Mineralized Terranes

Eastern Goldfields Superterrane (EGST)

(based on Y4 Final Report)

Introduction:

The EGST consists of three terranes:

- In the west, the Kalgoorlie Terrane is made up of a series of >2.76-2.63 Ga granite-greenstone domains
- The central Kurnalpi Terrane is a complex series of ~2.95-2.63 Ga granite-greenstone domains
- To the east is the Burtville Terrane, which is poorly defined by ~2.95-2.63 Ga granite-greenstone domains

The 5 Questions:

Q1 Geodynamic (structural and PTt history):

- Preferred Geodynamic model: para-autochtonous convergent margin model, which considers the granite/greenstone history pre 2.720 Ga where as most past tectonic models have only considered the post 2.720 Ga rock record. The rock record at >2.940 Ga is treated as basement most likely developed within a volcanic arc setting.
- Kalgoorlie is located in the deepest overall basin with the lowest part of the (main) stratigraphy at the lowest metamorphic grade exposed. The abundant komatiites that are part of an earlier world-class mineral system (Ni) show an efficient process of accessing the mantle.
- Synthesis of the geochronology, geochemistry, stratigraphy, geophysics, metamorphism, and structural geology (Czarnota et al., 2008) imply that an overall extensional margin dominated the geodynamic evolution of the Eastern Yilgarn.

- The Sm-Nd model age map was improved and highlights the main terrane subdivisions of the EGST. These patterns are strip-like and mark variable degrees of crustal contamination from a thinned Younami Terrane basement underlying the EGST. These patterns likely refute the strike-slip orogen settings of Krapěz and Barley (2007) and support a simple rifting – back-arc-extension model of Groves and Batt (1984).

Q2 Architecture:

- Kalgoorlie sits atop a large dome and has been the focus of an entire region's energy and mass flux. Not only is it atop a large dome, but this dome is part of a corridor (Golden Corridor) with opposing major fault systems (that were growth faults at the time of basin formation. These fault systems link to the mantle by deep-penetrating structures imaged in the seismic and inferred from big gravity worms and Sm-Nd patterns. Mantle tomography reveals a structural architecture at depth that may have influenced the system.
- A new structural evolution has been developed (Blewett and Czarnota, 2007; Blewett et al., 2008a) which equally treats the extensional and contractional events. A total of 7 main events (D1 to D7) are recognised across the EGST.
- D1 Extension was dominantly E- to ENE-directed, and likely reflected the shape of the eastern margin.
- Short periods of convergence late in the history (<2665 Ma) inverted this system. Most of the convergence direction was ENE perpendicular to

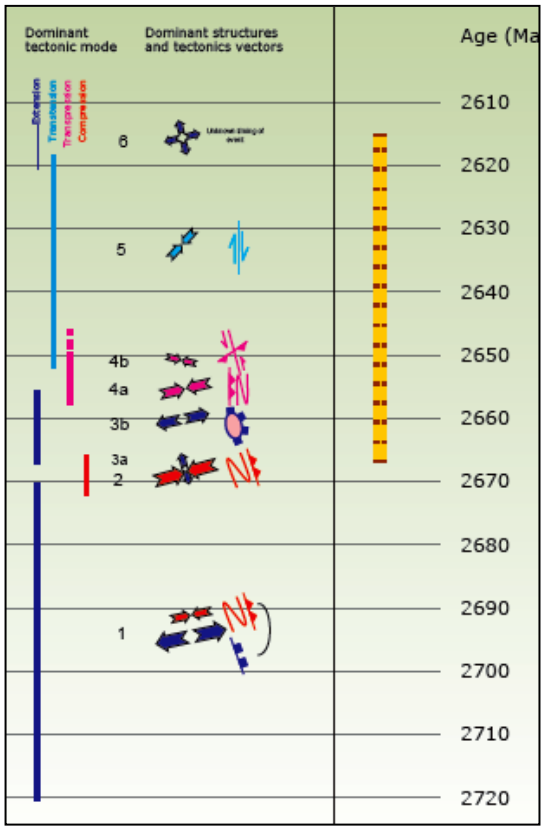

Figure 1

the margin (D2, D4a), with a short period (2650 Ma) when there was a far-field stress switch to an ESE orientation (D4b). This stress switch was also responsible for north-directed thrusts (previously called D1 – e.g., Swager, 1997) locally developed along dome hinges as accommodation of regional sinistral strike-slip faulting (D4b) within mostly inter-dome high-strain zones.

