Thunderbox gold and Waterloo nickel deposits

by

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Abstract

The Thunderbox gold mine and Waterloo nickel deposit are owned by LionOre Australia, a wholly owned subsidiary of LionOre Mining International. The Thunderbox gold mine was discovered in 1999 and began production in late 2002. It is a blind deposit, being concealed beneath a 25 m-thick sequence of lateritized Tertiary sediments, and has no obvious surface geochemical signature or direct geophysical signature. It is a largely porphyry-hosted mesothermal lode gold deposit, which is currently being mined by openpit methods. The resource comprises 27.8 Mt grading 2.25 g/t gold for more than 2 million contained ounces, and is open at depth beneath the present limit of drilling. It is an atypical mesothermal gold deposit in several ways. Firstly, it is a wide, evenly mineralized deposit rather than a constrained lode style deposit, which is largely due to the shape and rheology of the dacite porphyry host rock. Secondly, it appears to be situated in a major first-order shear zone rather than a second- or third-order structure. Thirdly, many features of the deposit suggest that mineralization was emplaced in multiple incremental episodes over a protracted period, commencing relatively early in the tectonothermal history of the district. These features have implications for models of the formation of mesothermal gold deposits, and the targeting methodologies used in the search for them. The lack of an obvious geophysical and surface geochemical signature at the project–prospect scale also has implications for the methodologies selected at the exploration stage.

The Waterloo nickel deposit was discovered in early 2002 within 5 km of the Thunderbox gold deposit, and is currently at a pre-feasibility stage. Waterloo is a komatiite-hosted magmatic nickel sulfide deposit comprising largely intact matrix and disseminated sulfides, together with local structurally remobilized massive sulfides within a serpentinized olivine mesocumulate or peridotitic ultramafic flow. It is similar in many respects to other komatiitic nickel sulfide deposits in the Archaean Yilgarn Craton of Western Australia, but is unusual in that it does not occur at the basal part of the ultramafic sequence, and it is situated to the east of the Perseverance Fault, a structure previously believed to mark the eastern limit of nickel-prospective stratigraphy. Despite being situated in an area of outcrop, Waterloo is also a blind deposit, commencing at a depth of 100 m and plunging shallowly to the south over a strike length of 1 km. The apparent tectono-stratigraphic position of the Waterloo ultramafic rocks and mineralization, above a thick sequence of thin flow fractionated komatiites, is at variance with the classic Kambalda model, in which mineralization occurs at the base of the lowermost, most MgO-rich, flow. Although this configuration could reflect structural repetition, it shows that it is important to not be too model driven. The role of structure in the remobilization of nickel sulfide deposits has also been overlooked, largely because of the emphasis previously placed on volcanological controls on emplacement. The apparent stratigraphic position of Waterloo could, however, have been controlled by structure as much as volcanology and, together with the demonstrated remobilization of sulfides at a small scale within the Waterloo deposit, and the large scale detachment of sulfides to form the nearby shear-hosted Amorac deposit, this attests to the importance of a holistic approach in the development of models, targeting criteria, and exploration methodologies. The discovery of Waterloo, and Leinster-style stratigraphy, to the east of the Perseverance Fault has not only disproved the conventional wisdom used for area selection in the region, but has highlighted the potential for the discovery of further deposits in a previously unrecognized district. Finally, the discovery of Waterloo in an area of outcrop with previous drilling emphasizes the frailty of exploration, the sensitivity of the outcome to the methodology and mentality of the explorer, and the potential for finding more.

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Introduction

The Thunderbox and Waterloo deposits are located about 700 km northeast of Perth and 300 km north of Kalgoorlie, adjacent to the Goldfields Highway some 40 km south of the township of Leinster (Bennett, 2003a). Both deposits are blind, with Thunderbox being concealed by a 25 m-thick lateritized Tertiary sedimentary cover sequence and recent alluvium, and Waterloo commencing at a depth of 100 m in an area of subcropping rock covered by a veneer of windblown sands derived from granite.

Thunderbox was discovered in 1999 through reconnaissance rotary air blast (RAB) drilling of a prospective trend concealed by lateritized Tertiary sediments and recent alluvium. The deposit comprises a resource of 27.8 Mt grading 2.25 g/t Au for more than 2 million contained ounces, and is open at depth beneath the present limit of drilling. Openpit mining commenced in 2002, with about 213 000 ounces of gold being produced in the first full year of production in 2003. The ore is processed through a conventional carbon-in-leach and carbon-in-pulp (CIL/CIP) plant at a nominal rate of 2.5 Mtpa for oxide ore and 2 Mtpa for primary ore. The openpit has an expected life of five years, and options for subsequent underground mining are currently being considered.

Waterloo is also a blind deposit, and was discovered in January 2002 in the first hole of a drilling program designed to test an electromagnetic conductor associated with a gossan derived from nickel sulfide and anomalous in platinum group elements (PGE), discovered earlier by LionOre in 1998. Delineation drilling proceeded throughout 2002 and 2003, and the deposit is currently subject to a pre-feasibility study.

