A new view of Coolgardie: Implications for correlations within the Kalgoorlie Terrane

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Introduction

The first recorded gold discovery in the Eastern Goldfields was at Coolgardie in 1892, and since over 2.5Moz of gold has been produced from Coolgardie. The Coolgardie District is located in the Coolgardie Domain on the western side of the Kalgoorlie Terrane, Norseman-Wiluna Belt. The Coolgardie Domain is bounded to the west by the Bullabulling Domain and to the east by the Zuleika Shear and Ora Banda Domain. The Coolgardie Domain is dominated by granitoids of the Woolgangie Supersuite dated at the Burra Granite (SHRIMP U-Pb zircon: 2687±6Ma, Hill *et al*., 1992; 2676±19Ma, Nelson, 1997), and internal plutons such as the Bonnievale tonalite (2680±5Ma, Hill et al., 1992) and Bali Monzogranite (2676±8Ma, Nelson, 1998). These ages are consistent with a *ca.*2680Ma peak for felsic magmatism spanning 2690 to 2650Ma throughout the Kalgoorlie Terrane. Napier (1993) estimates peak amphibolite facies metamorphism at Coolgardie occurred at between 2653±8 and 2650±5Ma using Ar-Ar on metamorphic amphiboles.

Stratigraphic Setting

Hunter (1993) subdivides the greenstone stratigraphy in the Coolgardie District into the basalt dominated Burbanks Formation and the ultramafic Hampton Formation, which are overlain by the Black Flag Group. Morris (1993) and Hunter (1993) correlate the Burbanks Formation with the Lower Basalt at Ora Banda and Kalgoorlie, and the Hampton Formation with the Siberia Komatiite at Ora Banda and the Hannans Lake Serpentinite at Kalgoorlie. The equivalent of the Upper Basalt in the Kalgoorlie Terrane is missing from the Coolgardie District.

New mapping, whole-rock, trace element and rare earth element data indicate that the stratigraphy needs revision, and that the Burbanks Formation in the Coolgardie Domain can not be directly correlated with the Lower Basalt in the Kalgoorlie Terrane. In detail, the lowermost unit at Burbanks Formation is the Burbanks Basalt a +900m thick pile of pillowed variolitic and porphyritic basalt that cores the Big Blow Anticline. The basalts are high-Fe tholeiitic basalts (HFTB) with Ti/Zr ratios of 235-305, higher than 80-106 quoted for the Lower Basalt elsewhere in the Kalgoorlie Terrane (Morris, 1993). A group of interflow sediments separates the Burbanks Basalt from the Brilliant Ultramafic a 150-700m thick basaltic komatiite with MgO of 18-27wt%, Cr of ~2000ppm, Ni of ~1100ppm, and Ti/Zr ratios of 100-135. The ultramafic is present on both sides of the Big Blow Anticline, however much is missing from the western limb due to tectonic removal and emplacement of the Calooli Monzogranite. A swarm of thin (to 80m thick) garnet-bearing diorite to dolerite dykes and sills intrude the base of the Brilliant Ultramafic and host the majority of gold deposits south of Coolgardie. These dolerite sills intrude bedding and discordant shear zones suggesting contemporaneous mafic magmatism and deformation.

The Brilliant Ultramafic is overlain by the Lindsays Basalt, a 900-1600m thick sequence of pillowed HFTB with 12wt% Fe_2O_3, 6wt% MgO and Ti/Zr of 245-560, also much higher the Ti/Zr ratio quoted for the Lower Basalt. Carbonaceous shales in the centre of the Lindsays Basalt are intruded by a variably differentiated dolerite, the Three Mile Sill. This sill is 150-800m thick and its granophyre zone hosts the bulk of the gold deposits north of Coolgardie.

Chilled dolerite from the Three Mile Hill Mine has 12wt% MgO, and 14wt% Fe_2O_3, which is different to the neighbouring Greenfields Sill, with 7wt% MgO and 13wt% Fe_2O_3. Pillow facing in the basalt is identical either side of the Three Mile Sill, and younging is consistently away from the core of the Big Blow Anticline and the Calooli Monzogranite, thus precluding the synclinal model of Hunter (1993).

