

Executive Summary

Hydrothermal Systems, Giant Ore Deposits, Yilgarn Atlas Volume III UWA Gold Module, Part 1, Weinberg, R.F., Groves, D.I., Hodkiewicz, P., van der Borgh, P., AMIRA Project P511

The SPIRT/LINKAGE segment of the gold module of project P511 is divided into two independent parts: the first focuses on the Yilgarn Craton, and the second on global characteristics of orogenic gold deposits. This project has derived a new and self-consistent structural history for the Norseman-Wiluna Belt, Yilgarn Craton, and provided new insights into the controls on gold mineralization. Essentially, the findings are that the belt underwent a late-Archean orogeny to produce the Kalgoorlie Orogen, which includes structures that reflect the regional deformation phases known as D_2 - D_4 . Deformation was a response to pure shear, and not sinistral transpression as previously proposed, and resulted from continuous ENE-WSW directed shortening. The orogen proceeded from a thickening phase D_2 , to a lateral extension phase characterized by strike slip shear zones D_3 , which became increasingly brittle as the crust cooled (D_4). During straining, the presence of competent granitoid bodies caused intense shearing and lateral escape of surrounding weaker greenstone sequences. Escape process was controlled by the interaction between the orientation of granitoid boundary and external stresses.

The orogeny was accompanied by low-Ca granitoid intrusion, metamorphism and gold mineralization. Mineralization took place in the later part of the history, except possibly for the Golden Mile, which had a prolonged history of mineralization. Zones of high straining, such as crustal scale shear zones, and rock competency contrast are the two key controls in the siting of mineralization. This is because shearing of rocks of contrasting strength lead to rock flow heterogeneities and dilation zones which focus fluid flow. Competency contrast is highest at greenschist facies temperatures, thus explaining, at least in part, why greenschist facies terranes tend to be more endowed than other terranes. In this context, weak ultramafic rocks or shales and strong granitoid or doleritic intrusions in mineralization play a key role in mineralization by providing very marked competency contrast with other rock types.

Sulphur isotope ratios of a number of deposits were investigated seeking to determine their relation to gold endowment. There is a tendency for large gold deposits to be associated with large variation in this ratio, but this is not universal. Another indicator for the location of potentially large gold deposits is complexity in the distribution of lithological contacts and

structures, as quantified by fractal dimensions. Complex zones generally host the large gold deposits, because these zones provide a number of possible hosts and increased likelihood for fluid focusing and traps. Surprisingly, the largest deposits are sited, not in the zones of highest complexity, but in zones of strong lateral gradient in complexity.

Gold exploration should focus on regions of lithological and structural complexity within greenschist facies belts, close to crustal-scale permeable shear zones. Within these areas, large deposits will be sited where there is strong lateral variation in complexity, as measured by variation in fractal dimensions. This project derived these conclusions by detailing and comparing the evolution of the Boulder-Lefroy, Zuleika and Ida Shear Zones. The main results are listed below in point format, further summarized at the beginning of each major section of this report, and discussed in *Section 5*.

Point Summary

Timing of deformation (Section 2.3):

- Relative timing of deformation phases previously established based on structures relative to granitoid intrusions is flawed.
- Timing of D_2 - D_4 regional deformation phases is later and of shorter duration than previously considered. It is now estimated to have taken place between 2650-2630 Ma instead of 20 Ma earlier. A new time chart for the structural evolution of the Norseman-Wiluna Belt is developed.
- A major late tectono-thermal event is defined by the regional deformation phases D_2 - D_4 , low-Ca granite intrusion, and gold mineralization.

Boulder-Lefroy Shear Zone (Section 2.4):

- The shear zone developed in two stages: a) D_2 reverse faulting and folding; b) D_3 sinistral shearing.
- There is no evidence for late important dextral shearing, commonly reported as significant in previous studies.
- Early structures developed at Kalgoorlie (Golden Mile Fault and Kalgoorlie Anticline), interpreted as abandoned early D_2 , are cross cut and refolded by later active structures.
- Weaker D_2 strain at Kambalda preserved early regional D_1 thrusts, and also led to further crustal shortening as well as sinistral movement during D_3 .

- The D_3 dextral, sinuous, N-S striking, *en-echelon* Charlotte set of shear zones formed as a result of NNW-sinistral shear.
- D_4 is represented by later, brittle structures, which also reactivated earlier formed structures.
- Small total D_3 sinistral displacement on the shear zone is confirmed.
- Gold, with the exception of the Golden Mile, was deposited late in the tectonic history of the shear zone, either during D_3 or D_4 .
- Gold at the Golden Mile was deposited earlier, possibly during the early stages of D_2 .
- General thermal arguments based on the depositional, magmatic and deformation history of the Kalgoorlie Terrane suggests that two broad metamorphic, and consequently mineralization, events took place: the first during crustal extension and extrusion of the mafic-ultramafic sequence and high-Ca magmatism; the second during the Kalgoorlie Orogen and low-Ca magmatism.

