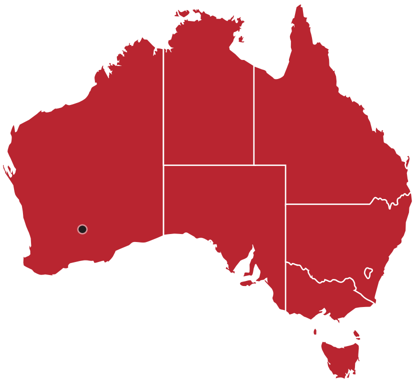

Bullabulling goldfield

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INTRODUCTION

The Bullabulling goldfield straddles the Great Eastern Highway, 25 km west of Coolgardie and 70 km south-west of Kalgoorlie in Western Australia at -31.02°, 120.90°. Gold was first discovered and mined in the late 1980s at Gibraltar, which is late in the history of gold discoveries in the Yilgarn. The Bullabulling goldfield is atypical in the eastern Yilgarn because gold at Bullabulling is not associated with greenschist facies metamorphic rocks or brittle-ductile higher-grade narrow quartz vein arrays or shear zones; instead it has similarities with high-tonnage low-grade gold deposits more commonly found in the US or Canada. Recent structural analysis and 3D geological mapping of the Bullabulling gold deposit clarified the understanding of controls on gold mineralisation, and identified new areas for exploration within the Bullabulling gold deposit and regionally. Subsequent drilling of the Bullabulling gold deposit produced a sevenfold increase of the gold resource, transforming the goldfield in terms of future production potential. Gold endowment of the Bullabulling goldfield is 122 t Au.

EXPLORATION AND MINING HISTORY

The Bullabulling goldfield has been systematically explored for nickel and gold since 1966. Gold production commenced in 1988 with the mining of the Gibraltar deposit in the south. Central Kalgoorlie Gold Mines NL mined several laterite deposits and established heap leach operations in 1989 (Figures 1 and 2), producing 2.64 Mt at 1.14 g/t Au from the Dicksons pit area (Figure 2). Resolute Ltd acquired the goldfield in 1993 and focused on developing hard rock gold resources at Bacchus and Phoenix, as well as building a 1.5 Mt/a carbon-in-leach processing facility (Figure 2). Between June 1995 and 1998, ore was mined from the Phoenix, Bacchus, Titan, Hobbit and Gibraltar open pits (Figure 2). When production ceased due to low gold prices, a reported resource totalling 9.3 Mt at 1.44 g/t Au for 430 000 oz of gold remained.

In 2010 Auzex Resources purchased the Bullabulling goldfield from Jervois Mining Ltd, who had been conducting a small-scale heap leach operation processing remnant stockpiles and supergene ore from the Hobbit and Edwards pits (Figure 2). By August 2011, Auzex Resources and a partner had conducted several phases of resource drilling that defined a large tonnage, low-grade orebody; it had an estimated Indicated and Inferred Resource of 78.84 Mt at 1.03 g/t Au for 2.61 Moz contained gold, using a 0.5 g/t Au cut-off. Norton Gold Fields Ltd became owners in 2013. The resource for the project as of 31 December 2014 is 95.3 Mt at 1.05 g/t Au; that is, 100 t Au (Table 1).

