PILBARA BIF-HOSTED IRON ORE

INTRODUCTION

- Rising iron ore prices from 2007 to 2011 broadened exploration and research in Western Australia beyond the mining centres of the Hamersley Basin, to the smaller but high-grade (>55 wt% Fe) iron ore deposits in the Yilgarn and Pilbara Cratons.
- Early genetic models for banded iron-formation (BIF)-hosted iron ore deposits were influenced by studies in the Hamersley Basin (e.g. Morris, 1980; Barley et al., 1999; Taylor et al., 2001), but later incorporated results from district-scale studies in the Yilgarn Craton (e.g. Angerer et al., 2015).
- Iron ore deposits of the Pilbara Craton (Fig.1) have only recentlybeen examined, providing a state-wide perspective on iron ore styles and genesis.
- This study addressed the following questions:
  - What are the characteristics of the Pilbara iron ore deposits?
  - How did the deposits form?
  - Which exploration tools are useful for their discovery?

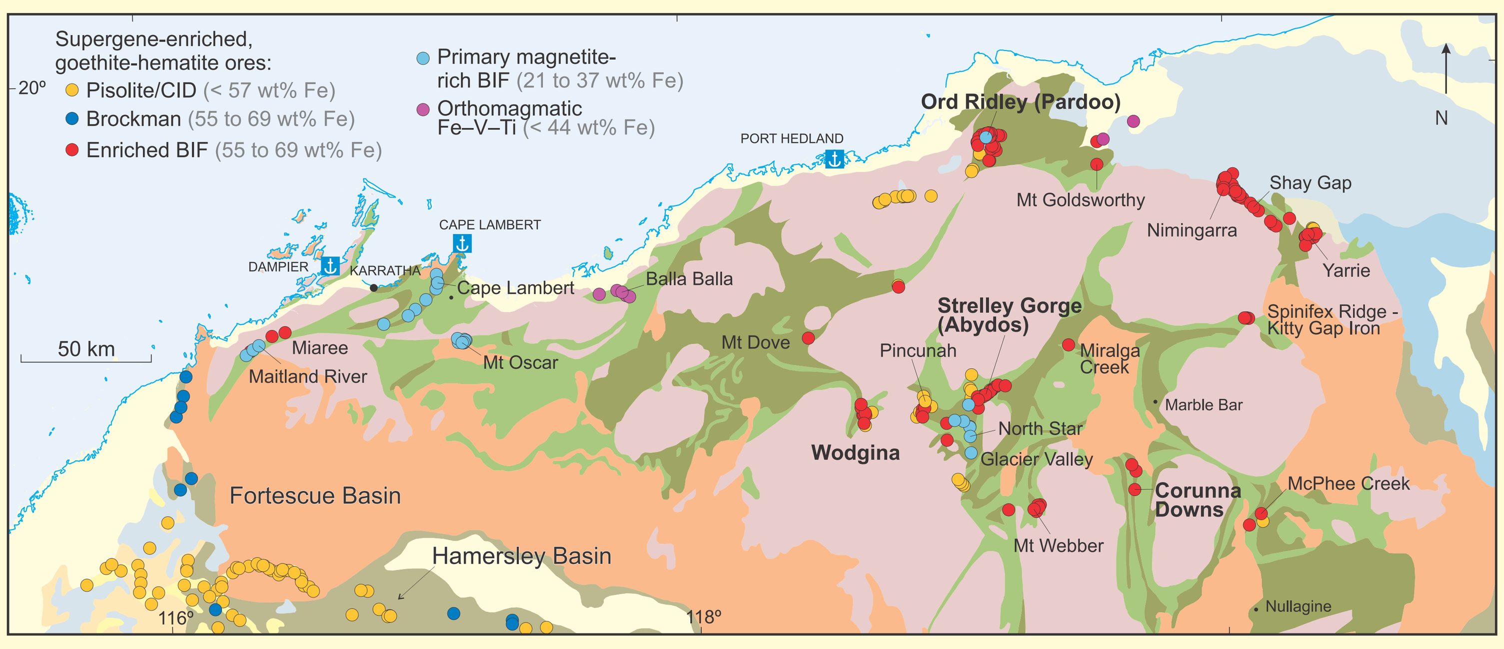


Figure 1. Iron ore deposit styles in the northern half of the Pilbara Craton. Iron ore occurrences are sourced from DMP's MINEDEX database, June 2016. Geology is sourced from the 2016 geological map of Western Australia. Green polygons represent greenstone belts and pink polygons indicate granites. Other colours represent Proterozoic and Phanerozoic rocks that surround the Pilbara Craton.