Overlying the Lindsays Basalt is the Hampton Formation a 1700-2500m thick sequence of komatiite, komatiitic basalt and high-Mg tholeiitic basalt. Pillow facing in the basalt is towards the northeast. Felsic sediments and volcaniclastics of the Black Flag Group overlie the Hampton Formation, although the contact is intruded by the 200-600m thick differentiated dolerite, Greenfields Sill. Tabular cross bedding in wacke-sandstones of the Black Flag Group young towards the north, consistent with facing derived from basalt pillows.

Structural Setting of the Coolgardie District

The Coolgardie Domain is characterised by greenstones draped around ovoid granitoid plutons without any major through going shear zones. As a consequence structures in the Coolgardie Domain are influenced by the shape and proximity of granitoids, and the stress field recorded in the rocks is indicative of local stress, rather than far-field stress.

Folds

There are two principal fold structures in the Coolgardie District: the NNE-oriented Big Blow Anticline and the E-W oriented Barbara Anticline. The Big Blow Anticline is a megascopic, tight, doubly plunging, anticline with a NNE-striking fold axial plane, dipping steeply to the east. Folds plunge steeply north and south and the limbs dip steeply east. A non-penetrative cleavage and mild flattening of pillows are the main fabrics outside of two NNE-striking ductile shear zones: the Redemption Fault and the Big Blow Fault. The eastern limb of the Big Blow Anticline is structurally thickened by the E-W trending Barbara Anticline, which is a close-tight, east-plunging upright fold with a subvertical axial plane. East-west directed folds are rare in the Eastern Goldfields Province, suggesting the intrusion of the Burra Batholith is the main influence on this fold shape.

Faults

Faults in the Coolgardie District consist of early, prograde faults formed under ductile to brittle-ductile conditions, and later retrograde faults formed in the brittle regime. Prograde faults are 5-50m wide and characterised by a recrystallised gneissic foliation of coarse-grained amphibole interleaved with wispy feldspar and quartz. In ore zones, the prograde assemblage is overprinted by actinolite and biotite. Retrograde faults are narrower (1-20m thick) and often discordant to stratigraphy, rework prograde fault zones, and are characterised by brecciation, fault gouge, fracturing and net veining. Alteration is a pervasive chlorite+calcite+quartz+sericite+pyrite assemblage, and gold mineralisation occurs in these faults at the Lindsays and Three Mile Hill deposits.

Structural Evolution of the Coolgardie District

Swager *et al*. (1990) propose a tectonic evolution of the Kalgoorlie Terrane comprising four compressional deformation events after the deposition of the greenstone rocks. However, Krapez *et al.* (2000) recognise significant extension during deposition of the Black Flag Group contemporaneous with granitoid plutonism between 2700 and 2655Ma; an event attributed to compressional event D_2 by Swager *et al*. (1990). Clearly the tectonic model needs revision and observations in the Coolgardie district may help resolve these issues.

First Compressional Deformation Event (D_1)

The first compressional deformation event (D_1) is well preserved in the Coolgardie District in the form of thrust repetition of the Lindsays Basalt and Hampton Formation across a major

arcuate E-W-striking fault system (Coolgardie Fault-East Dam Fault) extending from the Calooli pluton in the west, to well east of the Greenfields Mine in the east. The sense of displacement is north-block over south-block, which is opposite to that inferred in the Kambalda Domain by Swager *et al*. (1990). The thrust décollement occurs at the base of the Brilliant Ultramafic and this structure facilitated the build-up of the Calooli Monzogranite pluton at *ca*.2676Ma (assuming the Bali Monzogranite is comagmatic with the Calooli Monzogranite), which constrains the age of D_1 thrusting to prior to this age.

Second Compressional Deformation Event (D_2)
According to Krapez *et al*. (2000), the deposition of the Black Flag Group must have occurred contemporaneous with granitoid emplacement and volcanic basin-wide extension. However, the intrusion of the granitoids in the Coolgardie Domain locally drove compressional structures such as folds and reverse faults in the greenstones sandwiched between the plutons. Development of the Big Blow Anticline was in response to doming and tilting by the Calooli monzogranite. Development of the E-W oriented Barbara Anticline followed, in response to the intrusion of the Burra Batholith at *ca.*2686Ma to 2676Ma. The NNW-striking Redemption Fault and Big Blow Fault systems initiated in the Burbanks Basalt late in this event.