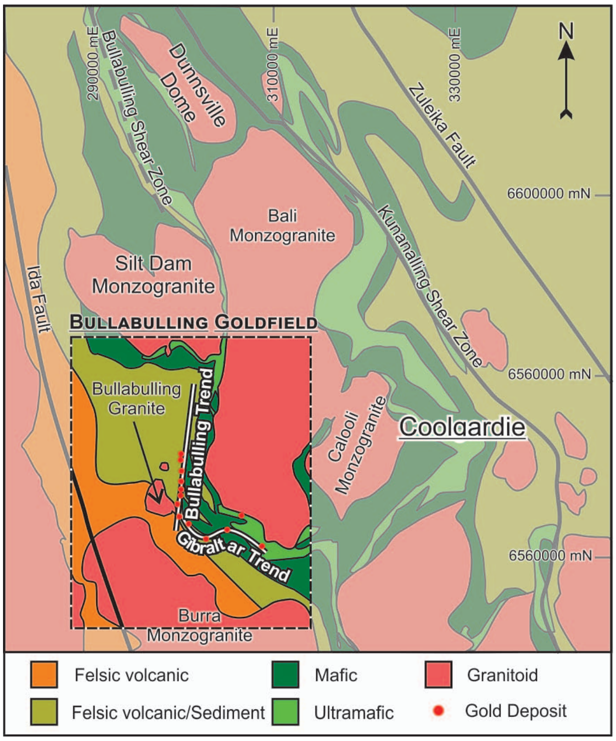

FIG 1 – Geology of the Bullabulling region showing the goldfield in relation to gold occurrences, gold trends and regional structures.

PREVIOUS RESEARCH

There has been no significant independent research or papers published on the Bullabulling goldfield. Research to date has been at the regional scale (Swager, 1994) with unpublished company studies including the regional structural geology and targeting criteria for goldfield-scale exploration. It was associated with a D_1 thrust and the Bullabulling Shear Zone (Figure 1), and postulated gold mineralisation occurred early in the deformation history.

Structures hosting the gold are localised in a domain of high strain rather than shearing, and this domain was wider (1.8 km) than previously mapped (200 m), suggesting the potential for additional resources in both the hanging wall and footwall of the historic pits (Figure 2). This model was confirmed by diamond drilling in 2010, which in turn led to

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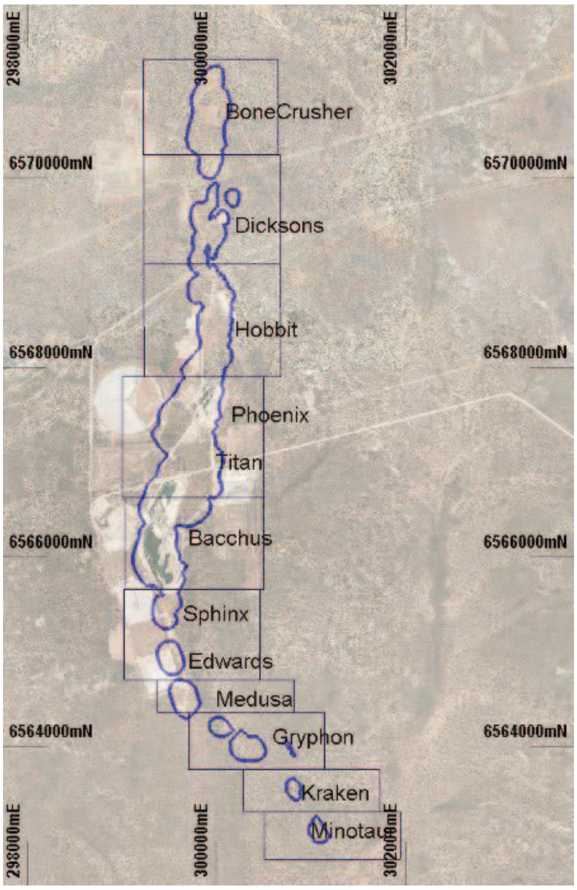

FIG 2 – Bullabulling Trend with historic pits in relation to optimised pit outlines.

TABLE 1 – Bullabulling Mineral Resource using a 0.5 g/t Au cut-off Resources and Reserves estimate at 31 December 2016. Note: The Bullabulling Trend resource is quoted for blocks with a grade of greater than 0.5 g/t and the impact of barren pegmatite dykes has been modelled geologically, with 35 Mt of pegmatite dykes excluded from the resource estimate.

Mineral Resources	Tonnage (Mt)	Au grade (g/t)	Au (Moz)
Bullabulling Inferred Resources	23.08	1.21	0.90
Gibraltar Inferred Resources	3.74	1.14	0.14
Bullabulling Indicated Resources	68.53	0.99	2.18
Total Resources	95.35	1.05	3.22

a further 131 km of exploration and infill resource drilling, resulting in an increase in the gold resources from 0.430 Moz to 3.21 Moz of gold.