- A diachroneity of process during the late inversion with events around 5 Myr younger in the southeast (southern Kalgoorlie Terrane) marks an obliquity between the far-field convergence zone and the eastern margin of the system.
- A crucial intra-contractional lithospheric extensional event (D3) marked the delamination of the lower crustal eclogitic restite from earlier TTG magmatism and magmatic crustal thickening (Czarnota et al., 2008). The vector of extension was NE and resulted in complex accommodation zones between the D3 and earlier D1 extensional faults, and the development of late basins. The main locus of this extension was the Ida and Ockerburry Fault Systems (bounding structures of the Kalgoorlie Terrane), with late basins developed in the hanging wall. Since these late basins are a feature of many granite-greenstone belts (e.g., in Superior, Slave, Pilbara, Barberton, and West African Cratons) this reinterpretation of their significance raises broader questions regarding the geodynamics of granite-greenstone belts.
- The D1/D3 extension breaks the crust and develops a deep-penetrating fault system and facilitates access to a metasomatised mantle melt (as seen in deep seismic profiles and magnetotellurics; Blewett et al., 2008b).
- The faster the rate and the greater volume of new crust formation and its transition to cratonisation the more favourable the terrane/province (fast/voluminous and slow/less voluminous: *cf.* EGST and Younami; Yilgarn/Superior and Pilbara/Barberton)
- Structurally, texturally and mineralogically these systems record a number of gold mineralisation events and yet commonly only the youngest dated

ages are quoted (e.g., at St Ives, Agnew and Laverton). With a better understanding of the structural and mineralisation paragenesis a renewed effort should be made to date the various paragenetic stages within the deposits. Greater understanding of the phosphate minerals dated, especially the younger ages obtained from the low-U minerals.

- New techniques such as 3D scanning of veins show that at least some are complex multiphase features and are used and reused throughout the mineralisation history (see Cleverley and Nugus, 2008).

Relationship of mineralisation to magmatism

- Complex accommodation zones developed during D3 extension favoured emplacement of Mafic-type and early Syenite-type magmas that were sourced from metasomatised mantle (wedge) – this event marks the beginning of significant gold mineralisation (e.g., Lancefield, Kalgoorlie, Sunrise Dam, Leonora and St Ives)
- Many deposits have mineralisation ages younger (10+ Myr) than the porphyries that host the deposit. However, 3D mapping of the complex granite-cored domes show that they are multi-phase and beneath all the giant deposits. Most of the granites (and especially the Late Low-Ca granites) do not intrude into the greenstones, rather they freeze at the lower basalt or komatiite levels in the stratigraphy (Henson et al., 2005; 2008). These vertically zoned systems likely provided fluids through the same pathways that earlier, small magma volumes (e.g., deposit scale porphyries) had passed (see also Mueller, 2007; Cleverley and Nugus, 2008). The early architecture was critical in facilitating early magma emplacement which in turn set up local sites of anisotropy. These sites localised strain during multiple phases of reactivation and also guided subsequent (magmatic?) fluids into the same sites.

Relationship of mineralisation to metamorphism

- There are multiple metamorphic events (five) of differing metamorphic gradients, including locally developed M1 high-P granulites (up to 8.7 Kb) in the oldest greenstone sequences adjacent to granite downs (Goscombe et al., 2007).
- The D3 extensional event was associated with tight anticlockwise M3a PTt paths in the upper plate that exhumed older higher pressure (with clockwise path) assemblages in the footwall. These extensional systems developed adjacent to major granite domes. See Deliverable 3 for more details including reports, maps and databases.
- Regional exhumation during D4 to D5 times is recorded by low pressure M3b assemblages (~1 kb) and was associated with regional retrogression and alteration. Maps of redox of the alteration mineralogy illustrate the regional scale of these hydrothermal systems.
- Low-Ca granites are crustal melts that were emplaced at high levels across the entire craton and mark decompression and uplift of the exposed crust to high crustal levels (<1 kb) resulting in final cratonisation 10-15 My after the inferred delamination of the eclogitic restite. This time delay is consistent with the thermal diffusivity through the known crustal thickness of the Yilgarn.

Relationship of gold mineralisation to the structural history

- D1 extension to 2670 Ma set up the dominant architecture and the NNW-trending grain of 'orogen' and influenced all subsequent events (including Au and probably Ni mineralisation).
- All of the major deposits have D1 growth faults (e.g., Golden Mile, Agnew-Lawlers, Sunrise Dam and St Ives) that are subsequently inverted and host mineralisation (Blewett et al., 2008a).
- Gold deposits are traditionally described from contractional settings, however clear extensional gold (during D3) has been documented at Leonora, Lancefield, Leinster and at Kunanalling. All these sites are

adjacent to granite domes. The deposits are restricted to the shear planes (C and C') of the extensional foliations and have very deep extents down the stretching direction. These are a new gold play and have been under-explored (see Part II for target descriptions and ideas).

