map of Australia sulphide mineral relationships within the GA-Curtin mineral network analysis (MNA) app.

Mineral network graphs take the form of “ball and spoke” based models (Fig. 2), where the layout of the model provides key information on the relationships between heavy minerals:

1. Mineral abundance: every mineral present in a sample is represented by a node (represented as a ball or circle in Fig. 2), with the size of each node proportional to the abundance of the mineral within the sample population, and its color representing mineral groups (e.g. sulphides in blue). In Figure 2, pyrrhotite (714 samples), pyrite (645 samples), chalcopyrite (305 samples), and galena (96 samples) are amongst the most abundant sulphide minerals observed.
2. Mineral co-occurrence: minerals that co-occur in at least one sample are linked by connectors or spokes (represented as straight lines in Fig. 2), whose thickness is proportional to the number of samples where the minerals are found to co-occur. In Figure 2, the pyrite-pyrrhotite pair co-occurs in 433 samples, whereas the pyrite-galena pair only co-occurs in 29 samples.
3. Mineral exclusivity: node proximity and connectivity is a reflection of the exclusivity of a mineral co-occurrence. An example of mineral exclusivity in Figure 2 is the association of cobaltite with only pyrite, pyrrhotite, or chalcopyrite out of the eleven cobaltite-sulphide mineral pairs possible, relegating cobaltite visually to the rim of the network. Another observation that can be made is that no sample contains both bornite and arsenopyrite, as visualized by the lack of a connector between the bornite and arsenopyrite mineral nodes (Fig. 2).

continued on page 10

Heavy mineral exploration on the continental scale

continued from page 8

ZINC MINERAL NETWORKS

Australia's Curnamona Province and Delamerian Orogen host significant Zn-Pb deposits within metamorphic sedimentary rocks, including the world-class Broken Hill Pb-Zn-Ag deposit in New South Wales (O'Brien et al. 2015; Tott et al. 2019). The MNA for the HM tool was configured to search for the network of minerals containing Zn in the HMMA dataset (Fig. 3). Gahnite ($ZnAl_2O_4$) is one of the most commonly observed Zn minerals, found in 837 of the 1315 samples (64%). Ecandrewsite was found in only 38 samples (3%), with many of these occurrences in the vicinity of Broken Hill (Fig. 4), the type locality for ecandrewsite (Birch et al. 1988). Similar co-relationships are observed for gahnite-zincochromite ($ZnCr_2O_4$), gahnite-zincostaurolite [$Zn_2Al_9Si_4O_{23}(OH)$] and gahnite-tongxinite (Cu_2Zn) pairs in the Broken Hill area. In regard to the Delamerian Orogen, observations of elevated gahnite concentrations in drainages near Victor Harbour may have some affinity to the mineralization 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).

An unexpected finding was the occurrence in ~14% of the samples of grains of a copper-zinc alloy. These grains are typically very fine (<100 µm), elongate, and liberated, but are also seen to co-occur with cuprite (Cu_2O) in ~3% of samples. Concern was initially raised that the alloy phase may have been introduced as a contaminant during the sampling or sample processing stages in the form of brass, however, no brass tools or fittings were used at any stage during sample collection. Given the presence of both stainless steel and brass sieves within the processing lab, pure silica sand was used to test the sieving process as a source of brass/zinc-copper alloy contamination.

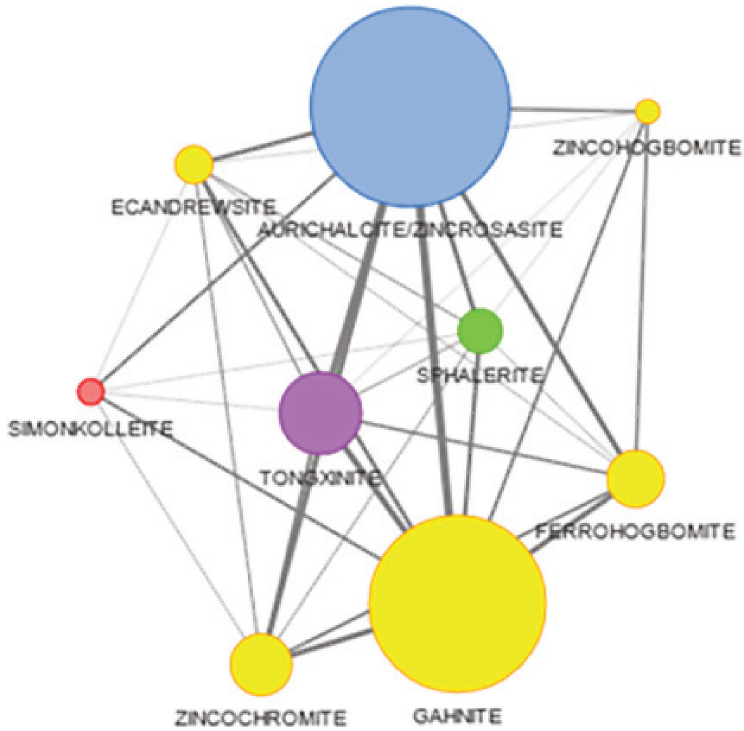

Fig. 3. Visualization of Heavy Mineral Map of Australia Zn-bearing mineral relationships within the GA-Curtin mineral network analysis (MNA) app. Colours pertain to mineral type: carbonate (blue); oxide (yellow); halide (red); sulphide (green); alloy (pink).