Thunderbox gold deposit

Discovery and resources

The Thunderbox deposit was discovered in 1999 by reconnaissance RAB drilling beneath transported cover comprising lateritized Tertiary sediments and recent alluvium (Bennett et al., 2001; Bennett and Buck, 2001). The deposit was discovered in the last two holes of a RAB drilling program designed to test an area considered to be prospective for gold on the basis of various lines of general district-scale conceptual criteria and specific local-scale empirical evidence, as follows:

- recognition of its location within the southern pinchdown of the Yandal greenstone belt;
- recognition of a major throughgoing shear system, which appears to broadly control mineralization at Mount McClure to the north and Gwalia to the south;
- recognition of the presence of a granite batholith to the west and a felsic igneous complex to the east, which appear to constrain and focus deformation at this location;
- recognition of the presence of a widespread blanket of lateritized Tertiary sediments and recent alluvial cover where previous soil sampling was unlikely to have been effective;
- the occurrence of known gold mineralization at the Double A and Goanna Patch localities some 6 km along strike to the north;
- a lack of previous exploration in the immediate area, other than a single reconnaissance RAB traverse drilled some two years earlier;
- the presence of deep weathering and intense shearing in these RAB holes, indicating the presence of a major structure;
- the presence of coincident saprolitic gold and arsenic anomalism in one of these RAB holes, with one 4 m composite sample grading 1.4 g/t Au.

The weight of evidence was considered sufficiently compelling to drill two additional RAB traverses some 400 m to the north and 400 m south of the original reconnaissance traverse. The last two holes of this program (LWDR411 and 412), on the end of the northern traverse, proved to be the discovery holes by intersecting significant mineralization in what is now termed Zone A of the deposit. Key intercepts included 4 m at 11.7 g/t Au from 20 m and 5 m at 8.28 g/t Au from 47 m in LWDR411, and 4 m at 5.68 g/t Au from 69 m and 10 m at 4.93 g/t Au from 88 m in LWDR412. Mineralization was strongly associated with a visually distinctive yellowish-brown clay containing fragments of laminated silica and goethitic gossan, which appeared to be a weathered silica–sulfide-altered rock.

Three reverse circulation (RC) drillholes (LWDC025–027) were subsequently drilled to verify the RAB results, and determine the geometry and dip of mineralization. The deepest of these holes intersected fresh mineralization in the form of silica–arsenopyrite hydrothermal alteration. This was followed by several stages of RAB drilling along strike to scope out the strike extent of the oxide mineralization, which delimited Zone A to a strike length of 400 m (in the depth penetration range of RAB) and identified a minor zone (Zone B) to the north of Zone A. The last hole of this program (LWDR438) intersected the southern end of what is now termed Zone C. Intersections in this hole included 10 m at 4.19 g/t Au and 14 m at 2.4 g/t Au to the end of the hole. Subsequent RAB drilling confirmed the overall magnitude of Zone C, with wide zones of the distinctive goethitic clay being intersected. These zones, which are now known to be the main oxide ore position over Zone C, typically returned intersections of 40–70 m at 2–5 g/t Au in 80 × 40 m spaced drillholes over a 400 m strike length.

A major program of RC and diamond delineation drilling commenced in October 1999, and has since confirmed the internal integrity and downdip continuity of the deposit. The resource remains open at depth beneath the limit of drilling, some 400 m below surface.

Geological setting

The Thunderbox deposit is situated at the extreme southern end of the Yandal greenstone belt, in an area where several major intra-greenstone shear zones converge and join with the Perseverance Fault. This shear system continues south beyond the pinchout of the Yandal greenstone belt to the Leonora district, where it is associated with other major gold deposits such as Tarmoola and the Gwalia camp. The

Thunderbox Shear Zone forms the western boundary of this shear system and appears to be a major geological discontinuity, defining the boundary between two distinct geological domains:

- the Perseverance domain to the west, which is contiguous with the Wiluna – Mount Keith – Leinster – Mount Clifford sequence and characterized by classic deformed ultramafic- and mafic-dominated greenstone stratigraphy intruded by granitoid plutons;
- the Teutonic domain to the east, dominated by sedimentary rocks, bimodal felsic–mafic volcanic rocks and felsic intrusive complexes, and the Teutonic Bore volcanic-hosted massive sulfide (VHMS) prospective stratigraphy.

Geology

The Thunderbox deposit is a mesothermal lode gold deposit hosted largely within a thick lens of porphyritic dacite in the immediate hangingwall of a major shear zone, which is offset by late north-northeasterly striking faults displaying an apparent dextral displacement. The mineralization is strongly hostrock controlled and is coplanar with highly deformed stratigraphy, which strikes north-northwesterly and dips 70–75° to the west (Fig. 1). The deposit comprises two main mineralized zones, termed A and C, which are currently interpreted to be separated and offset by a late north-northeasterly fault. The bulk of the known mineralization occurs within Zone C, which has true widths of up to 75 m, a surface strike length of about 400 m, and plunges to the south. Zone A is narrower, having a true width of up to 25 m, but also has a strike length of about 400 m and plunges to the south.

The deposit is blind, being truncated by an unconformity that probably represents a Permian glacial peneplain, which is completely concealed by a 20–30 m-thick sequence of Tertiary sediments. The cover sequence comprises a mixture of quartz gravels, smectitic lacustrine clays, locally derived colluvium, and alluvial channel fills of unconsolidated ferruginous gravel. The entire Tertiary cover sequence, together with the uppermost parts of the Archaean basement, has been deeply lateritized and is, in turn, covered by a veneer of active alluvial sheetwash containing a surficial ferricrete layer known locally as Wiluna hardpan.