PILBARA IRON ORE DEPOSIT CHARACTERISTICS

- The Hamersley Basin hosts >76 % of Western Australia's reported iron resources, whereas the Yilgarn and Pilbara Cratons contain about 12 and 11 %, respectively.
- In the Pilbara Craton, primary BIF and supergene-enriched BIF-hosted iron deposits contain >96 % of all iron resources in terms of their contained Fe. Primary magnetite iron deposits have greater reserves, but the higher costs of refining commonly renders them sub-economic. Supergene-enriched BIF ores are higher grade and the main target for exploration. Pisolitic, detrital, and orthomagmatic Fe-V-Ti iron ore prospects are generally too small for mining (Fig. 2).
- Pilbara iron ore deposits share common physical and chemical characteristics:

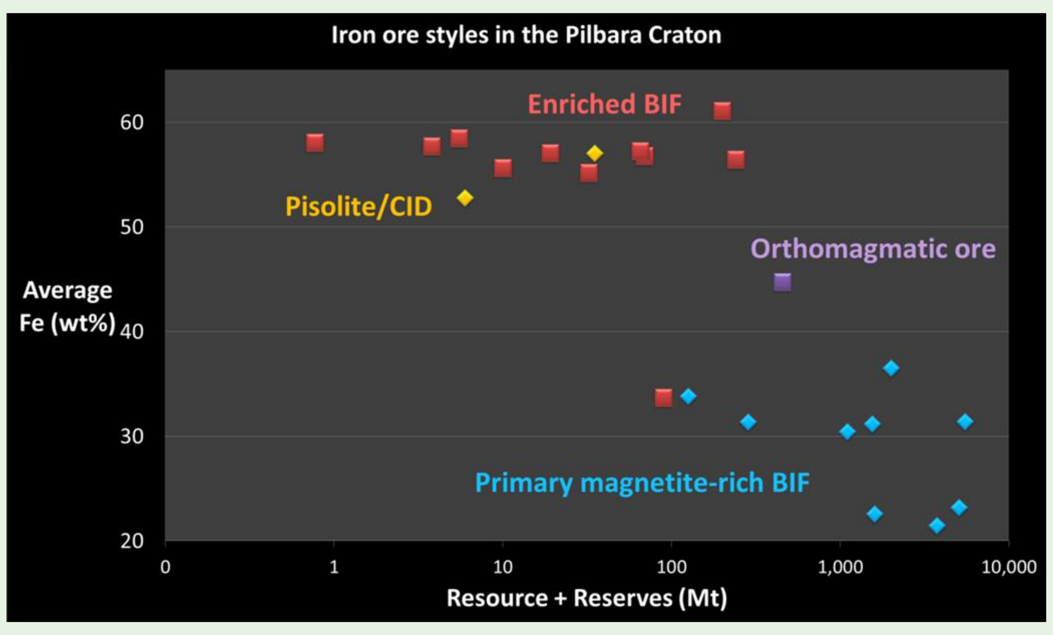


Figure 2. Relative size of iron ore styles

BIF Fertility

- BIFs of the 3022-3016 Ma Cleaverville Formation are the main host to high-grade iron ore deposits. They are relatively thick (up to 1 km) and more iron-rich (31-39 wt% Fe) compared with other major BIF units of the Pyramid Hill, Paddy Market and Cardinal Formations (Fig. 3).

