



South Australian magnetite global comparison study

Amira Global Project P1356



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As guests on Aboriginal land, the Department for Energy and Mining (DEM) acknowledges everything this department does impacts on Aboriginal country, the sea, the sky, its people, and the spiritual and cultural connections which have existed since the first sunrise. Our responsibility is to share our collective knowledge, recognise a difficult history, respect the relationships made over time, and create a stronger future. We are ready to walk, learn and work together.

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Foreword

This report, commissioned by the Geological Survey of South Australia and authored by AMIRA Global, presents an independent analysis of South Australia's magnetite resources in comparison to domestic and international magnetite projects.

Following an updated compilation of South Australia's magnetite resource information by the Geological Survey of South Australia in 2024, the absence of a comprehensive global dataset was identified as a major limitation to understanding the relative quality and potential of South Australia's magnetite resources in the context of global competitors.

To address this knowledge gap, this project set out to achieve the following:

1. Create a global database of publicly available magnetite deposit information.
2. Use this database to compare South Australian magnetite resources to projects across the globe.
3. Through this comparative analysis, develop a better-informed understanding of the advantages, challenges and potential opportunities of South Australian magnetite.

This study takes a wholistic, state-wide approach to investigating the quality of South Australia's magnetite resources, primarily focussing on deposit scale, amenability to beneficiation, and concentrate grades. These attributes are compared to operating mines and Direct Reduced Iron (DRI) specifications, although it is important to note that not all projects may be targeting DRI-grades.

This study does not aim to address all factors that underpin magnetite project economics, particularly regarding mining and infrastructure requirements, which are crucial in determining the economic viability of magnetite projects and are beyond the scope of this report.

The information in this report and the attached database was collated in November 2024. It is acknowledged that additional information has been published by companies subsequent to the completion of this report, and therefore readers are referred to company reports and media releases for the most recent information.

This project was undertaken as part of Action 1 of South Australia's Green Iron and Steel Strategy to demonstrate the magnitude, quality and development potential of South Australia's iron ore deposits.

More information on South Australian magnetite, including a summary table of South Australia's magnetite resources, can be found on the Department for Energy and Mining website: <https://www.energymining.sa.gov.au/industry/geological-survey/gssa-projects/magnetite-south-australia>

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South Australian Magnetite Global Comparison Study

2024 to 2025



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Data attachment – Global Magnetite Database

Click to download the global magnetite database (.xlsx 175 KB) from the attachments panel.

Acrobat Reader is recommended for access.

Preparation

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Welcome

We respectfully acknowledge the Traditional Custodians of the lands on which we live and work. In Perth, we acknowledge the Whadjuk people of the Noongar Nation, and in Adelaide, the Kaurna people. We pay our respects to their Elders, past and present, and extend that respect to all Aboriginal and Torres Strait Islander peoples.

Executive Summary

The steel industry, which accounts for 7–9% of global greenhouse gas emissions, is shifting towards high-grade magnetite ($\geq 67\%$ Fe) to reduce its carbon footprint. This transition is expected to drive up prices and create challenges for lower-grade hematite producers, particularly in Western Australia's Pilbara region. Magnetite ores present a significant opportunity for green steel production through the Direct Reduced Iron (DRI) process, where hydrogen replaces carbon as the reducing agent, offering a more sustainable alternative to conventional steelmaking. Notably, recent studies (Geymond et al., 2023) have also identified magnetite as a potential natural hydrogen source. Consequently, magnetite deposits—especially those hosted in Banded Iron Formations (BIF) and metasedimentary ironstones in Western and Southern Australia—are attracting increasing interest for exploration and mining.

In line with this shift, this Amira Global-CSIRO research project (Project No. P1356) commissioned by the Department for Energy and Mining (DEM) through the Geological Survey of South Australia (GSSA), aims to develop a comprehensive global database of magnetite deposits. The project enables systematic comparisons between South Australian deposits and global counterparts by integrating geological, mineralogical, and processing data. The project aims to provide a measure of the competitiveness of South Australian magnetite resources by benchmarking deposits against global resources, and through comparison, identifying data gaps and processing challenges in South Australia, leading to optimised beneficiation strategies.

Globally, magnetite deposits are located in North America, Europe, Australia, South America, Africa, and other regions. Magnetite ores can come from a range of deposit styles including Banded Iron Formations, Mafic-Ultramafic layered intrusions, Iron Oxide Apatite, Skarns, and Iron Oxide-Copper-Gold. Variations related to each of these mineralisation styles and within individual deposits significantly impact the economic potential of the resource. This extensive compilation of global public and private data sources indicates there is no global standard for data reporting and sharing. The South Australian dataset on magnetite resources is globally one of the most comprehensive pre-competitive datasets across multiple testing parameters.

In order to better understand the opportunities within South Australia, a comparison of geological settings of magnetite mineralisation types in significant magnetite producing jurisdictions has been completed, with reference to; mineralisation style, important processing indicators and data availability. Key findings include:

- The presence of BIF-hosted magnetite deposits in South Australia similar in style to some currently exploited deposits (e.g. Iron Bridge in Western Australia; Scully, Carol Lake and Bloom Lake in Canada; Northshore, United Taconite, Minntac and Keetac in the USA).
- South Australia, by magnetite tonnage, ranks third globally following Canada and Western Australia.
- Based on head and concentrate grades, magnetite recovery rates in South Australian deposits are comparable to those seen in economically viable mines currently operating in Western Australia and Canada.
- Grinding size is variable across the deposits with some allowing for coarse grinding ($>100\ \mu\text{m}$), representing a significant advantage compared to many competitors globally.

- Bond work demonstrates that some South Australian deposits host less abrasive magnetite ores compared to other regions.
- Asbestos is uncommon within the South Australian magnetite deposits.
- South Australia's magnetite competitiveness lies in striking the right balance between deposit scale, grind size, concentrate quality and comminution efficiency.

South Australian magnetite concentrates demonstrate promising suitability for Direct Reduced Iron (DRI) production, particularly in terms of Fe grade, impurity control, and grind size. Most projects produce concentrates that meet or closely approach the practical thresholds for Fe grade and deleterious elements. However, achieving the preferred specification of <2 wt% acid gangue ($\text{SiO}_2 + \text{Al}_2\text{O}_3$) remains a key challenge, typically requiring flotation—as currently demonstrated at the Middleback Range project. Alumina and manganese levels, while elevated in some deposits, are generally well controlled in concentrate products and align with international benchmarks, including those from Canadian DRI-oriented projects. Continued optimisation of flowsheets to enhance silica rejection—particularly without reliance on excessive grinding—will be essential to fully position South Australian magnetite as a competitive feedstock for low-emission steelmaking.

The information contained within this report is to be used in accordance with clause 10.2 contained within the CRLA.



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Database Methodology and coverage

Author(s): Yoram Teitler, Erick Ramanaidou

The database aggregates publicly available data from key global regions, including Australia, Canada, South America, Europe, and Africa, and currently includes 198 deposits across 115 projects—of which 46 deposits within 19 projects are located in South Australia. Detailed comparative analysis focuses primarily on projects in other Australian states and Canada, with subsets selected based on data availability: 6 operating projects for processing parameters, 20 operating projects for resource/reserve and production data, 25 projects for recovery versus concentrate grade, and 29 projects for grinding size versus Fe concentrate grade. However, significant gaps remain, particularly for key competitors in Brazil, China, India, and Russia.

- The available data for South Australia provides an extensive understanding of deposits from exploration stage to production, with visibility of 33 main parameters of significance for resource evaluation. Globally there is comparable data available for 3 regions (South Australia, Western Australia and Canada) and limited availability for 4 regions (USA, Europe, Latin America and Africa). No data is available for Brazil, China, India and Russia. Transparency in data reporting from geological surveys and industry reports, under specific regulatory frameworks (JORC, NI43-101, PERC, SK-1300), is crucial to enable effective understanding of opportunities in each region. Tonnage and Fe head grade data are available for all projects globally, but reserve data are less frequently reported.
- South Australia, Western Australia, Tasmania and Canada provide recovery rates, such as Davis Tube Recovery (DTR) and 'FeMagnetic', for 55% of their deposits. Reporting of recovery rates in the USA is 33%.
- There are inconsistencies in reporting of deleterious elements with head grades across projects. The most commonly reported elements include SiO₂, Al₂O₃, P, and S, particularly in BIF-hosted magnetite and high-grade iron ores. Deleterious element concentrations with head grades are reported for 60% of deposits in South Australia and in Western Australia, and only for 30% of deposits in Canada.
- South Australia and Western Australia report concentrate data, primarily for Fe, which serves as an indirect indicator of the project's advancement in terms of processing feasibility, for 50% of deposits. Canada (Quebec, Newfoundland and Labrador provinces) have the most consistent reporting of concentrate data, with data available for nearly 90% of deposits.
- Among deposits that report concentrate Fe grades, around 85% of South Australian and Western Australian deposits include deleterious element concentrations in their concentrate data. Canada's reporting of deleterious elements in the concentrate is predominantly for SiO₂ (80% of deposits), with only 30% of Canadian deposits reporting other deleterious elements.
- Canada provides the most comprehensively reported comminution data, with approximately 60% of deposits, reflecting their adherence to the NI 43-101 reporting standard in Canada. In comparison, only about 25% of South Australian magnetite deposits report comminution data, which may reflect a difference of the reporting standards between the JORC Code and NI 43-101.
- The variability in testwork scale—ranging from lab-scale (e.g. DTR) to pilot and full-scale operations—limits the reliability of cross-project comparisons, particularly for comminution and concentrate quality data.
- Given the profile of South Australia, having one project in production, four projects with a granted mining lease or completed feasibility studies, and eight exploration projects with

JORC compliant resources, the quality of data available to characterise the deposits is considered to be leading and represent a significant advantage for exploration and development in the region.

Magnetite-bearing deposits

Author(s): Yoram Teitler, Erick Ramanaidou

Within South Australia there is over nineteen billion tonnes of magnetite ore, including almost eight billion tonnes of economically demonstrated resources (Government of South Australia, 2024). These are distributed across 3 main magnetite-rich areas; Braemar, North Gawler and Eyre Peninsula. These regions each contain significant and notable deposits, predominantly hosted in Banded Iron Formations (BIF) and metasedimentary ironstones, and to a lesser extent, in skarns.

Magnetite-bearing deposits occur in a range of geological settings (Figures 1 and 2), each presenting distinct mining and processing challenges which may affect the quality of the deposit from a processing and production perspective. The principal operating magnetite projects worldwide are listed in Table 1 (by tonnage).

Banded Iron Formations (BIF), formed by chemical precipitation in ancient marine basins, are the primary source of magnetite ore globally. These deposits, found in Archaean to Paleoproterozoic cratons and some Neoproterozoic basins, include major examples such as the Hamersley Province in Western Australia and the Sokoman Formation in Canada. In South Australia, BIF hosting magnetite deposits were deposited through several geologic periods, from Neoarchean, to Late Paleoproterozoic and Neoproterozoic (Davies and Twining, 2018). Some South Australian deposits, although noted as BIF in previous publications, are preferentially classified as metasedimentary ironstones (Braemar deposits) or magnetite gneisses (Warrambo) due to evidence for detrital sedimentation and other processes that differentiate them from BIFs (E.g., Lane et al 2015). These deposits also have mineralogy and chemical characteristics that are distinct from BIF deposits. The metamorphic grade of these deposits influences magnetite grain size, which in turn determines grinding requirements. In Western Australia, most BIF-hosted magnetite deposits occur in Archean BIF units within the Pilbara and Yilgarn cratons, rather than in the Paleoproterozoic Hamersley Basin. These deposits, exemplified by the Iron Bridge Project, typically contain fine-grained magnetite. In contrast, the Sokoman Formation in Quebec, Labrador, and Newfoundland (Canada) has undergone amphibolite-facies metamorphism, resulting in coarser magnetite (e.g. the Scully Mine). Granulite-grade magnetite gneisses at the Warrambo deposit (resources of 4.4 Gt) in the Eyre Peninsula (South Australia) feature very coarse magnetite grains.

Mafic-Ultramafic Layered Intrusion deposits form through magmatic differentiation and cumulate processes within large igneous provinces, such as the Bushveld Complex in South Africa and the Balla Balla deposit in Western Australia. These deposits typically contain coarse-grained magnetite, allowing for simpler beneficiation, although the presence of ilmenite, chromite, and vanadium-bearing titanomagnetite often necessitates advanced processing techniques.

Iron Oxide-Apatite (IOA) deposits are significant sources of high-grade magnetite, often enriched in phosphorus (apatite) and rare earth elements (REE). The Kiruna deposit in Sweden, one of the world's largest IOA systems, contains massive magnetite bodies with significant apatite and REE content, requiring advanced flotation techniques to remove phosphorus. In contrast, the El Laco deposit in Chile hosts magnetite in volcanic flows with minimal gangue minerals, enabling simplified beneficiation.

Skarn deposits form through high-temperature metasomatic reactions at the contact between intrusive igneous bodies and carbonate-rich sedimentary rocks. These polymetallic systems frequently contain copper, zinc, and tungsten, alongside magnetite. The Savage River deposit in Tasmania,

Australia, is a prime example, with coarse magnetite intergrown with garnet and pyroxene gangue minerals. Beneficiation typically involves low-intensity magnetic separation (LIMS) to recover magnetite. While flotation is not necessary at Savage River, it may be required in other skarn deposits to remove calc-silicate impurities.

