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Recent Advances in BIF-related Iron Ore Models and Exploration Strategies

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ABSTRACT

Recent research on BIF-related high-grade iron ore mineralization has resulted in new genetic models that emphasize the structurally controlled hypogene alteration and upgrade of BIF to high-grade (>65% Fe) iron ore. Conventional structural and stratigraphic mapping and reconstructions of the tectonic history of iron districts, in combination with high-tech geochemical analyses such as laser ICP-MS analyses of in situ oxides and fluid inclusions, stable (C-O-H) and radiogenic (Sr) isotopes, provide the iron explorationists with an invaluable set of tools to discover concealed iron ore bodies, deposits and districts. Two case studies from Western Australia illustrate: (1) the power of a tectonic reconstruction of the Paraburdoo Ranges and its significance for the location of high-grade hematite mineralization, and (2) the interpretation of structural controls on iron mineralization in the C deposit and its implications for resource estimation.

INTRODUCTION

The past 15 years has seen significant new research conducted on BIF-related iron ore mineralization leading to new genetic models that emphasize the role of hypogene alteration and structurally controlled hydrothermal fluid flow in the upgrade of BIF (35% Fe) to high-grade iron ore (>65% Fe). The application of hydrothermal alteration techniques such as stable isotopes, fluid inclusions, 3-D structural and ore geometry visualization (e.g., Leapfrog modeling) and geophysical methods paired with state-of-the-art numerical modeling has provided exploration geologists with significant new sets of tools to discover concealed ore bodies in established iron deposits, and hopefully new deposits in existing, and to be discovered iron districts.

This contribution highlights the recent developments in the genetic models for BIF-related iron mineralization, provides an overview of geophysical and geochemical methods that can be used to explore for, and distinguish between high-grade iron deposits and styles, and presents two case studies highlighting the role of fault zones and associated fluid flow in the formation of high-grade BIF mineralization and improved resource estimation.

RECENT ADVANCES IN GENETIC MODELS

In the mid-1990's Hamersley Iron established a task force to investigate the potential of exploring for concealed iron ore bodies in the Hamersley Province of Western Australia. Emphasis was placed on the regional analysis of the evolution of the Hamersley Province, and review of the genesis of the high-grade iron ores. The ultimate objective was to decipher the key processes, which had created the known giant high-grade deposits, and to use this understanding to explore in locations where similar processes had occurred. This work re-ignited academic interest in the genesis of high grade iron ore deposits, and eventually led to a renewed "hypogene" ore genesis concept for deposits in the Hamersley Province in Australia and worldwide (Barley et al., 1999; Taylor et al., 2001; Dalstra et al., 2002, Hagemann et al., 2005).

Conventional wisdom in the early to mid 1990's was that high-grade Fe ores were formed by the supergene upgrading of BIF (35% Fe) to high-grade ore (>65% Fe) during the Mesozoic time (Morris, 1980, 1985). The validity of the "young" age for the mineralization (upgrade) process was questioned by Martin et al. (1998) who applied SHRIMP U-Pb zircon age dating on zircons from volcaniclastic breccias within the lower Wyloo Group and indicated that hematite detritus in that group was derived from hematite ores older than 2209 +/- 15 Ma. This result casted doubt on the timing of the supergene model of

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Morris (1980, 1985) who proposed a long period of surficial exposure between deposition of the Turee Creek and Wyloo Groups. This date is compatible with the enrichment of iron through hypogene fluids as first proposed by Li (1993). Barley et al. (1999) used textural evidence paired with fluid inclusion data on quartz from quartz-hematite veins to propose a largely hydrothermal origin for high-grade iron mineralization at Mt Tom Price. Powell et al. (1999) used new geological mapping, basin analysis, and calculated fluid compositions (based on stable isotope data) to propose that the microplaty hematite, and possibly martite-goethite ore bodies in the Hamersley Province were formed by heated fluids (>200o to 400oC) driven by early Paleoproterozoic Ophthalmian orogenesis (~2450 - 2200 Ma). Hagemann et al. (1999) applied detailed microthermometry, ion-chromatography and oxygen and hydrogen isotopes on quartz, carbonates, oxides and sheet silicates to propose a 2 stage hypogene hydrothermal model of oxidation and leaching reactions for the upgrade of BIF to high-grade iron ore. Ascending fluids were derived from basinal brines whereas late, descending fluids were likely meteoric waters. Oliver and Dickens (1999) conducted stable isotope and fluid inclusion analyses of sets of regional samples from the Hamersley Province and concluded that largely meteoric waters penetrated BIF layers during active foreland fold- and-thrust belt formation and exhumation. As these fluids descended and warmed, they removed silica, locally transported iron, and oxidised magnetite-rich BIF's to produce hematite. In 2001, Taylor et al. (2001) published the so far most comprehensive genetic model for the high-grade hematite ore bodies in the Hamersley province. They used an integrated structural, hydrothermal alteration and fluid chemistry approach to show that the hematite ores resulted from a multi-stage, sequential removal of gangue minerals and oxidation processes through hypogene fluids. The final, purely supergene stage of upgrading penetrated deep below the present surface and produced the final product of highly porous hematite ore characterized by martite and microplaty hematite interbedded with kaolinitic shale bands. In 2002, the Australian Institute of Mining and Metallurgy (AUSIMM) conducted a conference on iron ore, with a conference proceedings containing 10 papers that dealt with various aspects of hypogene alteration and mineralization in the Hamersley (Brown and Oliver, 2002; Webb et al., 2002), Iron Quadrangle (Pires, 2002; Verissimo et al., 2002), Carajas (Guedes et al., 2002) and Northern Cape Province (Carney and Mienie, 2002) Three papers evaluated the genetic models (Beukes et al., 2002; Morris 2002, and Lascelles, 2002). Webb et al., (2003) used detailed mineralogy and geochemical analyses on samples from the Dales Gorge Member and surrounding shales from type sections near Wittenoom and the Mt Whaleback mine near Newman which revealed that: (1) no single process can produce all of the altered rocks at Mt Whaleback, (2) oxidation of magnetite to hematite can occur independently of silica removal or replacement, and (3) the main mineralization event postdates metamorphism. Spier et al. (2003) published the first comprehensive geological and geochemical description of the worldclass Aguas Claras and Pico iron mines in the Quadrilatero Ferrifero. They propose that the soft high-grade ores and iron-rich itabirites are related to supergene processes whereas the hard high-grade ores are of hypogene origin. Ohmoto (2003) published an alternative mechanism for the transformation (upgrade) of magnetite-rich BIF to hematite-rich ores:

$$Fe_3O_{4(mt)}+2H^+ \text{---} Fe_2O_{3(hm)}+Fe^{2+}+H_2O$$

i.e., the leaching of Fe2+ from magnetite through hydrothermal fluids. This reaction has significant implications for any epigenetic model as now the same "deep" hydrothermal fluids that leached silica (de-silicification) would have leached Fe^{2+} from magnetite and converted it to hematite. Consequently the downwards penetrating O_2-rich meteoric waters and resulting oxidation reactions are not anymore a necessary process for the formation of high-grade iron ore. Brown et al. (2004) linked detailed fluid chemistry data to the deformation events at the Mt Whaleback iron ore district and concluded that large amount of heated fluids (200-300oC) were expelled during D2regional folding and thrusting. This fluid flow either continued through to the time of D3aregional extension, or two or more pulses of fluid corresponded with these deformation events. Webb et al. (2004) investigated the carbonate alteration beneath the martite-microplaty hematite ore deposit at Mount Whaleback and concluded that the lack of carbonate-rich, silica-poor rocks in the overlying Dales Gorge Member at Mount Whaleback is consistent with pervasive oxidation of most rocks in the region during or after ore genesis, a process that removed carbonates. McLellan et al., (2004) applied for the first time numerical modeling to simulate surface- and basinal-derived fluids through sites of iron ore during the Proterozoic deformation in the Hamersley province. Their model supports mixing of deep basinal brines and heated meteoric fluids and formation of ore in a 2 stage process via deep "basement"-penetrating, high permeability faults.

Thorne et al., (2004) proposed a two-stage hydrothermal-supergene model for the formation of the North ore body in the Mt Tom Price deposit: Early 1a hypogene alteration involved the upward movement of hydrothermal, CaCl2-rich brines (150-250oC) from the carbonate-rich Wittenoom Formation within large-scale folds of the Dales Gorge Member. Fluid-rock reactions transformed unmineralised BIF to magnetite-siderite-iron silicate BIF, with concomitant de-silicification of the chert bands. Stage 1b hypogene alteration is characterised by an increase in temperature (possibly to 400oC) and the formation of hematite-ankerite-magnetite alteration and finally the crystallization of microplaty hematite. Late Stage 1c hypogene alteration involved the interaction of low temperature (120oC) basinal brines with the hematite-ankerite-magnetite hydrothermal assemblage leaving a porous martite-microplaty hematite-apatite mineral assemblage. Stage 2 supergene enrichment in the Tertiary resulted in the removal of residual ankerite and apatite and the weathering of the shale bands to clay. Rosiere and Rios (2004) investigated fluid inclusions in hematite using infra-red microthermometry technique. They showed the Conceicao ore deposit in the Iron Quadrangle contains two types of high-grade ore bodies: hard massive, practically concordant bodies developed during the Transamazonian orogeny (2.1- 2.2 Ga), and tabular schistose bodies controlled by shear zones that formed during the Brasiliano orogeny (0.8 to 0.6 Ga). The evolution of the hard massive ore is complex and contains two types of hematite with different fluid characteristics. No fluid data for hematite I are available. Hematite II contains low temperature, low to medium salinity hydrothermal fluids of possible (modified) meteoric fluids. The shear zone related ore bodies contain a third hematite type formed by low temperature, high salinity fluids. A final fluid pulse characterized by high temperature and high salinity facilitated deformation and produced specularite. Dalstra and Guedes (2004) proposed that BIF-hosted high-grade hematite deposits form a coherent genetic group with proto-ores forming under relatively oxidizing conditions at temperatures near the surface to reduced conditions at temperatures above 500oC at depth. Mueller et al. (2005) constrained the maximum age of iron ore mineralization (i.e., upgrade of BIF via hypogene hydrothermal fluids) in the Hamersley Province to 2008 Ma, thereby strongly linking it to continental extension possibly related to the breakup of Paleoproterozoic Australia. A second AUSIMM conference on iron ore contained conference proceedings with 17 iron related geological papers. These included: a review paper about iron formation-hosted iron ores in the Hamersley Province (Clout 2005), and a paper that presented discrete genetic models for the Hamersley, Carajas, and Iron Quadrangle iron ore provinces (Hagemann et al., 2005). In addition, there are several regional papers about iron ore deposits or districts in Africa (4), Brazil (4), Iran (1), and Australia (6) (see AUSIMM Publication Series No 8/2005 for detailed references). Gutzmer et al. (2006) published a summary paper about oxygen isotope composition of hematite and genesis of high grade BIF-hosted iron ores. They concluded that when oxygen isotope composition of magnetite and hematite in the BIF protolith are compared with hypogene hydrothermal ore the latter are significantly depleted in 18O. Importantly, this shift is not evident in hematite ores of ancient supergene origin. The oxygen isotope composition may become a tool to categorize high-grade iron ore deposits of unknown origin, especially in geologically complex or poorly exposed areas. Lascelles (2006) published the results of the first modern geological investigations on the iron ore in the Archean Mount Gibson BIF in the Yilgarn craton of Western Australia. He suggests that deep saprolite in situ high-grade ore may be produced by diverse processes, including hydrothermal replacement of chert mesobands by carbonates with subsequent supergene leaching of the carbonate, and by the oxidation of chert-free BIF, in which chert bands either never developed or were apparently removed during diagenesis. Importantly, neither processes requires supergene selective leaching of quartz (chert) during deep weathering. Lascelles (2006) provides a syn-genetic model for the Hope Downs iron ore deposit in the Hamersley Province. Density currents transported reworked iron silicates and hydroxides in colloidal suspension onto an unstable sea floor. The amorphous silica produced during diagenesis of Al-poor iron silicates formed the characteristic chert bands of BIF but some of the hydrous amorphous silica was lost prior to lithification to form chert-free BIF. Weathering of the chert-free BIF produced the high-grade hematite ore that is exposed today.