GEOLOGY

The Bullabulling goldfield is located on the western edge of the Coolgardie Domain of the Kalgoorlie Terrane in the Yilgarn Craton of Western Australia (Swager, 1997; Cassidy *et al*, 2006; Figure 1). The Coolgardie Domain is bounded by the Zuleika Shear and the Ida Fault to the east and west respectively, and contains a greenstone sequence of basalt, ultramafic, felsic volcanic and sedimentary units intruded by extensive granites. The greenstones were metamorphosed to greenschist and amphibolite facies grades to the east and west of the granite intrusions respectively (Swager, 1997; Cassidy *et al*, 2006; Figure 1). Gold deposits are clustered around the granite, with the Coolgardie goldfield situated on the eastern side of the Calooli Monzogranite and the Bullabulling goldfield west of the Bali Monzogranite.

The mine sequence along the trend of Bullabulling mineralisation and pits dips 30–40° to the west and consists of fine-grained ultramafic and mafic rocks, including quartz amphibolite at the base of the sequence. The hanging wall to this sequence comprises a package of felsic amphibolite facies lithologies with centimetre-scale banding and thinly bedded fine-grained metasedimentary rocks intruded by several generations of pegmatite and granite. Metamorphic mineral assemblages include hornblende, cummingtonite, garnet, sillimanite and cordierite at some localities. The sequence contains two marker units: one is actinolite-rich with elevated nickel (to 500 ppm Ni) and can be traced from Bacchus East to Phoenix (the protolith of this rock was probably a high magnesian basalt); the other is an ultramafic amphibolite comprising tremolite (actinolite), Mg-chlorite, serpentine and magnetite that has a close spatial association with gold (Figures 1 and 2). This unit is characteristically magnetic and highly anomalous in nickel (to 1.2% Ni, with pentlandite identified in thin section), which permits accurate logging and mapping in both fresh and highly weathered environments using a hand-held X-ray fluorescence (XRF) analyser and magnetic susceptibility data.

The banded felsic amphibolite facies lithologies that comprise the hanging wall of the mine sequence are felsic to intermediate in composition and are less deformed than the mine sequence rocks. Granite and pegmatite dykes, sills and sheets are present in the mine sequence and are interpreted to be related to the Bullabulling Monzogranite, a magnetically anomalous intrusion that crops out immediately west of the Bacchus pit (Figures 1 and 2). This intrusion was emplaced late compared to deformation metamorphism and mineralisation based on cross-cutting contact relationships. Drilling deep into the footwall of the Bullabulling mine indicates the mine sequence is parallel to the shallow-dipping south-western margin of the Bali Monzogranite. At depths of around 200 m these contacts become steeper dipping. The Gibraltar deposit is hosted by similar host rocks to the Bullabulling Trend, but they are shallowly south-dipping instead of west-dipping.

Overprinting relationships, from structural analysis of tectonic structures in the Bacchus South, Phoenix and Gibraltar pits, have been used to define five deformation events (Table 2). Three of these events correspond to those recognised by Swager (1997). The preserved deformation history is dominated by bulk inhomogeneous shortening, rather than shearing, that produced a network of high strain zones and folds at all scales that are locally mineralised. The deposit-scale host structure consists of a stack of at least three subhorizontal to moderately W-dipping D4 high strain zones with top-to-the-east shear senses that are folded by west-block-down rotation along N–S striking corridors of high strain in D5. High strain zones and folds that belong to D1 to D3 are preserved between the D4 high strain zones. The dominant structural fabric observed in drill core and outcrop is a fine crenulation cleavage (S4) that dips gently to the west.

GOLD MINERALISATION

The N–S striking Bullabulling Trend hosts most of the gold found to date in the Bullabulling goldfield, with the WNW-striking Gibraltar Trend subordinate to this (Figure 1). The Bullabulling Trend is a continuously mineralised zone that can be traced along strike for 11 km; it is up to 300 m wide and dips about 45° to the west (Figure 2). Laterite caps over primary gold deposits are typically enriched to ore grades,

TABLE 2 – Summary of deformation events recognised in the Bullabulling goldfield and their relationship to regional deformation events and gold mineralisation.