Iron Oxide-Copper-Gold (IOCG) deposits are hydrothermal systems characterised by magnetite, hematite, and copper-gold mineralisation. Notable examples include the Marcona and Pampa de Pongo deposits in Peru, which exhibit high Fe grades and substantial volumes. In these deposits, magnetite is intergrown with chalcopyrite and bornite, requiring a combination of magnetic separation and flotation to effectively recover iron and base metals. The oxidation state of mineralising fluids controls the type of iron oxides (hematite vs. magnetite) in IOCG deposits. In the world-class Olympic Dam IOCG deposit (South Australia), hematite largely predominates over magnetite, making it unattractive in the perspective of magnetite production.

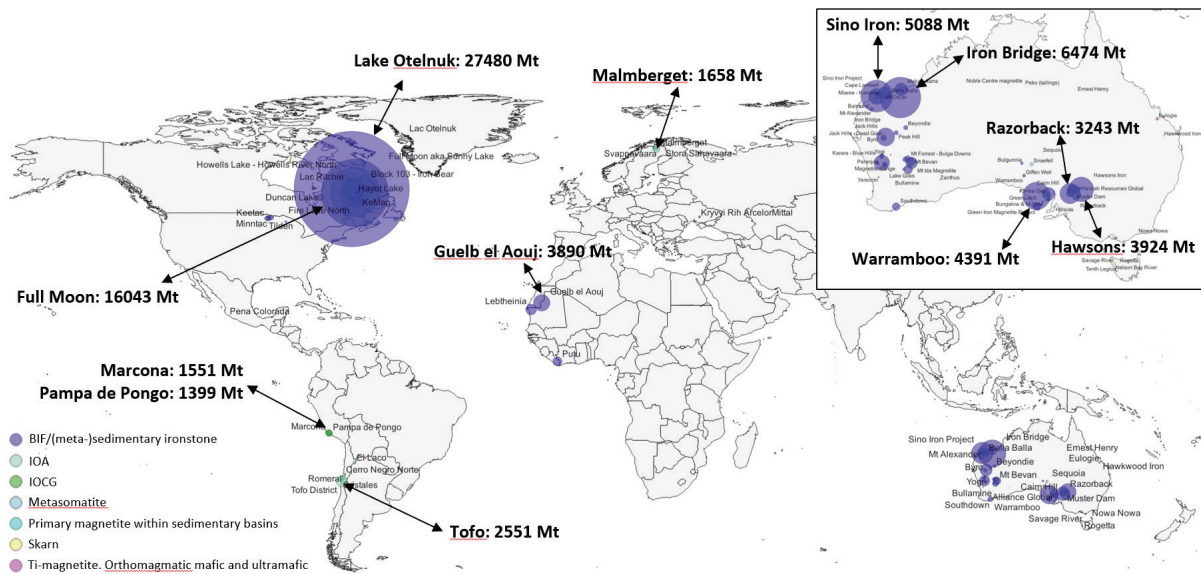


Figure 1: Global and Australian distribution of magnetite projects, highlighting their locations and associated resource tonnages.

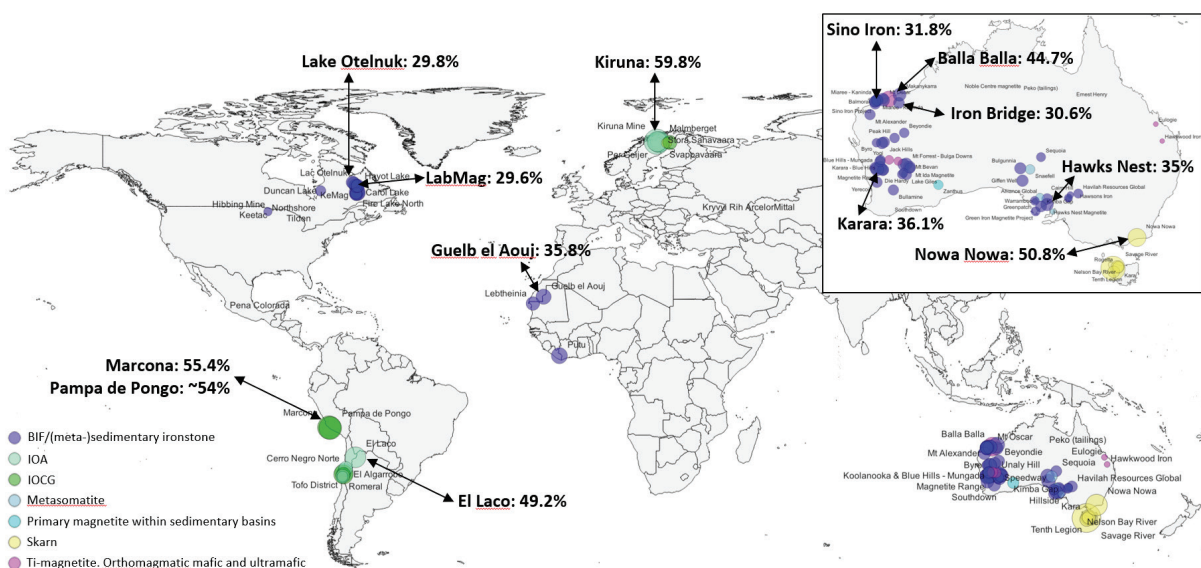


Figure 2: Global and Australian distribution of magnetite projects, highlighting their locations and associated Fe head grades.

Operating Project	Country/state	Geology	Resource Quantity (Mt)	Reserves (Mt)
Iron Bridge	Western Australia	BIF	6474	
Karara - Blue Hills	Western Australia	BIF	2490	950.8
Sino Iron Project	Western Australia	BIF	5088	
Middleback Range Magnetite	South Australia	BIF	2064.4	
Savage River	Tasmania	skarn	480.1	96.7
Carol Lake	Canada	BIF	1666	1076
Scully	Canada	BIF	985.3	477.9
Bloom Lake	Canada	BIF	1498.5	716.2
Northshore	USA	BIF	1171.1	822.4
United Taconite	USA	BIF	756.3	
Minntac	USA	BIF	1244.7	931.3
Keetac	USA	BIF	1198.5	
Tilden	USA	BIF	485.8	
Kiruna Mine	Sweden	IOA	815	726
Svappavaara	Sweden	IOA	676.5	91
Malmberget	Sweden	IOA	1658	306
Kryvyi Rih ArcelorMittal	Ukraine	BIF	527	514
Los Colorados	Chile	IOA	943	509
Romeral	Chile	IOA	455	101
Marcona	Peru	IOCG	1551	
Pena Colorada	Mexico	IOA	39	115

Table 1: Principal operating magnetite projects worldwide.

Key Indicators for Mining and Processing

Author(s): Yoram Teitler, Erick Ramanaidou

The economic viability of mining and processing magnetite ores is influenced by several key factors, including tonnage, head grade, recovery rates, mineralogy, and crystal size. A crucial determinant is the liberation size of magnetite, which significantly impacts beneficiation efficiency. The key factors affecting liberation size include:

- Ore Texture. The intergrowth and grain size of magnetite within the ore body directly influence liberation efficiency.
- Mineralogy. The hardness of associated minerals affects liberation size and processing energy requirements. For example, quartz is harder than magnetite, increasing grinding energy demand in BIF-hosted deposits.

Research on the Iron Bridge deposit in Western Australia (Ramanaidou et al., 2023) highlights the importance of mineral hardness in optimising recovery rates. While a magnetite-quartz association produces a cleaner concentrate at a higher energy cost, a softer magnetite-stilpnomelane association may leave impurities in the final product meaning each case needs specific assessment.

Table 2 provides an overview of the mineralisation styles discussed in the previous section and a generalised overview of ore characteristics.

Deposit types/Key Indicators	BIF	Skarn	IOCG	IOA	Layered Intrusions
Tonnage (Mt)	Very large (up to several Gt)	Small (<500 Mt)	Variable (up to 1.5 Gt)	Variable (up to 2 Gt)	Small (<500 Mt)
Head Grade (% Fe)	20–35%	25–68%	10–55%	25–60%	15–45%
Gangue mineralogy	Quartz ± carbonate, silicates	Calc-silicates (e.g., garnet, pyroxene)	Sulfides, quartz, carbonates	Apatite	Ilmenite, spinel, serpentine, olivine, pyroxene
Penalising Elements	Low Al ₂ O ₃ , P, S	Low Al ₂ O ₃ , P, S	High S	High P	Ti
Grinding Size (µm)	38–150	~300	Variable	Medium to coarse	75–150
Recovery Rates (%)	20–45	30–50	No data	No data	No data
Concentrate Grade (% Fe)	65–70	~68	66–67	No data	~58
Processing Technology	LIMS ± flotation	LIMS ± flotation	Magnetic separation, flotation, gravity	LIMS, flotation	LIMS, HGMS, gravity

Table 2: Summary of key indicators for magnetite deposits.

The recovery of magnetite from magnetite ores involves a combination of crushing, grinding, magnetic separation, and sometimes flotation. There is typically up to 3 stages of crushing followed by primary and secondary milling, depending on the ore, to achieve the required P80 grind size, typically 38–75

microns. Parameters such as mass recovery, concentrate grades (Fe and deleterious elements), grinding size and comminution parameters (ore grindability and abrasiveness) are important to understand the quality and economic implications of each deposit. Within the global database, mass recovery, concentrate grade and grinding size were quite readily available (about 40% of projects) while comminution data was not widely shared (about 13% of projects), meaning the comparisons are informed by both data and geological knowledge.

The first separation step generally employs drum magnetic separators (wet or dry) to recover coarse magnetite particles using Low-Intensity Magnetic Separation (LIMS). For ores with complex mineralogy or finer grain size, High-Intensity Magnetic Separation (HIMS) or High-Gradient Magnetic Separation (HGMS) is used to remove weakly magnetic minerals or contaminants. In some operations, reverse flotation is applied to remove silica and sulphur-bearing minerals (e.g. pyrrhotite).

Comparison of Processing Flowsheets in High-Grade (>65 wt% Fe) Iron Projects

Author(s): Yoram Teitler, Erick Ramanaidou

Comparisons have been made between South Australia and other global regions of magnetite and high-grade hematite concentrate (>65 wt% Fe) production, combining available data with global understanding of geological settings and deposit characteristics.

In South Australia, the Middleback Range Magnetite project (BIF-hosted) is the only operating magnetite mine, currently producing a ~65 wt% Fe concentrate to make blast furnace pellets. Studies have been completed to increase the quality of concentrate produced to a direct reduction specification grade of ~70 wt% Fe via the implementation of reverse flotation at the back end of their existing magnetite concentrator. This concentrator upgrade has been demonstrated at pilot plant scale and is planned to be implemented in the first stage of the Middleback Range Magnetite Expansion Project (MEP). Reverse flotation follows three stages of dry crushing, wet grinding/milling (P80 of 38 μ m) and low-intensity magnetic separation (LIMS). This workflow can be compared to those from other operating magnetite projects worldwide (Table 3):

Western Australia – Iron Bridge (Magnetite BIF)

- Uses a dry circuit with 2-stage HPGR (High-Pressure Grinding Rolls) and air classification (P80 53 μ m).
- Uses stir mills, significantly reducing energy and water consumption compared to conventional circuits.
- Produces a 67 wt% Fe concentrate, tailored for direct reduction applications.

Tasmania – Savage River (Skarn)

- Employs autogenous (AG) milling and magnetite separation, with spirals further refining the product (concentrate grade of 67.9 wt% Fe).

Canada – Bloom Lake (Hematite BIF)

- Utilises AG mills, followed by gravity spirals and magnetic separation.
- The P80 grinding size is coarser at 425 μ m, allowing for lower energy costs.
- Produces a 66.2 wt% Fe concentrate without flotation.

Canada – Scully (Hematite BIF)

- Follows a wet AG milling and spiral separation circuit (P80 of 75 μm), producing 65.6 wt% Fe concentrate, without flotation.

USA – Northshore (Magnetite BIF)

- Employs rod/ball milling (P80 of 45 μm) with reverse flotation, producing 70 wt% Fe concentrate.

Sweden – Kiruna (IOA)

- Applies wet grinding, magnetic separation, and flotation to remove phosphorus, producing a final concentrate grading 71 wt% Fe.

It is worth noting that Bloom Lake and Scully Mines in Canada produce a mostly hematite concentrate with minor amounts of magnetite, hence why meeting the 67 wt% Fe specification for DRI is a challenge for these projects. Scully in particular uses high intensity magnetic separation to segregate hematite from silicates and Manganese oxides.

Key Takeaways:

- While staged grinding and low-intensity magnetic separation (LIMS) are widely used across magnetite projects to improve energy efficiency, the ultimate grind size is determined by the liberation characteristics required to reach the target concentrate grade.
- South Australia's Middleback Range's fine grinding and flotation maximises Fe recovery for high-grade pellet feed.
- Iron Bridge's HPGR circuit is a dry processing alternative, reducing energy and water demand.
- Savage River, Bloom Lake, and Scully operate with coarser separation sizes achieving satisfactory liberation.
- Tilden and Northshore rely on flotation for silica removal, with Northshore using a rod/ball mill system.
- Kiruna employs flotation for phosphorus removal, ensuring low P in final pellets.