In summary, the past 15 years research on high-grade iron deposits and districts worldwide resulted in a significant advance in the understanding of the transformation of BIF to high-grade ore.

RECENT ADVANCES IN EXPLORATION STRATEGIES

The recognition of a hydrothermal input to BIF-related high grade iron ore will have a profound effect on exploration strategies, specifically for the exploration of concealed iron ore bodies. Recently, some exploration groups have already applied exploration techniques to characterize fault zones and associated hydrothermal alteration that surround high-grade iron ore and defined structural and alteration vectors towards those high-grade ore bodies.

In the past exploration for BIF-related iron mineralization has been dominated by detailed lithostratigraphic and structural mapping of iron districts at different scales. In many cases, existing outcrop of BIF was mapped in detail to better constrain the geometry and possible disruptions of the BIF in three dimensions. Subsequent drilling of the area resulted in the delineation of BIF and the high grade equivalents. Under pressure from diminishing ore reserves in the Mount Tom Price deposit, Hamersley Iron started the search for concealed ore bodies which necessitated a “fresh” approach in terms of new and innovative exploration tools. Recently, CVRD has embarked on a detailed re-appraisal of the giant Carajas iron deposit and has applied new and innovative geochemical tools to constrain the hydrothermal alteration and mineralization footprint of the mineralizing system in order to better constrain potential vectors towards high-grade ore (cf. Lobato et al., 2005). The following sections discuss recent advances in the use of geophysical and geochemical techniques in the exploration for BIF-related, high-grade iron ore mineralization, in light of the advances in understanding the genesis of the BIF-iron mineral system.

GEOPHYSICAL ADVANCES

Geophysical techniques for exploration for iron have been in existence for several centuries. At the forefront of these has been the magnetic method, given the highly magnetic nature of the magnetite rich rocks that host the deposits. As the method has technically improved, from the imprecise and hard to use “compass” style of equipment, to the precise, fast, and easily operated magnetometers of today, the method’s efficacy has dramatically improved also. Gross geology mapping surveys, in which the host rocks were being sought, has given way to structure mapping, stratigraphy identification, and finally direct detection of mineralized systems. This has been achieved through increased resolution, both spatially, i.e., data density, and spectrally, i.e., dynamic range. Taken to the air in increasingly nimble and stable platforms, entire iron-rich basins can be assessed easily, quickly and cheaply and to a resolution undreamt of in the past. Regional differences could thus be observed, making for easier comparison and anomaly recognition. That anomaly recognition moved from the “bump” detection of the early to mid 20th century, to recognition of features supporting the currently understood ore genesis models. Faults controlling hypogene and supergene fluid movement, the absence, through dissolution, of carbonate-rich sections of the stratigraphy, and reduction in magnetic intensity through the oxidation of magnetite to hematite are now easily detected (e.g., Kerr et al, 1994). An example of this is the removal of

Wittenoom Formation dolomite from between the Marra Mamba and Brockman Iron Formations, which can be directly tested by recognizing the separation between the magnetic anomalies caused by the two.

The magnetite destruction associated with magnetite oxidation and deep weathering to hematite is directly measurable with the magnetic method. An example of this can be found in the Paraburdoo Eastern Ranges where the iron ore deposits form clear magnetic lows with respect to the unmineralized iron formations.

In parallel with developments in instrumentation, the magnetic properties of host rocks and ore have become better understood. Clark and Schmidt (1994) demonstrated relationships between pre- and post-tectonic magnetic remanence and used this to predict mineralization timing relationships. Further, they observe that BIF tends from highly laminated and bedded to massive as it is upgraded to ore, leading to the identification of the destruction of magnetic anisotropy, or magnetic fabric, in the ore. The emergence of full vector and tensor magnetic surveys, together with development of sophisticated numeric modeling tools, suggests an increasing ability to directly outline areas of zero anisotropy.

The gravity method is the second oldest and most widely deployed geophysical technique used in the search for iron. Both magnetite and hematite are considerably denser than the most common gangue mineral in BIF's, i.e., quartz. The removal of the quartz component, by both hypo- and supergene processes should have a dramatic effect on the observed gravity anomaly.

Once again, through the advent of cheaper, robust, digital gravimeters, together with GPS surveying and a burgeoning of airborne gravity gradiometry systems large tracts of perspective terrains are now being assessed with the method. Direct detection and correct interpretation of iron ore is somewhat complicated, however, by the ambiguity in the density contrast. The stripping of silica from BIF's to produce high grade iron ores can result in increased porosity, and hence a lower density, or an increased density if the process includes deposition of secondary iron (or replacement by secondary iron) in the pore spaces. In any case, the gravity method's use as a valuable mapping tool is assured.

Most other geophysical methods have been used at some stage in the exploration cycle or as problem-specific solutions. These include radiometric, DC resistivity, induced polarisation, electromagnetic, and seismic methods. As with magnetics and gravity, their deployment in regional surveys, for example as large airborne surveys (particularly radiometrics and EM) they serve to assist in stratigraphic and structural mapping.

At a local level the most useful of these has been the down-hole radiometric method. The iron rich stratigraphy in the Hamersley Basin, for example, is regularly punctuated by thin shale bands that are conveniently mapped by the method (Harmsworth et al., 1990). While not a direct exploration tool, it has been used extensively by workers to accurately correlate intercepts between holes and elucidate complex structure in an otherwise extremely regular stratigraphy. Despite its demonstrated successful application in the Hamersley Province, down hole gamma logging is rarely used in other iron ore provinces. While regionally the aeromagnetic application of the radiometric method adds little to mapping in well-known areas such as the Hamersley Basin, it provides important lithological information in less well mapped iron provinces.

An increasingly important method that is currently gaining widespread favor is the airborne Transient Electromagnetic TEM method. In its frequency domain guise (FEM) the method has been long known for its ability to differentiate magnetite (Fraser, 1981), suggesting it may be used to directly discern the spatial genesis from magnetite rich proto-ore to hematite ore. In its deeper "looking" time domain guise TEM offers the hope of direct detection of that transition.

