The Kalgoorlie gold: A review of factors of formation for a giant gold deposit

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Contents

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Abstract: The Archaean Yilgarn craton in Western Australia is a granite greenstone belt with abundant economically important mineral reserves, including several world-class gold deposits such as the giant Kalgoorlie deposit.

Structural controls on gold deposition and the fact that most deposits were formed later in the craton's tectonic history, has resulted in the general acceptance of a late-orogenic structurally-controlled model for gold mineralization in the Yilgarn craton. However the early establishment of fracture networks and conduits for vertical fluid transport during D1 are considered integral for formation of the Kalgoorlie deposit. This structural evidence has led to contrasting theories on the timing of formation of the Kalgoorlie gold. It also suggests that the factors of formation of the Kalgoorlie gold are possibly different from those of other gold deposits in the Yilgarn.

This review paper suggests that the major factors of formation of the giant Kalgoorlie deposit include: 1. Host rock characteristics, such as the anomalous thickness resulting from regional deformation during D1, as well as competency contrasts which increases permeability and thus ore fluid infiltration; 2. Deformational movement creating structural controls and pathways for large-scale fluid transport and efficient fluid focusing, as well as resulting in suitable sites for gold deposition, such as breccias and quartz veins; 3. A protracted mineralization period spanning up to 45 million years, resulting in prolonged periods of fluid focusing and gold deposition.
However none of these factors are considered solely responsible for producing a world-class gold deposit. Instead it is suggested that favourable conditions for several factors occurred in conjunction to produce a highly efficient fluid focusing system, and thus the giant Kalgoorlie deposit.

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1 Introduction

The Archaean Yilgarn craton in Western Australia is a granite greenstone belt with abundant economically important mineral reserves, including world-class gold and nickel deposits (Wyche et al. 2008).

The craton can be divided into six terranes: the Kalgoorlie Terrane, Kurnalpi Terrane and Burtville Terrane, which combine to form the Eastern Gold-fields Superterrane (East Yilgarn craton), the central Youanmi Terrane, and the Narryer and South West Terranes in the western Yilgarn (Fig 1; Cassidy et al. 2006). Division is based on major shear zone boundaries (Swager et al. 1995) and differences in geological history (Myers 1995). This can be exemplified by the shift from dominating granite and granitic gneiss in the west to greenstone belts separated by granite and granitic gneiss in the Younmi Terrane and Eastern Yilgarn Superterrane (Czarnota et al. 2010).

An episode of tectonic activity, which amalgamated different crustal fragments between 2780 and 2630 Ma, is believed to have resulted in the formation of the Yilgarn craton (Myers 1995). This orogenic event resulted in large-scale east-west deformation, faulting and granitoid emplacement, culminating during the period 2.66 – 2.63 Ga (Witt and Vanderhor 1997). It is during this period of deformation most of the Yilgarn gold deposits are believed to have formed (Witt and Vanderhor 1997).

The lode-gold deposits of the Yilgarn belong, as do most other Archaean gold ores, to a coherent genetic group of structurally controlled lode-deposits (Groves 1993). The widely accepted Crustal continuum model suggests that Archaean gold deposits have formed under a wide range of conditions varying over at least 15km crustal depth, with PT conditions ranging from 180°C at <1 kb to 700°C at 5 kb (Groves 1993). Thus gold mineralization varies greatly from setting to setting, which is certainly true in the Yilgarn craton.

Although the majority of gold deposits in the Yilgarn craton occur in Fe-rich hosts, such as dolerite, basalt and banded iron formations, large gold deposits can be found in nearly all of the main rock types (Witt and Vanderhor 1998). Gold deposits also occur in a wide range of structural settings, such as simple quartz veins and quartz vein systems, brittle faults and brittle–ductile shear zones (Witt and Vanderhor 1998).

However the different styles of gold mineralization in the Yilgarn craton also have common characteristics, such as being broadly contemporaneous, 2640 – 2620 Ma, and linked to deformation events late in the tectonic history (Czarnota et al. 2010). These observations, together with deposits being generally structurally controlled (Wyche 2007), have lead to a late-orogenic structurally-controlled model being generally accepted for the Yilgarn gold deposits (Myers 1995). However, the early establishment of fracture networks and vertical conduits for fluid transport at Kalgoorlie during D1, has resulted in varying opinions on the timing of the Kalgoorlie gold. For example the model proposed by Swager (1989) suggests that gold deposition occurred earlier at c. 2670 Ma, during the D1 event (Bateman and Beirlein 2007).

Some of the most highly mineralized regions in the world occur in Archaean greenstone belts (Groves and Barley 1990). In regards to Archaean greenstone gold production, the Timmins deposits in the Abitibi greenstone belt, Superior Province, Canada is the largest, with total production as of 2006 at 1800 tonnes, followed by the Golden Mile deposits in Kalgoorlie at 1300 tonnes (Fig. 1, Bateman and Bierlein 2007). Total gold reserves in the Golden Mile are estimated at c.1400 tonnes (Bateman and Hagemann 2004). This compares with the world's largest gold production area, the Witwatersrand Basin in South Africa, which has produced 50 000 tonnes (Jolley et al. 2004). However the much smaller area of Kalgoorlie, the so called Golden Mile (3 km^2), makes it unmatched worldwide in terms of production value per area (Phillips et al. 1996).

Gold in the Kalgoorlie Terrane was first discovered in the 1890's and triggered a major gold rush in the region (Hagemann et al. 2001). Thanks to modern and more effective gold extraction methods and rising gold prices there has been a second "gold rush" in the region since the 1980's (Hagemann et al. 2001). This situation continues today with total gold sales in WA (Western Australia) for 2011-12 at c. 1.644 tonnes giving a revenue of AUD$9.4 billion (GSWA 2013). Due to the economic importance of gold production in this region there is thus great interest in research involved with factors of formation of large gold deposits and this study focuses on the giant Kalgoorlie deposit.

The aim of this report is to present a background to gold mineralization in the Kalgoorlie Terrane, including the tectonic history and metamorphism, followed by a detailed discussion of the factors resulting in the world-class Kalgoorlie deposit. The report will specifically examine:

- The importance of deformation events and structural control related to gold mineralization.
- The source of auriferous ore fluids and their characteristics.
- The importance of host rock characteristics.

2 Regional Setting

The East Yilgarn craton in Western Australia is a highly mineralized area that contains several large gold deposits, including the giant Kalgoorlie deposit (Bateman and Hagemann 2004). The craton is composed of extensive areas of granite and granitic-gneiss separated by greenstone belts (Phillips 1986). It's surrounded by the Phanerozoic sediments of the Perth Basin and the Officer Basin to the west and east respectively, Proterozoic sediments of the Nabberu Ba-
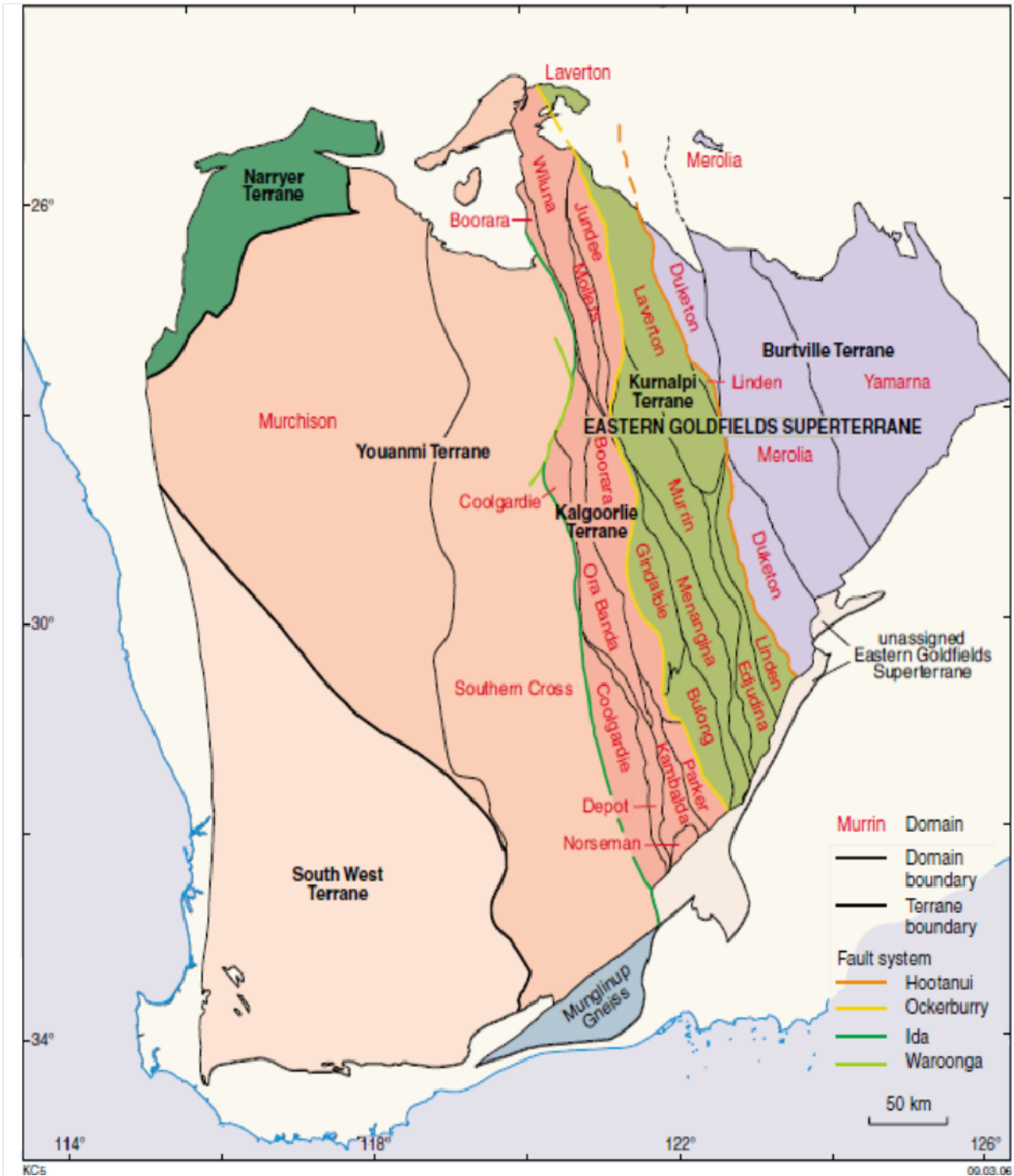
Fig.1. Map of the Yilgarn craton in Western Australia showing subdivision by terranes and domains, and major fault systems in the Eastern Goldfields Superterrane (East Yilgarn craton) and the Kalgoorlie Terrane (Cassidy et al. 2006).

sin to the northwest, and the Proterozoic complexes of the Gascoyne and Albany-Fraser Provinces to the northwest and south-southeast respectively (Hallberg and Glikson 1981).