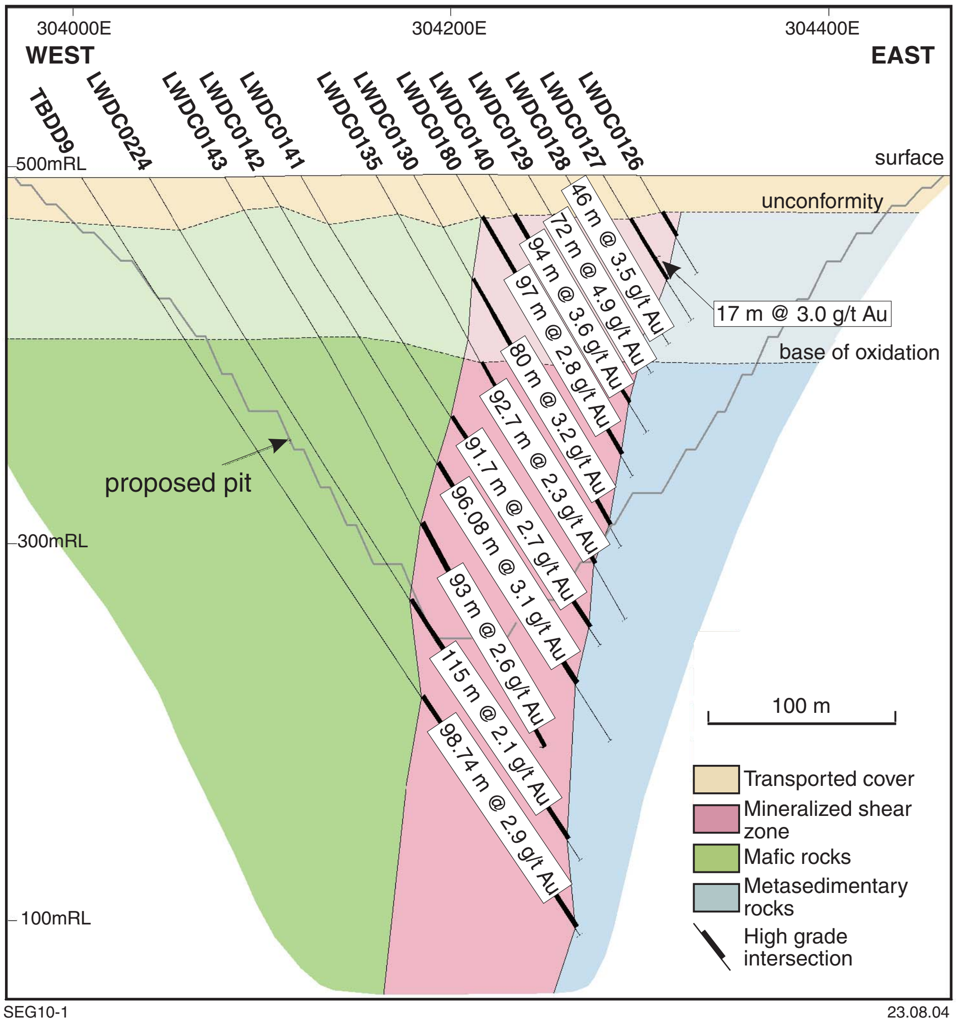

Figure 1. Cross section of the Thunderbox deposit at 6879880N showing simplified geology and mineralization, and location of drillholes

Mine tectono-stratigraphy

The footwall sequence comprises a relatively undeformed, upright facing, thick sequence of thinly bedded quartz to lithic wackes and epiclastic rocks. The footwall sequence is separated from the mineralized porphyry by a major steeply west-dipping shear zone occupied by an intensely foliated and crenulated chlorite–tremolite–carbonate–talc rock, which contains tectonic clasts of the mineralization itself. This unit is an intensely deformed and carbonated ultramafic rock, which appears to have acted as a preferential glide plane and fluid conduit during deformation. The presence of mineralized porphyry clasts within this shear zone indicates that movement, at least in part, postdates mineralization.

Mineralization is largely hosted within a well defined, intensely altered, and strongly deformed porphyritic dacite, which is currently interpreted to be a high level intrusion. Rare relict primary igneous fabrics comprise quartz, plagioclase, K-feldspar, and hornblende phenocrysts in a fine-grained quartzofeldspathic groundmass. The porphyry is, however, pervasively altered and severely deformed, exhibiting a variety of superimposed brittle and ductile deformation styles that vary locally from mylonitic, cataclastic, hydraulically brecciated, quartz veined, to folded, and are largely coplanar with the enclosing tectono-stratigraphic sequence.

Key structural features of the mineralization and adjacent rocks in the hangingwall sequence include the occurrence of two westerly dipping foliations, subhorizontal extensional veinlets, and south-plunging mineral stretching lineations, intersection lineations, and fold axes. These features are mutually consistent and suggest stretching along shallowly south-southeast-plunging fold axes, which could have formed by drag folding in the immediate hangingwall of a steep reverse shear system. This folding is also locally evident in the mineralization itself.

An unusual banded rock fringes the margins of the mineralized porphyry, and appears to be a tectonically hybridized rock comprising layers of altered porphyry, basalt, ultramafic rock, and wacke. The banded rock is modestly mineralized and is thickest along strike and downdip of the terminations of the main porphyry, where it interleaves with the porphyry. The configuration of the hybrid rock at hand specimen and deposit scales strongly suggests its derivation by tectonic transposition of various rock types, and that it has been squeezed into pressure shadows around the terminations of the relatively rigid, dacite porphyry body.

The hangingwall sequence comprises a thick sequence of strongly foliated chlorite-altered and calcite-veined basalts, which exhibit intense ductile deformation characteristics. The calcite veins in the hangingwall basalts are relatively early and have been transposed into the foliation. Petrographic studies (Du Puy, 2003) indicate that the basalt contains traces of a prograde hornblende–plagioclase–chlorite–calcite–ilmenite assemblage largely overprinted by a retrograde chlorite–quartz–albite–epidote–ankerite assemblage. Fluid inclusion studies (Du Puy, 2003) suggest a peak metamorphic temperature of 500 ± 50°C, close to the greenschist–amphibolite facies boundary.