GEOCHEMICAL ADVANCES

With the change in the genetic model for high-grade BIF-related iron ore mineralization from supergene to a mixed hypogene and supergene genetic model a change in the choice of geochemical techniques has been observed. In the past, routine XRF and ICP-MS analyses were used to constrain the iron content and contaminants of the enriched BIF. Today a more sophisticated approach is used to constrain the P-T-X conditions of the upgrade from BIF (35% Fe) to low-grade (40-50% Fe) proto-ore to high-grade (>65% Fe) iron ore. Furthermore, specific vectors to high grade iron ore are applied that may assist the explorationist to identify fertile fault or fold systems early in the exploration campaign and specifically for the exploration and exploitation of concealed ore bodies.

Geochemical techniques used include: (1) electron microprobe and laser ICP-MS analyses of oxides and carbonates in order to constrain the mineral chemistry, (2) carbon and oxygen isotopes on the different carbonate species, (3) oxygen isotope analyses of the different oxide species, and (4) microthermometry of fluid inclusion trapped in carbonates and quartz and infra-red microthermometry of oxides. The following paragraphs illustrate examples of the application of these techniques in the use of constraining mineral and isotopic vectors towards high-grade iron ores.

The understanding of the spatial distribution of alteration associated with high-grade iron ore deposits, particularly the textures and mineralogy of quartz, quartz-carbonate and carbonate veins is essential in defining mineral vectors towards high-grade ore. An example is the spatial distribution of the Mn content in carbonates with respect to the proximity to high-grade iron ore (Figure 1) At both the Mt Tom Price and Paraburdoo iron deposits the Mn content increases markedly in vein hosted carbonates with proximity to the ore bodies.

The carbon isotope signature of the different carbonate species from the Hamersley Province (Figure 2) displays a systematic change in $\delta^{13}C$ between unmineralized BIF and hypogene carbonate alteration (cf. Thorne et al., 2004). The similar oxygen isotope compositions, but increasingly heavy carbon isotopes from magnetite-siderite-iron silicate to hematite-ankerite-magnetite alteration zones, suggest the progressive exchange (mixing) with an external carbon-rich fluid with a heavy carbon isotope signature.

Recent analyses of the ^{18}O composition of hypogene iron oxides in the Southern Batter fault zone,located in the central portion of the Mt Tom Price deposit (Figure 3) revealed a distinct ^{18}O gradient from $\delta^{18}O$ values of -9‰ in the core to -

2.5‰ at the edges of the fault zone (Thorne et al., in press),. The spatial variation in $\delta^{18}O$ values are interpreted to be controlled by higher hydrothermal fluid flow (high water/rock ratio) in the proximity of the fault zones. Results also show that supergene overprint of hypogene formed proto-ore (i.e., carbonate alteration) has little no effect on the $\delta^{18}O$ isotopic composition of high-grade ore (cf. Gutzmer et al., 2006). The latter may be a powerful tool to discriminate between supergene and hypogene formed iron oxide ore.

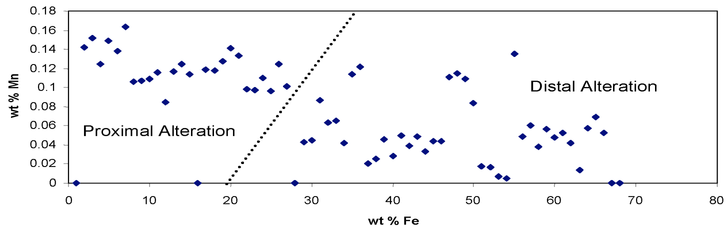

Figure 1: Mn versus Fe content plot of vein carbonates at the Mt Tom Price and Paraburdoo iron deposits with respect to the proximity to high-grade iron ore.

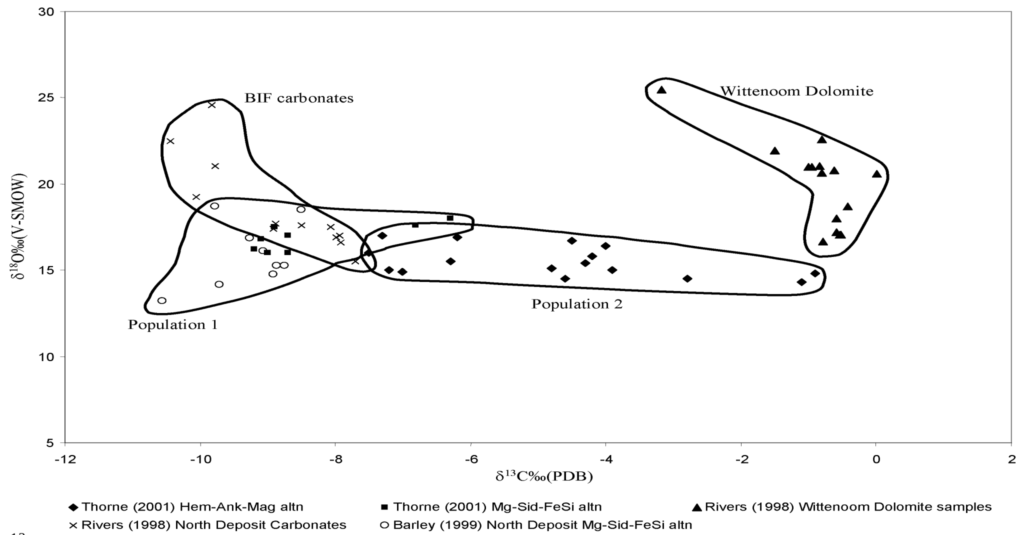

Figure 2: $\delta^{18}O$- $\delta^{13}C$ diagram showing the isotopic composition of the various carbonate populations in the North and Mt Tom Price deposits