It can be divided into three tectonostratigraphic terranes, based on differences in volcanic facies, geochemistry and volcanic age, from west to east: the Kalgoorlie, Kurnalpi and Burtville Terranes (Cassidy et al. 2006). The Kalgoorlie Terrane, located in the green-

stone Norseman-Wiluna Belt, comprises predominantly c.2.7 Ga old volcano-sedimentary rocks with a complex subduction-related tectonic history (Barley and Groves 1990). The terranes are bounded and intersected by fault systems, with the western and eastern boundaries of the Kalgoorlie Terrane formed by the the Ida and Ockerbury Faults respectively (Fig. 1; Czarnota et al. 2010).

The Kalgoorlie goldfield consists of one giant

deposit, the main Fimiston lodes (consisting of western and eastern lodes) and the lesser Oroya Shoot, located in the so-called Golden Mile, as well as two relatively smaller deposits to the northwest, Mt Charlotte and Mt Percy (Bateman and Bierlein 2007).

Three styles of gold mineralization occur in the Kalgoorlie goldfield, Fimiston, Oroya and Charlotte, with the majority of gold production centred on the Fimiston and Oroya lodes in the 4 km x 2 km "Superpit" opencut mine (Fig. 2; Bateman and Bierlein 2007). The predominant host rocks for gold mineralization are a differentiated tholeiitic sill, the Golden Mile Dolerite, and to a lesser degree, the underlying mafic rocks comprising the Paringa Basalt (Phillips, 1986).

Structural architecture obviously played an important role in gold distribution in the Golden Mile, which is characterized by a large-scale anticline, the Kalgoorlie Anticline (Weinberg et al. 2005). Major deposits in the Kalgoorlie Goldfield are located within a 5-km-wide corridor of uplifted mafic-ultramafic volcanic rocks (Phillips 1986). The Golden Mile is situated immediately east of the Boulder-Lefroy Fault Zone, which cuts the Kalgoorlie Anticline (Weinberg et al. 2005), and the majority of economically important gold deposits are concentrated in reactivated brittle-ductile to brittle shear zones (Clout et al. 1990).

3   Geology of the Kalgoorlie Goldfield

The geology of the Yilgarn craton consists mostly of greenstones and granites that formed between 3000 and 2600 Ma and crystallized and formed at low-grade metamorphism (Myers 1995). A variation in ages is represented by a general younging trend from west to east. The oldest rocks occur in the northwest parts of the craton in the Narryer Terrane eg. Meeberrie Gneiss, which formed from 3730 Ma tonalite and 3680 to 3600 Ma granite (Myers 1995). Detrital zircons, found in sedimentary rocks deposited on this gneiss and granite between 3100 and 2700 Ma, have yielded U-Pb ages up to 4270 Ma (Froude et al. 1983). The volcanic rocks of the Kalgoorlie Terrane however are younger, having formed between 2700 and 2600 Ma (Swager et al. 1990).

The stratigraphy of the Kalgoorlie area consists of a 1500m thick stratigraphic succession of mafic-ultramafic volcanic rocks (Wyche 2008), unconformably overlain by a 3000m thick succession of volcanic and sedimentary rocks (Czarnota et al. 2010). The volcanic rocks include lava and pyroclastic flows, and range from rhyolite to andesite but are predominantly dacitic (Myers 1993). This succession is interbedded with siltstone and sandstone, and is unconformably overlain locally by a unit of poorly sorted sandstone and conglomerate (Wyche 2008).

The lower mafic-ultramafic succession corresponds to the 2715-2690 Ma Kambalda Sequence and consists of: a lower basalt with tholeiitic chemistry, i.e. having slightly depleted LREE patterns, and positive εNd; overlain by komatiite magmas which are interbedded with felsic volcanic rocks. Overlying this komatiite unit are mafic rocks with elevated LREE patterns, suggesting enrichment processes (Czarnota et al. 2010).

The felsic volcanic rocks correspond to the 2690–2665 Ma Kalgoorlie sequence and have predominantly a tonalite-trondhjemite-granodiorite (TTG) composition (Czarnota et al. 2010). The geochemical signature is characterized by steep REE patterns, depleted in HREE, no Eu anomaly and elevated Sr/Y ratios. These characteristics suggest that magma was derived by a garnet-bearing source rock, with high-pressure slab melting caused by shallow subduction at a convergent margin as a possible scenario (Czarnota et al. 2010).

The most important rocks in regard to gold deposits are: the Golden Mile dolerite, a sill intrusion lying between the mafic-ultramafic and felsic volcanic-sedimentary successions (Phillips 1986) and accounting for more than 80% of gold deposits in the area (Wyche 2008); the Paringa Basalt, lying at the top of the mafic-ultramafic sequence; and the Black Flag Beds, overlying the Golden Mile Dolerite (Fig. 2; Phillips 1986).

In the Golden Mile area the Golden mile dolerite is a 400 m thick tholeiitic gabbro sill that has been regionally metamorphosed to upper greenschist facies, shown by the albite-actinolite-chlorite-epidote-quartz assemblage (Phillips 1986). The Golden Mile Dolerite has been subdivided into ten mappable units, based on texture, oxide type and morphology (Travis et al. 1971). It is generally basaltic in composition and varies from near-ultramafic near the lower margins up to a highly differentiated granophyre and feldspar-phyric section. However the average composition of the sill is similar to the chilled margins, thus indicating in situ differentiation of a single tholeiitic magma (Phillips 1986).

The Paringa basalt shows pillowed flow and breccia structures, varies upward from high magnesian to tholeiitic basalt, and typically shows as a fine to medium-grained assemblage of albite laths, quartz, and actinolite. Gold mineralization, carbonation and breccias increase upward in the sequence (Phillips 1986).

The Black Flag Beds in the Golden Mile occur as a narrow wedge, separating the so-called western and eastern lodes, and are the major component of the Kalgoorlie Syncline (Phillips 1986). In the Kalgoorlie mine area, the Black Flag Beds consist mostly of sulfidic, carbonaceous black shales, graywackes, and thin cherts (Phillips 1986).
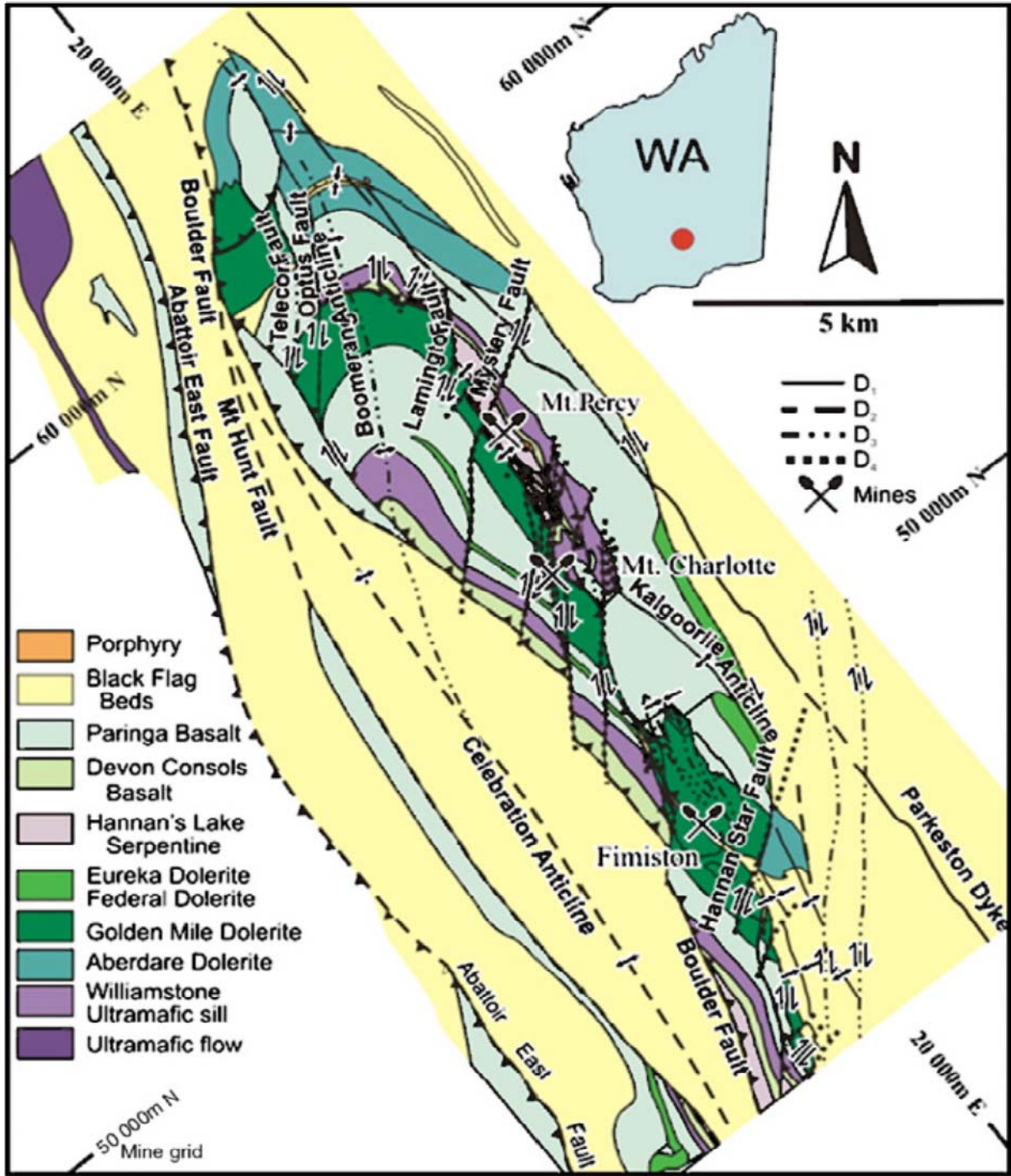
Fig. 2. Geological map of the Kalgoorlie greenstone belt, showing major gold deposits, lithostratigraphy and major structures (Bateman and Bierlein 2007).

