Structural Geology in Unfamiliar Terrane; Controls on Laterite-Hosted Nickel Mineralisation at Ravensthorpe, W.A.

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Introduction

The regolith is not the usual terrane to find a structural study; in fact laterite is generally seen as a curse, destroying useful fabrics, and is something you walk over to get to more interesting, deformed, and 'fresher' outcrop. Investigations into structural controls on mineralisation in regolith are rare and mostly focussed on gold. A paper by Brand (et. al., 1996), investigating structural controls on lateritic nickel mineralisation at Cawse, in Western Australia, seems to be the most recent.

In 2010 Jigsaw Geoscience was hired by First Quantum (FQML) to undertake a review of the geology in its newly purchased Ravensthorpe Nickel Laterite mine (Reserve: 246.5Mt @0.627% Ni, 0.028% Co (http://www.first-quantum.com/Our-Business/operating-mines/Ravensthorpe/Reserves-Resources/default.aspx). The brief was to map the partially mined Halley's pits with special emphasis on structure in saprolitic and fresh bedrock and identify their impact on grade and ore geometry in laterite-hosted nickel mineralisation. BHP-Billiton mine geologists and FQML resource geologists suspected that bedrock structure had some importance in controlling higher grade nickel mineralisation, however nothing had been quantified or documented. The results of this study confirmed their suspicions and advanced our understanding of structural controls on nickel mineralisation at Ravensthorpe, and the stratigraphic and structural setting of the Bandalup Ultramafic in the Ravensthorpe Greenstone Belt.

Regional Geology

The Ravensthorpe Nickel Laterite mine is located 450km SE of Perth, within the Ravensthorpe Greenstone Belt (Griffin, 1990), a small greenstone belt located at the southern limit of the Late-Archaean Youanmi Terrane. The area has been mapped by GSWA geologists at 1:250,000 scale by Thom et. al. (1977), and 1:100,000 scale by Witt (1995). Witt (1998) divided the Ravensthorpe Greenstone Belt into a central Ravensthorpe Terrane, flanked in the east by the Carlingup Terrane and in the west by the Cocanarup Greenstone. The Ravensthorpe Terrane comprises a calc-alkaline complex dated at c. 2.99-2.97Ga., juxtaposed against the Carlingup Terrane. The Carlingup Terrane is subdivided, from the base, into the felsic volcanic and siliciclastic Chester Formation, Bandalup Ultramafic, Maydon Basalt (siliceous high-Mg basalt) and the sedimentary Hatfield Formation at the top. The only published age constraint in the Carlingup Terrane is a SHRIMP U-Pb zircon age of 2958±4Ma for a felsic volcanic just east of the Bandalup Ultramafic (Nelson, 1995). The Ravensthorpe Nickel mine is hosted within the Bandalup Ultramafic, a 1.5km thick sequence of komatiitic volcanics and subordinate high-Mg basalts and gabbro. The Archaean rocks are overlain by an allochthonous block of metasediments correlated with the Mesoproterozoic Mount Barren Group. The allochthon is a fold-thrust belt preserving up to four deformations episodes associated with uplift and overthrusting of the Fraser Mobile Belt during the Mesoproterozoic Albany Fraser Orogen. Dolerite dykes striking parallel with the Northeast-Southwest striking Jerdacuttup Fault cut across much of the Carlingup Terrane.

Geological Setting Of The Ravensthorpe Mine And The Bandalup Ultramafic

Witt (1998) describes the Bandalup Ultramafic as being volcanic flows with upper spinifex-textured A-zones overlying adcumulate B-zones. Komatiite-hosted nickel sulphide mineralisation occurs at the base of such rocks at RAV-8. However, at Bandalup Hill, mapping in the Halley's Pits shows the Bandalup Ultramafic consists of two dunitic adcumulate intrusions, intruded discordant to bedding in sedimentary country rocks. The two intrusions are split by a complex fault zone, the Medial Fault, which hosts a variety of rocks including pillowed high-Mg basalt, gabbro, pyroxenite, hornblendite, and chlorite schist. Geochemistry shows a zone of high-Al coincides with the Medial Fault. Cr is also elevated in the medial zone at levels similar to the margins of the dunite. Volcanic textures and structures are not recognised in the Bandalup Ultramafic.