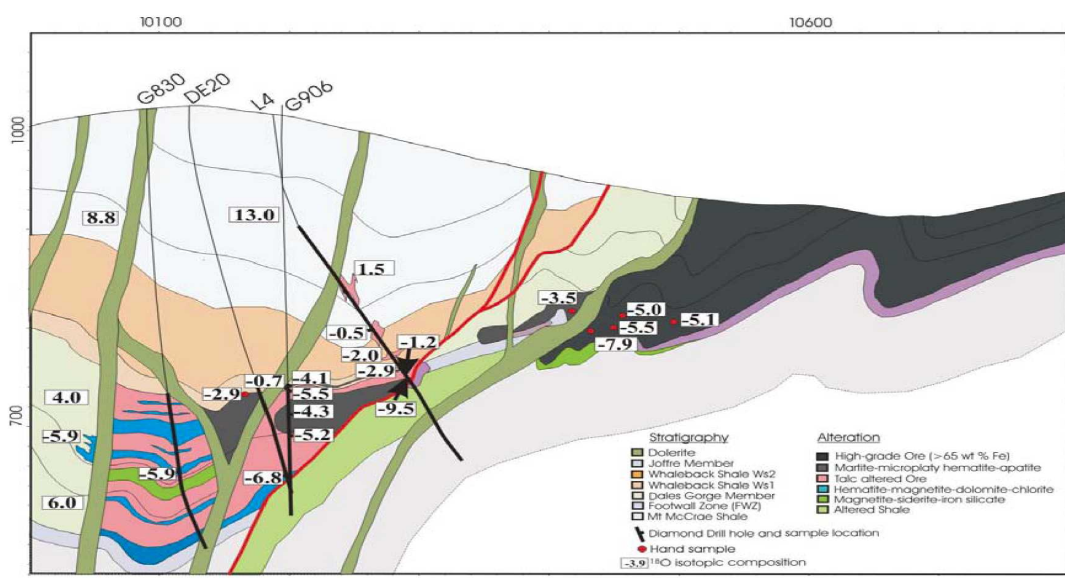

Figure 3: Sample distribution, hypogene alteration zonation and $\delta^{18}O$ compositions of iron oxide samples through section 14000E, Mt Tom Price Deposit.

CASE STUDY 1-PARABURDOO RANGES

Structure is the most important control on high grade hematite deposits, and therefore understanding the structural framework of Proterozoic iron ore basins is critical for locating new deposits (cf. Dalstra 2005). Because high-grade iron ore deposits in the Hamersley Province formed relatively early in the tectonic history (c.f. Powell et al., 1999; Taylor et al., 2001), some of the ores have undergone several phases of deformation, metamorphism and hydrothermal alteration associated with the formation and re-activation of fault zones subsequent to ore formation. To understand the setting at the time of mineralization it is therefore critical to reconstruct the structural geometries through step by step removal of the later events. One area where a reconstruction of the fault zones has helped to identify and explain concealed high-grade iron ore bodies is the Paraburdoo Range in Western Australia. The following case-study based on the detailed structural analysis by Dalstra (2005) illustrates the significance of the structural unraveling of a given mineralized area in the exploration for concealed ore bodies.

The Paraburdoo high-grade iron deposits are located about 65 km south of the Mount Tom Price deposits and contained a pre mining ore reserve of more than 300 Mt at 64% Fe and 0.08% P (Taylor et al., 2001). Several separately named deposits constitute the Paraburdoo Resource, including, among others, 11West, 4West, 4East, 23East, Eastern Ranges, 64East, and Channar (Figure 4). The Hamersley Group BIF's host the ore, and dip steeply to the south. These are overlain unconformably by the Wyloo Group (Taylor et al., 2001). The flat 4W and 4E Basal faults and the steeply northeast-dipping 18E faults and Ratty Springs Fault displace the Hamersley Group and also cross-cut the Lower Wyloo Group unconformity (Figure 4, 5A). They are, in turn, truncated by the Upper Wyloo Group unconformity at the base of the Mount McGrath Formation, then rotated by the Capricorn folding event, which has imposed the southerly dip on all beds. Prior to the Capricorn folding the flat faults that now underlies both the 4W and 4E iron ore bodies were steep, north-dipping normal faults (Taylor et al., 2001; Dalstra 2005).

Dalstra (2005) pointed out that in order to reconstruct the setting of ore formation at Paraburdoo the hematite conglomerates beds at the base of the Mt McGrath Formation (Figure 5A) need to be back-rotated in order to assume their near horizontal depositional setting. In the western section of the Paraburdoo Ranges, the conglomerate beds dip 40-50* SSW indicating that the mineralized geometry was significantly modified during the Capricorn orogeny (Dalstra 2005). Back rotation of the 4 East deposit to syn-Upper Wyloo Group deposition shows that the steeply dipping reverse 18 East fault likely originated as a moderately steep SW dipping normal fault (see Figure 5 B). Analysis of the geometry of the fault system depicted in Figure 5B also suggests that the hematite ore formed in an extensional graben at least 500 to 800 m below the McGrath unconformity.