4 Tectonic history of the East Yilgarn craton

There have been several different interpretations of the Yilgarn craton's tectonic history (Myers 1995). Up until the 1980's it was suggested that remnants of primordial crust, represented by the craton's greenstones, had been deformed by the diapiric emplacement of granite batholiths (Glikson 1979). In the 1980's, internal rifting of continental crust was thought to have produced the granites and greenstones (Gee et al. 1981). Myers (1995) suggests that the Yilgarn craton was formed by a major episode of plate tectonic activity between 2780 and 2630 Ma. This resulted in diverse crustal fragments, such as volcanic arcs, back arc basins and micro-continents, being pushed together and amalgamated.

The following parauthochtonous convergent margin model, proposed by Czarnota et al. (2010), has been used to explain the tectonic history of the eastern Yil-

garn craton. The model implies that tectonics relating to gold mineralization in the East Yilgarn craton began with rifting off the eastern margin of the Youanmi Terrane at c. 2810 Ma, establishing the craton's north-northwest structural trend (Czarnota et al. 2010). This rifting event is associated with localized extension and craton-wide mafic underplating. It is important to note that the event is designated D1in the Czarnota et al. (2010) model, however it precedes D1 in the Swager (1989) model below (Fig. 3). As extension was localised in an area known for large scale gold deposits, it is interpreted as being critical for gold mineralization (Czarnota et al. 2010).

This was followed by the formation of a convergent margin at the eastern boundary of the East Yilgarn craton with a resulting west-dipping subduction zone being initiated at 2715 Ma (Czarnota et al. 2010). A suggested mantle thermal anomaly at c. 2705 Ma (Smithies and Champion 1999), associated with a likely mantle plume, resulted in a westward shallowing of the subducting slab, which in turn led to a westward younging of arc volcanism and eventual slab melting (Czarnota et al. 2010). This resulted in the first of three major phases of magmatism and the extrusion of komatiites and felsic volcanic rocks (Smithies and Champion 1999). Crustal contamination of mafic magmas of the Kambalda Sequence occurred during this period (Czarnota et al. 2010).

2690 Ma – 2670 Ma slab melting, the second magmatic phase of Smithies and Champion (1999), resulted in tonalite-trondhjemite-granodiorite (TTG) and high-Ca granite magmatism across the East Yilgarn Terrane, resulting in major crustal thickening (Czarnota et al. 2010).

Large scale emplacement of high-Ca slab melts at the base of greenstones resulted in crustal interaction through melting, assimilation, storage and homogenisation (MASH) processes (Winter 2010; Czarnota et al. 2010). This produced voluminous granites with a crustal signature, as well as an eclogite-rich restite layer, resulting in both crustal thickening and instability caused by a density anomaly (Czarnota et al. 2010). It is suggested by Czarnota et al. (2010) that instability resulted in crustal delamination, which subsequently caused an advection of metasomatised mantle melts through breaks in the delaminated slab and into the base of the crust. This introduction of mantle fluids thus established connectivity between the mantle and crust (Czarnota et al. 2010). The heat input into the crust resulted in the production of crustal melts, initially high-Ca granite and later low-Ca granite with greater thermal diffusion through the crust.

Continued shallowing of the subducting slab resulted in a short-lived ENE contraction (D2) across the East Yilgarn Superterrane at 2670 and 2665 Ma, in the east and west respectively, and the development of NNW-striking upright folds (Czarnota et al. 2010). According to the literature, it was this event that helped trigger the crustal delamination event discussed above (Czarnota et al. 2010). This event corresponds to D1 in the Swager (1989) model for Kalgoorlie discussed below.

According to Czarnota et al. (2010), lithospheric extension in response to crustal thickening and/or subduction slab roll-back defines the D3 event. Extensional detachment shear zones around granite domes, granite and greenstone exhumation in these shear zones, and the deposition of late basins, are characteristic structural features of this deformation episode (Czarnota et al. 2010). U-Pb dating of foliation in D3-extensional shear zones, cross-cutting syenite and mafic granites, obtained an age of c. 2665 Ma for the event (Blewett and Czarnota 2007).

Erosion of exhumated granite domes resulted in deposition of siliciclastic sediments in late basins that had formed during the D2 contractional event. Further extension resulted in the burial of these late basins to 10-15 km.The dewatering of basal brines and dehydration of hydrous minerals contained in basin sediments subsequently resulted in an introduction of fluids into the crust.These fluids were later focused towards the surface, during D4, and emplaced into high strain, ductile extensional shear zones. This process resulted in the formation of extension-related gold deposits such as those found at Gwalia, 230 km north of Kalgoorlie (Czarnota et al. 2010).

Therefore, through the establishment of necessary architecture, transport mechanisms between the mantle and crust, and a supply of hydrous fluids, the D3 extension episode initiated the gold mineralization of the East Yilgarn Terrane (Czarnota et al. 2010).

Renewed contraction then took place during D4, resulting initially in reverse dip-slip faulting of D3 extensional structures and upright folding of late basins. This was followed by sinistral transpression along NW to NNW striking structures at 2650 and 2645 Ma, in the east and west respectively. This brittle-ductile deformation resulted in inversion of the D3 domal architecture, as well as creation of effective fluid focusing sites with a high degree of complexity in regards to structure and stress fields. Efficient fluid focusing and subsequent localized hydrothermal alteration events during this deformation episode, resulted in large scale gold mineralization (Czarnota et al. 2010).

A shift to northeast-southwest contraction resulted in the development of north-northeast-striking brittle-ductile dextral strike-slip faults, which together with the emplacement of low-Ca granites, defines D5 and the last phase of gold mineralisation. The termination of low-Ca magmatism was diachronous across the East Yilgarn Superterrane and marked the end of tectonic activity (Czarnota et al, 2010).

The timing of termination of low-Ca granite magmatism is related to earlier lower crustal delamination , as it reflects the time taken for crustal diffusion of the heat associated with the event. Therefore as low-Ca granite magmatism ended later in the Kalgoorlie Terrane, at c. 2620 Ma, compared to 2630 Ma and 2640 Ma in the Kurnalpi and Burtville terranes, respectively, it indicates that fluid circulation was prolonged in the Kalgoorlie Terrane (Czarnota et al. 2010).

5 Regional Deformation History of the Kalgoorlie Terrane

Due to the complex and anomalous structural morphology at Kalgoorlie, the east Yilgarn models cannot easily be used to explain Kalgoorlie's deformation history (Bateman and Hagemann 2004). This structural complexity has also resulted in widely varying interpretations of the deformational processes involved (Bateman and Hagemann 2004).The widely accepted deformation model of Swager (1989,1997) suggests deformation at Kalgoorlie resulted from four main phases, D1 – D4 (Bateman and Hagemann 2004). It is important to note that D1 in this model corresponds to the D2 thrusting event of the Czarnota et al. (2010) model for the east Yilgarn craton. To avoid confusion, the order of deformation events for the rest of this discussion will refer to the Swager model. This model describes an early thrusting event followed by transpression, with local right-lateral strike slip faulting within a regional left-lateral strike slip system, and overall NE-SW shortening (Table 1; Bateman 2001).

Witt (1994) suggests an extensional collapse stage preceding D1, based on the presence of a detachment north of Kalgoorlie that is interpreted to have resulted from E-W extension. Weinberg and Borgh (2003) also suggest there was an early extension, $D1_E$, characterized by doming of low-density granite masses resulting from horizontal stretching (eg.the Raeside Batholith). Structures recorded around the Raeside Batholith near Leonora, 235 km north of Kalgoorlie, are interpreted to be early extensional structures resulting from a regional extension phase (Passchier 1994). The above interpretations follow more closely with D1 in the model proposed by Czarnota et al. (2010), and not the thrust-related D1 event proposed by the following Swager (1989) model.