The entire sequence is also dismembered by a series of later northeasterly to north-northeasterly striking faults, and is transected by an east–west joint set. Some of these joints have been intruded by late lamprophyre dykes, further suggesting that the shear zone is a deep crustal feature.

Mineralization

Beneath the unconformity, the deposit comprises an oxide zone, which extends downwards from the base of the cover sequence to a vertical depth of about 70 m, and a transitional zone, which extends to a vertical depth of 100 m. The oxide mineralization comprises orange-brown clays, which contain abundant fine-grained sugary quartz derived from the weathering of silica alteration and variable proportions of laminated quartz, vein quartz, and fragments of goethitic clays and gossanous iron oxides derived from the oxidation of sulfides. There is evidence of vertical leaching and supergene enrichment within the oxide profile. This is especially marked in the centre of Zone C, where an upper pallid leached zone containing quartz ribbons overlies a goethitic ferruginous clay zone with enriched gold grades.

In the primary zone, the porphyry is pervasively altered to a silica–albite–ankerite–dolomite–arsenopyrite–pyrrhotite assemblage, which is associated with much of the gold mineralization. Gold is intimately associated with recrystallized arsenopyrite and tends to occur on the grain boundaries. Much of this alteration is also affected by subsequent increments of deformation, and some of the silica has been annealed, indicating that much of the gold pre-dates peak metamorphism and deformation, and this free gold could have exsolved from an earlier As–Fe sulfide.

There is also free gold in veinlets of various generations, particularly in association with minor sphalerite and galena. Some of these quartz veinlets are boudinaged, folded, rotated, or a combination of these, into the penetrative ductile deformation fabric, and obviously predate much of the ductile deformation. Some are laminated and coplanar with the penetrative fabric, and appear to be coeval with the main deformation. Others are undeformed and flat, clearly crosscutting the penetrative ductile fabric. The latter, together with irregularly distributed hydraulic breccia lodes, clearly postdate much of the ductile deformation.

The common occurrence of features such as early folded quartz–arsenopyrite veins, layer-parallel ductile fabrics and laminated veins, later crosscutting quartz–gold veins, intact and dismembered hydraulic breccia lodes, folding of the ore, and clasts of mineralization within the footwall ultramafic shear zone, provides substantial evidence of mineralization being emplaced and perhaps mobilized in multiple incremental episodes before, during, and after peak metamorphism and ductile deformation events.

The gold mineralization is also overprinted by a later brittle vein set comprising small irregular quartz–calcite–

chlorite–pyrrhotite veins distributed throughout the deposit, and by a later alteration assemblage characterized by the presence of euhedral pyrite that is spatially associated with the late crosscutting and offsetting brittle faults.

Geological and genetic model

The intensity and complexity of deformation within the Thunderbox Shear Zone suggests that it is a major first-order shear zone and a significant control on mineralization. At the deposit scale, the hangingwall sequence west of the shear is strongly deformed and altered, and typical of upper greenschist to lower amphibolite facies metamorphosed greenstones, and the footwall sequence east of the shear comprises relatively undeformed rythmically graded quartz- and lithic wackes and epiclastic rocks. This contrast in the degree and nature of deformation mirrors the stratigraphic contrast observed at a district scale, suggesting that it is a domain-bounding structure. The occurrence of mineralized clasts within this structure does, however, indicate that at least some of the movement on this shear zone postdates mineralization, and therefore the mineralization is either relatively early or there is significant late-stage movement on the shear zone.

The mineralization is almost entirely hosted within a large lens of porphyritic dacite in the immediate hangingwall of the shear zone. The shear zone itself, being a zone of chlorite–tremolite–carbonate–talc rock, appears to have acted as a preferential glide plane and a strain buffer between the hangingwall sequence and the undeformed footwall sequence. In contrast to the deformed ultramafic rock in the footwall shear zone and the hangingwall basalts, the porphyry host rock apparently behaved in a more brittle manner, also containing various brittle fabrics such as flat quartz vein arrays, microveining, and hydraulic brecciation, as well as relatively steeply orientated ductile fabrics.

The exact timing relationships of the various brittle and ductile events are not yet understood, but the overall abundance of steeply orientated ductile planar fabrics, together with flatter brittle planar fabrics, and shallowly plunging fold axes are consistent with deformation within a compressive tectonic regime. The presence of annealed quartz, boudinaged quartz veins, folded quartz veins, layer-parallel laminated shear veins, exsolved gold associated with pre-peak metamorphic arsenopyrite, mesoscale folding of the deposit, dismembered hydraulic breccia lodes, late-stage undeformed hydraulic breccias and veins with free gold, flat extensional quartz veins, and clasts of mineralization within the footwall ultramafic shear zone indicate that mineralization occurred over a lengthy period, commencing relatively early in the tectonic and metamorphic history of the district, and continuing beyond peak metamorphism and deformation.

Waterloo nickel deposit

Discovery and resources

The Waterloo deposit is blind and was discovered in January 2002 as a result of drilling a subtle electromagnetic (EM) anomaly associated with a serpentinized ultramafic unit containing minor nickel and copper anomalism and a nearby gossan derived from nickel sulfide (Bennett, 2003b).