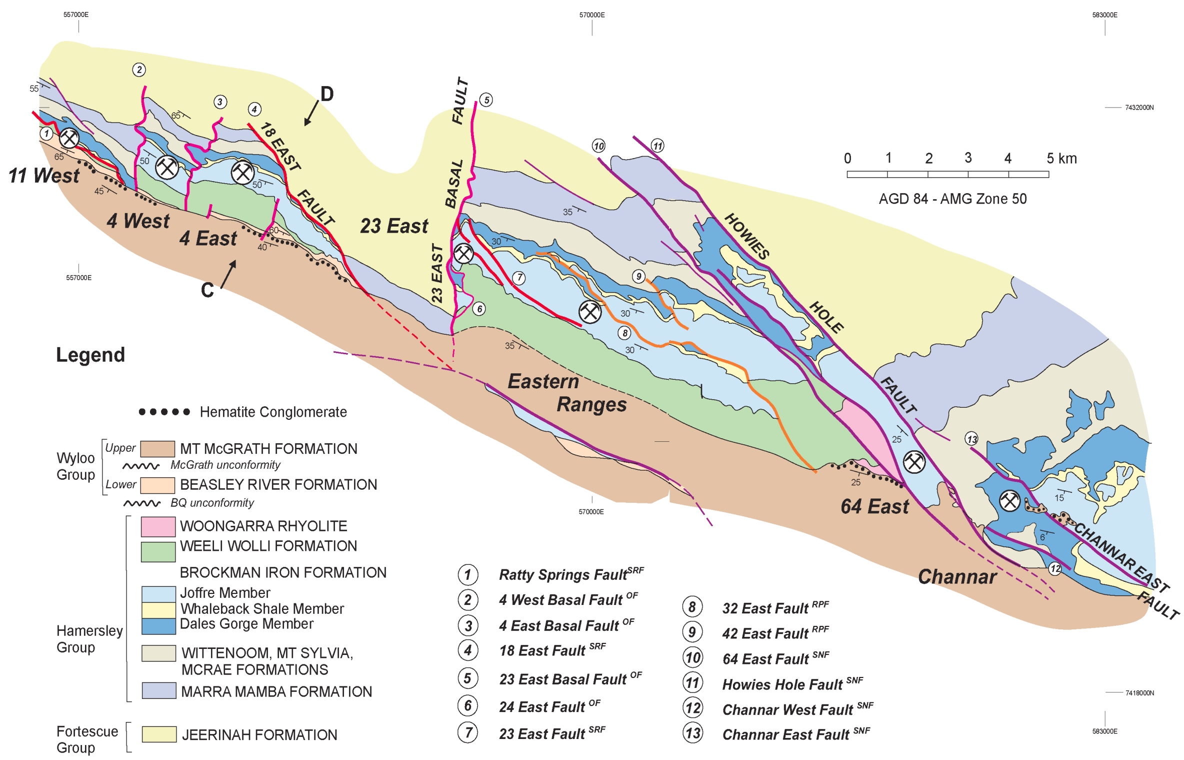

Figure 4: Geological map of the BIF-related high-grade Paraburdoo deposits in the Hamersley Province of Western Australia displaying location of ore bodies and open pits. Also shown are the lithostratigraphic setting, major fault systems, and unconformities. This map is the result of detailed Hamersley Iron Pty Ltd open pit and regional mapping as well as interpretation of drill hole data.

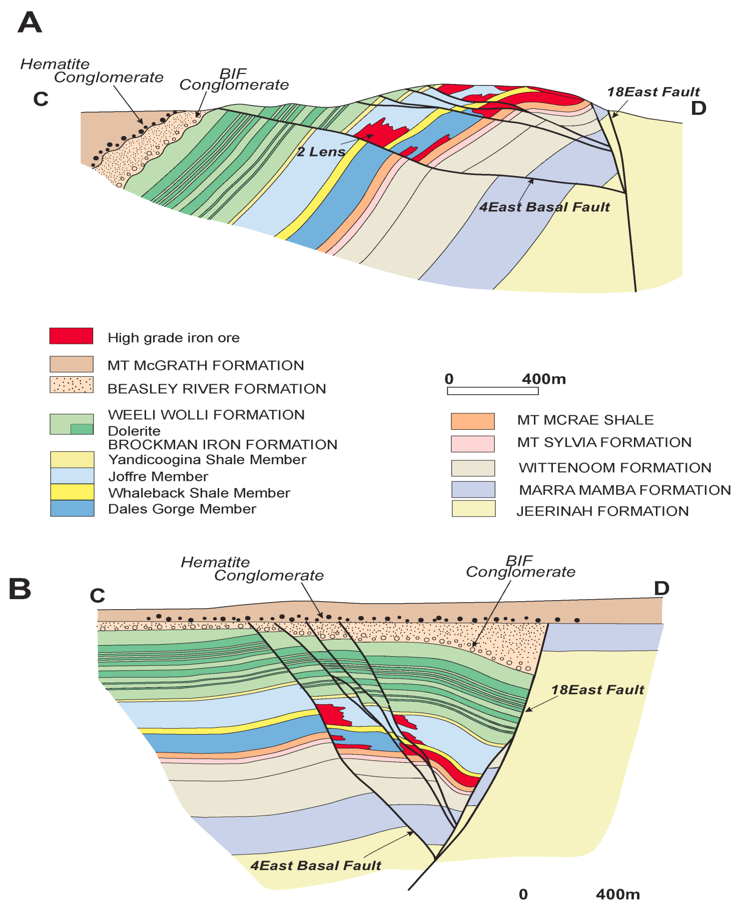

Figure 5: A Cross-section 1820E through the Paraburdoo 4 East deposit, looking west (modified after Taylor et al. 2001). B Reconstructed cross-section 1820E through the 4 East deposit during the syn-Wyloo Group deposition and prior to the F4 Capricorn orogeny; modified after Dalstra, 2005).

A reconstructed long section through the Paraburdoo Ranges syn-Upper Wyloo group deposition indicates that the proto-hematite ore bodies had already formed at that time and that some were actively eroding, forming hematite conglomerates (Dalstra 2005). The long-section also shows that ore bodies at 4 West, 4 East and 64 East formed in grabens or half-grabens, at least several hundred of meters below the surface, thus were shielded from erosion and thus preserved. Only the 11 West and Channar iron deposits formed on horsts and are still preserved; ore bodies on the Ratty Springs- and 18 East Horsts that may have been present prior to the erosion before Lower-Wyloo Group deposition likely were eroded with their ores now making up the hematite conglomerates that are located immediately adjacent to these horsts.

Reconstructing the geology of the Paraburdoo Ranges, syn-Lower Wyloo group deposition, i.e., prior to the iron ore mineralization suggests that the geometry of the area is a series of half grabens progressively stepping down to the ENE (Dalstra 2005). Oblique reactivation of these early extensional normal faults prior to the Upper Wyloo Group may have been instrumental to tap into the underlying dolomites and create fluid pathways. These pathways are essential for silica-undersaturated, hypogene hydrothermal fluids to ascend upwards into the BIF, causing large-scale silica removal and subsequent iron enrichment that formed the giant iron ore bodies.

Tectonic reconstruction of the mineralized environment of the Paraburdoo Ranges results in a number of testable predictions, both for exploration and future research. The most critical prediction is that proto-ores to high-grade hematite deposits can form at least several hundreds of meters below Proterozoic unconformity surfaces, and possibly much deeper. It also predicts that there could be a range in depths for proto-ore formation, the Channar and 11West Deposits representing the shallowest systems and the 4East the deepest at Paraburdoo. All deposits in the Paraburdoo Ranges however formed most likely significantly closer to the paleosurface than the giant Whaleback and Mt Tom Price Deposits, both of which are characterized by an absence of Proterozoic unconformity surfaces nearby.