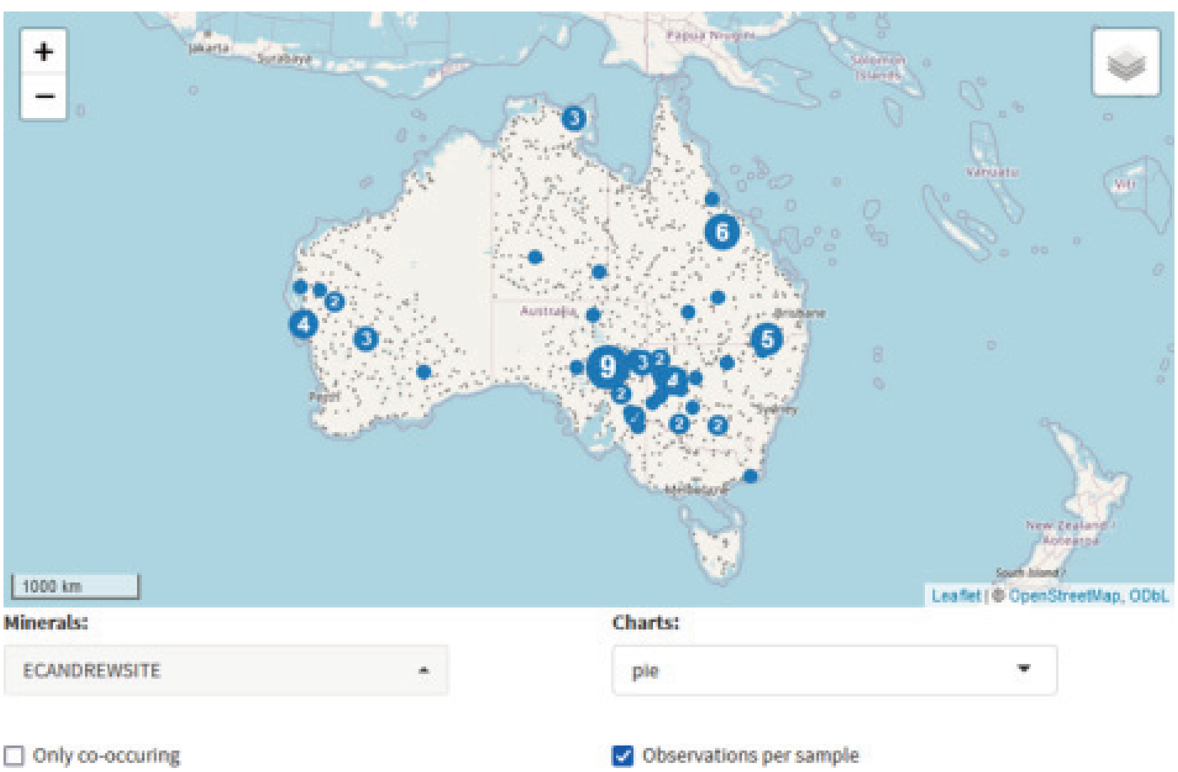

Fig. 4. Distribution of ecandrewsite ($(Zn,Fe^{2+},Mn^{2+})TiO_3$) occurrences within the Heavy Mineral Map of Australia dataset across Australia. Image from the GA-Curtin mineral network analysis (MNA) app.

continued on page 11

Heavy mineral exploration on the continental scale

continued from page 10

Aliquots of silica sand were sieved through brass sieve stacks for multiple sieving cycles with HMCs produced for TIMA analysis. No alloy particles were observed within the silica sand mounts, and brass is not found elsewhere within the HMMA workflow.

The closest naturally occurring mineral to these alloy grains in terms of composition is tongxinite (Cu_2Zn) or so-called zinciferous copper (Sun et al. 2003; Mindat.org 2022). Tongxinite is not formally recognized by the International Mineralogical Association, but minerals with comparable compositions have been reported in several localities world-wide, including within an Australian mineral deposit, since the 1990s (e.g. Jambor and Roberts 2000; Zhang et al. 2002; Yuling et al. 2006; Tuisku 2010; Wulser et al. 2011; Xiong et al. 2018; Kostin 2021). From an exploration vectoring perspective, the presence of tongxinite in Australian drainages is significant due to its high implied density (8.29 g/cm^3; Webmineral 2022) and possible association with a range of mineral deposit types (e.g. Luo and Wang 1999; Tuisku 2010; Kostin 2021).

CONCLUSIONS

No country, let alone a continent, has pre-competitive datasets that provide internally consistent data about the baseline distribution of heavy minerals at a regional scale. The generated results include presence/absence of HMs, absolute HM abundances (observations), and HM abundance relative to the mass of bulk sediment analyzed (wt %). HM abundances can be displayed as maps using the Geoscience Australia portal or downloaded for detailed analysis and visualization using custom techniques.

The HMMA dataset, now complete after three years of work, constitutes mineralogical “big data”. The development of novel visualization methods to aid exploration of the HMMA data has demonstrated 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 HMMA’s quantitative HM mineralogy will be a useful input to exploration geoscience, and lead to more efficient mineral discovery in Australia.

ACKNOWLEDGEMENTS

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continued on page 12

Heavy mineral exploration on the continental scale *continued from page 11*

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continued on page 13

Heavy mineral exploration on the continental scale

continued from page 12

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