The ultramafic unit and the Ni–Cu anomalism was originally identified in drilling undertaken by Seltrust in the late 1970s, but the prospective basal contact of this unit was not tested. No further nickel exploration was undertaken until 1998, when LionOre identified a nickel sulfide gossan containing 3 g/t combined PGE during geological mapping. This gossan resembles a typical lateritic ferricrete and would not have been identified if not for systematic sampling, PGE analysis, and recognition of relict violaritized pentlandite textures in polished section. It was not immediately followed up due to the nearby discovery of the Thunderbox gold deposit in 1999, and the reprioritization of work programs.

Nickel exploration recommenced in 2001 with the reinterpretation of the Seltrust data, which indicated that the ultramafic sequence contained a thick serpentinized olivine cumulate unit with localized Ni–Cu anomalism in the weathered zone of this unit. A single line of three aircore holes, drilled to test the near-surface portion of the basal contact, intersected a Ni–Cu–PGE anomalous gossan on the basal contact of the serpentinite. Subsequent moving loop and fixed loop EM surveys also identified several EM anomalies within the ultramafic stratigraphy (Mutton and Peters, in press). LionOre personnel prioritized one of the weakest EM conductors based on its position midway between the PGE-bearing nickel gossan some 300 m along strike to the south, and the Ni–Cu anomalism identified in the previous Seltrust drilling and LionOre aircore drilling some 200 m along strike to the north. The first hole was drilled in January 2002 and intersected 10.68 m of disseminated, matrix, and massive sulfides grading 5.08% Ni.

Subsequent drilling has defined a south-plunging elongate ribbon of sulfide mineralization over a strike length of >1 km associated with the lower contact of the serpentinite unit. At the northern end, mineralization is a mere 10 m below the end of one of the Seltrust drillholes, which failed to reach the lower contact. While resource definition drilling was underway at Waterloo, drilling of a second EM conductor nearby led to the discovery of the Amorac deposit. This mineralization differs in style compared with Waterloo, and is structurally controlled within an undulating planar shear zone and not associated with any appreciable ultramafic stratigraphy.

Geological setting

The Waterloo nickel deposit is situated in an area previously viewed as unprospective, and consequently relatively unexplored. It is hosted by a folded remnant of ultramafic stratigraphy located within an enclave of greenstones at the southeastern margin of the Perseverance granitoid, which is itself situated at the confluence of two dominant geological trends within the northeastern Goldfields of the Yilgarn Craton — the southern extension of the nickel-prospective Agnew–Wiluna greenstone belt and the Perseverance Fault to the west, and the southern extension of the gold-prospective Yandal greenstone belt to the east.

A major regional shear zone east of the Waterloo locality defines the boundary between the eastern edge of the Perseverance granitoid and the western edge of the Yandal greenstone belt, and controls gold mineralization at Thunderbox and associated prospects. This structure, informally termed the Thunderbox Shear Zone, is a major deformation corridor and seems to represent a fundamental boundary between mafic–ultramafic-dominated stratigraphy analogous to that of the Agnew–Wiluna belt to the west, and stratigraphy to the east that is dominated by sedimentary and felsic volcanic rocks. On the basis of the degree of deformation associated with this structure, and the broad lithostratigraphic differences either side, it is interpreted to be a domain boundary.

To the west, the geology is dominated by the Perseverance granitoid, whose western margin is defined by the Perseverance Fault, which is a constituent of the so-called Keith–Kilkenny Lineament. Further west still, on the western side of the Perseverance Fault, are structurally attenuated ultramafic units that are interpreted to represent the southerly strike continuation of the Perserverance ultramafic stratigraphy of the Agnew–Wiluna nickel belt, and which continue further south to the Marshall Pool and Mount Clifford ultramafic sequences. The Agnew–Wiluna belt is the most richly endowed nickel belt in the Yilgarn Craton, and hosts the world's largest examples of komatiite-associated nickel sulfide deposits, including Mount Keith, Yakabindie, Perseverance, Rockys Reward, and Honeymoon Well. All these deposits, and their host ultramafic and greenstone sequences, are situated west of the Perseverance Fault, which has traditionally been regarded as being a fundamental delimiter of nickel sulfide prospectivity.

Waterloo is the first nickel deposit to be discovered east of the Perseverance Fault. This, together with the similarity of the Waterloo stratigraphy to that of the Mount Keith – Leinster area, suggests that the Thunderbox Shear Zone (to the east of Waterloo) is a more fundamental domain-bounding structure than the Perseverance Fault, and therefore the Perseverance Fault does not represent the easterly limit of nickel-prospective ultramafic stratigraphy in this region.

Geology

The Waterloo deposit primarily comprises a south-plunging elongate ribbon of matrix and disseminated style sulfide mineralization situated at the lower contact of a serpentinized ultramafic cumulate unit (Figs 2 and 3). The elongate geometry is pronounced — although the mineralization has a downplunge extent of over 1 km, the massive–matrix component rarely exceeds a thickness of 2–4 m and a cross-sectional dip extent of 50 m. At the northern end of the deposit, these sulfides have been thickened (up to 15 m) in the hinge zone of a south-plunging recumbent fold in the hangingwall of a subhorizontal shear zone, which truncates the lower limits of mineralization. All measured structural fabrics (including fold axes, mineral stretching lineations, and intersection lineations) plunge to the south at the same angle as the recumbent fold axis, and the deposit as a whole. Although there is considerable evidence attesting to localized structural remobilization, overall the deposit appears to be an intact magmatic sulfide deposit situated at the base of a komatiitic lava flow.