This highlights the Middleback Range's approach to producing high-grade concentrate through fine grinding and flotation, whereas other regions tailor their processes to energy efficiency, water conservation, and ore-specific constraints.

Mine	Country	Deposit Type	Head Grade (wt% Fe)	Concentrate Grade (wt% Fe)	P80 Grinding Size (µm)	Processing Type	Crushing & Grinding Complexity	Separation Method	Flotation Used
Kiruna	Sweden	IOA	59	71	Not stated	Wet	Wet grinding, magnetic separation, flotation	Magnetic separation, flotation	Yes
Middleback Range	Australia (SA)	BIF	30	70	38	Wet	Ball mill, reverse flotation	Magnetic separation, flotation	Yes
Northshore	USA	BIF	25	70	45	Wet	Rod mill, ball mill, reverse flotation	Magnetic separation, flotation	Yes
Savage River	Australia (TAS)	Skarn	Not stated	67.9	Not stated	Wet	AG mill, magnetic separation	Magnetic separation, spirals	No
Iron Bridge	Australia (WA)	BIF	30.6	67	53	Dry	HPGR, air classification	Air classification	No
Bloom Lake	Canada	BIF	28.5	66.2	425	Wet	AG mill, gravity & magnetic separation	Gravity, magnetic separation	No
Scully	Canada	BIF	34.9	65.6	75	Wet	AG mill, spiral separators, magnetic separation	Magnetic separation, drying	No

Table 3: Summary of processing parameters in some operating magnetite and high-grade hematite (>65 wt% Fe) mines worldwide.

South Australian Magnetite Resource Profile within Global Context

Author(s): Yoram Teitler, Erick Ramanaidou

BIF-hosted magnetite projects represent the largest global source of magnetite, with Australia leading in project numbers, while Canada hosts larger resources. South Australia's magnetite resources are dominantly hosted in metasedimentary ironstone and BIF deposits. Many projects lack defined or publicly reported reserves, with notable exceptions such as the Central Eyre Iron (Warramboo) and Razorback projects in South Australia.

Ore Tonnages

South Australian magnetite deposits, particularly those in the Eyre Peninsula and Braemar regions, contain substantial resources, totalling approximately 19,000 Mt of resources and 6,000 Mt of reserves. In terms of total ore tonnage, South Australia ranks third globally, after Canada and Western Australia. Metasedimentary ironstones host majority of South Australia's magnetite resources, including the largest South Australian magnetite project Warramboo, which accounts for 4.5 Gt of resources and 3.7 Gt of reserves, followed by the Razorback project with 3.2 Gt of resource and 2 Gt of reserves.

Head and Concentrate Fe Grades

South Australian deposits exhibit a wide range of Fe head grades, from as low as 15 wt% to around 35 wt% (Figure 15). While most South Australian projects fall within the 25–35 wt% head grade range, several large-tonnage deposits (Warramboo, Razorback and Muster Dam) report lower head grades between 15 and 20 wt%. Regionally, deposits in the North Gawler Iron region tend to exhibit higher head grades compared to those in the Eyre Peninsula and Braemar regions, although significant variability exists within each. In comparison, most operating BIF-hosted magnetite mines globally, including Iron Bridge, Sino Iron (Western Australia), report head grades of 30–35 wt%, with some reaching up to 38 wt% (Carol Lake, Canada). A few North American operations, such as Keetac, Hibbing

Mine, and United Taconite in the United States, operate at head grades around 20 wt%, though it remains unclear whether their concentrate products consistently meet DRI-grade specifications.

Reported South Australian concentrate grades typically range between 67 and 70 wt%, comparable to those produced by BIF-hosted magnetite operations elsewhere (Figure 3), and meeting the preferred threshold for DRI suitability (>67 wt% Fe; Lu et al., 2015; Nicholas & Basirat, 2022).

Mass Recovery

Davis Tube Recovery (DTR) data shows that magnetic separation yields variable magnetite recovery rates in South Australian deposits, ranging from 15% to 40% (Figure 3), similar to their Western Australian and Canadian counterparts.

Grinding Size

Globally, most documented P80 grinding sizes range from 38 to 75 microns, though significant variability exists within South Australian magnetite deposits. Around 50% of South Australian projects require fine grinding (38 microns), while the Warrambo, Maldorky and Sequoia deposits have coarser grind sizes (>100 microns). Among these, the Warrambo deposit hosts very large tonnage capable of competing, size wise, with Tier 1 deposits in Western Australia and Canada. It is worth noting that Warrambo concentrate data is reported with two grinding sizes, with only the finer size enabling DRI-suitable Fe concentrate grade (69.7 wt% Fe at P80 = 53 μ m; 66.6 wt% Fe at P80 = 106 μ m), whereas test work from the Sequoia deposit suggests it can meet DRI-suitable Fe concentrate grade (69.4 wt% Fe) at a P80 = 143 μ m grind size. Outside South Australia, notable examples of operating projects reporting grinding size include Iron Bridge (Western Australia, 53 microns), Bloom Lake and Scully (Canada, 425 and 75 microns, respectively). Consequently, only a subset of South Australian magnetite projects holds a competitive advantage in terms of grinding size when compared to global analogues.

Penalising Elements in Ores and Concentrates

Direct Reduced Iron (DRI) production typically requires high-purity magnetite concentrates, with benchmark compositional targets of >67 wt% Fe, <2-3.5 wt% SiO₂ + Al₂O₃, <0.015 wt% P₂O₅, and <0.015 wt% S (Lu et al., 2015; Nicholas and Basirat, 2022). Table 4 summarises both practical and preferred limits for deleterious element concentrations in magnetite concentrates.

Element/compound (wt%)	Nicholas and Basirat, 2022		Lu et al., 2015
	Practical limits	Preferred limits	Preferred limits
Fe	>66	>67	>67
SiO ₂ + Al ₂ O ₃	<3.5	<2.0	<3.0
CaO	<2.5		
MgO	<1.0		
P ₂ O ₅	<0.03	<0.015	<0.07
Cu	<0.03	<0.01	
S	<0.025	0.015	<0.008
TiO ₂	<0.35		<0.15

Table 4: Concentrate chemical requirements for DRI (Lu et al., 2015; Nicholas and Basirat, 2022)

While SiO₂ concentrations in magnetite concentrates are commonly reported, Al₂O₃ values are often omitted, making it difficult to consistently assess compliance with the DRI specification limit for combined SiO₂ + Al₂O₃ (referred to as the acid gangue). South Australian deposits tend to exhibit elevated Al₂O₃ head grades compared to Canadian and Western Australian deposits—reaching up to 12.5 wt% in the Warrambo deposit. These levels are generally well managed across the state, with Warrambo producing the highest Al₂O₃ concentrate among South Australian projects—2 wt% at P80

= 106 μm . However, this is reduced to 1.1 wt% at P80 = 53 μm , which is within acceptable limits for DRI production. As Al_2O_3 levels in concentrate are typically low relative to SiO_2 , the SiO_2 content alone often provides a reasonable indication of DRI suitability with regards to the acid gangue content. It should also be noted that Al_2O_3 and SiO_2 have very different effects in Electric Arc Furnaces (influence on foaming and viscosity for Al_2O_3 ; lower metallisation, thermal penalty - melting point for SiO_2).

Among South Australian deposits where both SiO_2 and Al_2O_3 concentrate data are available, only Warrambo (P80 = 53 μm), Bungalow & Minbrie (Eyre), Muster Dam, and Olary Flats (Braemar) fall well below the practical $\text{SiO}_2 + \text{Al}_2\text{O}_3$ threshold of <3.5 wt% without flotation (Figure 21). Razorback (Braemar), Giffen Well, and Hawks Nest (North Gawler) lie close to this threshold, with combined values between 3.5 and 3.7 wt%. In contrast, Middleback Range, Warrambo (P80 = 106 μm), Green Iron Project (Eyre), and Maldorky (Braemar) exceed this threshold by a notable margin. However, individual deposits within the Green Iron Project (Eyre) report highly variable $\text{SiO}_2 + \text{Al}_2\text{O}_3$ concentrate data between 2.8 and 9.3 wt%, indicating some deposits within the project fall below or lie close to the practical threshold for DRI at P80 = 75 μm without flotation. It is also noted that additional test work indicates some of these deposits can produce concentrate grades of >69 wt% Fe at a grind size of P80 = 45 μm , without flotation. For other South Australian projects, only SiO_2 data are reported; however, their concentrates consistently contain <3 wt% SiO_2 , suggesting that they likely comply with the practical $\text{SiO}_2 + \text{Al}_2\text{O}_3$ requirement without flotation. Meeting the more stringent preferred target of <2 wt% $\text{SiO}_2 + \text{Al}_2\text{O}_3$ is uncommon—both in South Australia and globally—and generally requires flotation. For example, the Middleback Range project reports 8 wt% SiO_2 prior to flotation and 1.8 wt% after, with negligible Al_2O_3 content in either case. Bench-scale standard freshwater flotation test work at the Razorback Project has also achieved a concentrate grade of 70.2 wt% Fe and 0.8 wt% $\text{SiO}_2 + \text{Al}_2\text{O}_3$. Comparatively, the efficiency of SiO_2 removal in South Australian magnetite projects is substantially higher than in Western Australia and approaches the concentrate quality achieved in leading Canadian operations.

Sulphur, phosphorus, and manganese may occur in elevated concentrations in head grades (Figures 17-19), but are generally well controlled in concentrate products (Figures 22 and 23). Within South Australia, phosphorus levels are notably higher in Braemar deposits (typically ~0.2 wt%) compared to deposits in the Eyre and North Gawler regions (~0.05 wt%), yet are consistently reduced to acceptable levels in concentrates, with the exception of Maldorky (0.06 wt% P). Manganese presents a more distinct challenge at Warrambo, which reports MnO head grades around 1.2 wt%, significantly higher than other South Australian deposits (<0.2 wt% MnO). This is comparable to some Canadian operations such as Kami (~1.5 wt% MnO), and Hayot Lake, Full Moon, and Scully (~0.6 wt% MnO). Warrambo's concentrate contains ~1 wt% MnO at P80 = 106 μm , similar to Kami, or 0.74 wt% MnO at P80 = 53 μm . At Scully, a dedicated Manganese Removal Circuit (MRC)—comprising Low-Intensity Magnetic Separators (LIMS), High-Intensity Magnetic Separators (HIMS), High-Tension (HT) separators, and cleaner stages—is employed to reduce MnO content from 3.16 wt% to below 2.5 wt%, fulfilling product requirements while preserving iron recovery.

Importantly, asbestos is not common in South Australian ores, offering a notable health and safety advantage over some Western Australian deposits, such as the Sino Iron mine operated by Citic Pacific Mining.

Comminution

The Bond Abrasion Index (Bai) measures ore abrasiveness, while the Bond Ball Mill Work Index (BBWi) and Bond Rod Mill Work Index (RWi) assess ore grindability, with higher values indicating greater equipment wear. Despite limited available data, South Australian deposits—particularly metasedimentary ironstone deposits Maldorky and Razorback—tend to be less abrasive and easier to grind than many global deposits (Figure 3), suggesting a competitive advantage.

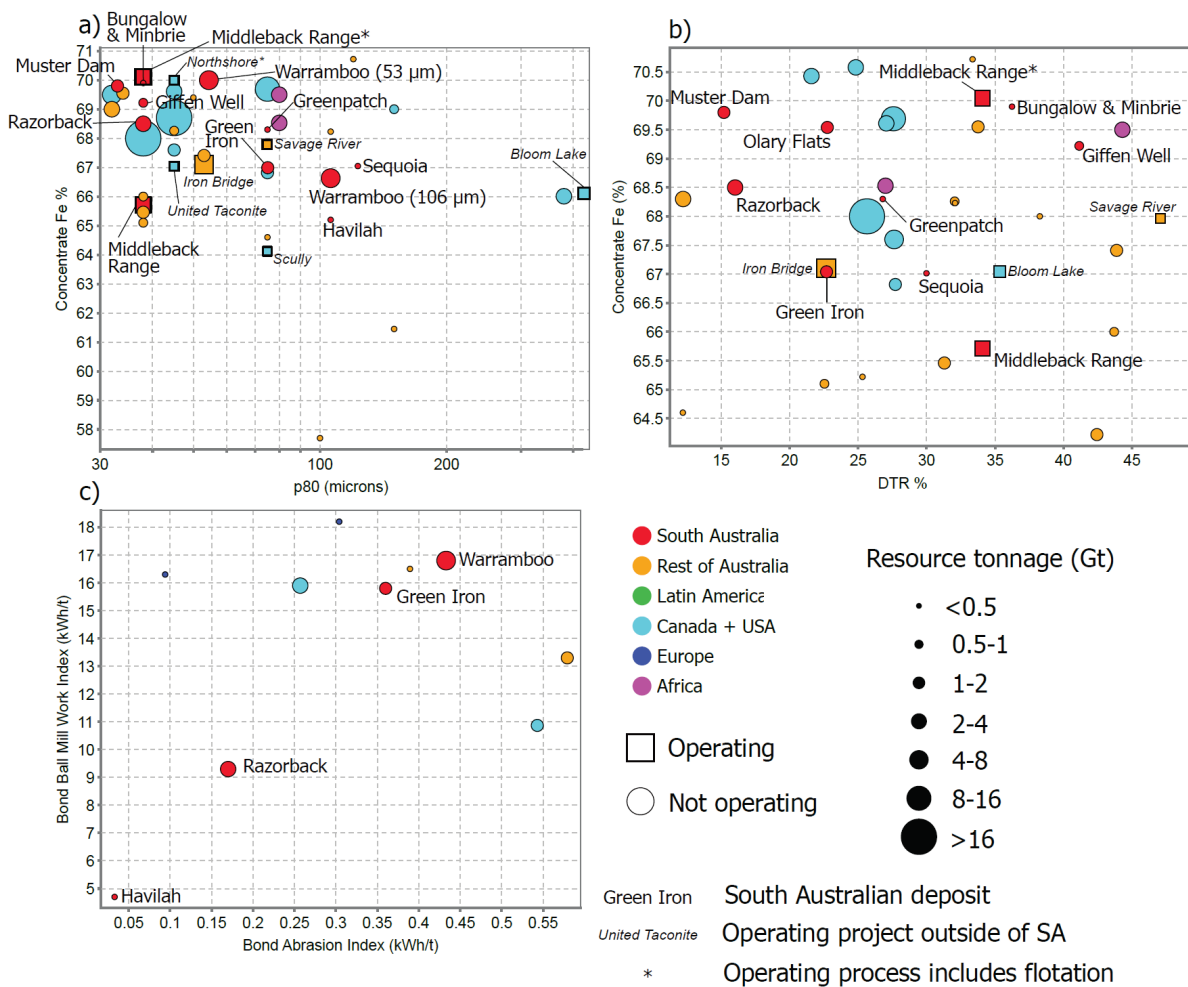


Figure 3: Comparison of some key parameters between magnetite projects worldwide (a) Fe concentrate grade vs. P80 grinding size. (b) Fe concentrate grades vs. DTR mass recovery. (c) Bond Ball Mill Work Index vs. Bond Abrasion Index.