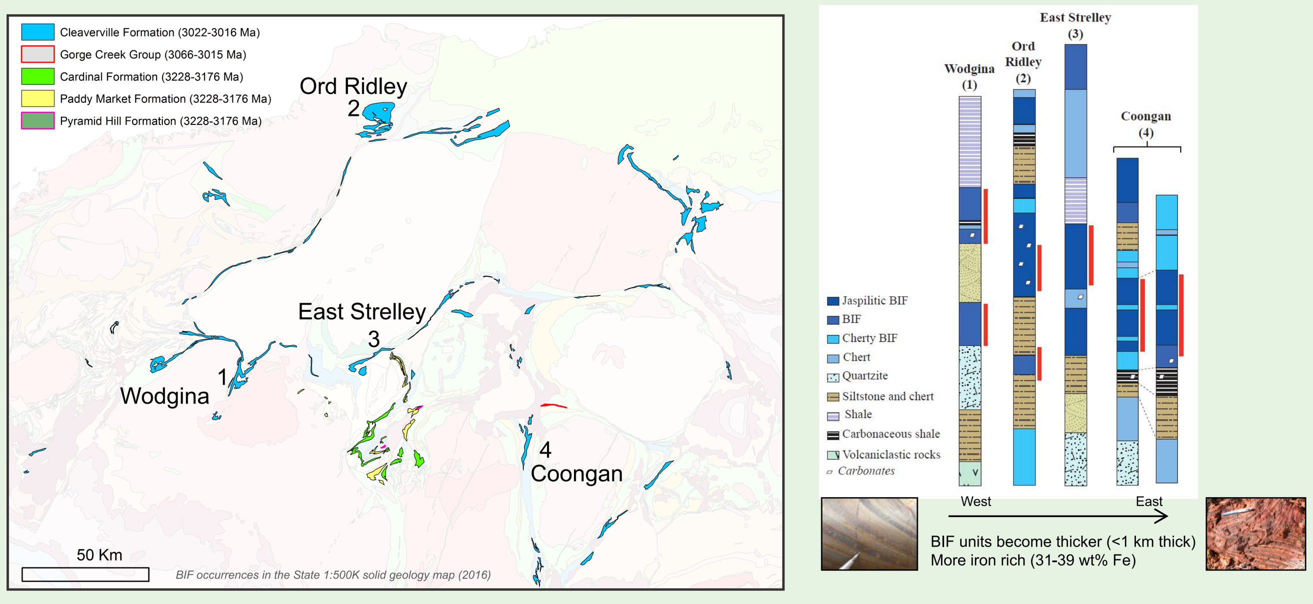


Figure 3. Primary BIF fertility controls on iron ore

Structural Controls

- Iron orebodies are mostly centred on kilometre-scale fold hinges that are intersected by shear zones or fault zones (e.g. Corunna Downs, Wodgina, and Pardoo camps), demonstrating the importance of secondary thickening of BIF units and their coincidence with broad damage zones. The enhanced permeability of these damage zones promotes hydrothermal fluid flow and chemical exchange with BIF, resulting in intense alteration and high-grade iron orebodies (Fig. 4).