CASE STUDY 2 THE C DEPOSIT

Area C is located approximately 100 km northwest of Newman and contains ~1100 Mt of Marra Mamba and Brockman M-G (martite-goethite) iron mineralization. Ore-grade mineralization in the C Deposit of Area C is hosted almost entirely in the Mount Newman Member of the Marra Mamba Formation. The dominant structures in the vicinity of Area C are variably east-west trending folds (Figure 6), which formed during two major north-south compressional tectonic events. During the Opthalmian Orogeny (~2450 - 2200 Ma), an arcuate fold and thrust belt formed, with associated south-dipping thrust faults and north-verging asymmetric to overturned folds. During the Ashburton Orogeny (~1800 - 1650 Ma), broader, more open and upright folds formed, including the Weeli Wolli anticline at Area C. All Area C deposits are located on the northern limb of the Weeli Wolli anticline (Figure 6).

Mining operations in the C Deposit bulk sample test pit in 2002 exposed deposit-scale thrust faults and overturned folds (Figure 7), which are significant controls on the distribution of higher-grade mineralisation (> 60% Fe). In detail, these controls include: (1) south-dipping thrust faults that developed along the Mount Newman/West Angela contact, (2) folds associated with thrust fault development, (3) steeply dipping stratigraphic contacts in the hangingwall and footwall of thrust faults, and (4) gently north-dipping stratigraphic contacts. The thrust fault and folds are significant for two main reasons (Hodkiewicz et al.,

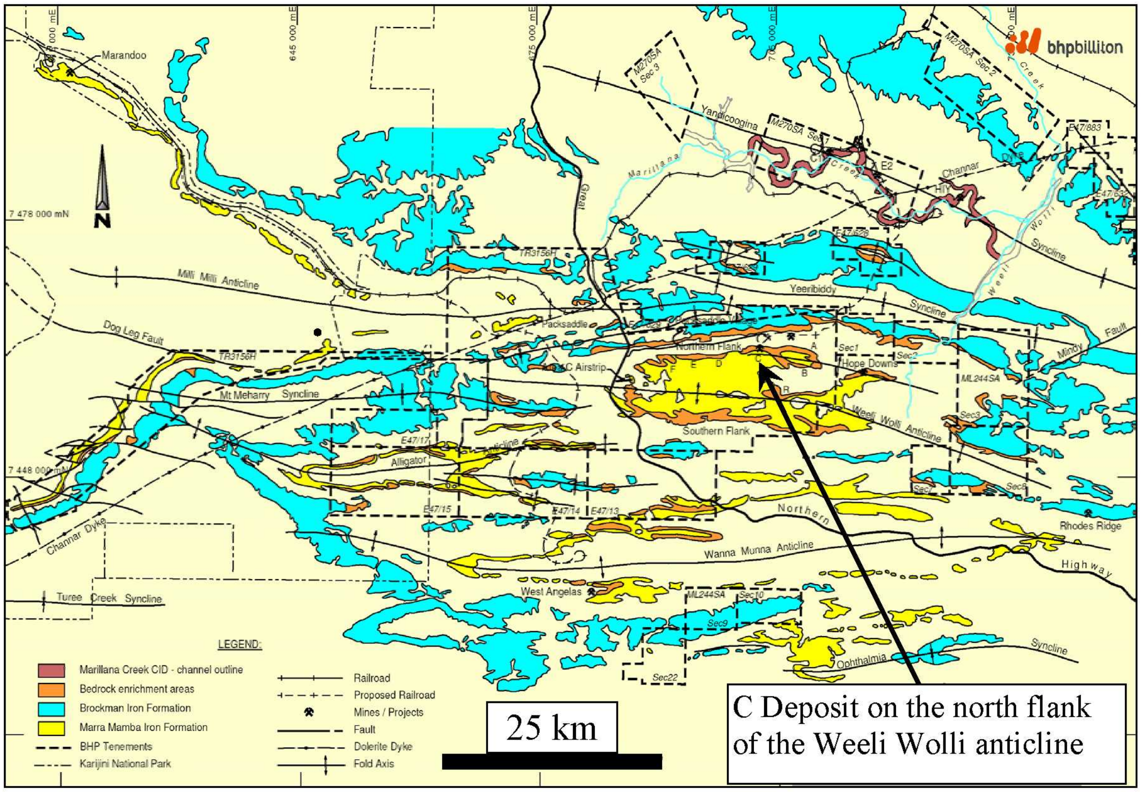

Figure 6: Plan geology of Area C, showing regional east-west folds and the location of the C Deposit on the north flank of the Weeli Wolli Anticline. Modified from Kepert (2001).

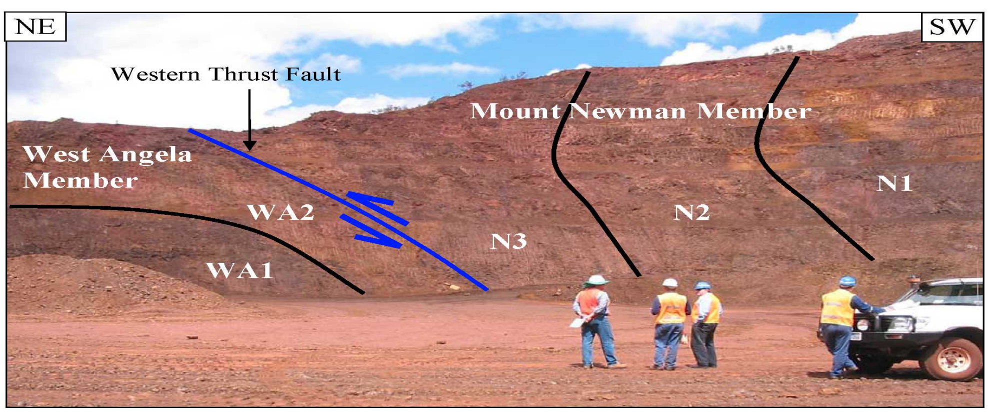

Figure 7: View looking southeast in the C Deposit bulk sample test pit, showing sub-vertical Mount Newman units (N1, N2 and N3) in the hangingwall of the Western Thrust Fault, overlyingWest Angela units (WA1 and WA2) in the footwall.