South Australia's magnetite competitiveness lies in striking the right balance between deposit scale, grind size, concentrate quality and comminution efficiency. South Australia's magnetite resources, distributed across three key provinces (Eyre Peninsula, North Gawler and Braemar) exhibit distinct geological characteristics, processing considerations, and economic implications.

The Eyre Peninsula hosts metasedimentary ironstone and BIF-style magnetite deposits with moderate to high Fe head grades, relatively low impurity levels, favourable grind sizes, and variable Davis Tube Recovery (DTR) responses. It is the leading magnetite province in South Australia in terms of ore tonnage, followed by the Braemar region, though the deposits on the Eyre Peninsula differ markedly in their characteristics.

The Middleback Range magnetite deposits, currently in production, are defined by a relatively high Fe head grade (~30 wt%), high DTR (~34 wt%), and a fine grind size (P80 = 38 µm), with low impurity content. These attributes support efficient beneficiation and align with market requirements, making it a cornerstone of magnetite production in South Australia.

In contrast, Warrambo exhibits a lower Fe head grade (~16 wt%) and lower DTR (~15 wt%), but offers a naturally coarse grind size (P80 = 53 or 106 µm), which contributes to lower comminution energy requirements and reduced operating costs. Despite its lower head grade, Warrambo delivers a high-

quality concentrate (69.7 wt% Fe at P80 = 53 μm), outperforming some operating Western Australian producers, such as Iron Bridge (67.1 wt% Fe at the same grind size).

The Green Iron project also exhibits a similar DTR and Fe concentrate grade to Iron Bridge, although it achieves this at a coarser grind size (P80 = 75 μm), highlighting potential processing efficiencies.

Beyond the Eyre Peninsula, several deposits in the Braemar and North Gawler regions present notable competitive advantages, whether in tonnage potential (Braemar), head grade (North Gawler), grind size (e.g. Sequoia in North Gawler; Maldorky in Braemar), or comminution characteristics (Maldorky, Razorback). However, the economic viability of these deposits is influenced by the interplay between resource scale, processing efficiency, and beneficiation requirements, meaning that no single factor determines their competitiveness. In these regions, infrastructure development, logistics costs, and impurity management strategies will be key to unlocking long-term production potential.

Infrastructure development and proximity to export markets are crucial for enhancing the viability of these deposits, which hold significant potential for high-quality concentrate production. Interestingly, none of the major iron ore mining companies operating in Western Australia have a significant presence in South Australia. Exploring the reasons behind this absence could provide valuable insights.

Finally, it is worth noting that, although magnetite ores represent the preferential ore type for lower emissions steelmaking, there is a growing interest from competitors in the production of green steel from high-grade hematite concentrates. Notable examples include:

- The NeoSmelt collaboration (Bluescope-BHP-Rio Tinto-Woodside Energy), aiming to produce steel through Direct Reduced Iron - Electric Smelting Furnace (DRI-ESF) technology, from Pilbara iron ore.
- ArcelorMittal Mining Canada (AMMC) is investing CAD\$205 million to convert its entire 10 Mt/year pellet production at the Port-Cartier plant into direct reduced iron (DRI) pellets by the end of 2025. The plant processes concentrate sourced from AMMC's hematite-dominated Mont-Wright and Fire Lake operations and is expected to become one of the world's largest producers of DRI-grade pellets. As part of this transition, a flotation system is being implemented to significantly reduce silica content in the pellets, enhancing their suitability for DRI applications.

Such growing interests in the development of green steel from hematite ores is to be taken into consideration as these will represent significant competitors to magnetite-sourced green steel projects.

Project deliverables

Public Magnetite Database: A comprehensive database of magnetite ore deposits, compiled from publicly available data sources, ensuring transparency and accessibility.

Data Source Compilation: A detailed compilation of the data sources used for publicly available information, providing clear documentation and traceability.

Confidential Magnetite Databases (for DEM/GSSA internal use only): (1) A confidential database of magnetite-related projects, sourced from proprietary S&P Capital IQ Pro database. (2) A confidential variation of the Public Magnetite database, incorporating comparisons on tonnage data between publicly available sources and proprietary S&P Capital IQ Pro database.

Presentation: A PowerPoint presentation summarising the key findings, methodologies, and insights from the study.

Final Report: A detailed report encapsulating the objectives, methodologies, findings, and conclusions of the project.

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Appendix 1 – Additional Figures

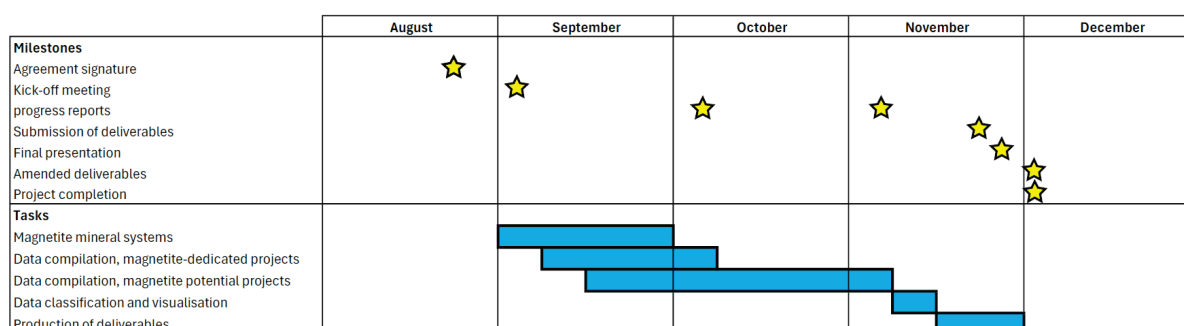


Figure 4: Project delivery timeline

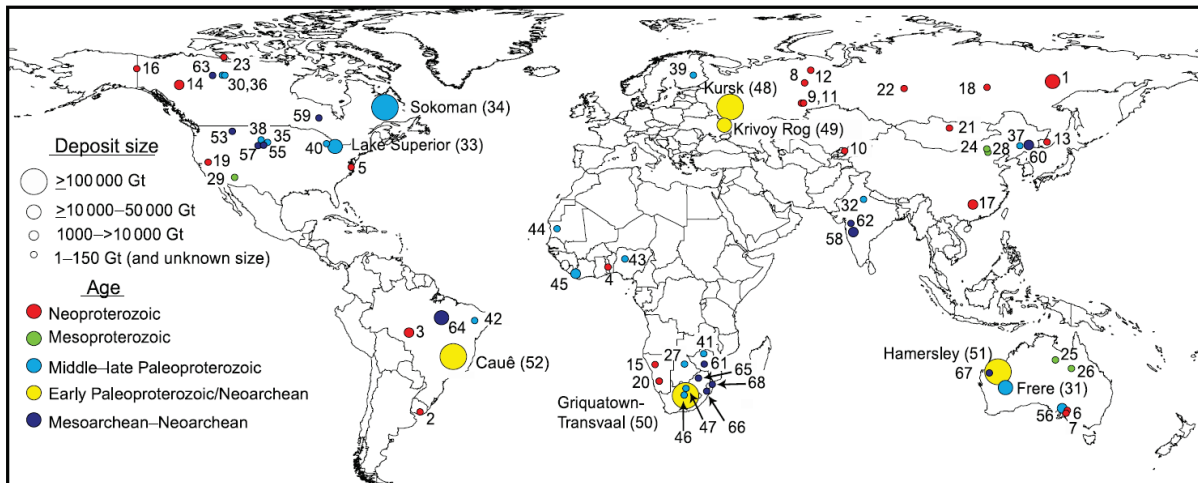


Figure 5: Geographical and size distribution of iron formations through time (Konhauser et al., 2017)

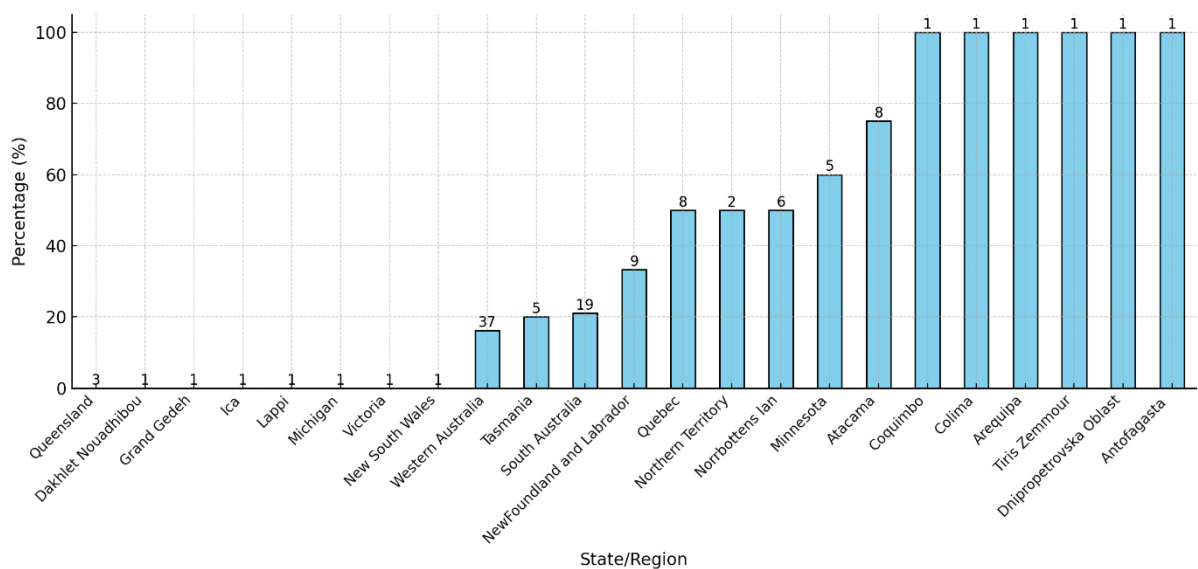


Figure 6: Proportion of projects reporting reserve tonnage and head grades within each mineral state or region. The numbers above the bars indicate the total number of magnetite projects listed in the database for each area.

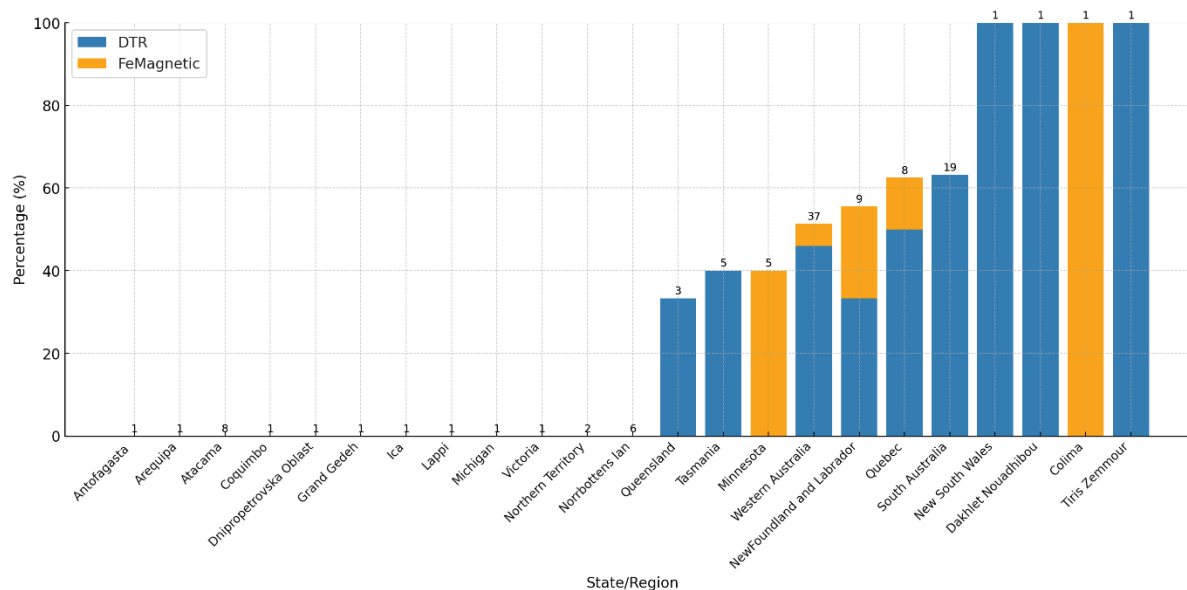


Figure 7: Proportion of projects reporting recovery rates within each mineral state or region. The numbers above the bars indicate the total number of magnetite projects listed in the database for each area.