According to the Swager (1989) model, D1 involved local north-east-over-south-west thrusting that led to the formation of the Golden Mile Fault and the Kalgoorlie Anticline (Bateman and Hagemann 2004). This is slightly different to the Wyche (1998) interpretation of the regional D1 event as a N-S shortening event associated with thrust stacking and recumbent folding. A regional example illustrating this is the repetition of mafic-ultramafic sequences around Coolgardie, indicating regionally extensive thrust sheets (Wyche 1998). According to Bateman (2001) D1 east over west thrusting along the Golden Mile Fault at c. 2670 Ma resulted in a similar repetition of local greenstone stratigraphy. E-W thrusting during D1 is also proposed by Bateman and Bierlein (2007) to have resulted in the giant Fimiston-style lode gold deposits in Kalgoorlie. Also Bateman (2001) suggests that mineralization of the Fimiston deposit was contemporaneous with D1 thrusting. As the 2675 Ma Golden Mile Dolerite (Woods 1997) cuts the Fimiston lodes, the Golden Mile Fault is suggested to have formed post-2675 Ma and before the Swager (1997) age for D2 of c. 2660 Ma (Bateman and Hage-

mann 2004).

The Kalgoorlie Orogen is generally considered to have begun with D2, though there are various interpretations of this event (Weinberg and Borgh 2008). According to the Swager (1989) model D2 is represented by a regional NE-SW compression resulting in N-NW-striking thrust faults and gently plunging upright folds, with an inferred age of 2675-2657 Ma (Nelson 1997; Bateman and Hagemann 2004). D2 structures in the Kalgoorlie area which overprint D1 features include the Boulder-Lefroy Fault, Mt Hunt fault, Abattoir East Fault and Celebration Anticline (Bateman and Hagemann 2004).

An important tectonic structure defining the western boundary of the Kalgoorlie Terrane, the Ida Shear Zone, is a steep ductile shear zone linked to D2 crustal shortening (Weinberg and Borgh 2008). However the east-dipping Ida fault, associated with this zone, is interpreted by Weinberg and Borgh (2008) to have formed late in the Kalgoorlie orogeny, due to it's planar structure and lack of folding by earlier deformation phases. The principal shear zones bounding the Kalgoorlie mining district, for example the Boulder-Lefroy and Parkeston Faults, are interpreted to have formed during this deformation episode, and are defined by NNW-trending sinistral shear sense (Mueller et al. 1988). The lower stratigraphic levels exposed on the eastern side of the Boulder-Lefroy Fault are interpreted as evidence of D2 east over west thrusting (Bateman and Hagemann 2004). On a mine-scale, reverse faulting is represented by the Oroya hanging wall and footwall shears of the Fimiston "Superpit", which is interpreted by Bateman (2001) to have formed during D2, cutting across the earlier formed Fimiston lodes (Bateman 2001).

D3 is interpreted by Nelson (1997) to have an age of between 2660 and 2632 Ma. Structures defining D3 vary greatly in the literature depending on the author's interpretation of the timing of the event. Swager et al. (1995), interpret shear zones that form domain and terrane boundaries, such as the Ida Shear Zone, to be associated with this deformation event. Witt and Swager (1989) define D3 by NNW-trending sinistral shear zones and en-echelon folds, in agreement with the Czarnota et al. (2010) model, but in conflict with the interpretation by Mueller et al.(1988) who define D3 by the later dextral shear regime. This interpretation of N-S or NNE-trending dextral shear zones as a D3 event is also supported by Passchier (1994).

The contrasting interpretations of D3 are most probably caused by the difference in D3-related structures on a regional and local scale. According to the Swager (1989) model, D3 is defined on a mine-scale by right lateral strike-slip faulting, which is represented at Kalgoorlie by the N-NE-striking, ductile, sigmoid Golden Pike and Adelaide Faults (Bateman and Hagemann 2004). However on a regional scale, left-lateral strike-slip movement along the Boorara Shear and Boulder Fault defines the D3 event (Bateman and Hagemann 2004).

A tectonothermal event in the Eastern Goldfields,

defined by Smithies and Champion (1999) and characterized by the intrusion of low-Ca granites and alkaline granitoids, together with large-scale gold mineralization, occurred between 2650 and 2620 Ma (Czarnota et al. 2010). According to Witt and Swager (1989), the emplacement of these granitoids (post-D2 to syn-D3 in the Swager (1989) model), such as the Silt Dam Monzogranite in the central-southern part of the Kalgoorlie terrane, resulted in the creation of fault systems. An example being the NE–ENE-trending faults associated with the displacement of the Kurrawang Syncline axis near Siberia.

D4 is defined, in the Swager (1989) model, by swarms of parallel N-NE-striking faults that show right lateral oblique slip movement (Bateman and Hagemann 2004). These dextral shear zones characterize a shift to dextral shear, interpreted as D5 in the Czarnota et al. (2010) model. According to the model of Swager (1989), these faults are interpreted to manifest the last deformation event at c. 2630 Ma because they cut across all other structures in the Kalgoorlie area (Bateman and Hagemann 2004). The N-NE- trending fault zones are generally <2 m wide, brittle-ductile and are characterized by the formation of quartz veins (Bateman and Bierlein 2007).

An example of these syn-D4 formations relating to gold mineralization are the sheeted quartz veins of the Mt Charlotte deposit (Fig. 3; Bateman and Bierlein 2007). Such tensional quartz veins also occur in the syn-D2 gold-rich Oroya Shoot, indicating their importance for gold mineralization (Mueller et al. 1988).

6 Metamorphism in the Kalgoorlie Terrane

A wide range of metamorphic conditions existed during formation of the Kalgoorlie Terrane, ranging from low grade (phrenite-pumpellyite facies) in eastern areas away from greenstone margins, to moderate-high grade (mid-upper amphibolite facies) around greenstone margins and along the eastern margin of the Ida Fault (Wyche 1998). Gold deposits are associated with a range of metamorphic conditions, however the majority of large deposits occur in greenschist facies, for example the giant Kalgoorlie deposit (Phillips et al.1996).

According to Binns et al. (1976) high grade metamorphism is found in the high strain areas along granite-greenstone contacts. This agrees with Archibald et al. (1981), who suggested that regional metamorphic gradients resulted from differential uplift and the associated intrusion of granitoids along the margin of greenstone belts. Swager et al. (1995) suggest that peak metamorphism occurred during post-D2 to syn-D3 shortening events and was contemporaneous with granitoid emplacement during a differential uplift event. U-Pb SHRIMP data obtained from these granitoids suggest that the timing of this event was c. 2660 Ma (Nelson 1995). The widespread occurrence of andalusite and low amounts of garnet in metapelitic rocks in the area east of the Ida Fault, suggests that temperature was a more important factor than pressure (Wyche 1998).

Depending on fluid concentrations, areas of high grade metamorphism (amphibolite facies or higher) often undergo complete recrystallization, with mafic rocks being characterized by hornblende as well as infrequent garnet and metamorphic clinopyroxene. Ultramafic rocks may contain some metamorphic olivine (Wyche 1998). There is widespread evidence of retrograde alteration in the kalgoorlie Terrane, seen for example by chloritization of hornblende, talccarbonate alteration of ultramafic rocks, and sericitization and chloritization of metapelites, with extensive carbonation and hydration localized around major fault systems (Wyche 1998). Sodium metasomatism of intrusive porphyries is suggested to be linked to gold mineralization (Witt 1992).

According to Goscombe et al. (2009) and Czarnota et al. (2010), the metamorphic history of the EYC can be divided into five distinct metamorphic events, M_a, M1, M2, $M3_a$ and $M3_b$, with large-scale gold mineralization occurring during $M3_b$ ie. 2650 – 2620 Ma.

M_a: Granulite metamorphism is rare in the EYC and occurred at 2720-2685 Ma. It is defined by high temperature (T) and high geothermal gradient (G), linked to high heat flow in magmatic arc environments.

M1: Medium pressure (P) at 6-8.7 kbar, high T ($>600^0$c) and low G ($\leq 20^0$/km) metamorphic assemblages also occurred at 2720-2685 Ma and are found in high-strain shear zones (eg. Ida Fault) near granite dome margins.

M2: Regional metamorphism across greenstone belts with medium T (300-500^{0}c) and medium G (30-40^{0}c/km) occurred at 2685-2665 Ma ie. syn- to post-peak high-Ca granite intrusion.

M3a: Extension related High G (40-50^{0}c/km) metamorphism contemporaneous with late basin deposition at 2665-2650 Ma.

M3b: Metamorphism associated with the switch from D3 dip-slip extension to D4-5 strike-slip deformation, according to the Czarnota et al. (2010) model, and multiple hydrothermal alteration events between 2650-2620 Ma, resulting in large-scale gold mineralization.

Hydrothermal alteration events are associated with elevated thermal gradients, resulting from D3 extension, a possible delamination event, as well as voluminous emplacement of low-Ca granites (Czarnota et al. 2010). The heat generated by these events resulted in the dehydration of hydrous minerals in late basins and the subsequent injection of large volumes of hydrous fluids into greenstones (Czarnota et al. 2010). According to Czarnota et al. (2010) hydrothermal alteration during the main phase of gold mineralization, suggested as 2650-2640 Ma, is associated with moderately elevated G (30-50^{0}c/km), however later episodes of alteration and Au-mineralisation occurred at remaining elevated T (250-350^{0}c), but shallower crustal depths ie. low P (1 kbar), resulting in high G ($>70^0$c/km) (Czarnota et al. 2010).

Hydrothermal alteration associated with gold mineralization is represented at Kalgoorlie by the re-

Table 1: Summary of D1-D4 deformation in Kalgoorlie area, including age of deformation events, deformation types, and structures and gold deposits related to each deformation event (after Swager 1989).