2005): (1) their formation resulted in the thickening of the main ore-hosting units in the Mount Newman member, and (2) associated structures and folded lithological contacts were conduits for fluids that influenced the formation of iron mineralisation. Similar thrusts faults and small- to medium-scale north-verging folds occur throughout the district. The faults and folded contacts in the C Deposit (Fig 7) were structural pathways for fluid flow and are therefore significant controls on the distribution of mineralisation.

Mineralization domains correspond to geologically and statistically homogeneous zones (Guibal, 2001), and the construction of accurate 3D wireframe models of mineralised domains is a critical component of any constrained resource estimation. In this study, Leapfrog™ software was used to create 3D wireframes based on drill-hole composites, in order to determine the continuity and geometry of mineralisation and to compare with existing BHPBIO geological interpretations and wireframe models.

Leapfrog™ is specialist software developed by SRK Consulting and ARANZ for 3D contouring of drill hole data and the rapid construction of wireframes. Wireframes of assay data highlight the geometry of mineralised domains and assist in the interpretation of structural and stratigraphic controls on mineralisation at a variety of scales.

A simplified cross-sectional view of wireframes through the bulk sample test pit in C Deposit is shown in Figure 8. The wireframes at 64%, 60% and 54% iron highlight structural and stratigraphic controls on mineralisation, including the sub-vertical orientation of mineralisation along folded units in the hanging wall and foot wall of the Western Thrust Fault, and the gently north-dipping mineralised domains associated with lithological contacts. Significant changes in dip of the mineralisation confirmed the locations of dip-domain boundaries that had been identified by BHPBIO geologists for use in the resource estimation.

In Figure 8 only three iron wireframes are shown for clarity. However, in this study, iron was modelled at 1% increments from 55% to +62%. The resulting wireframes clearly highlight the distribution of mineralisation and specific controls associated with a complex network of variably oriented faults and folded stratigraphic contacts, which are critical for iron mineralization.

An improved understanding of controls and the geometry of iron mineralisation at a range of cut-off grades is important for the construction of valid wireframe models of mineralised domains

Understanding the nature of the structural controls on mineralisation is fundamental to designing appropriate data acquisition methods for resource estimation. As seen in Figure 8, initially all resource definition drill holes in C Deposit were drilled vertically, and therefore oriented parallel to stratigraphy in upright folds, where stratigraphy is also vertical. Based on an improved understanding of structural features in C Deposit, BHPBIO geologists designed angled drill holes to provide better sample coverage for geological modelling and resource estimation.

Grade interpolation methods should also take into account the stratigraphic and structural controls on mineralisation such that samples are correlated appropriately. Grade contours shown in Figure 8 show that, while the overall morphology of the mineralised domain (illustrated by the 54 %Fe contour) appears sub-horizontal, the control of higher grade (>60% Fe) mineralisation is sub-vertical where strata have been folded and displaced by thrust faulting.

Deposit-scale structural controls on iron mineralisation in C Deposit reflect regional-scale tectonic features in the Hamersley Province. The major controls are distinct fold styles associated with the Opthalmian and Ashburton orogenies, which were dominantly north-south compressional events. Early Opthalmian structures include an arcuate, east-west trending fold and thrust belt with associated south-dipping thrusts and north-verging folds. Broader, more open, east-west folds formed during the Ashburton, including the Weeli Wolli anticline, which hosts the Area C deposits.

Recent mining operations in C Deposit have exposed thrust faults and overturned folds that control higher-grade iron mineralisation. These structures thickened the main ore-hosting units in the Mount Newman Member and provided conduits for fluids that influenced iron mineralisation. Detailed mapping provided the basis for updated geological interpretations and the construction of valid 3D wireframe models at a range of cut-off grades. These were critical for defining domains used in the resource estimation and for designing more appropriate data acquisition programs.

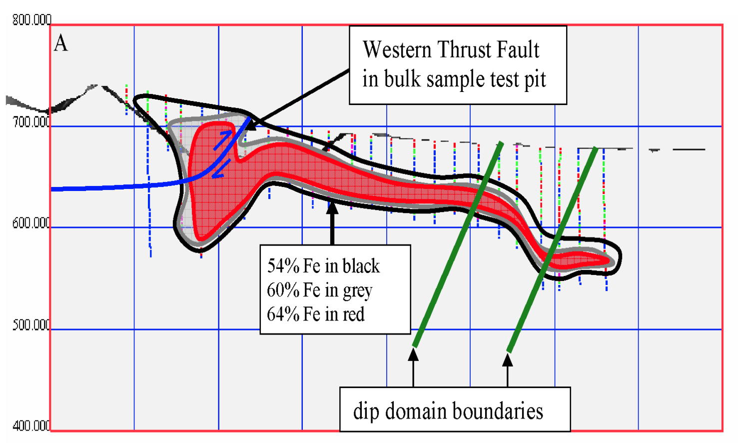

Figure 8: Cross section through the C Deposit looking west, showing mineralised domains at 64%, 60%, and 54% Fe. The thicker high grade zones to the south (left side of the section) in folds associated with the Western Thrust Fault.

SUMMARY AND CONCLUSIONS

The identification of distinct hydrothermal alteration zonation around the Hamersley and Carajas deposits, and the identification of high- and low-temperature and -salinity fluid inclusions in hematite species from the Iron Quadrangle strongly suggests that structural controlled fluid flow and hydrothermal processes do indeed play a significant role in the transformation of BIF (35%Fe) into high-grade (>60% Fe) iron ore. As a consequence new genetic models have been developed that propose a dual hypogene-supergene origin for BIF-related iron ores worldwide.

These new genetic models have changed the exploration strategy for the major iron ore producers. Today many explorers target concealed, high-grade iron ore by applying a combination of traditional exploration tools such as downhole gamma logging with modern academic techniques such as laser ICP-MS analyses, microthermometry and stable isotopes. The future will undoubtedly see further refinements of the genetic models and development of high-tech analytical tools. In combination, and paired with the capability of the modern explorationist to rapidly understand the geological controls of specific iron province, this will lead undoubtedly to new and exciting discoveries of high-grade iron bodies.

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