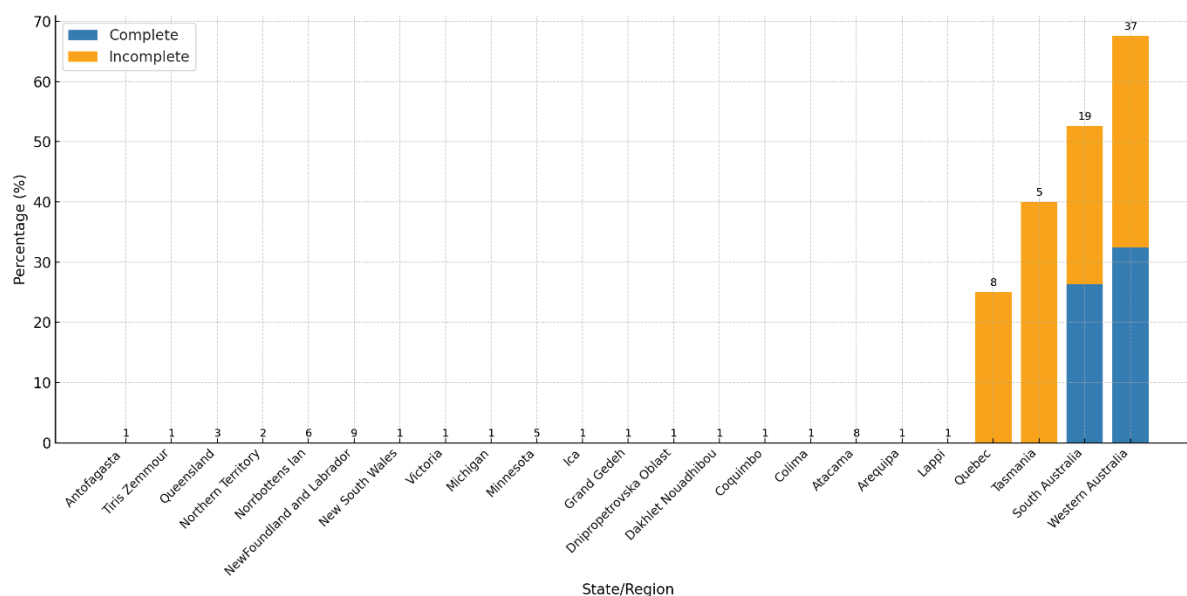


Figure 8: Proportion of projects reporting deleterious element concentrations in head grades (SiO_2 , Al_2O_3 , P, S) within each mineral state or region. 'Complete' indicates that all four elements are reported, while 'Incomplete' refers to projects reporting one to three elements. The numbers above the bars represent the total number of magnetite projects listed in the database for each region.

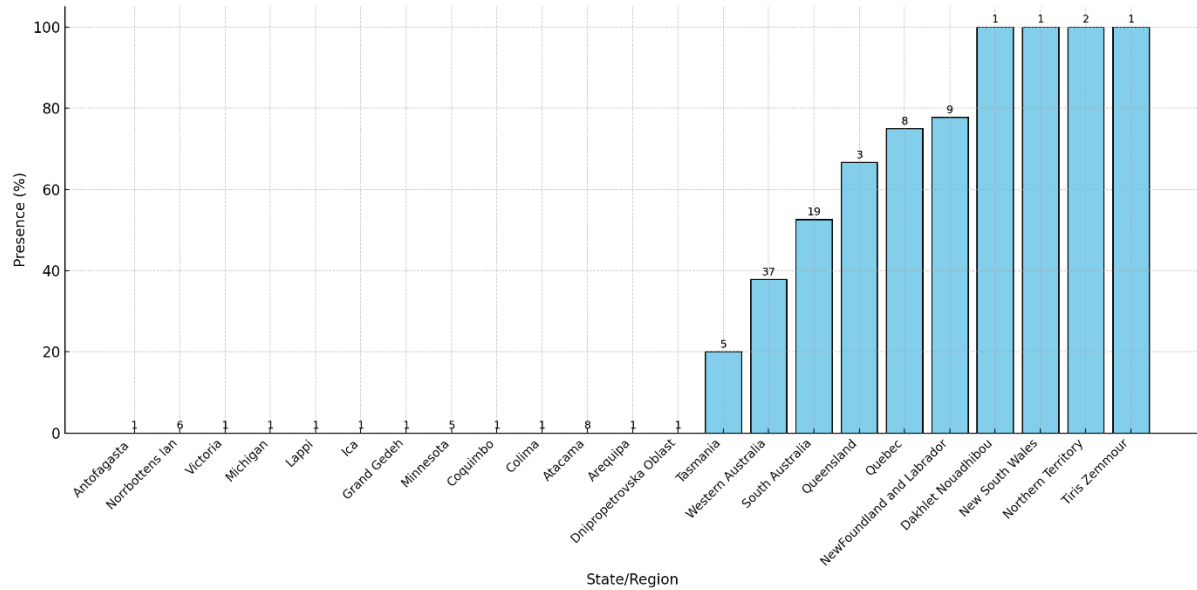


Figure 9: Proportion of projects reporting Fe grade in concentrates. The numbers above the bars indicate the total number of magnetite projects listed in the database for each region.

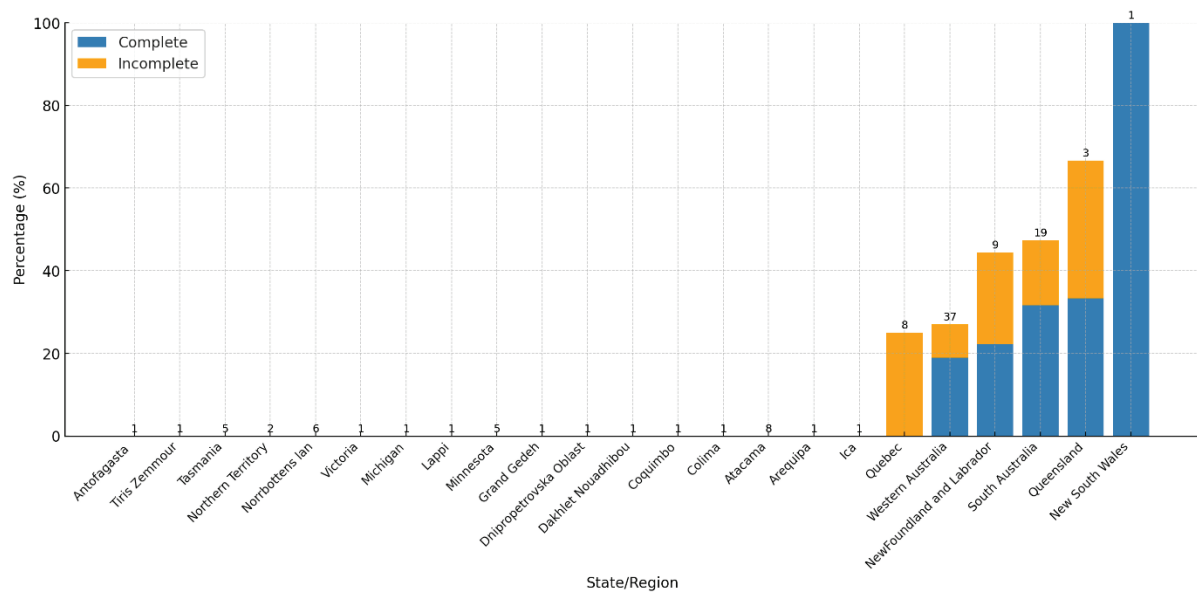


Figure 10: Proportion of projects reporting deleterious elements (SiO₂, Al₂O₃, P, S) in concentrates. The numbers above the bars indicate the total number of magnetite projects listed in the database for each region.

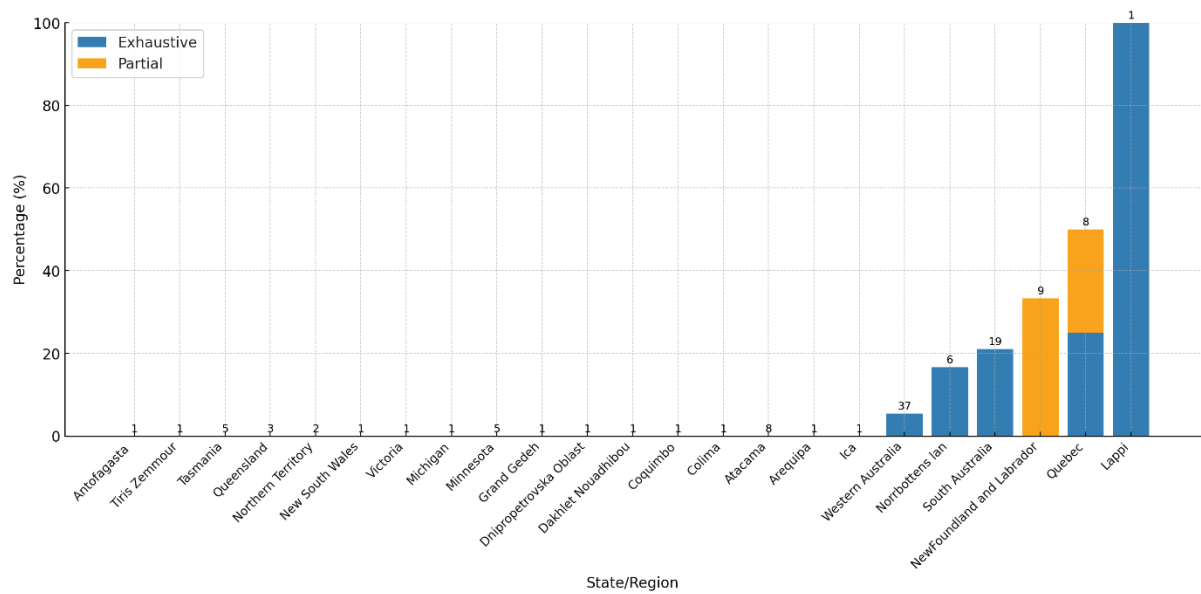
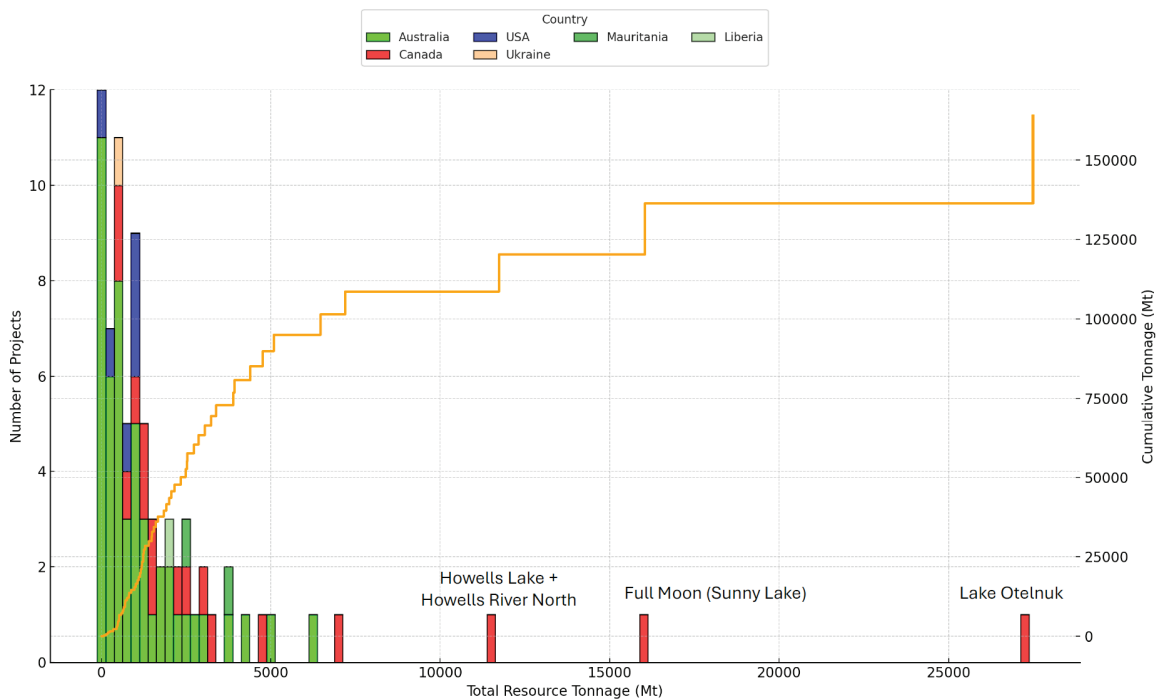


Figure 11: Proportion of projects reporting comminution data. The numbers above the bars indicate the total number of magnetite projects listed in the database for each region. 'Exhaustive' refers to projects reporting three or more comminution parameters.