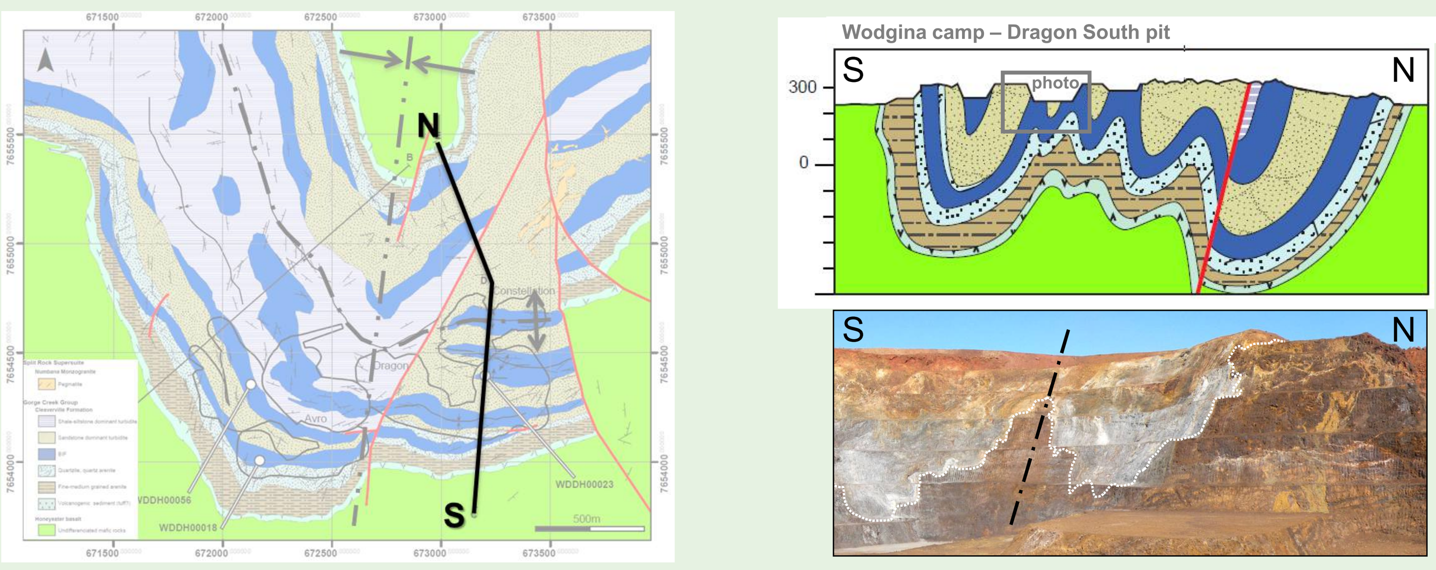
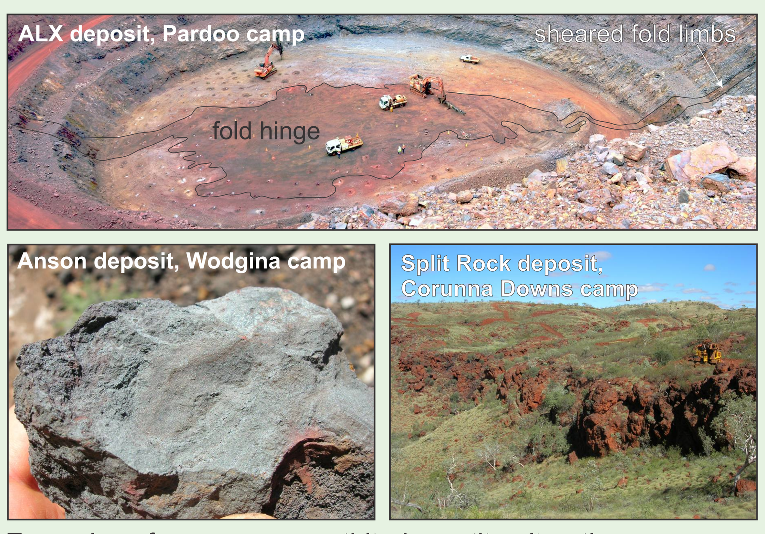


Figure 4. Structural architecture controls - folds and shear zones

Alteration History

- Early hypogene magnetite ± hematite ± quartz ore zones are steeply dipping and extend to depths of > 200 m, but are narrow (<10 m wide) and low-to moderate-grade (37-55 wt% Fe). Overprinting supergene goethite ± martite ores are broader and high-grade, and they extend from surface to depths of about 100 m. Only at Wodgina are the hypogene ore zones wide enough to be potentially economic (Fig. 5).