Deformation event	Age	Deformation and related structures	Kalgoorlie gold deposits
D1	2682-2670 Ma (Swager 1989)	NE over SW thrusting: thrust faults (Golden Mile Fault) and regional folding (Kalgoorlie Anticline)	Fimiston lode, (Oroya Shoot?)
D2	2675-2657 Ma (Nelson 1997)	Regional NE-SW compression; N-NW-striking thrust faults (Boulder-Lefroy Fault); upright folds (Celebration Anticline)	Oroya Shoot
D3	2660-2632 Ma (Nelson 1997)	Regional: left strike-slip (Boorara Shear Zone) Local: right strike-slip (N-NE ductile faults eg. Adelaide Fault)	
D4	2630-2620 Ma (Swager 1989)	Dextral shear zones; N-NE-trending brittle-ductile faults; tensional quartz veins	Mt Charlotte

placement of regional greenschist-facies mineral assemblages with a 3 km^3 alteration envelope. This alteration envelope consists generally of proximal alteration zones containing ankerite and siderite, as well as distal zones containing calcite-chlorite (Fig. 4; Phillips et al. 1996).

Closer to the Fimiston lodes the alteration progressively changes to an ankerite–sericite–quartz–pyrite mineral assemblage, which in turn becomes sericite–ankerite–siderite–quartz–haematite–pyrite–telluride within a few tens of metres of the lode core. On the other hand, in the Oroya Shoot, muscovite–ankerite–quartz–siderite–haematite–pyrite–telluride alteration is typical (Fig. 5; Bateman and Hagemann 2004). The Oroya Shoot also has the most intense Au-Te mineralisation at Kalgoorlie and is well known for its so-called "green leader" alteration caused by high vanadium contents in mica (Bateman and Hagemann 2004).

7 Timing of mineralization

Interpretations of the timing of mineralization at Kalgoorlie vary greatly (Bateman and Bierlein 2007). According to the structural–hydrothermal model of Bateman and Hagemann (2004), based on critical timing relationships between deformation and hydrothermal alteration processes, mineralization occurred early in the tectonic history, towards the end of D1. On the other hand, Czarnota et al. (2010) propose that the main mineralization at Kalgoorlie occurred later between 2655 – 2640 Ma, and was associated with extension and low-Ca magmatism. However, although there are contrasting theories there is a common thread throughout much of the literature, in that Kalgoorlie has a protracted mineralization history involving multiple gold mineralization events (Weinberg et al. 2005).

The majority of structural and geochronological evidence has constrained timing of gold mineralization in the Boulder-Lefroy Shear Zone to D3 ie. syn-tectonic, late mineralization (Weinberg et al. 2005). McNaughton et al. (2005), for example, obtained a SHRIMP U-Pb age of 2638± 6 Ma for zircon in a lamprophyre dyke interpreted to be of similar age to the Oroya mineralization (Weinberg et al. 2005). However there exists some controversy over the timing of mineralization of the largest deposit, the Fimiston lode at Kalgoorlie (Weinberg et al. 2005).

Czarnota et al. (2010) suggest that the Fimiston lode formed between 2655-2640 Ma, as a result of multiple hydrothermal alteration events during $M3_b$. They

suggest that voluminous fluids produced by large-scale Ca-magmatism, together with contemporaneous strike-slip deformation, resulted in highly efficient fluid focusing.

However, according to Bateman and Hagemann (2004) the majority of the Kalgoorlie gold was deposited during the early stages of mineralization before D2-D3 strike-slip events. They believe there are several reasons to suggest that the Fimiston mineralization occurred during D1, possibly as early as 2675 Ma. Reasons to suggest this include: 1. The Golden Mile Fault and subsequent faults crosscut the lodes (Bateman and Hagemann 2004); 2. Overprinting by the D2 Oroya Shoot (Bateman and Hagemann 2004); and 3. $^{40}Ar/^{39}Ar$ dating of D2-D3 sericite-rich foliation, that overprints Fimiston lodes, yielding an age of 2655 Ma (Bateman et al. 2001).

Weinberg et al. (2005), however, believe the crosscutting relationship between the Fimiston lode and Oroya Shoot is the result of changes in stress and rheology across the thrust plane controlling the growth of the Fimiston lode, and that the two deposits were actually formed in the same mineralization event during regional D2 shortening. They believe that formation of these two deposits during the same mineralization event is also suggested by similar host rock alteration, in terms of Te and Au contents, as well as the presence of V micas (Fig. 5 and 6; Weinberg et al. 2005). However although the abundance of Te minerals is a noticeable feature of both deposits, Te deposition and the concentration of V micas is significantly higher in the Oroya Shoot than the Fimiston lodes (Bateman and Hagemann 2004).

The quartz veins in the granophyric unit 8 of the Golden Mile Dolerite hosting the Mt Charlotte deposit are believed to have been formed in the footwalls of parallel faults resulting from D4 reactivation of D3 dextral shear zones (Weinberg et al. 2005). D4-associated mineralisation suggests therefore that the Mt Charlotte deposit formed 25-30 Ma after the Fimiston and Oroya Shoot lodes, supporting the theory of a protracted period of mineralisation at Kalgoorlie (Weinberg et al. 2005).

8 Major factors resulting in Kalgoorlie gold mineralization

Several factors during the formation of the Kalgoorlie deposit, from ore fluid source through to gold precipitation at depositional sites, are responsible for it's anomalous size (Phillips et al. 1996). These factors include: the nature of and controls on ore fluids, including structural setting; and host rock characteristics such as it's chemical and physical properties (Phillips et al. 1996).

8.1 Host rock chemistry

An important chemical characteristic of the Golden Mile Dolerite, with regards to gold mineralization, is it's high Fe/(Ca + Fe + Mg) (Phillips 1986). Another important point is that gold is carried in the ore fluids as a reduced sulfur complex (Phillips and Groves 1983). The high Fe/(Ca + Fe + Mg) host rock properties results in the breaking down of Fe-Mg-bearing silicates in the ore fluids to form pyrite, as well as the destabilization of reduced sulfur complexes, and subsequent precipitation of gold out of solution, see Eq.1 below (Neall and Phillips 1987).
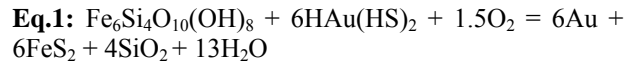
Eq.1: $Fe_6Si_4O_{10}(OH)_8 + 6HAu(HS)_2 + 1.5O_2 = 6Au + 6FeS_2 + 4SiO_2 + 13H_2O$
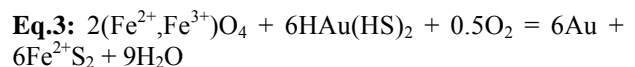Chlorite + Au–S complex + oxygen = gold + pyrite + quartz + water

The auriferous ore fluids responsible for the Kalgoorlie deposit were more oxidised than for those resulting in the smaller surrounding deposits (Mikucki and Ridley 1993). Oxidised ore fluids are indicated by the presence of magnetite in locally-occurring alteration zones (Fig. 7; Phillips and Gibb 1993), as well as the low $\delta^{34}S$ values shown by pyrite (Phillips et al. 1986). Lambert et al. (1984) and Phillips et al. (1986) suggest that ascending CO_2-rich ore fluids became oxidized through wall-rock reactions with magnetite-rich Unit 8 of the Golden Mile Dolerite.

According to Neall and Phillips (1987) the Fe-rich host rock increased oxidation of the ore fluids, which resulted in formation of magnetite in the Golden Mile Dolerite (Phillips and Gibb 1993). The major wall-rock reaction caused by ore fluid-induced alteration is carbonation (Phillips 1986). According to Phillips et al. (1996) the formation of siderite in the alteration mineral assemblage, through the carbonation of magnetite, involves the oxidation of ore fluids see Eq.2 below.
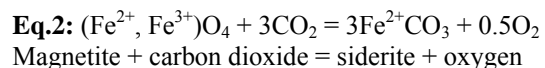
Eq.2: $(Fe^{2+}, Fe^{3+})O_4 + 3CO_2 = 3Fe^{2+}CO_3 + 0.5O_2$
Magnetite + carbon dioxide = siderite + oxygen

Phillips et al. (1996) also suggest that the presence of magnetite promotes destabilization of the gold-bearing reduced sulphur complexes, see Eq.3.

Eq.3: $2(Fe^{2+},Fe^{3+})O_4 + 6HAu(HS)_2 + 0.5O_2 = 6Au + 6Fe^{2+}S_2 + 9H_2O$
Magnetite + Au-S complex + oxygen = gold + pyrite + water

This oxidation of ore fluids and resulting destabilization of reduced sulfur complexes suggests that the presence of magnetite facilitates gold deposition, and is thus partly responsible for the anomalously large size of the Kalgoorlie deposit (Phillips et al. 1996).

8.2 Host rock physical characteristics

It follows from the discussion above that the volume of available reactive host rock is a constraining factor for the size of a deposit (Phillips et al. 1996). Therefore it is significant that the Golden Mile Dolerite is both anoma-

lously thick compared to other late-Archaean sills in the Norseman-Wiluna Belt, as well as the fact that it has been duplicated around the Kalgoorlie Anticline during folding events (Phillips et al. 1996).

Deposit size is also related to stress fields and competency contrasts in the host rock. According to Ridley (1983), if the regional far field stress is at a high angle to layered successions with contrasting competency, mean stress will be lower in the competent layers. Fluid flow is controlled by these heterogenous stress fields, resulting in focused fluid flow in areas of lower mean stress. On a district scale of 1 m to 1 km strong rheological contrasts occur within the volcano-sedimentary succession at Kalgoorlie, eg. between the competent Golden Mile Dolerite and adjacent phyllosilicate-rich rocks of low competency (Weinberg et al. 2005). Intense mineralization of this dolerite, which lies in a broadly N-NW-trending succession that has undergone regional E-W compression, supports this theory (Phillips et al. 1996).