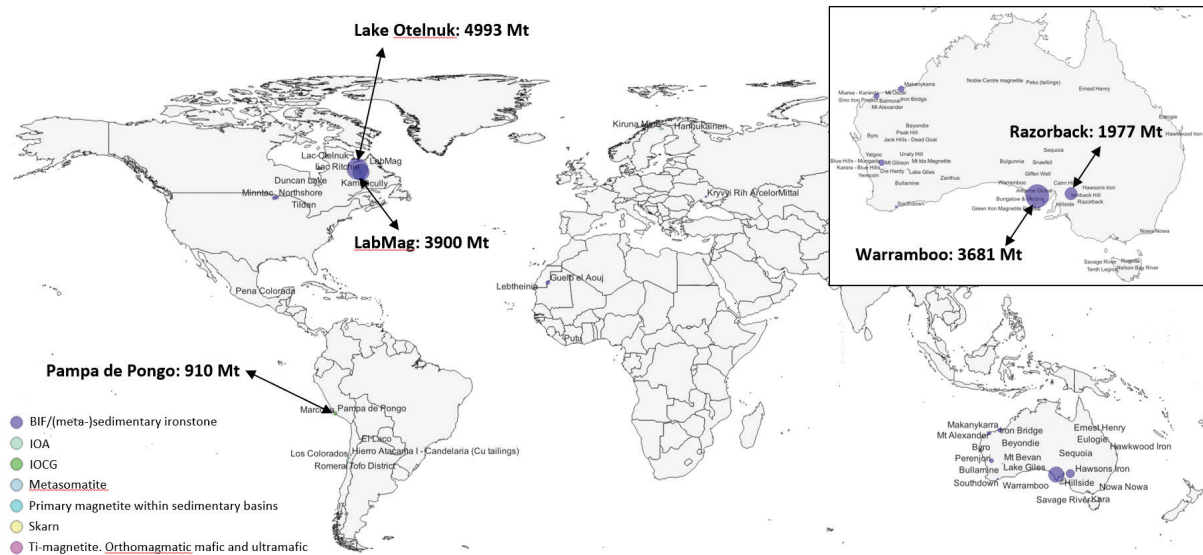


Figure 13: Global and Australian distribution of magnetite projects, highlighting their locations and associated reserve tonnages.

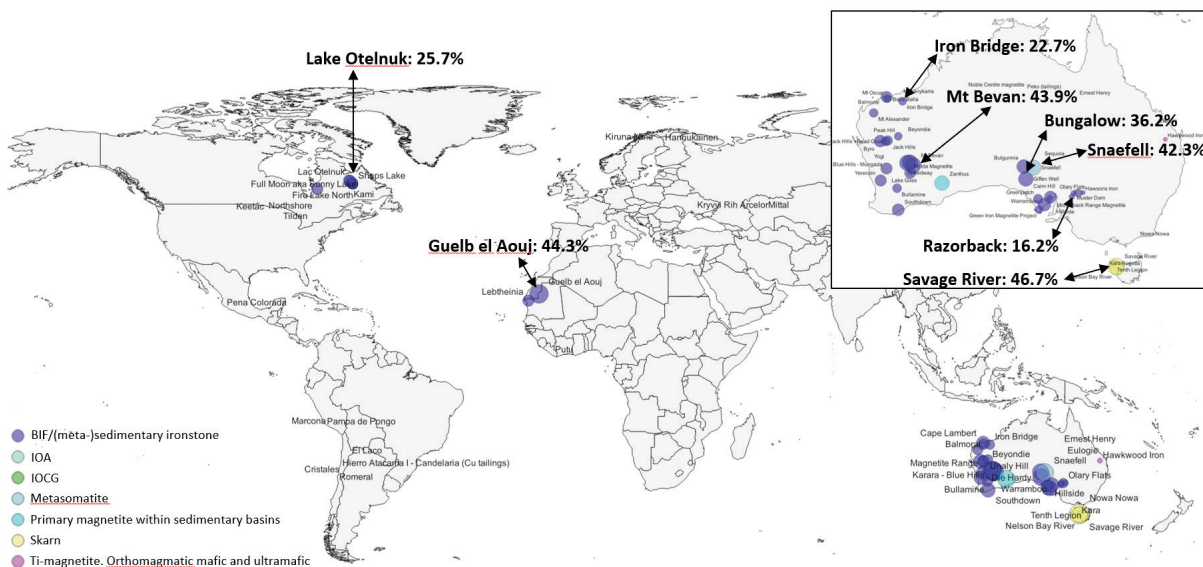


Figure 14: Global and Australian distribution of magnetite projects, highlighting their locations and associated DTR recovery rates.

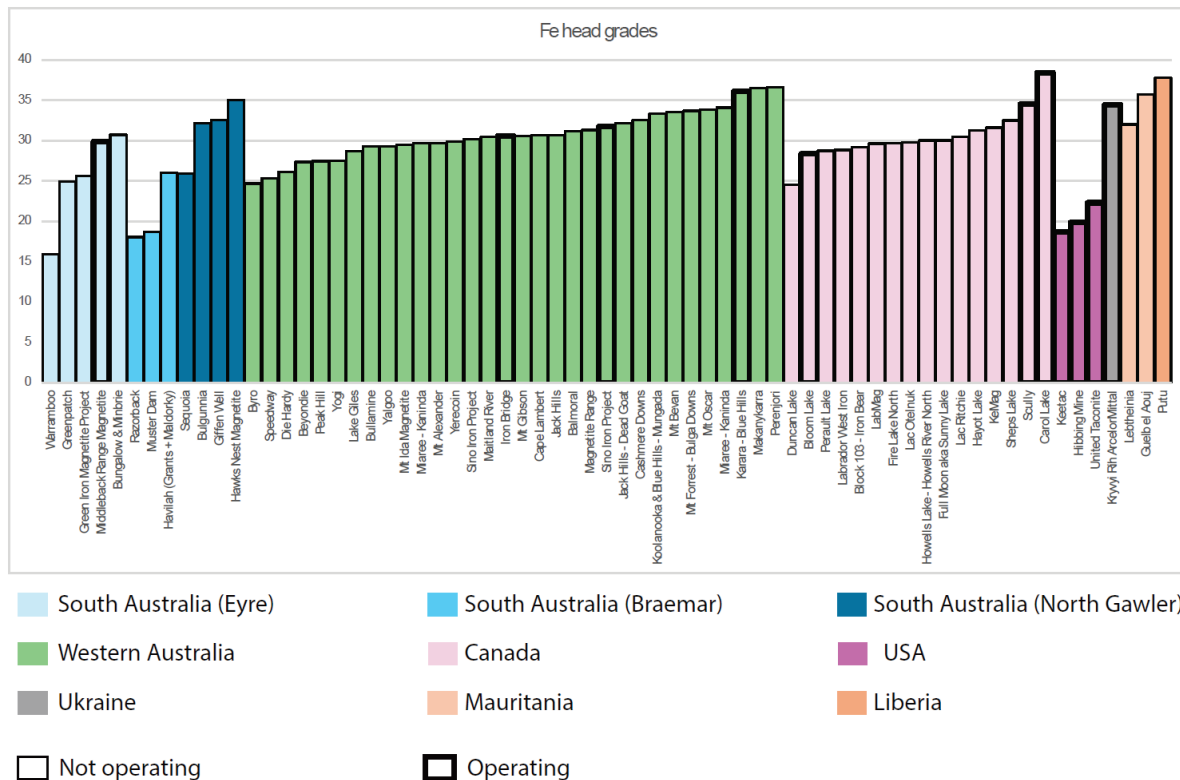


Figure 15: Fe head grades in BIF-hosted and metasedimentary magnetite deposits, grouped by country, state or region.

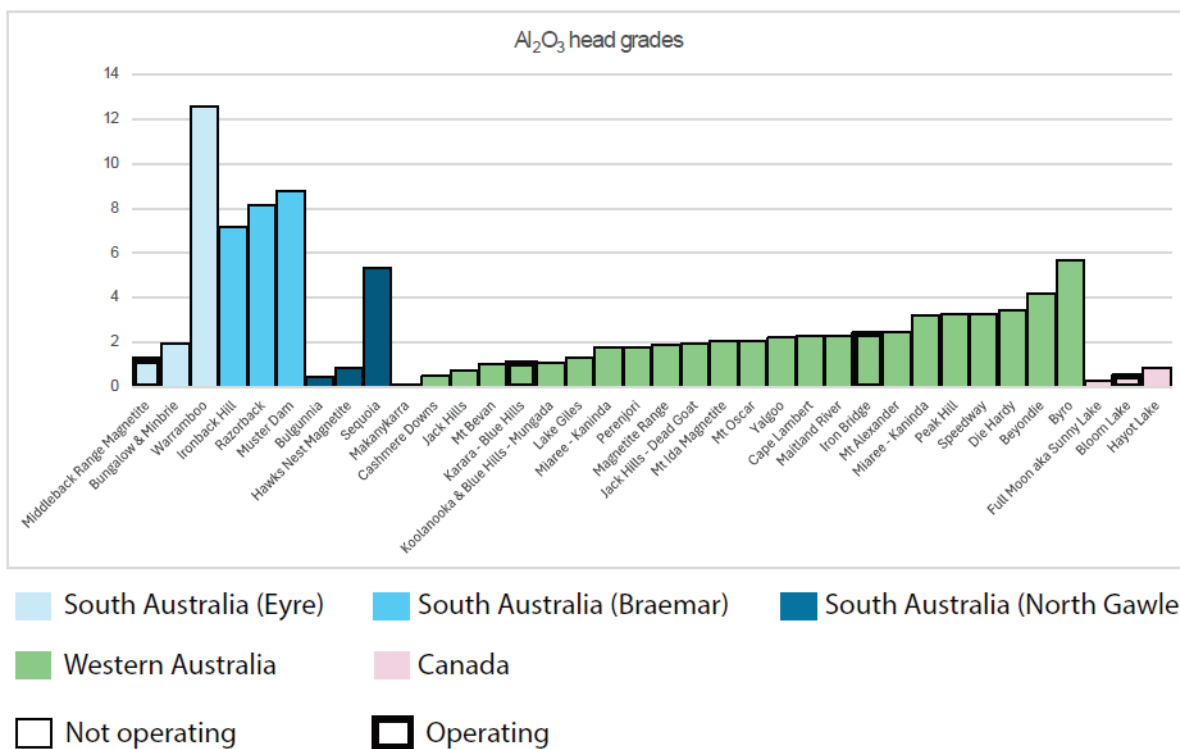


Figure 16: Al₂O₃ head grades in BIF-hosted and metasedimentary magnetite deposits, grouped by country, state or region.

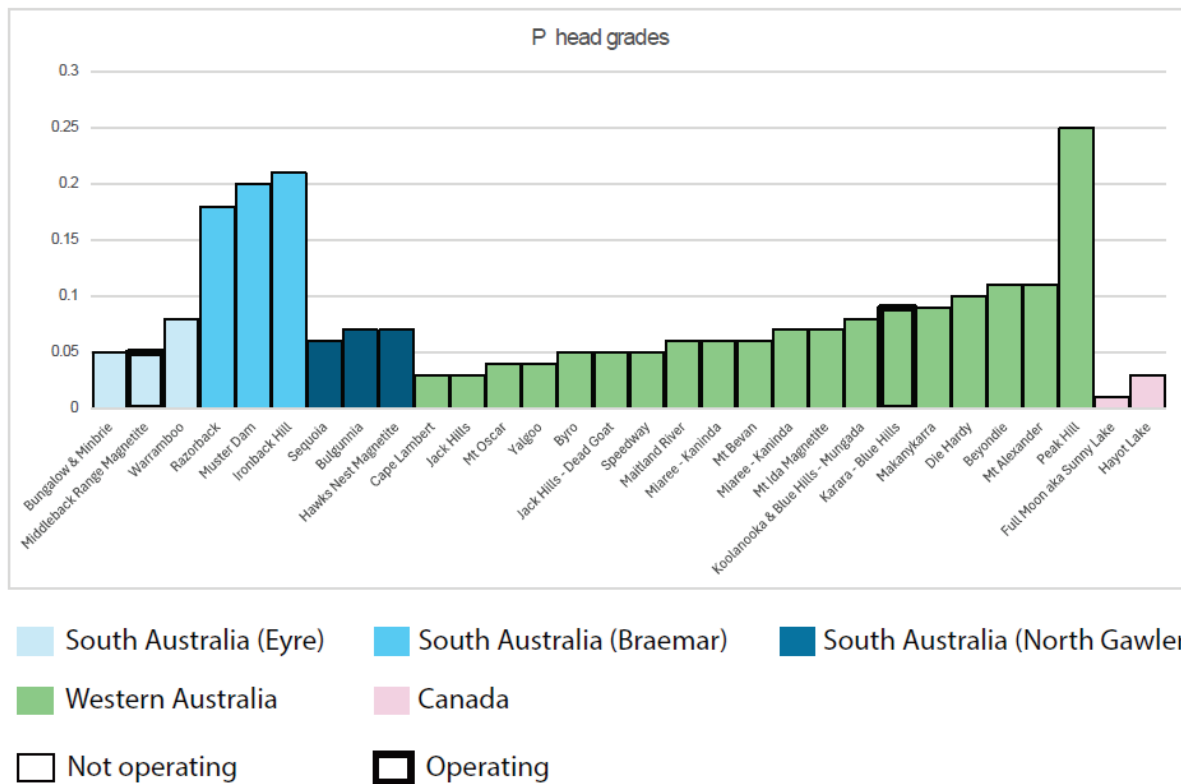


Figure 17: Phosphorus (P) head grades in BIF-hosted and metasedimentary magnetite deposits, grouped by country, state or region.