East of the dunite is a sequence of metamorphosed sandstone, wacke, siltstone, felsic volcanics and volcaniclastics intruded by amphibolite. Bedding is well preserved and dips steeply to the east and north-east, and

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is overprinted by two foliations. Bedding and amphibolite sills are folded about Type-3 fold interference patterns and sheath folds indicating a complex early structural history of isoclinal folding (F_1), refolded by tight to isoclinal F_2 folds plunging gently (0-30°) to the south and southeast. An early weak foliation (S_1) is developed parallel with bedding and is overprinted by a second, more penetrative, foliation that is axial planar to the F_2 folds. The vergence relationship between S_0/S_1 and S_2 consistently points to an F_2 synformal closure lying to the west. The F_2 fold axis is parallel with a mineral elongation lineation on S_2. Retrograde shear zones of intense biotite-chlorite foliation (S_3) overprint the earlier foliations and dip 75° towards the Southwest. A swarm of sub-vertical, West Northwest-East Southeast-striking dolerite dykes intrudes the sedimentary sequence, yet few extend any significant distance into the dunite sill.

Structure Within the Bandalup Sill

Structure within the Bandalup Sill in the Halley's Pits is considerably less complex than the fold interference patterns displayed by the sedimentary country rocks. The style of deformation in the sill is predominantly brittle-ductile fault and vein networks. There are two major structures exposed by the Halley's Pits: the Medial Fault and the Eastern Shear Zone.

Medial Fault

The Medial Fault is a major fault zone developed between the two dunite sills in the centre of the Halley's Pits. The fault zone is 50m wide and consists of an anastomosing network of talc-chlorite shears wrapping lithons of dunite and country rock. The talc-chlorite assemblage is relatively resistant to weathering and is commonly preserved in upper saprolite. Wallrock to these shears is a coarse-grained porphyroblastic rock composed of fibrous amphibole (tremolite or anthophyllite) overprinting earlier Mg-carbonate porphyroblasts set in a talc-rich matrix. The fault contains lithons of massive hornblendite, pillowed high-Mg basalt, gabbro, and rare blocks of dolerite enveloped by sinuous chlorite-talc shears. The Medial Fault strikes Northwest-Southeast with steep (~80°) dips to both the Southwest and Northeast. Inside the fault an earlier foliation (S_2) is crenulated by the main chlorite-talc shear fabric (S_3). F_3 crenulations and drag folds plunge moderately to the SE. Kinematic indicators such as S/C fabrics and the vergence of crenulations, kinks and drag folds suggest that reverse shear with a component of sinistral is the dominant movement sense within the Medial Fault Zone.

Talc-chlorite-altered shears developed along the margins of East-West striking dolerite and pegmatite dykes (presumably Archaean in age) are exposed in the western wall of Halley's 11 pit. S/C fabric relationships indicate reverse movement along these faults. Both types of dyke terminate against the Medial Fault and their continuation to the east has not been identified. The Medial Fault is displaced by up to 100m in a sinistral manner across a 70° south-dipping shear zone midway along Halley's 11 Pit. In the north wall of Halley's 13 Pit, the Medial Fault is cut by a Northeast-Southwest striking dolerite dyke without any evidence of shearing along its margins, and it is speculated this may be a younger Mesoproterozoic dyke instead of an Archaean dyke.

Eastern Shear Zone

The other major structure in the Bandalup Sill in the Halley's Pits is a 150m wide zone of strong foliation that dips sub-vertical and strikes Northwest-Southeast in the eastern half of the dunite. The foliation (S_2?), is defined by flattened adcumulate olivine crystals. No kinematic indicators were recognised. The foliation is overprinted by buckles or open folds that have horizontal axial planes, and there can be inferred to have formed during uplift after D_2.

Regolith Profile at Ravensthorpe

Laterite-hosted nickel deposits can be subdivided into three groups: Oxide, Clay and Silicate types (M. Elias pers comm. 2012). Ravensthorpe is an Oxide-type lateritic nickel deposit. Oxide-type laterite deposits are characterised by Fe-oxy hydroxide (goethite) and silica (up to 80%) in the upper saprolite and pedolith. They are low grade (~1% Ni) and have formed under high water tables. Oxide lateritic nickel deposits can form over dunite irrespective of drainage conditions, and over peridotite only in well-drained settings. Under the semi-arid conditions of the Tertiary, the lowering of the water table resulted in precipitation of silica, manganese oxides, and magnesite above the water table. A stable craton with deep weathering, poor drainage, and a rate of chemical weathering that exceeded the rate of physical erosion, are considered critical conditions for the production and preservation of such deposits. Other examples of oxide-type lateritic nickel deposits in the Yilgarn Craton include Cawse-Siberia, Marshall Pools, and Weld Range.