The sulfide assemblage comprises pyrrhotite–pentlandite in the primary zone, and both minerals are variably violaritized in the supergene zone. At a broad scale, the sulfides appear to be in situ, forming a classic massive–matrix–disseminated sequence on the lower contact of the serpentinite. At a detailed scale, however, the matrix and disseminated sulfides form a metamorphic sulfide–silicate intergrowth that has an incipient foliation, suggesting centimetric scale recrystallization and remobilization. Furthermore, most of the massive sulfide zones comprise tectonic breccias containing clasts of superjacent serpentinite and subjacent dacitic volcanic footwall rock, or are tectonically banded and recrystallized lenses of massive sulfides that have been mechanically remobilized. Many of the zones are interpreted to be related to flat shear zones that locally transect and disrupt the in situ sulfides. All sulfide styles are high tenor, which translates into high grades for the massive ore (10–17% Ni), matrix ore (5–10% Ni in ore containing 40–60% sulfide), and disseminated ore (1–3% Ni). The Waterloo deposit also contains unusually high levels of copper and PGE, with the copper content commonly exceeding 0.5% and total PGE (Pt, Pd, Os, Ir, Rh, and Ru) content commonly exceeding 1–2 g/t in the sulfide intersections.

The host serpentinite unit is at least 1 km long, varies from 20 m to 100 m in thickness, and is lenticular in cross section. Although the primary igneous fabric of the rock has been totally destroyed by metamorphism, its bulk rock chemistry and mineralogy suggest that it was originally an olivine mesocumulate or peridotite.

The stratigraphy enclosing the mineralization and the serpentinite is poorly understood, but appears to comprise (from base to top):

- a thick sequence of variably silicified dacitic felsic volcanic units;
- a sequence of thin flow fractionated komatiites with locally preserved A and B zones indicating upright facing;
- a dacitic felsic volcanic unit, which forms the immediate footwall to the serpentinite and sulfide mineralization;
- the serpentinite;
- a thick hangingwall sequence dominated by pillow basalts, mafic tuffs, and epiclastic rocks with minor komatiitic interflow units.

This sequence is variably disrupted by low angle shearing and associated folding, and the footwall dacites are intruded by a poikiloblastic pyroxenite. The pyroxenite displays intrusive relationships with the surrounding rocks, is relatively undeformed, and has been retrogressively metamorphosed into a tremolite–chlorite rock, suggesting that it was intruded into the sequence after peak deformation and before later stages of metamorphism.

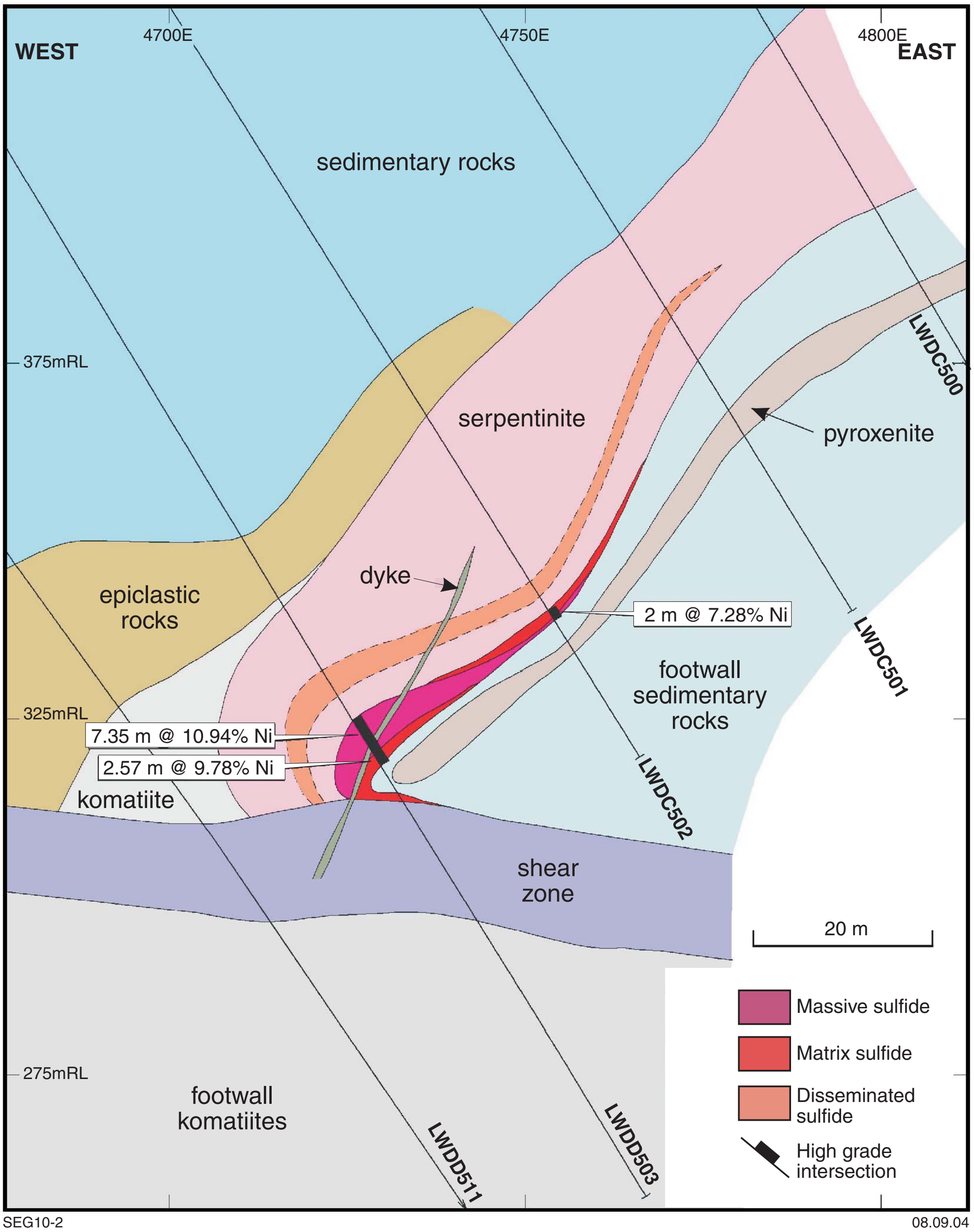

Figure 2. Cross section of the Waterloo deposit at 10020N (local mine grid) showing geology and mineralization, and location of drillholes