The high degree of differentiation within the Golden Mile Dolerite, also creates large competency contrasts, thus increasing the efficiency of fluid focusing and mineralization systems (Phillips et al. 1996). High quartz content in the most competent unit in the Golden Mile, Unit 8, creates a strong competence contrast with adjacent units (Bateman and Hagemann 2004). This unit also shows the most developed carbonation alteration in the Golden Mile, supporting suggestions that contrast in competency is an important factor for enhanced fluid flow and thus gold deposition (Phillips 1986).

8.3 Tectonics

8.3.1 Early thrusting

Early thrusting followed by transpressional deformation were key factors in the formation of the Kalgoorlie deposit (Bateman and Bierlein 2007). Early thrust stacking resulted in a network of fractures that were repeatedly opened during progressive deformation and acted as vertical conduits for large volumes of auriferous fluids (Bateman and Bierlein 2007). According to Bateman and Hagemann (2004), the formation of breccias and open cavities by thrust-related fracturing late in D1 increased fluid flux and also formed suitable depositional sites for the giant Fimistone lode.

Subsequent strike-slip movement along the Boulder-Lefroy Shear Zone extended this array of fractures. It also resulted in the formation of dilational jogs that effectively focused the ore fluids into individual channels, creating anomalously high fluid flux and subsequent gold deposition (Bateman and Bierlein 2007). The formation of such a dilational jog along the contact between the Golden Mile Dolerite and the Paringa Basalt resulted in the Oroya Shoot mineralization (Weinberg et al. 2005).

D4 reactivation of D3 dextral shear zones resulted in the formation of parallel faults. According to Weinberg et al. (2005) these NNE-trending faults are the main controlling structures of the Mt Charlotte deposit. The grano-

phyric unit 8 of the Golden Mile Dolerite in the footwall of one these faults (Mt. Charlotte Fault) subsequently accommodated ore-bearing fluids, resulting in the sheeted quartz-carbonate-scheelite veins of the deposit (Fig. 4; Bateman and Hagemann 2004). The above examples suggest therefore that early thrusting and later strike-slip movement were important factors in formation of the Kalgoorlie deposits (Bateman and Bierlein 2007).

8.3.2 Uplift

Reactivation of existing shear zones, caused by regional sinistral shearing in the D3 deformation event (Weinberg et al. 2005), resulted in uplift of the mafic-ultramafic host rock of the Golden Mile relative to adjacent sequences (Phillips et al. 1996). Uplift reduces the confining pressure on ore fluids, enhances the relative fluid pressure and thus promotes hydraulic fracturing of the host rock (Phillips 1996). According to Phillips et al. (1996) hydraulic fracturing greatly increases the permeability of the host rock and promotes focused fluid flow. Such hydraulic fracturing was important in formation of the Oroya Shoot (Phillips et al. 1996).

8.4 Ore Fluids

The origin of the ore fluids responsible for the Kalgoorlie gold is widely debated and several conflicting theories have been put forward. According to Phillips et al. (1996), the ore fluids resulting in the Kalgoorlie deposit are generated by hydrothermal systems on a crustal scale. Evidence for this includes the formation of gold deposits over a range of depths; a common deep ore fluid source for gold deposits; and isotopic evidence suggesting a range of greenstone and granitoid reservoirs as potential fluid sources (Gebre-Mariam 1995). The extensive distribution of distal gold-related alteration assemblages (calcite-chlorite) around Kalgoorlie indicates a high degree of fluid-wallrock interaction, suggesting anomalously high fluid flux in the area (Phillips et al. 1996). Significant structurally induced permeability in the host rock was required to accommodate this anomalously high fluid flux, suggesting that structural controls were an important factor in controlling the size of the Kalgoorlie deposit (Phillips et al. 1996).

8.4.1 Fluid characteristics/source

The c. 1400 tonnes of gold in the Golden Mile was generated from thousands of cubic kilometres of source rock (Bateman and Hagemann 2004). The auriferous ore fluid responsible for gold mineralization in the Norseman-Wiluna belt was of low salinity; H_2O-CO_2-H_2S with variable CH_4; had a temperature of between 300-350°c; and was deposited in a greenschist facies metamorphic setting (Phillips et al. 1996). The relatively high temperature is interpreted by Phillips et al. (1996) to suggest a deep metamorphic source with relatively rapid transport via vertical channelways. Large volumes of fluids were produced during D3 (Czarnota et al. 2010 model), when

Fig. 3. Photo of tensional quartz veins typical of the Mt Charlotte deposit (Hagemann et al. 2001).

the burial of early basin sediments resulted in the dehydration of hydrous minerals (Phillips et al. 1996). However, data obtained by various workers suggests that the fluids can also have had a shallower source. For example, sulfur isotope studies of pyrites in the Fimiston and Oroya lodes carried out by Hagemann et al. (1999) show enriched [34]S values, suggesting possible multiple sources. $\delta^{18}O$ fluid composition values of -0.5 to 1.9 ‰ for Fimiston ore samples obtained by Clout (1989), suggest a seawater and/or meteoric source (Bateman and Hagemann 2004).

This data also supports a model proposed by Perth-based exploration geologist, Peter Schwann, suggesting sea water as the predominant fluid source, with some mixing of fluids produced by dehydration of intrusive and sedimentary rocks. The model proposes a submarine Archaean setting, and consists of downward infiltration of sea water aided by structural conduits, a thermal engine created by granite magmatism, and pH-controlled mineralisation. Heating results in the formation of large convection cells, circulation of sea water, and the creation of effective metal-scavenging fluid systems (Schwann 2013). The convection cells heat seawater to 750°c, which results in leaching of metals from the wall-rock and Au being transported as a tetrachloride complex. Upon ascending the tetrachloride complex becomes unstable at about 400°c and Au is subsequently transported as a reduced sulfur complex, resulting in wall-rock alteration reactions such as carbonation and sulphidation (Schwann 2013).

With regards to the conflicting data on fluid composition, it is therefore most likely that the ore fluids responsible for the Kalgoorlie gold are the result of the mixing of downward penetrating seawater with ascending, deep hydrothermal fluids (Bateman and Hagemann 2004). This possible mixing of fluid sources is indicated by the pyrite sulfur isotope compositions at Fimiston, as well as other complex and conflicting data obtained from ore fluid studies (Bateman and Hagemann 2004).

Although potentially multiple fluid sources are indicated, according to Phillips et al. (1996) ore fluid characteristics in the Norseman-Wiluna belt are still generally typical for global Archaean lode-gold deposits. Also, although there exist widely differing thoughts on the source of Kalgoorlie ore fluids and solutes, available data suggests that ore fluids were similar to those of smaller deposits in the region (Phillips et al. 1996). For example data from the Norseman-Wiluna belt show a range of isotope ratios from ore-related sulfides, and isotopic ratios of the Kalgoorlie deposit fall within this range (McNaughton et al. 1993).

However one noteworthy feature of the Fimiston and Oroya Shoot deposits is the anomalously high Au-Te concentration. Telluride mineral concentrations are irregular but are highest in proximal alteration halos and in the Fimiston lodes can reach up to 1000 ppm in gold-rich zones (Fig. 6; Bateman and Hagemann 2004). However it is the V-rich so-called "green leader" alteration zones of the Oroya Shoot that show the most anomalous Au-Te concentrations with gold tenor reaching up to 100 000 g/T Au, compared to an average of 50 g/T Au for alteration zones overall in the Kalgoorlie gold camp (Bateman and Hagemann 2004).