The weathering profile at Ravensthorpe is complex. The surface landform is rolling hills capped by duricrusts of cemented pisolitic gravels, cemented detritus derived mainly from silica cap, overlying palaeochannels filled with sand, and silt with a clay–rich base (green nontronitic smectite and blue kaolinite). Three such channels have been identified in the Halley's Pits sited along the flanks of the hills and infilling valleys. Weathered ultramafic is marked by coherent and partially collapsed silica cap overlying upper saprolite that can be carbonate-rich or smectite-rich. Hematite weathering is ubiquitous through the upper saprolite except where smectitic weathering has occurred or where the hematite is overprinted by goethite weathering associated with 'limonitic ore'. In general a narrow band of goethite weathering overlies hematite weathering, however the relationship is complex. Such an arrangement is the opposite of the norm in weathering profiles in the Yilgarn Craton, whereby a dehydrated hematitic profile typically overlies a hydrated, reduced, goethite-rich profile defining a redox boundary. Transient or perched goethitic weathering zones can be developed higher in the profile indicating marked movement of the palaeo-watertable.

At Ravensthorpe hematite weathering is well preserved where magnesite and calcite veining is ubiquitous in the saprolitic ultramafic. Where these veins are overprinted by goethite weathering they are pseudomorphed by secondary silica with a lattice-like habit. Primary shape and continuity of each carbonate vein is perfectly preserved when pseudomorphed by silica. This is relationship is best observed at the margins of fault zones and indicates goethite weathering is later, acidic, reduced and silica supersaturated compared to dehydrated and oxidised conditions of the hematite weathering. The timing relationship between early hematite and younger goethitic events is unequivocal: goethite palaeo-watertables always cut across hematite weathered zones. Lateritic nickel mineralisation or 'limonitic ore' is hosted within these goethitic zones, and the main ore horizon is a perched watertable that is also focussed into deeply incised weathering troughs developed down shear zones in the bedrock.

The dunite east of the Medial Fault has two modes of weathering profile: egg-carton weathering in the western half, and a broad strike-continuous weathering trough in the east. The egg-carton weathering is the product of an intersecting mesh of narrow Northwest-Southeast, East-West, and West Southwest-East Northeast striking shears marginal to the Medial Fault. These structures have v- and y-shaped profiles depending upon their dip. Between the faults the dunite is more resistant to weathering resulting in domed-shaped profile (cf. core stones). In the Eastern Shear Zone the weathering profile is different with serpentine and smectitic clay altered saprolite profile in direct contact with 'limonite'. Hematite weathering and carbonate veins are absent, and secondary silica is ubiquitous. Clearly structure in the bedrock has a significant impact on the geometry of the ore.

Nickel Grade Versus Structure

The distribution of nickel grade in the Halley's 11, 13 and 14 pits is strongly influenced by the weathering profile and by bedrock structure. The impact of bedrock structure can be both positive and negative. The Halley's reserve grade is quoted as being 0.627% Ni and niche sampling shows the highest grade nickel mineralisation in the Halley's Pits is developed within parts of the Medial Fault zone as well as inside a Northwest-Southeast striking dolerite dyke (Mesoproterozoic?) at the north end of Halley's 13 Pit. Nickel grades are highly variable within the Medial Fault, with grades up to 2.6% Ni developed in talc-chlorite shears in the eastern branch of the fault. This branch is uniformly higher grade (i.e. consistently above 1.0% Ni) than shears in the centre and along the western margin of the Medial Fault. Fault-bounded lithons of high-Mg basalt, pyroxenite, amphibolite and dolerite contain nickel levels that are sub-ore grade, and high in Al. Shear zones developed on the margins of dolerite and pegmatite dykes in the west wall of Halley's 11 and 13 Pits carry low nickel grades of 0.2-0.3% Ni and therefore represent waste and sub-grade trends striking West Northwest-East Southeast and West Southwest-East Northeast. The Northwest-Southeast striking dolerite dyke in the northern wall of Halley's 13 Pit displays erratic nickel grades. For example on 203mRL berm grades range from 0.21 to 4.22% Ni (mean: 1.22% Ni) in ferruginous mafic saprolitic clay, however on the next berm (197mRL) the range is 0.15-0.55% Ni (mean: 0.39% Ni) – still anomalous for a mafic dyke.