- Gold occurs in all events up to and including D5, but the highest grade and tonnage occur from D3 times onwards (this is the time the metasomatised mantle was accessed and late basins developed).

Q3 Fluid sources and reservoirs:

- The presence of enriched mantle magmas (sanukitoids and lamprophyres) in the region and the deposits suggest a fertile source area was not only present, but had communicated with the upper crust. A contrast in mineralogical and alteration types between oxidised and reduced end members indicates differing fluid sources in this system.
- The question regarding one or multiple fluids has been debated for decades. There are clearly multiple (3-4 fluids) end member fluids involved in this gold system. As the magmatism, metamorphism and tectonic setting evolved through time and space, so to have the fluids and their sources. The multiple gold events and their differences in PT conditions, redox, allied mineralogy and metal associations, together with wall rock alteration all indicate an evolving system of fluid sources.
- Evidence for a range of fluid sources is provided by the extreme range of O, S, C isotopes and the range of redox inferred from these and from the mineralogy (see Walshe et al., 2006; 2008a; 2008b). Within vein systems themselves, fluid dominates over wall rock so the chemistry reflects different sources of fluids and not necessarily the influence of reactions with local wall rocks.
- Noble gases from a mantle reservoir have now been identified in D4b gold-bearing veins at St Ives. This is a significant finding. How indicative this finding is to other deposits remains to be determined.

- Geochemical modelling shows that there were likely at least two fluids – a mafic fluid and a granitic fluid (although this work by Bastrokov favours sulphidation as the gold depositional process).

Source of gold

- Gold source has been problematic for decades, and it is likely that there are multiple sources.
- Lamprophyres and metasomatised mantle melts (Mafic porphyries and Syenites) are clearly temporally associated with major gold mineralisation in the Abitibi subprovince of Canada (Beakhouse, 2007). The diachroneity in these magmas (north to south) perfectly matches the diachroneity in mineralisation – illustrating a clear link.
- There is a less clear link between gold and these magmas in the EGST as there are multiple overprinting gold events. However, the first significant gold was deposited at the same time period as metasomatised mantle magmas were emplaced – may be the metasomatised mantle was the ultimate source and the magmas reflect a melt fraction and common pathway from this source.
- Once gold is deposited in the system it can be remobilised (e.g., Plutonic and Tropicana? as Proterozoic reworking), it is not clear if the remobilisation can occur within a few million years (D3 to D4 and D5) within the same deposit or whether multiple gold sources should be invoked. The addition of base metals together with gold suggest basinal input (late basin inversion) and tellurium suggests magmatic input (Low-Ca granites and High-Ca crustal melts post 2655 Ma) for associated metals. These deposits are the same ones that host classical orogenic gold and yet could be classified as anomalous metal association and intrusion-related respectively (see Groves et al., 2003). This coincidence in space (but separated in time) suggests that splitting deposits into different types is not particularly helpful in understanding these systems.

- If a greenstone (mafic source) is invoked then it has one chance to release its metal and fluid. This source is a problem (if it is the only one invoked) as there are many sequential gold events (Sheldon et al., 2008).

Q4 Fluid flow drivers and pathways:

- The presence of both extension and later contraction as evident in the 2D-3D map patterns and supported by structural analysis tell us about system drivers and linked to this are the suitable pathways defined by the complex architecture. The magnetotellurics (and seismic) indicate that the system's pathways had operated effectively to alter the character of the crust, with Kalgoorlie sitting atop a giant alteration cell.
- Maximising the flow of a focused fluid and creation of permeability (dilation) is critical for the formation of high grades. At a macro-scale this means being along or near domes such as Laverton, Leonora, Kalgoorlie-Kambalda and Kanowna Belle and not in the tight domains between. These regions have a favourable architecture in terms of fluid focus (inherent domal geometry) and are areas of stress transfer (structural complexity) between high to low strain domains.
- Pathways can be imaged in mantle tomography, deep 'worms', magnetotellurics, and deep seismic reflection profiling

Q5 Metal transport and deposition:

- The fact that large chemical gradients occur in and around Kalgoorlie tell us that the necessary (critical) chemical contrasts existed to form an efficient depositional site for formation of giant deposits.
- There are four main ways to deposit gold (phase separation, fluid-rock reaction, vapour condensation and mixing across chemical gradients).
- Clearly all four processes have been documented in the EGST – so it is banal to suggest that it is one process *vs.* another.
- The question remains what makes the giant deposits and the high grades – the Y4 project believes that fluid mixing across chemical gradients is the

most efficient method. The range of data showing gradients in operation with multiple fluid sources are now very compelling.

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