8.4.2 Effect of structural control on fluid focusing

On a regional scale the Boulder-Lefroy shear zone is the major control of gold mineralization (Weinberg et al. 2005), with deposits in the Golden Mile located predominantly within this shear zone, in shear-related faults and highly fractured pipe-like zones of brecciation (Phillips et al. 1996). Most gold deposits occur in second and
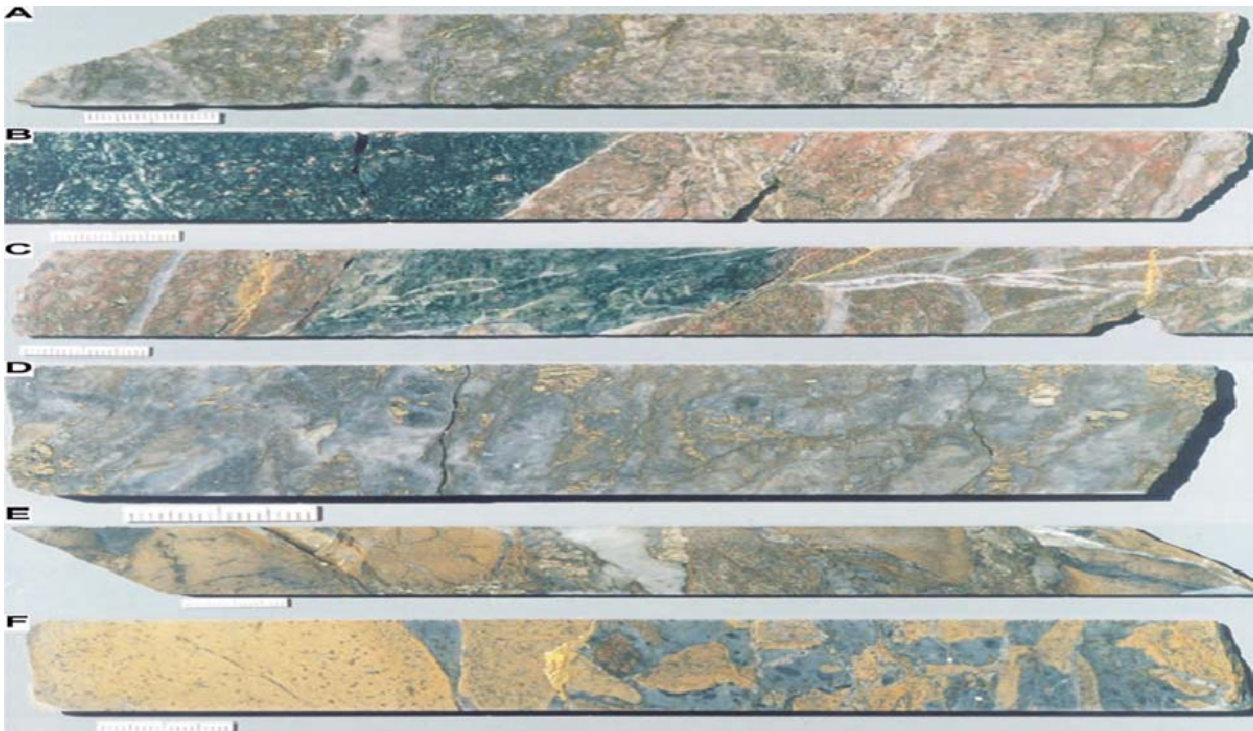
Fig. 4. Golden Mile diamond core samples of hydrothermal altered and mineralised Golden Mile Dolerite and Paringa Basalt (scale bar = 1cm). A: Sample from Lake View lode showing pyritisation; B: Dolerite sample from Lake View lode showing sharp contact between distal and proximal alteration zones; C: Dolerite from Lake View lode showing chlorite-rich distal alteration zone and pyrite-rich proximal alteration zone; D: Paringa Basalt from Oroya Shoot proximal alteration zone showing pervasive pyritisation; E: Paringa Basalt hydrothermal breccia from Oroya Shoot showing carbonatisation and sericitisation of the wall rock; F: Paringa Basalt from Oroya Shoot showing contact between carbonated and seriticised wall rock and hydrothermal breccia (Bateman and Hagemann 2004).

third order structures (Witt 1993) rather than major deformation zones, suggesting that these first order structures are not the initial conduits for auriferous fluids but instead act as structural controls during later mineralization (Phillips et al. 1996). Kalgoorlie is situated in a bend of the Boulder-Lefroy Fault, which can also have localised fracturing, aiding the formation of vertical conduits (Bateman and Bierlein 2007).

Phillips et al. (1996) suggest also that major deformation zones act as structural controls determining the gross orientation of greenstone successions, including heterogeneities in orientation and lithostratigraphic succession, creating terranes with structures susceptible for reactivation during later deformation. The highly mineralized belt surrounding Kalgoorlie is a classic example of such a terrane. According to Phillips et al. (1996), gold mineralization at Kalgoorlie is related to zones where local stress fields have heterogeneous stress orientations at a high angle to the pre-existing geometry of regional deformation zones. Knight et al. (1993) made a similar observation at the neighbouring Coolgardie goldfield, noting that mineralization was strongly correlated to zones with local heterogeneous stress orientations compared to the predominant E-W regional stress field.

8.4.3 Effect of stress on fluid flow

Fluid flow can be focused upwards by sites of low mean stress (Ridley 1993). According to Ridley (1993) if the regional far-field stress lies at a high angle to layered successions of contrasting competency in greenstone belts, then the competent layers in the succession will experience lower mean stress (Phillips et al. 1996). In the case of the greenstones at Kalgoorlie this would suggest that the competent layers, trending broadly NNW-NNE and situated in an area with a E-W regional field stress (Witt 1993), experienced a higher fluid flux relative to adjacent areas, which thus resulted in a higher degree of mineralization (Phillips et al. 1996). Focusing of fluid flow to create high fluid flux is suggested to be a major factor for the anomalously large size of the Kalgoorlie deposit (Phillips et al. 1996).

8.4.4 Effect of anomalous geometry

The Kalgoorlie deposit is situated in an area with anomalous geometry on both a regional and goldfield scale (Phillips et al. 1996). On a regional scale, the refolding of initial thrust sheets to form large-scale anticlines, e.g. Kalgoorlie Anticline, which has resulted in the isolation and thickening of the relatively competent NNW- trending mafic-ultramafic sequence by the surrounding less-competent sedimentary rocks (Phillips et al. 1996). On a
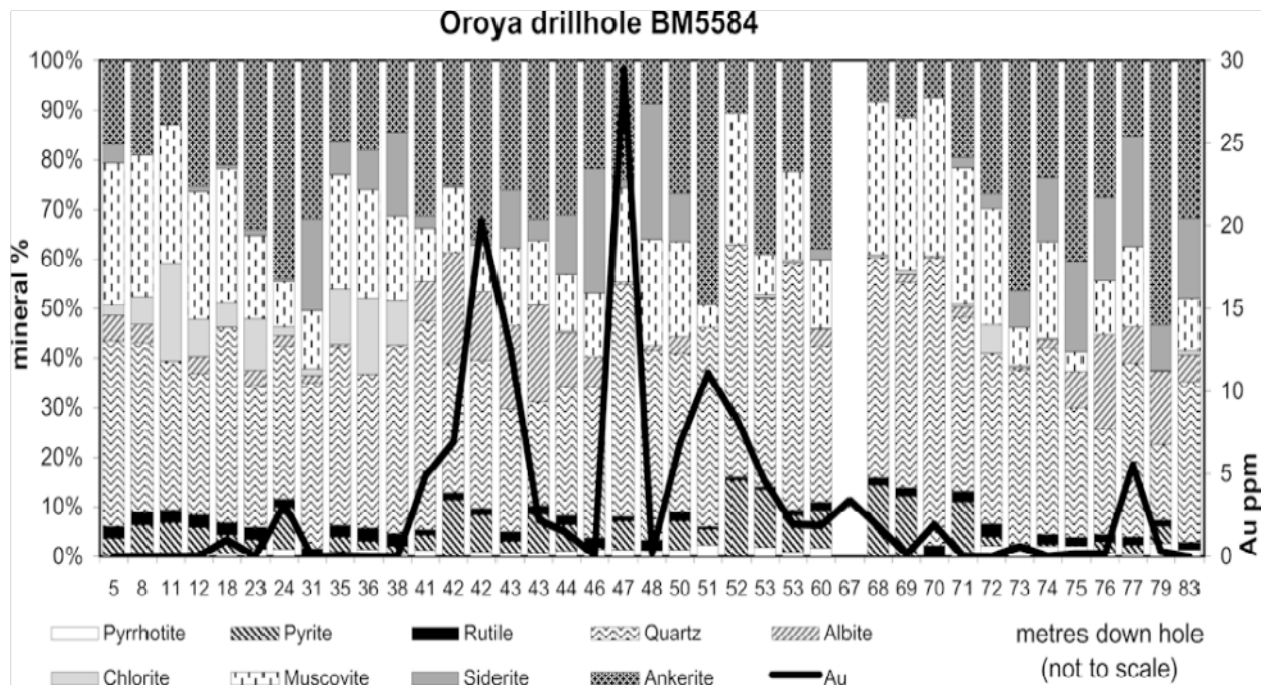
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Fig. 5. Downhole profile near the Oroya Shoot, showing gold grade variation and mineralogy. Note the high values for quartz, muscovite, siderite and ankerite associated with the typical Oroya Shoot mineral assemblage (Hagemann et al. 2001).

goldfield scale this refolding, together with the later formation of N-trending faults, resulted in the isolation of a slab of the host rock within the Golden Mile.

N-trending faults have resulted in the formation of block-like geometry in the host rock north of the Golden Mile (Phillips et al. 1996). Blocks in this anomalous geometry have been shown to have low mean stress (Groves et al. 1995) and the Golden Mile Dolerite within them has acted as a zone of structurally induced permeability linked to gold mineralization of the large Mt Charlotte deposit (Mengler 1993).

Therefore it is reasonable to suggest that anomalous geometry caused by folding and N-trending faults is responsible, at least partly, for focused fluid flux within the Golden Mile and is thus also a factor affecting the size of the Kalgoorlie deposit (Phillips et al. 1996).

8.5 Duration of Mineralisation

An important requirement for the formation of a giant gold deposit is that efficient mineralization processes occur over a long period of time (Bateman and Bierlein 2007). Formation of the Kalgoorlie deposit occurred during extended episodes over a period of up to 45 million years, from mineralization of the Fimiston deposit through to the Mt Charlotte deposit (Fig. 7; Bateman and Hagemann 2004). The diachronous D2 deformation in particular, with a progression from east to west, spanned at least 20 million years (Bateman and Bierlein 2007). This extended period of deformation resulted in repeated reactivation of structures, resulting in establishment of

more efficient vertical conduits and fluid-focusing systems. During this period there was also a prolonging of fluid circulation and uptake of gold, fluid focusing, as well as gold deposition processes (Bateman and Bierlein 2007).

9 Conclusions

Ore fluids that generated the Kalgoorlie gold were low salinity $H_2O + CO_2 + H_2S \pm CH_4$, which is generally characteristic of most other Archaean gold deposits (Phillips et al. 1996). Various theories have been put forward to explain the source of these fluids, including the dehydration of early basin sediments and the infiltration of seawater. Although there are some anomalous characteristics of the ore fluids that generated the Kalgoorlie gold, especially Au-Te concentrations, it is suggested that these were mostly a result of extremely effective fluid focusing systems (Bateman and Hagemann 2004). Also, available data suggests that ore fluid characteristics at Kalgoorlie, as well as other smaller deposits in the Norseman-Wiluna belt, are still generally typical for global Archaean lode-gold deposits (Phillips et al. 1996). It is suggested therefore that the nature of the ore fluid is not considered to be a vital factor in this discussion.