Examples of supergene goethite-hematite alteration

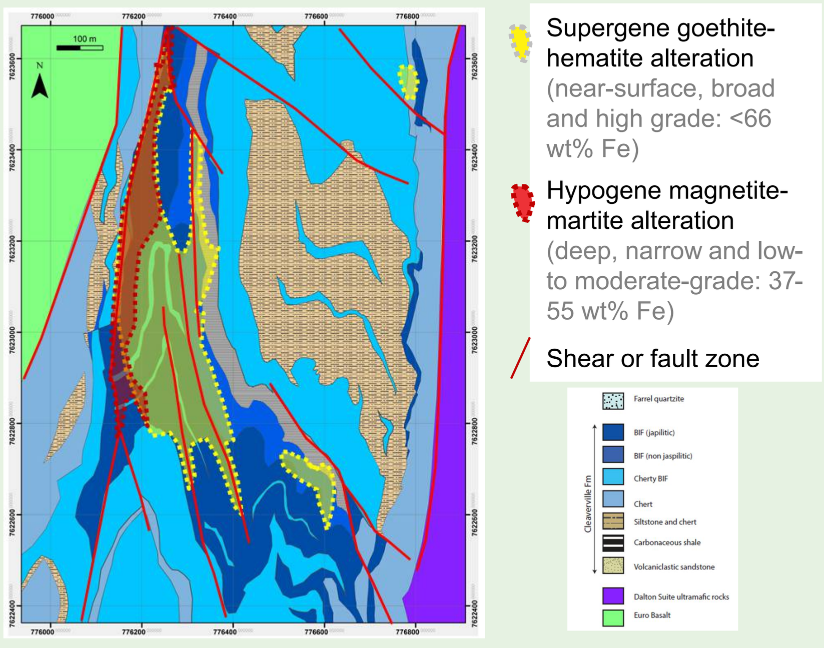


Figure 5. Alteration history - hypogene overprinted by supergene alteration minerals

Chemical and Physical Signatures

- Least-altered BIF is enriched in Fe, LOI, P, Zn, and Ni and depleted in SiO_2 with supergene alteration. Other geochemical trends are camp-specific (Fig. 6).
- Demagnetized zones in the 1st vertical derivative aeromagnetic images correspond with the location of supergene goethite-hematite orebodies due to oxidation of magnetite in BIF (Fig. 7).

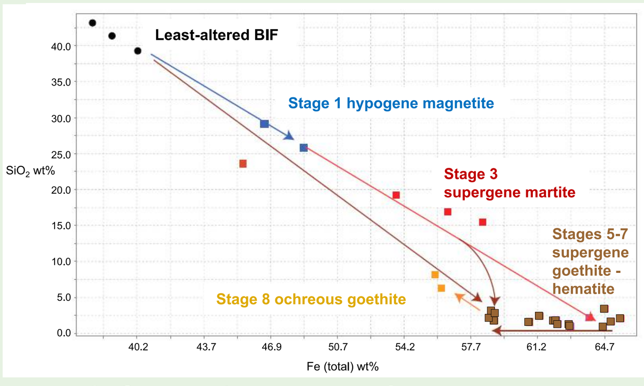


Figure 6. Chemical signatures of iron ore

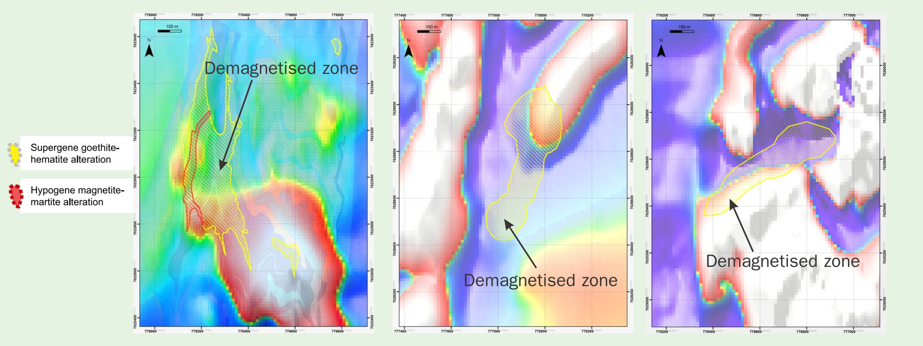
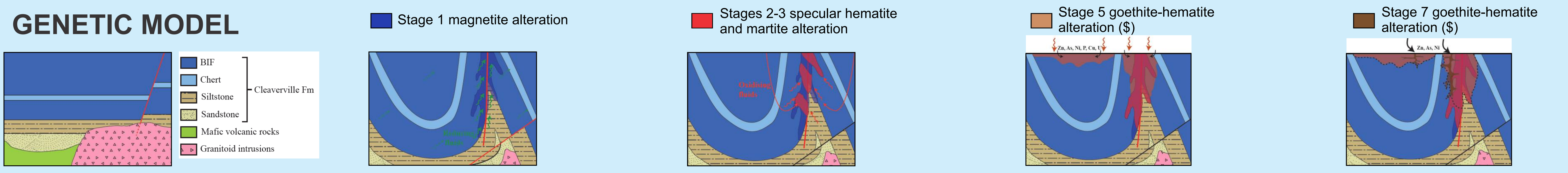


Figure 7. Geophysical signatures of iron orebodies

GENETIC MODEL



3020 Ma: Deposition of the Cleaverville Formation BIF within the George Creek basin. Local extensional growth faults.

2950-2940 Ma: North Pilbara orogeny. Steeply plunging tight folds and shear zones host Stage 1 magnetite.