A series of subvertical brittle fault zones, striking Northeast-Southwest, are developed along the western wall of Halley's 11 Pit, on the western side of the Medial Fault. These structures have classic alteration zonation patterns with a core of secondary silica flanked by goethite with replacement of carbonate veins by secondary silica. This 'limonitic' assemblage overprints hematitic and calcareous weathering. Channel sampling shows these faults represent zones of significant depletion in nickel, cobalt and chromium (mean: 0.08% Ni) relative to the surrounding country rock. The goethite-rich nature of these faults has meant that they have been selectively mined as 'limonitic' ore, however the niche sampling show these zones are waste rock and as such not all limonitic looking material should be treated as ore.

The Origin Of Magnesite Veins In The Regolith

Magnesite is a common product of weathering of ultramafic rocks and magnesite is particularly well developed in the Bandalup Hill dunite. There are two modes of magnesite development at Ravensthorpe: podiform concretions and planar vein arrays. Podiform concretions are common north of Bandalup Hill (i.e. Trial Pit and magnesite mines north of here), where irregularly shaped nodules and concretions of massive magnesite have precipitated within open cracks and relict foliation in the top of the profile. In contrast, in Halley's 11, 13 and 14 Pits, magnesite veins form ubiquitous arrays of veins in highly ordered vein networks proximal to the Medial Fault. Vein shape and geometry mimics that of extensional vein arrays more commonly associated with shear zones in metamorphic/hydrothermal systems. Veins can be horizontal or steep-dipping, and are often arranged en echelon within shear zones. Steep-dipping banded magnesite veins are frequently flanked by arrays of extension veins. Sigmoidal shapes associated with sub-horizontal shear vein arrays are common. These are quite unique modes for magnesite developed in a weathered environment. Similar vein behaviour is displayed by metamorphic magnesite veins in The Alps (Abu-Jaber & Kimberley, 1992). It seems the best explanation for the distinct structural style of the magnesite veining at Ravensthorpe is that the weathering related magnesite is pseudomorphing original metamorphic/hydrothermal carbonate, serpentine, or talc veins produced during alteration of the serpentinite. It is inferred that this veining formed in a damage zone peripheral to the Medial Fault, probably during reverse faulting assigned to D3.

Conclusion

Lateritic nickel deposits are not the typical realm of structural studies however detailed structural mapping at the Ravensthorpe oxide-type lateritic nickel deposit has shown that structures in the bedrock play a significant role in controlling the nature, geometry and continuity of lateritic nickel ore. The Bandalup Ultramafic in the Halley's Pits is a structurally repeated dunite sill intruded into felsic sediments and volcaniclastics. A major reverse fault, the Medial Fault zone, transects the centre of the ultramafic and structurally interleaves pillowed high-Mg basalt, pyroxenite, amphibolite and dolerite with talc-chlorite schists derived from alteration and shearing of the dunite. Narrow reverse and sinistral shears splay off the Medial Fault along the margins of pegmatite and dolerite dykes. Wallrock to the Medial Fault is serpentinised adcumulate dunite cut by extensive arrays of carbonate, serpentine, or talc veins pseudomorphed by magnesite during weathering. The other major structure in the dunite is wide zone of foliated serpentinite, the Eastern Shear Zone, in which no carbonate, serpentine, or talc veins are developed.

The regolith profile at Ravensthorpe is complex with 'limonitic ore' forming a sub-horizontal blanket over a dehydrated and oxidised saprolitic weathering profile. The bulk of the limonitic ore represents a perched palaeo-watertable that overprints a dehydrated hematitic profile. Structures in the ultramafic bedrock channelize goethite-rich limonitic mineralisation deep into the lower saprolite along the margins of dykes, brittle faults and also the Medial Fault. The dip of the bedrock structure dictates the shape of the ore zone: v- or y-form. The highest nickel grades recorded in niche sampling have been returned from the Medial Fault, however their high-Al and variable Si contents require careful material blending. High-grades up to 4.6% Ni can be developed in dolerite dykes overprinted by the palaeo-watertable. Not all faults are beneficial to ore; some brittle faults with silica-rich limonitic assemblages are strongly depleted in nickel and have dilutionary impact on ore. Not all limonitic ores are created equal. Careful mapping of faults and dykes in benches, berms and batters will aid sectional interpretation of grade control and block modelling, and minimise loss of ore to waste dumps.

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