However, an extensive supply of gold was required to feed this fluid focusing system, which was at least partly provided by the dehydration of previously deposited early basin sediments (Bateman and Hagemann 2004). Therefore the quantity of available source
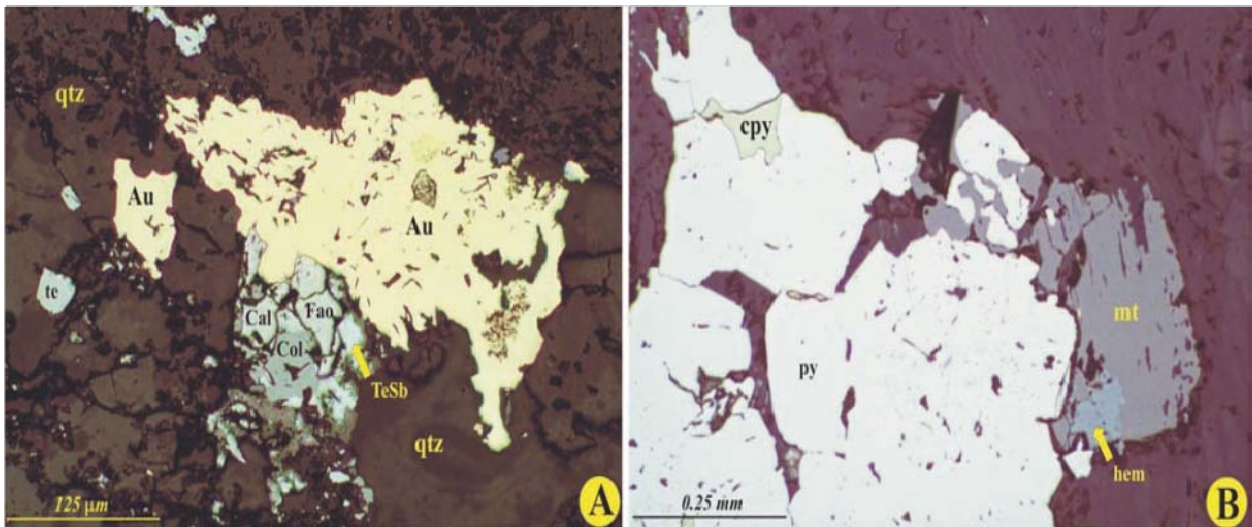
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Fig. 6. Photomicrograph of equilibrium mineral assemblages from the Fimiston deposit. A: Inclusion-rich gold grain with tellurium minerals. B: Pyrite-chalcopyrite-magnetite-hematite and pyrite-magnetite equilibrium assemblages (Hagemann et al. 2001).

rock needed to produce a deposit on the scale of Kalgoorlie, is certainly considered to be a controlling factor for the formation of a giant gold deposit.

Characteristics of the host rock are considered to be an important factor of formation of the giant Kalgoorlie deposit (Phillips et al. 1996). The physical characteristics of the host rock, the anomalous thickness as well as competency of the Golden Mile Dolerite, are considered vital factors for formation of the giant Fimiston deposit at Kalgoorlie (Bateman and Hagemann 2004). The high degree of rheological contrast in the volcanosedimentary sequence, as well as competency contrasts between Unit 8 and adjacent units in the Golden Mile Dolerite, resulted in increased permeability in the host rock and thermal fracturing. This assisted fluid focusing and was thus partly responsible for increasing gold deposition at Kalgoorlie (Weinberg et al. 2005).

The high $Fe/(Ca + Fe + Mg)$ host rock properties caused the breakdown of Fe-Mg-bearing silicates in the ore fluids to form pyrite, as well as the destabilization of gold-bearing reduced sulfur complexes, and thus subsequent deposition of gold (Phillips et al. 1996). However this is not the case with other giant Archaean gold deposits, (eg. Timmins deposit in the Albititi Province, Canada), so therefore Fe content of the Golden Mile Dolerite, although increasing gold mineralization, is not considered a major factor affecting the size of the Kalgoorlie deposit (Phillips et al. 1996).

Tectonic movement is considered a major factor in formation of the Kalgoorlie gold camp. Early thrust stacking resulted in a network of fractures that were repeatedly opened during progressive deformation and acted as vertical conduits for large volumes of auriferous fluids. The D1 thrust-related fracturing assisted fluid focusing and also resulted in the formation of breccias, which became the depositional sites for the giant Fimis-

tone lode (Bateman and Bierlein 2007). Subsequent D2 strike-slip movement along the Boulder-Lefroy Shear Zone extended this array of fractures, as well as creating dilational jogs which aided fluid focusing and resulted in formation of the Oroya Shoot deposit (Weinberg et al. 2005). Later D4 reactivation of D3 dextral shear zones resulted in the formation of north-trending parallel faults that hosted gold mineralization associated with the Mt Charlotte deposit (Bateman and Hagemann 2004).

The anomalously large wall-rock alteration zone around Kalgoorlie suggests enhanced fluid flow. According to Ridley (1993) the orientation of the mafic-ultramafic sequence at a high angle to the far-field stress created conditions of low stress in the more competent Golden Mile Dolerite. Also the anomalous geometry at Kalgoorlie formed by early thrusting, upright folding and later strike-slip movement, has effectively isolated the more competent ultramafic-mafic sequence from the surrounding less competent sedimentary rocks (Phillips et al. 1996). Subsequent N-trending faults further isolated a slab of the Golden Mile Dolerite, resulting in increased contrast in competency and thus creating conditions suitable for enhanced fluid flux in the host rock. These structural controls are therefore considered important for the anomalous gold deposition that occurred at Kalgoorlie.

The duration of gold mineralization processes at Kalgoorlie is also considered an important factor effecting it's size. Formation of the Kalgoorlie deposit involved extended episodes of mineralisation and possibly spans up to 45 million years, from main gold deposition of the Fimiston deposit through to formation of the Mt Charlotte deposit (Bateman and Hagemann 2004). This protracted mineralization resulted in a prolonging of fluid circulation and uptake of gold, fluid focusing and
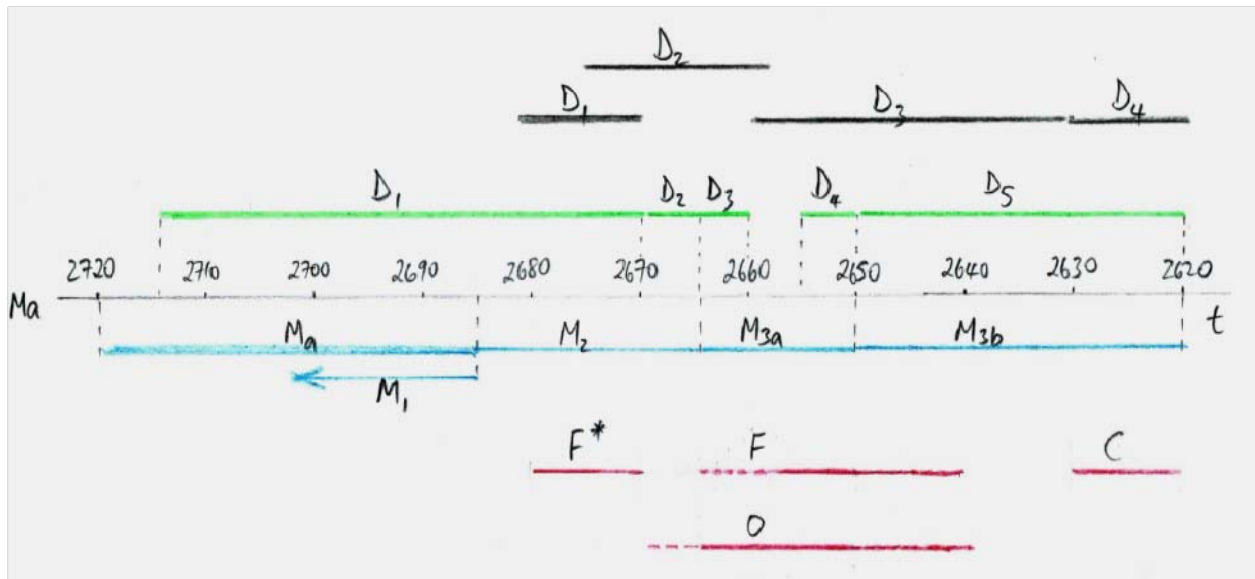
Fig. 7. Timeline in millions of years showing timing of deformation, metamorphism and gold mineralization at Kalgoorlie and the east Yilgarn craton (after Bateman and Hagemann (2004) and Czarnota et al. (2010)). Deformation events (D_{1-4}) at Kalgoorlie according to Swager (1989) model, in black; Deformation events (D_{1-5}) in east Yilgarn craton according to Czarnota et al. (2010) model, in green; Metamorphism events (M_{1-3b}), in blue; Gold mineralization at Kalgoorlie (F^*= Fimiston, after Bateman and Hagemann (2004), F=Fimiston, after Czarnota et al. (2010l), O=Oroya Shoot, C=Mt Charlotte), in red.

deposition processes, which resulted in increased gold mineralization (Bateman and Bierlein 2007).

The anomalous size of the Kalgoorlie goldfield is therefore considered to be due to highly efficient focusing of gold-rich ore fluids over an extended period of time. However one factor alone cannot be considered solely responsible for formation of this fluid focusing system. Instead it is put forward that favourable conditions for several of these factors occurred in conjunction to produce the giant Kalgoorlie gold deposit.

10 Acknowledgements

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