2215-2145 Ma: Heated oxidized supergene fluids circulate through the top few kilometres of the crust, resulting in the growth of coarse Stage 2 specular hematite and oxidation of magnetite to Stage 3 martite.

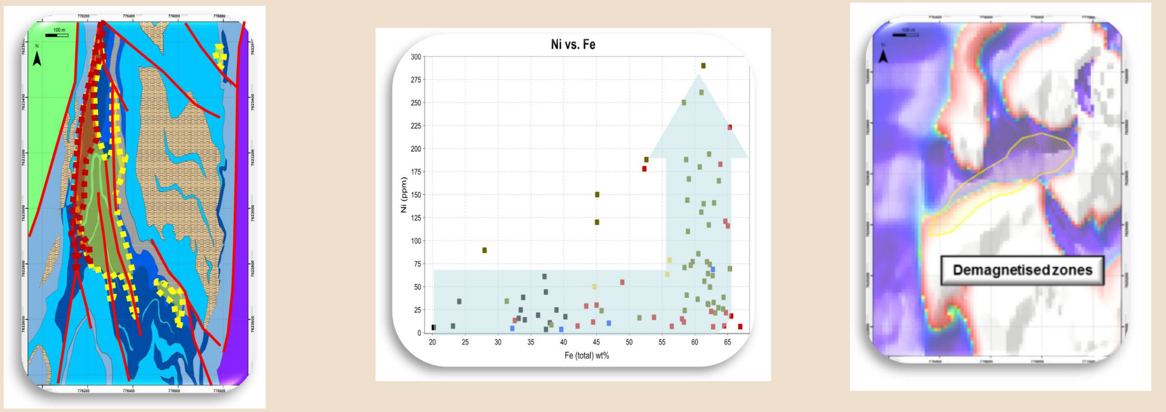
70-50 Ma: Early phase of recent supergene enrichment of iron under tropical (wet) climate. Magnetite oxidized to martite and deposition of Stage 5 goethite.

From 50 Ma to present: Late phase of supergene mineralization under a semi-arid, strongly seasonal climate, causing deposition of Stage 7 goethite.

IRON ORE EXPLORATION STRATEGY FOR THE PILBARA CRATON

- **Mapping:** Use remote methods and field observations to identify fold hinges in BIF and locate intersecting damage zones that served as pathways for fluids to interact with BIF. Hypogene magnetite alteration may form stand-alone orebodies, but more commonly forms proto-ores with moderate iron enrichment along old structures that are locally reactivated and upgraded during supergene alteration.
- **Geochemistry from surface and drill hole samples:** BIF ore across the Pilbara Craton is universally enriched in Fe, LOI, P and depleted in Si. However, camp-specific geochemical signatures suggest the importance of establishing a baseline chemistry for BIF and countryrocks before interpreting geochemical gradients in a camp.
- **Geophysics:** supergene iron orebodies may be indicated by coincident demagnetised zones and gravity lows, but should be validated with independently acquired mapping and geochemical data to avoid false-positive exploration targets.
- **Mineral System model:** Defines all mappable critical elements for formation and preservation of a BIF-hosted high-grade iron ore body. BIF fertility is indicated by the presence of a thick, Fe-rich primary BIF such as in the Cleaverville Formation. Structural architecture maps broad damage zones that intersect BIF and allowed interaction of a Si-undersaturated fluid with BIF to concentrate Fe, most likely an oxidized fluid derived from near surface (meteoric fluids). Preservation of BIF-hosted ore bodies requires a stable landsurface to promote the modification of BIF without subsequent erosion (Fig. 8).