Third Compressional Deformation Event (D_3)
Sinistral transcurrent shearing along major NW-striking shear zones is attributed to D_3 in the Kalgoorlie Terrane and the same is seen in Coolgardie. Gold mineralisation commenced during and persisted throughout D_3, in the brittle-ductile regime in the latter stages of the event. Ductile examples of D_3 systems are the Patricia Jean Lode and the Bayleys Reefs, and macroscopic ptygmatic folding of the dolerite sills at the Tindals mine. Brecciation and stockwork veining during gold mineralisation occurred later in D_3 under brittle-ductile conditions. The stress direction is interpreted to have migrated from a WNW-ESE direction to E-W by the end of D_3.

Fourth Compressional Deformation Event (D_4)
Deformation under E-W compression and brittle conditions initiated the rupture of N-S to NNE-striking dextral strike-slip faults across the Lindsays Basalt and parts of the Hampton Formation. D_4 faults are characterised by brittle textures, retrograde alteration assemblages and limited gold mineralisation.

Discussion and Conclusions

Recently Knight *et al.* (2000) and Witt *et al.* (1997), promoted a model whereby gold mineralisation at Coolgardie is syn-peak metamorphic and related to fluids driven laterally along a thermal gradient from the Calooli Monzogranite. Evidence for this interpretation is based upon 'zoned' syn-metamorphic alteration assemblages, zoned P-T estimations and lateral variations in δO^{18} away from the Calooli Monzogranite. Knight *et al*. (2000) recognise two types of inner alteration assemblage: a garnet+hornblende+plagioclase assemblage in gold deposits less than 2km from the Calooli Monzogranite, and an actinolite+biotite+plagioclase assemblage in deposits further a field. However the 'higher temperature' garnet-bearing assemblage is restricted to doleritic intrusions of the Tindals suite and the granophyric zone of the Three Mile Sill, indicating this variation in assemblage is totally lithological, rather than a temperature control. This view is backed by P-T estimations for the garnet assemblage (average = 522°C) and actinolite+biotite (average = 509°C), being identical given the ±25 to 50°C precision of the various techniques employed by Knight *et al.* (2000). The variations in δO^{18} are equally unconvincing.

It is clear that there is a considerable time gap between magmatism in the Coolgardie district (*ca.* 2680Ma), metamorphism (*ca*. 2650Ma) and gold mineralisation in the Kalgoorlie Terrane (*ca*. 2630Ma). This together with an absence of any convincing geologic gradients around the

Calooli pluton, do not support the lateral fluid flow model for mineralisation. An alternative source of heat and potentially gold-bearing fluids may be the parent of the enigmatic and as yet undated Tindals dolerite suite.

New work shows the greenstone stratigraphy at Coolgardie is geochemically different in comparison to the centre of the Kalgoorlie Terrane. A regionally extensive thrust décollement occurs at the base of the Brilliant Ultramafic into which the Calooli Monzogranite intruded. This thrust zone structurally repeated the Lindsays Basalt and Three Mile Sill with a north-over-south sense of movement, and juxtaposed the Three Mile Sill against the geochemically distinct Greenfields Sill. The intrusion of the Calooli Monzogranite, inferred to be comagmatic with the 2676Ma Bali Monzogranite, constrains the D_1 thrust event to prior to this age. The regional Big Blow Anticline and Barbara Anticline developed during D_2 in response to the emplacement of the Calooli and Burra Batholiths. D_2 is characterised by dome-driven shortening between the plutons along the western flank of the Kalgoorlie Terrane, whilst in contrast the centre the Kalgoorlie Terrane was in extension during deposition of the Black Flag Group. The third deformation event (D_3) signalled a change to a WNW-ESE far-field compressive stress under brittle-ductile conditions which resulted in further reverse displacement along the NNE-striking faults and sinistral movement on NW-striking faults. Gold-bearing fluid was focussed into D_3 shear zones during progressive fault evolution. The fourth deformation episode (D_4) shows a change in stress direction to E-W and northward growth of NNE to N-S striking, brittle dextral faults systems. Sinistral strike-slip movement occurred along NW-SE striking structures.

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