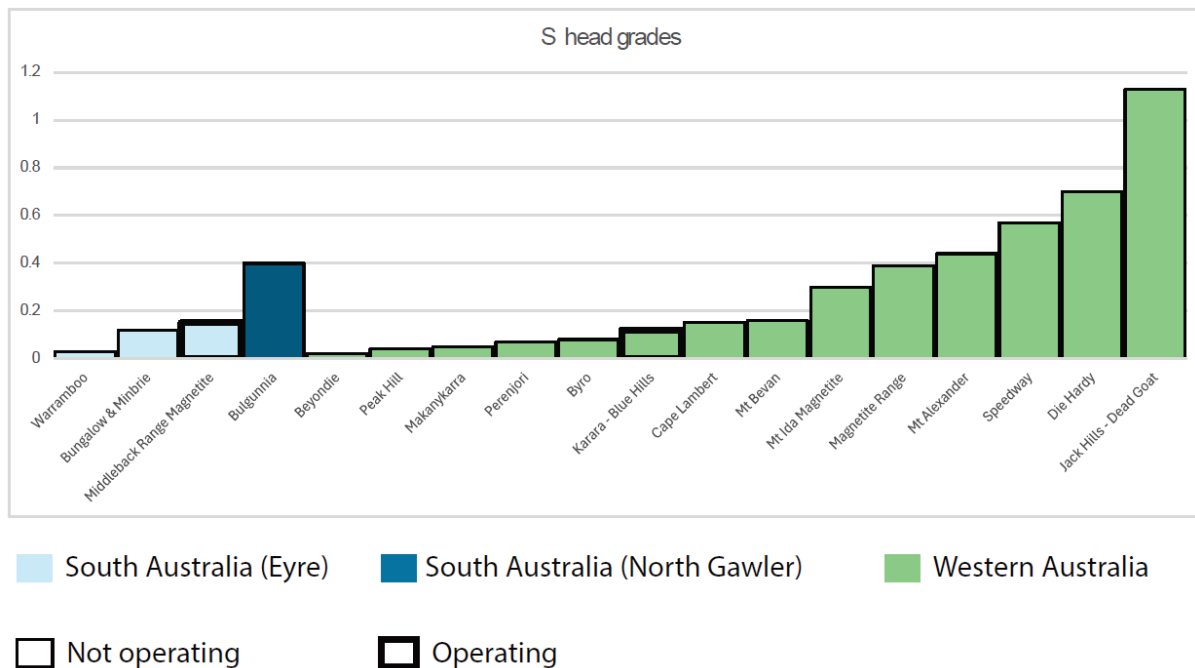


Figure 18: Sulphur (S) head grades in BIF-hosted and metasedimentary magnetite deposits, grouped by country, state or region.

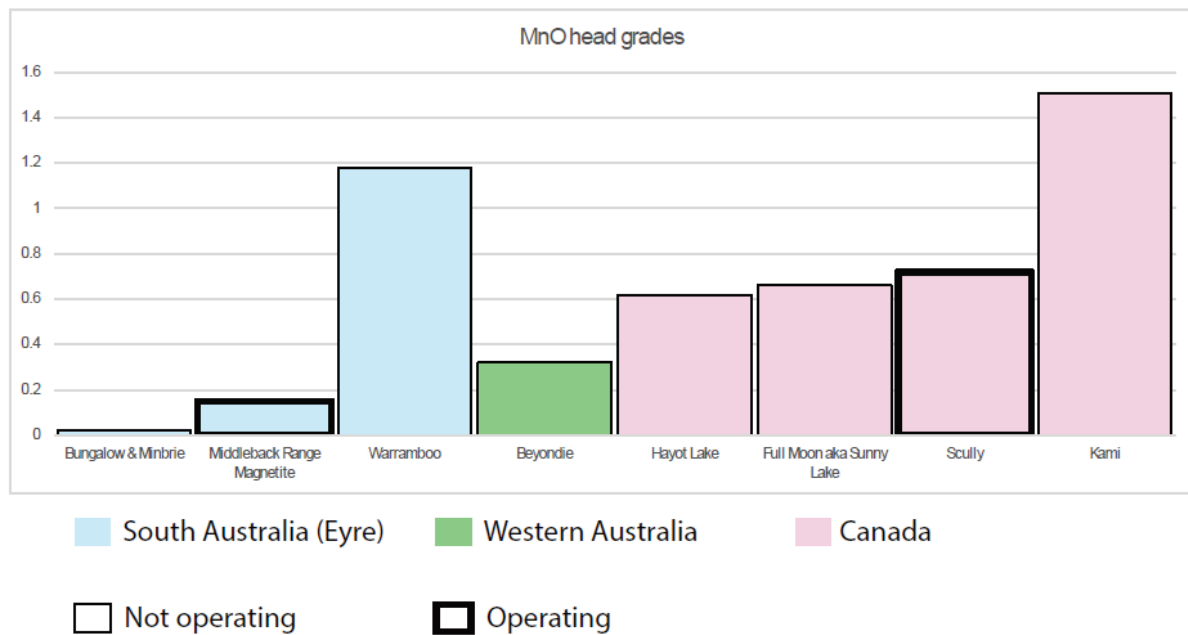
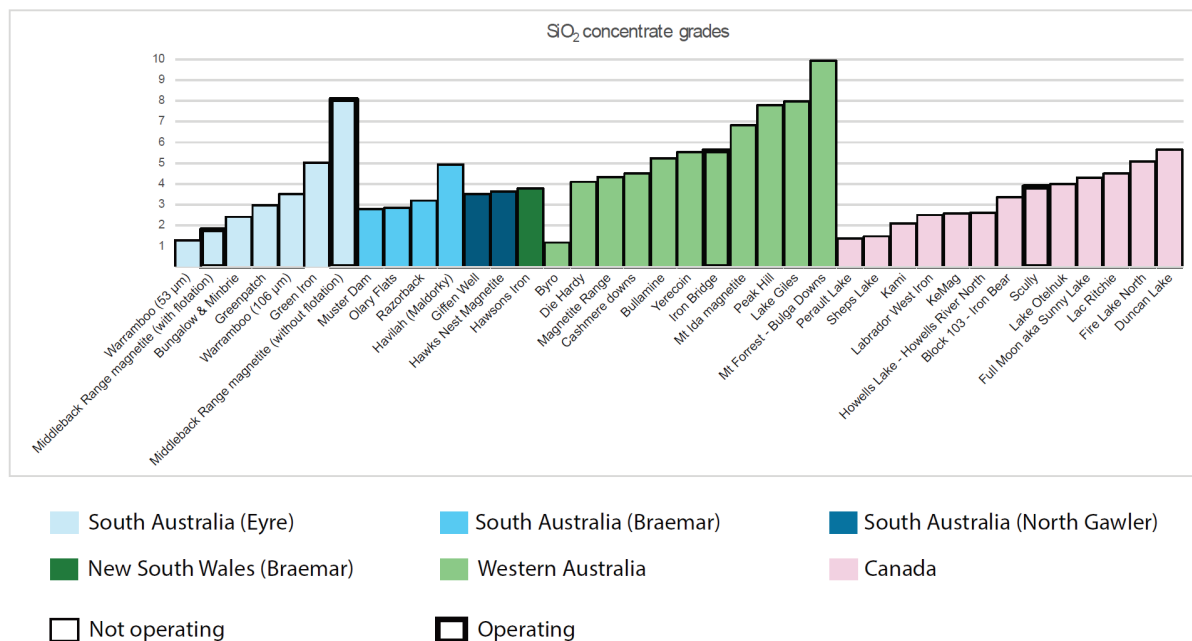


Figure 19: Manganese oxide (MnO) head grades in BIF-hosted and metasedimentary magnetite deposits, grouped by country, state or region.



Data for Green Iron project excludes the Eurilla and Rifle Range deposits

Figure 20: SiO₂ concentrate grades in BIF-hosted and metasedimentary magnetite deposits, grouped by country, state or region. MiddleBack Range Magnetite data is shown before and after flotation.

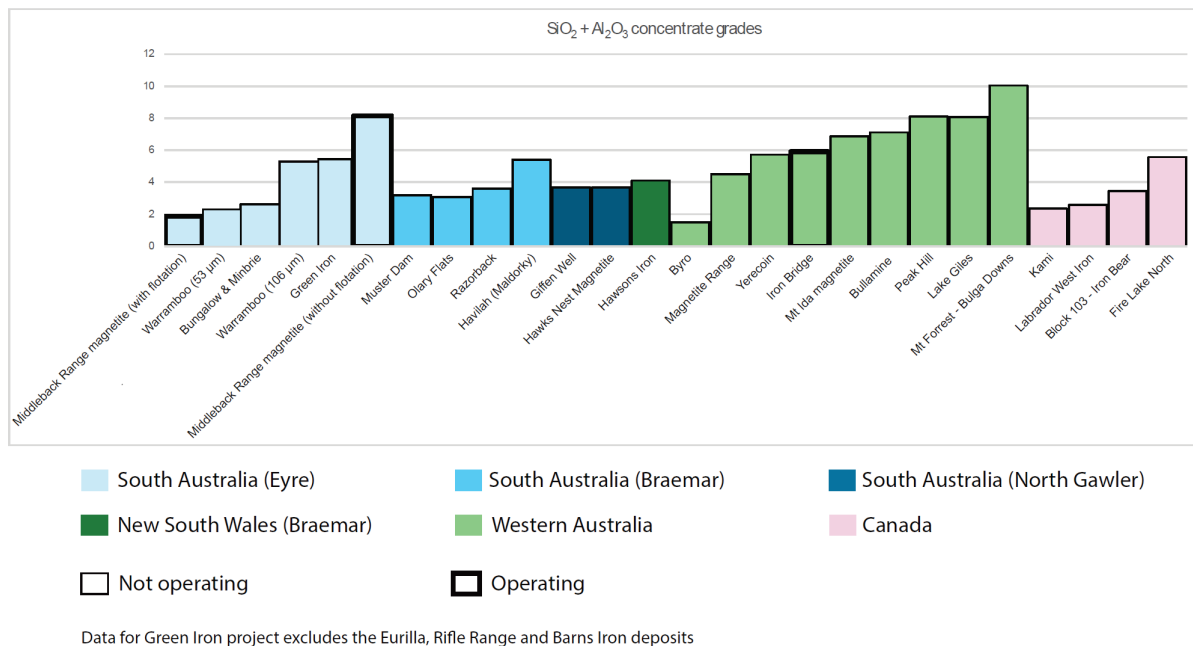


Figure 21: SiO₂ + Al₂O₃ concentrate grades in BIF-hosted and metasedimentary magnetite deposits, grouped by country, state or region. MiddleBack Range Magnetite data is shown before and after flotation.

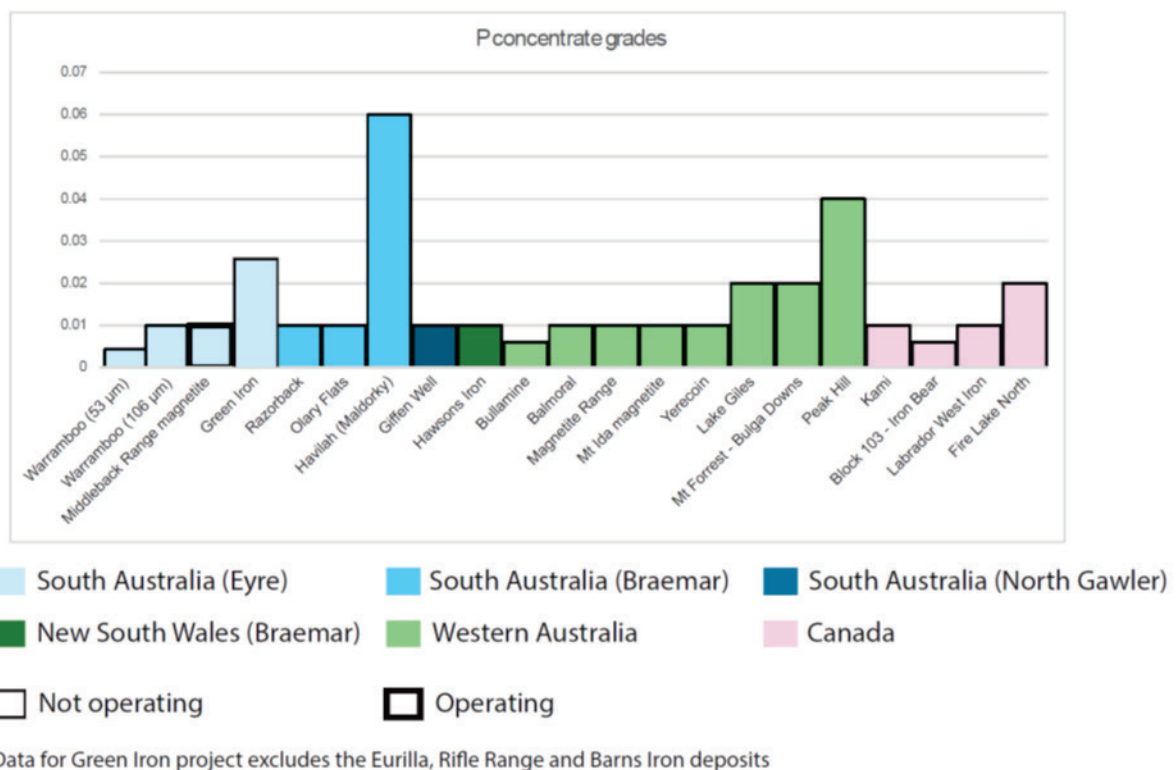


Figure 22: Phosphorus (P) concentrate grades in BIF-hosted and metasedimentary magnetite deposits, grouped by country, state or region.