Mapping (remote imagery and field observations) + Geochemistry (surface and drill hole) + Geophysics (magnetics and gravity) ⟷ Mineral Systems Model (based on all available data)



Critical Elements:

1. BIF fertility
2. Structural architecture
3. Si-undersaturated fluids
4. Exhumation and surficial modification of BIF
5. Preservation of ore bodies in grabens or underneath hard cap

Mapping	Geochemistry	Geophysics
Fold hinges	Universal signatures (Fe, Si, LOI, P)	Demagnetised zones
Intersecting damage zones	Camp-specific signatures	Coincident gravity lows
Hypogene magnetite	Requires establishing a baseline chemistry	Integration with independently acquired data

- No "silver bullets"
- Methodically build and test the model
- Model guides the collection of data…but new data refines the model
- Greatest opportunity lies in discovering covered orebodies: testing conceptual targets through drilling or remote methods

Figure 8. Exploration strategy for Pilbara BIF-hosted iron ore

CONCLUSIONS

- In the Pilbara Craton only the BIF-hosted, supergene-enriched ore type is economic. BIF of the Cleaverville Formation is the main primary host to high-grade iron ore deposits. Most deposits in the Pilbara Craton have early, narrow, hypogene magnetite-rich zones, with broader overprinting zones of higher-grade, near-surface supergene goethite-hematite orebodies.
- High-grade BIF-hosted iron ore deposits are formed via the supergene alteration of BIF.
- An exploration strategy includes a methodically built Mineral System model for BIF-hosted iron ore deposits. This defines how to detect iron ore by integrating mapping, geochemical, and geophysical methods to establish orebody signatures and define gradients to ore. Petrophysical and chemical baselines are used to separate ore body signals from background geological noise.

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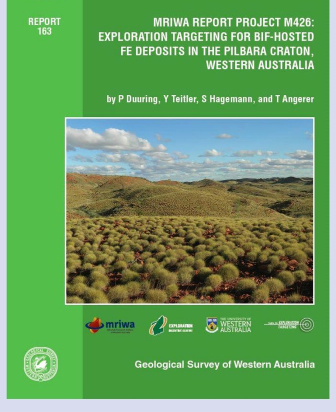
REFERENCES

Angerer, T, Duuring, P, Hagemann, SG, Thorne, W and McCuaig, TC 2015, A mineral system approach to iron ore in Archaean and Palaeoproterozoic BIF of Western Australia, in Ore Deposits in an Evolving Earth edited by GRT Jenkin, PAJ Lusty, I McDonald, MP Smith, AJ Boyce and JJ Wilkinson: Geological Society of London, Special Publication 393, p. 81–115.

Barley, ME, Pickard, AL, Hagemann, SG and Folkert, SL 1999, Hydrothermal origin for the 2 billion year old Mount Tom Price giant iron ore deposit, Hamersley Province, Western Australia: Mineralium Deposita, v. 34, no. 6, p. 784–789.

Morris, RC 1980, A textural and mineralogical study of the relationship of iron ore to banded iron-formation in the Hamersley Iron Province of Western Australia: Economic Geology, v. 75, no. 2, p. 184–209, doi:10.2113/gsecongeo.75.2.184.

Taylor, D, Dalstra, HJ, Harding, AE, Broadbent, GC and Barley, ME 2001, Genesis of high-grade hematite orebodies of the Hamersley Province, Western Australia: Economic Geology, v. 96, no. 4, p. 837–873, doi:10.2113/gsecongeo.96.4.837.



For further reading:

Duuring, P, Teitler, Y, Hagemann, S and Angerer, T 2016, MRIWA Report Project M426: exploration targeting for BIF-hosted iron deposits in the Pilbara Craton, Western Australia: Geological Survey of Western Australia, Report 163, 263p.

ACKNOWLEDGMENTS

- This work was undertaken as part of collaboration between the Mineral Research Institute of Western Australia (MRIWA), Atlas Iron Ltd, the Centre for Exploration Targeting (CET) at the University of Western Australia, RWTH Aschen University, and the Geological Survey of Western Australia.
- Project researchers Paul Duuring, Yoram Teitler, Steffen Hagemann, Thomas Angerer, Christina Hemme and Nils Kollert acknowledge the financial and logistical support of Atlas Iron Ltd.
- We thank Tony Bagshaw and Penny Atkins from MRIWA for their support and advice associated with project management, and members of the Centre for Microscopy, Characterisation and Analysis (CMCA) at the University of Western Australia, and Noreen Evans, Brad McDonald, Svetlana Tessalina (Curtin University), and Martin Van Kranendonk (University of New South Wales) for their technical advice and assistance.

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