Event	Description	Notes
D1	N–S shortening formed folds with vertical E–W striking axial planes and S1 axial planar cleavage.	Reported by other workers throughout the Eastern Goldfields Super Terrane; described as involving extensive thrusting.
D2	NE–SW shortening. Folds with vertical axial planes and axial planar cleavage.	Widely recognised throughout the Eastern Goldfields Super Terrane.
D3	NW–SE shortening. NE-striking high strain zones. Folds with vertical axial planes and axial planar cleavage.	Widely recognised throughout the Eastern Goldfields Super Terrane.
D4	Vertical shortening. Folds with subhorizontal axial planes. Top to the east shear sense at Bullabulling.	Main foliation high strain zone host gold deposits at Bullabulling.
D5	E–W shortening. Folds with vertical N–S striking axial planes and axial planar cleavages.	Gold mineralisation at Bullabulling.

with gold generally located in the top 5 m of the laterite profile. Supergene gold is present around 20 m below the lateritic gold with the two separated by a depletion zone. Alluvial gold was also mined immediately east of the Bacchus pit, and here gold was concentrated near the base of Cenozoic age clays and lesser grits, about 20 m below the surface. Gold in fresh rock is parallel to N and NW trending lithological contacts that dip 35° to 45° to the west as they wrap around the margin of the underlying Bali Monzogranite. The gold mineralisation is spatially associated with mafic lithologies adjacent to contacts with ultramafic lithologies. In the Bacchus-Phoenix segment of the Bullabulling Trend, high-grade ore zones are located where the host structure changes dip from 45° to 30° or where the orientation of this structure changes from N- to NNE-strike (Figure 2).

Microstructural and petrographic analysis of the relationship of gold-bearing sulfide minerals (pyrite, minor chalcopyrite and pyrrhotite) to the metamorphic banding and deformation fabrics suggest gold mineralisation was late in the metamorphic and deformation history, syn-D_5 and broadly predates the last phase of granite and pegmatite emplacement (Table 2). Individual ore lenses are up to 20 m thick and comprise disseminated sulfide and calc-silicate prograde alteration including hornblende (tschermakitic), diopside, biotite, albite, carbonate and quartz. Gold along the Bullabulling Trend is in a structural corridor containing at least three stacked D_4 high strain zones that are locally folded from their initial subhorizontal orientation to steeper W-dipping ones. Higher grade lodes within the wider structural zone are hosted by both D_4 high strain zones and D_1 and D_3 structures preserved in the low strain domains between them. Continuity within the high-grade shoots in the W-dipping lodes coincides with intersections with D_1 or D_3 structures; however, the dispersed distribution and narrow width of these lodes mean it is difficult to mine them selectively.

The Gibraltar deposit has a strike length of more than 1 km and a true thickness of approximately 20 m. The style of gold mineralisation at Gibraltar is like Bullabulling, except gold mineralisation is hosted by felsic schist below the main ultramafic contact and ore shoots tend to be more discrete and continuous.

3D GEOLOGY AND CONTROLS ON MINERALISATION

Gold mineralisation in the Bullabulling Trend is not confined to a major regional shear zone as previously hypothesised by Swager (1994), and the distribution of gold mineralisation is more extensive than originally defined. Thus, detailed 3D maps of the geology and structural architecture were developed to resolve mine- and regional-scale controls on the localisation of gold. The distribution of metamorphosed, altered and weathered ultramafic units was accurately mapped by analysing for nickel and chrome in all reverse circulation drill samples as proxies for ultramafic lithologies using a hand-held XRF analyser. The geochemistry helped resolve issues associated with subjective logging of lithological units, particularly in the regolith and for lithologies with a complex metamorphic and alteration history. Using the geological logging from the historic and resource infill drilling, it was possible to construct wireframes of two marker units along the entire length of the Bullabulling Trend. Other lithological units – constrained by the marker horizons and pegmatite volumes – were also mapped, and a 3D solid geological model was produced to geologically constrain geometric modelling of the mineralised lodes for exploration targeting and resource estimation.

Because the lithologies in the goldfield are moderately dipping and have distinctive petrophysical properties (including elastic and acoustic impedance, density and magnetism), seismic reflection data were collected to test the use of seismic data for mapping the 3D geology and structure in parts of the goldfield where drilling data were limited. Three 2D seismic lines were shot over the Bullabulling goldfield in 2012 by HiSeis Pty Ltd (Figure 3). The seismic data were processed to highlight structure, granite contacts and possible ultramafic units constrained by the known location of the two marker horizons and magnetic and gravity inversions. The marker horizons along the Bullabulling Trend were interpreted on each seismic section and other possible ultramafic units were interpreted where there were high amplitude signals (Figure 3). Granite contacts were mapped based on drilling information. The highly magnetic Bullabulling Granite was mapped in 3D using volumes developed from inversions plotted on the relevant seismic sections in 3D (Figure 3).