The position of the mineralized serpentinite above a thick sequence of thin flow fractionated komatiites apparently contradicts the classic Kambalda stratigraphic model, in which the thickest, highest MgO ultramafic flows (together with the strongest mineralization) occur at the stratigraphic base of the ultramafic sequence. It is not yet clear, however, to what extent the present apparent stratigraphic configuration reflects thrust repetition of the serpentinite over higher parts of the original stratigraphy.

Geological and genetic model

Current understanding of the geological and genetic controls on the Waterloo nickel deposit is only based on drilling data. Notwithstanding this, the current view is that:

- The Waterloo Ni–Cu–PGE mineralization formed at the basal contact of an olivine peridotite ultramafic lava erupted onto a substrate of dacitic felsic volcanic rocks, similar to elsewhere in the Mount Keith – Leinster district.

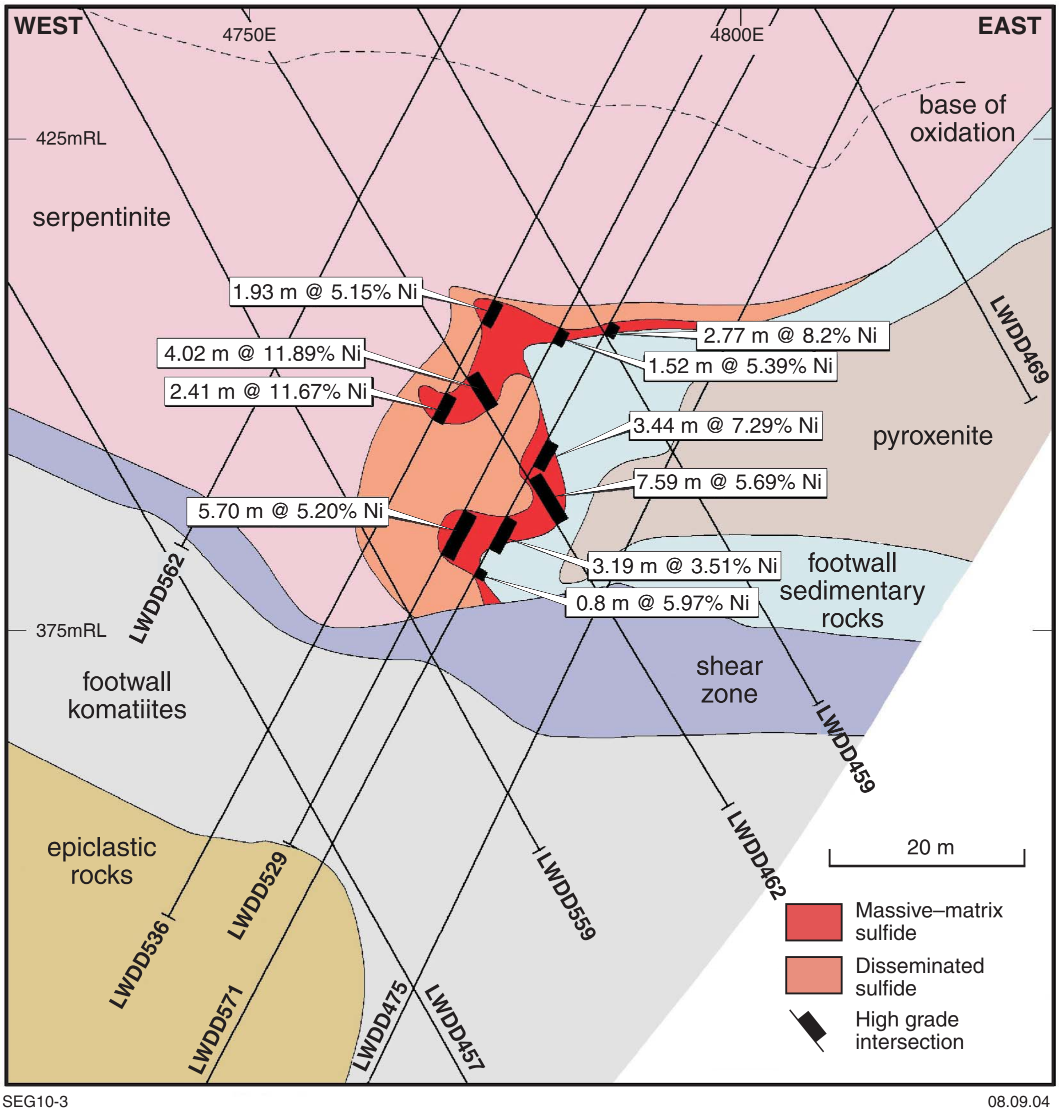

Figure 3. **Cross section of the Waterloo deposit at 10340n (local mine grid) showing geology and mineralization, and location of drillholes**