Zuleika and Ida Shear Zones (Section 2.5):

- The Zuleika Shear Zone has complex kinematics, with significant eastward thrusting at Kundana, and sinistral strike slip movement further north at Ant Hill/Bullant.
- Complexity results from internal deformation of the shear-zone bounded blocks and possibly an evolving deformation history.
- The Zuleika-Kunanalling Corridor, between the Kundana area and the Bali granite/Kunanalling area, is a pop-up structure, with fold tightening towards the two bounding thrust zones: the Zuleika and Kunanalling Shear Zones.
- The Ida Shear Zone is enclosed within a narrow, amphibolite facies greenstone sequence, intensely flattened and attenuated by impinging granitoid bodies.
- Stretching direction along the corridor is sub-horizontal on a sub-vertical foliation and shear sense indicators are poorly defined due to predominant pure-shear deformation. There is no evidence for late normal faulting.
- Gently-dipping seismic reflectors at depth are not obviously related to the surface expression of the Ida Shear Zone.

Contrasting Shear Zones and Gold Endowment (Section 2.6):

- Irregular margins of competent granite batholiths cause an added degree of complexity on the kinematics of neighbouring shear zones.

- Different endowment along shear zones is related to variety in rock types along the shear zone, metamorphic facies, and geometry (tight/gentle antiforms/synforms).
- Competency contrasts play a key role in localizing fluid flow within the crust by creating regions of dilation (strain incompatibility).
- Competency contrast is high in greenschist facies rocks (ductile talc- or chlorite-schist versus brittle dolerite or granitoid) and low in amphibolite facies rocks (ductile amphibole- or quartz dominated rocks). Amphibolite facies rocks retain low competence contrasts as they cool to greenschist facies conditions, as long as they are not strongly retrogressed.
- Homogeneous rock deformation leads to unfocused fluid flow and poor mineralization, as opposed to heterogeneous rock deformation.
- The giant gold deposit (Fimiston lodes) is the only one to have possibly been deposited either before or during early D_2 .

Kalgoorlie Orogen (Section 2.7):

- A late-Archean Kalgoorlie Orogen is proposed. There was an ENE-WSW continuum of shortening during orogen evolution, from D_2 crustal thickening to D_3 - D_4 lateral escape. Granitoid bodies control local rock flow and stress distribution.
- The pattern of deformation and distribution of regional shear zones resulted from the interaction between these external forces and the presence of large, competent granitoid bodies which impinged upon the weaker greenstone sequences, causing them to escape in the direction of least pressure.
- External stresses and the escape from impinging granitoids led to the development, at the scale of the Norseman-Wiluna Belt, of a conjugate pair of NW-striking sinistral shear zones and NE-striking dextral shear zones.
- D_2 - D_4 deformation resulted from pure shear due to ENE-WSW shortening, and not as a result of sinistral transpression.

Gold Distribution and Fractal Dimensions (Section 3.1):

- Gold distribution along the Boulder-Lefroy Shear Zone follows a very well determined pattern, with four peaks in gold endowment, corresponding to the major mining camps, spaced systematically every 30-40 km, and each peak followed by an area of very low gold endowment.

- Interestingly, the highest endowed area (the Golden Mile) is followed to the north and to the south along the BLSZ by the poorest areas, suggesting that either gold or fluids were focused towards the Golden Mile, depleting the immediate surroundings.
- Fractal dimension can be used to quantify complexity of lithological contacts and major structures. The largest gold deposits are sited, not at regions of maximum complexity (highest fractal dimensions), but in regions of greatest complexity gradients (fractal dimension gradients), representing tectonic/structural domain boundaries.
- Fractal dimension is proposed as a relatively simple and low-cost method to focus exploration studies.

Sulphur Isotopes (Section 3.2):

- Large variations in gold-related pyrite sulphur-isotope compositions (>10‰) in larger gold deposits (>1Moz) are typically related to specific structural settings, hydrothermal alteration assemblages and host rocks.
- Anomalous $\delta^{34}\text{S}_{(\text{py})}$ values and large variations are related to a sensitivity to ore depositional processes, which relate to local scale physical and chemical controls. Thus, variation in sulphur isotope ratios could be accounted for by local processes rather than specific fluid sources.
- A further source of sulphur isotope variation could be related to pyrites from unmineralized sedimentary rocks, which were found to have large variations in sulphur isotope composition, in contrast to previous studies. These are a potential sulphur source to deep-seated hydrothermal fluids.

Gold Endowment Analysis (Section 4):

- Parameters critical to the control of world-class gold deposits are defined through a combination of genetic studies and empirical analyses within a GIS environment.
- These are summarized in Table 4.1 in terms of a mineral system analysis. They can form the basis of endowment analyses, either semi-quantitative in nature or involving more sophisticated integration using fuzzy logic or artificial neural network methodologies.