There is a strong correlation between trends in the seismic data and the geology mapped in 3D from drilling (Figure 3). The ultramafic units are well-defined reflectors that can be traced from the eastern contact of the Bali Monzogranite, where ultramafic amphibolite facies lithologies crop out with shallow dips through to the Bullabulling Trend (Figure 3). The seismic maps show a sequence of subhorizontal units that form a broad basin structure, with several minor anticlines that taper out towards the Bali Monzogranite contact at depth. The same style of folding has been mapped at a smaller scale in the Bacchus and Gibraltar pits. The Bali Monzogranite contact appears to steepen underneath the Bullabulling Trend, with the ultramafic sequence defining a doubly plunging N-trending anticline on a scale of 400–600 m. West of the Bullabulling Trend, geological units

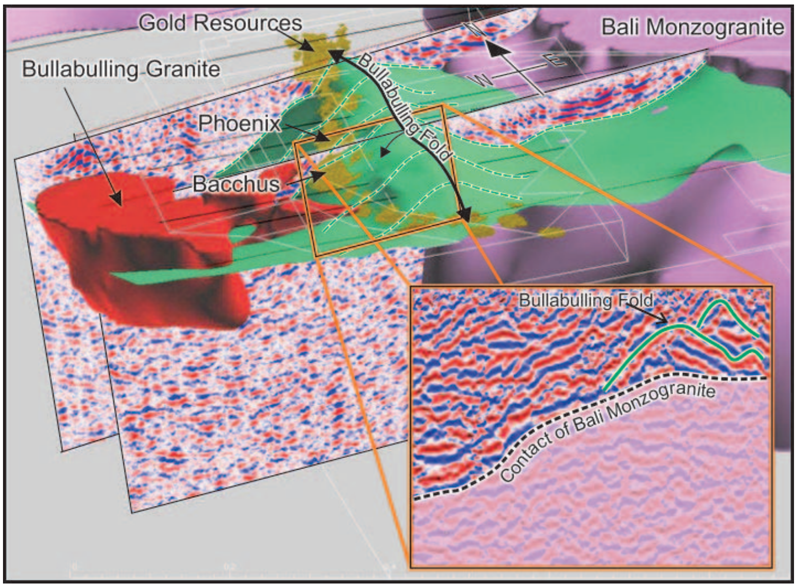

FIG 3 – Geological features interpreted from seismic data. Note anticlinal and dome-like features defined by the ultramafic amphibolite marker horizon in green mapped by the seismic associated with the main zones of gold mineralisation (in gold) and distinct discontinuity at depth that marks the top of the Bali Monzogranite (in purple) against which the folds terminate. The Bullabulling Monzogranite (in red) appears late and cuts the earlier structures and lithological contacts.

steepen to more than 40° as does the contact of the Bali Monzogranite. There is a clear spatial association between gold mineralisation with folds interpreted on the seismic sections. The largest gold resources along the Bullabulling Trend and at Gibraltar are spatially associated with the 100 m scale folds. Additionally, folds tend to be located where the contact of the Bali Monzogranite steepens to more than 40°. The history of overprinting ductile deformation events each comprising bulk inhomogeneous shortening can be recognised at all scales, and the overprinting of different structures over a wide zone appears to have provided structural heterogeneity and the required permeability for the formation of the broad, low-grade disseminated gold resource at Bullabulling. The resultant structural model and 3D geology model with respect to the location of gold in the goldfield has revealed several important implications for increasing the resource and exploring for new orebodies including: potential for exploration targets in D_5 high strain domains along the Bullabulling and Gibraltar Trends at depth; along the eastern limb of the Bullabulling Trend anticline; and beneath ultramafic amphibolite units elsewhere in the Bullabulling goldfield, particularly those that are spatially associated with anticlines.

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