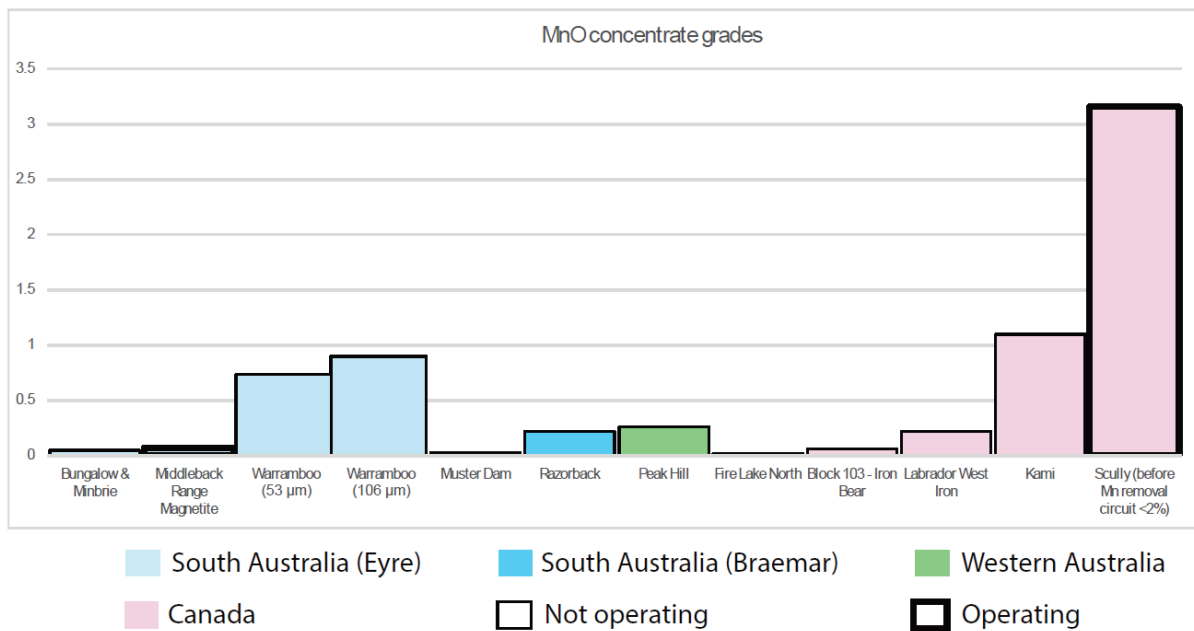


Figure 23: MnO concentrate grades in BIF-hosted and metasedimentary magnetite deposits, grouped by country, state or region.

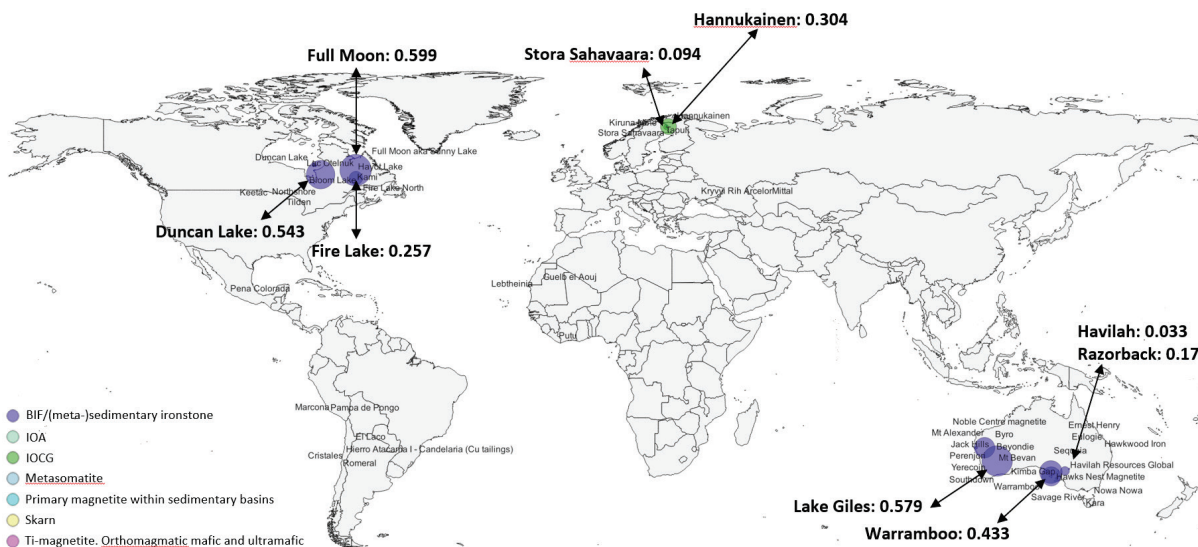


Figure 24: Location of magnetite projects and associated Bond Abrasion Index.

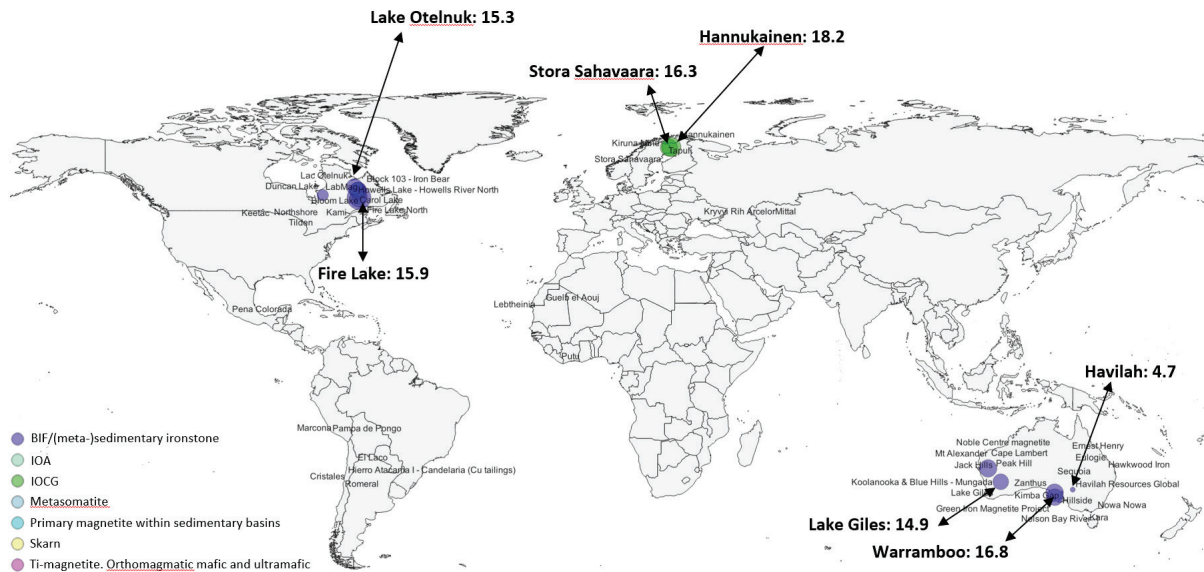


Figure 25: Location of magnetite projects and associated Bond Ball Mill Work Index.

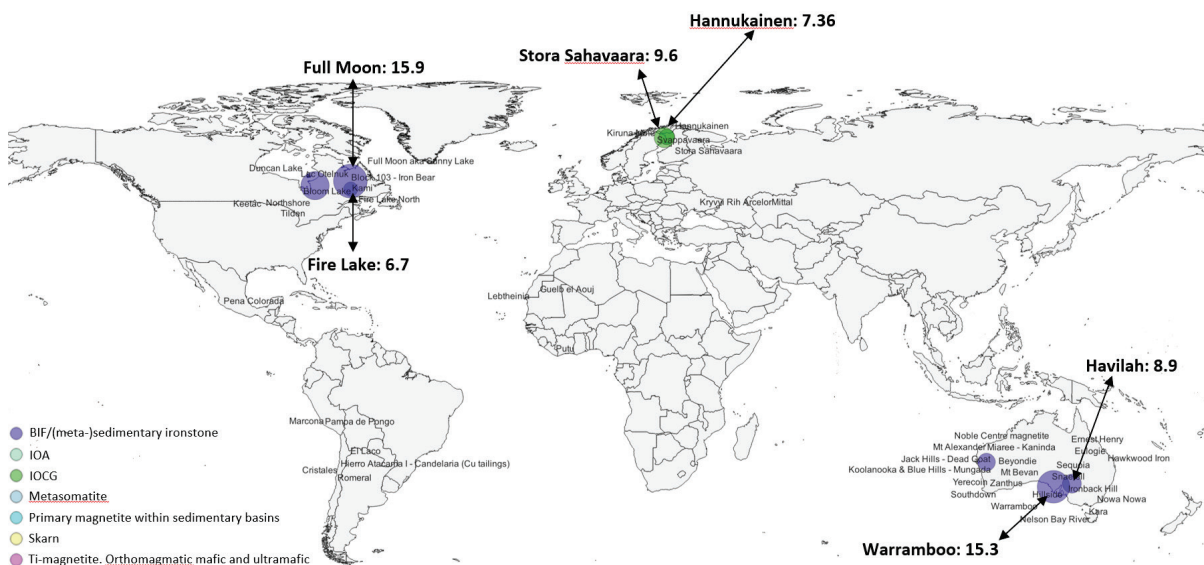


Figure 26: Location of magnetite projects and associated Bond Rod Mill Work Index.

Test	Purpose	Key Parameters/Indicators	Notes
Bond Ball Mill Work Index (BBWi)	Measure resistance to ball milling; estimate grinding energy for ball mills.	kWh/t (energy per tonne)	Higher values indicate harder ore for ball milling.
Bond Rod Mill Work Index (BRWi)	Measure resistance to rod milling; estimate grinding energy for rod mills.	kWh/t (energy per tonne)	Higher values indicate harder ore for rod milling.
Bond Impact Work Index (CWi)	Estimate ore's resistance to impact loading.	kWh/t (energy per tonne)	Assesses ore fragmentation under impact forces.
JK Drop-Weight Test	Characterise ore breakage under impact; predict SAG mill performance.	A, b, t_b	A and b describe breakage; t_b indicates ore-specific fragmentation.
SMC Test (DWI)	Simplified version of the JK Test; predict SAG mill performance.	A, b, t_b , DWI, M_{80} , M_{10}	DWI for hardness; M_{80} for grinding energy in AG/SAG mills; M_{10} for crushing circuits.
Abrasion Index (Ai)	Evaluate wear resistance of ore on grinding media and liners.	Ai (dimensionless)	Higher values indicate higher abrasion rates.
Davis Tube Test	Evaluate magnetic recovery of ore (common for iron ores).	Magnetic recovery (%)	Used for iron ore beneficiation studies.
Point Load Test	Estimate uniaxial compressive strength (UCS) of rocks quickly.	Strength Index (MPa)	Correlates with UCS but simpler and faster to perform.

Table 5: Summary of processing and comminution tests commonly reported for magnetite projects.

Feed Type	Reason for Testing	Implications for Results
Pilot Feed	Evaluate how typical processing feed performs in real-world conditions.	Provides baseline parameters for energy consumption and circuit performance.
Marketing Sample	Test material prepared for potential clients to ensure desired quality and behaviour.	Helps confirm grindability and product quality to match customer specifications.
Coarse-Grain Material	Assess how large, coarse particles break under impact or compression.	Indicates the energy required for initial size reduction (e.g., crushing).
Fine-Grain Material	Evaluate performance during fine grinding (e.g., ball milling).	Reflects behaviour during later stages of comminution.
Copper Concentrate	Analyse material after initial beneficiation (e.g., magnetic separation).	Determines additional grinding or upgrading required for final product specification.
Different Lithological Units	Understand variability across geological domains within the ore body.	Helps plan circuit flexibility and adjust processing strategies for different material types.

Table 6: Summary of feed types commonly reported for processing and comminution tests.

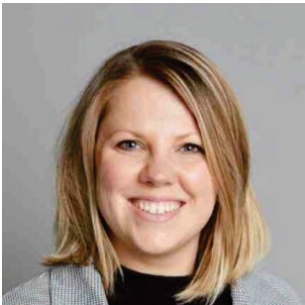
Appendix 2 – Amira P1356 Researchers & Management

Research Partners

Summary list of research partners involved in the project and their roles.

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Thank you

Thank you to all who have contributed to another collaborative Amira project.