- This lava formed an elongate lenticular flow with relatively little high-Mg ultramafic lava occupying lateral flanking positions.
- Regional metamorphism resulted in the pervasive serpentinization and complete destruction of original igneous fabrics, and localized retrogressive talc–carbonation in this ultramafic unit.
- Ductile deformation events locally modified the geometry of the serpentinite and remobilized the sulfides, but have not greatly altered the original sulfide–hostrock relationships.
- Likewise, metamorphism modified fabrics at a small scale but has not greatly altered the original relationships. A localized exception to this is the remobilization and flushing of disseminated sulfides from the serpentinized ultramafic unit during the talc–carbonate metasomatism.
- The distribution of the mineralization and host serpentinite is mimicked by a pyroxenite, which appears to have intruded into the footwall after most of the deformation and before cessation of metamorphism. The spatial, temporal, and genetic relationship of this unit to the mineralization is enigmatic.
- The unusual position of the serpentinite above a thick sequence of thin flow fractionated komatiites suggests that the Waterloo mineralization and host flow have been thrust over the hangingwall sequence.
- The nearby Amorac deposit was structurally emplaced within a shear zone, with sulfides having been mechanically remobilized over a distance of at least several hundred metres from their parent ultramafic unit, which is as yet unidentified.

Significance of the Thunderbox gold and Waterloo nickel deposits in exploration models

Thunderbox is an atypical mesothermal gold deposit in several ways. Firstly, it is a wide, evenly mineralized deposit rather than a constrained lode style deposit, due largely to the shape and rheology of the dacite porphyry host rock. Secondly, it appears to be situated in a major first-order shear zone rather than a second- or third-order structure. Thirdly, many features of the deposit suggest that mineralization was emplaced in multiple incremental episodes over a protracted period, commencing relatively early in the tectonothermal history of the district. These features have implications for models of the formation of mesothermal gold deposits, and the targeting methodologies used in the search for them. The lack of an obvious geophysical and surface geochemical signature at the project–prospect scale also has implications for the methodologies selected at the exploration stage.

Thunderbox is one example of a number of recent discoveries such as Granny Smith, Kanowna Belle, Tarmoola, and Wallaby that, unlike most of the previously known gold deposits in the Yilgarn Craton, are not hosted by banded iron-formation (Hill 50, Mount Morgan) or differentiated mafic rocks (Golden Mile, Victory–Defiance, Junction, Wiluna). This new generation of discoveries has broadened the previous widely held belief that Fe-rich hostrocks are a critical ingredient as chemical triggers for gold deposition in hydrothermal systems in the Yilgarn. The location of Thunderbox in a major shear zone considered to be a first-order domain-bounding structure is also somewhat at odds with the conventional wisdom widely used in genetic models and targeting for mesothermal lode gold deposits. Furthermore, the features of the deposit that suggest that mineralization was emplaced in multiple increments over a long period commencing prior to peak deformation and metamorphism add weight to the growing evidence from other deposits (e.g. Golden Mile and Gwalia) that some of the Yilgarn deposits formed relatively early — a situation somewhat at odds with the continuum model of a single late-stage event. If Thunderbox is an example of an early formed deposit, and there are other early formed deposits, they will not be located using the logic developed for targeting late stage deposits, which is based on the assumption that the current structural architecture is essentially that existing at the time of gold emplacement — a so-called dilational jog in a late structure will have absolutely no bearing on the location of an early formed deposit. These observations have fundamental implications for the development of models and the application of targeting criteria.

Being concealed by lateritized sediments, the deposit does not have an obvious surface geochemical signature, which renders traditional surface-sampling techniques ineffective. It appears that even long-term stabilized, relatively thin cover can effectively render a deposit geochemically invisible. Also, being in a first-order structure, individual stratigraphic elements tend to parallel the overall structural grain and, consequently, it is very difficult to use datasets such as aeromagnetics to generate structural targets in these areas, rendering them invisible to conventional structural targeting of the sort routinely used in the Yilgarn.

Many features of the Waterloo deposit have implications for komatiite-hosted nickel sulfide exploration models, practical aspects of exploration, and exploration in the northeastern Eastern Goldfields in particular.

In a general sense, the discovery of nickel sulfides and fertile ultramafic rocks east of the Perseverance Fault attests to the high potential of an area previously disregarded, and demonstrates the danger of dogma in the process of area selection or exclusion. Also, the position of the Waterloo deposit with respect to the enclosing ultramafic stratigraphic column, demonstrates the potential for mineralization to occur at horizons other than those popularized by models such as those developed at Kambalda, irrespective of whether this is due to stratigraphic or structural processes.

Variations in the degree of remobilization within the Waterloo deposit itself, and between the Waterloo and Amorac deposits, also demonstrate the importance of a balanced, holistic approach to exploration in order to find the spectrum of deposits, ranging from intact magmatic deposits associated with the basal contacts of high-Mg ultramafic units to entirely remobilized deposits hosted by shear zones and breccia zones within genetically unrelated stratigraphic sequences. Although igneous and volcanological models are important at the area selection stage, it is vital to consider the role of deformation in the potential reconfiguration and redistribution of these deposits during the exploration stage (at the deposit scale), and subsequent evaluation (at the mining scale).

In detail, the discovery and the geology of the Waterloo deposit have also shown that:

- areally insignificant ultramafic units can be as prospective as more extensive, thicker sequences;
- previous exploration can leave vital clues;
- even densely drilled areas are not necessarily effectively explored;
- there is no substitute for mapping and systematic rockchip sampling.

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