



Archean gold mineral systems in the eastern Yilgarn Craton

New knowledge to assist area selection and targeting

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Introduction

The eastern Yilgarn Craton of Western Australia is Australia's premier gold and nickel province (figure 1), and has been the focus of geological investigations for over a century. Geoscience Australia, in conjunction with collaborators in the Predictive Mineral Discovery Cooperative Research Centre, conducted a series of projects between 2001 and 2008 (Y4 Project team 2008). This article summarises the new findings from the research; many of which challenge previous paradigms regarding the tectonics and geological architecture, as well as the relationship of gold to structure, magmatism and metamorphism. Although the research was based on the Yilgarn Craton, the results have general implications for other Archean terranes and mineral systems.

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Predictive mineral discovery

The main goal of the research was to develop a comprehensive mineral systems understanding for gold in the eastern Yilgarn Craton, and to use this knowledge for predictive mineral discovery. A methodology was developed of four nested scales of prediction: 1) craton/province; 2) district/camp; 3) deposit; 4) ore shoot.

This article presents the second, or district-scale prediction, which resulted in the generation of a new gold target map (figure 1) for the eastern Yilgarn Craton. The details are presented in Czarnota and others (2010a). The map represents the culmination of mineral systems analysis, it encapsulates the critical processes of the geodynamics, architecture, fluid sources, fluid pathways and drivers, and gold deposition mechanisms.

The critical processes were translated into a series of independent proxies that could be regionally mapped. Four separate maps were generated in a GIS (geographic information system). The first map defined the pre-gold endowment, and used the crustal age and the metamorphic distribution. The second map defined the key features of a major lithospheric extensional event, including identifying the main detachments and associated transfers, mantle magmas and deep structures in gravity and mantle tomography. The third map defined the contractional inversion features, and included the fault network, upper plate distribution and 3D shape of granite domes. The fourth map defined the regional alteration associated with loss-on-ignition in geochemical datasets and redox gradients defined from petrography and field site mineralogy.

These four maps were then integrated, resulting in the generation of this new target map for gold without the input of any gold deposit layer (figure 1). The map predicted 75 per cent of the known gold in less than five per cent of the total area. Importantly, the map identified

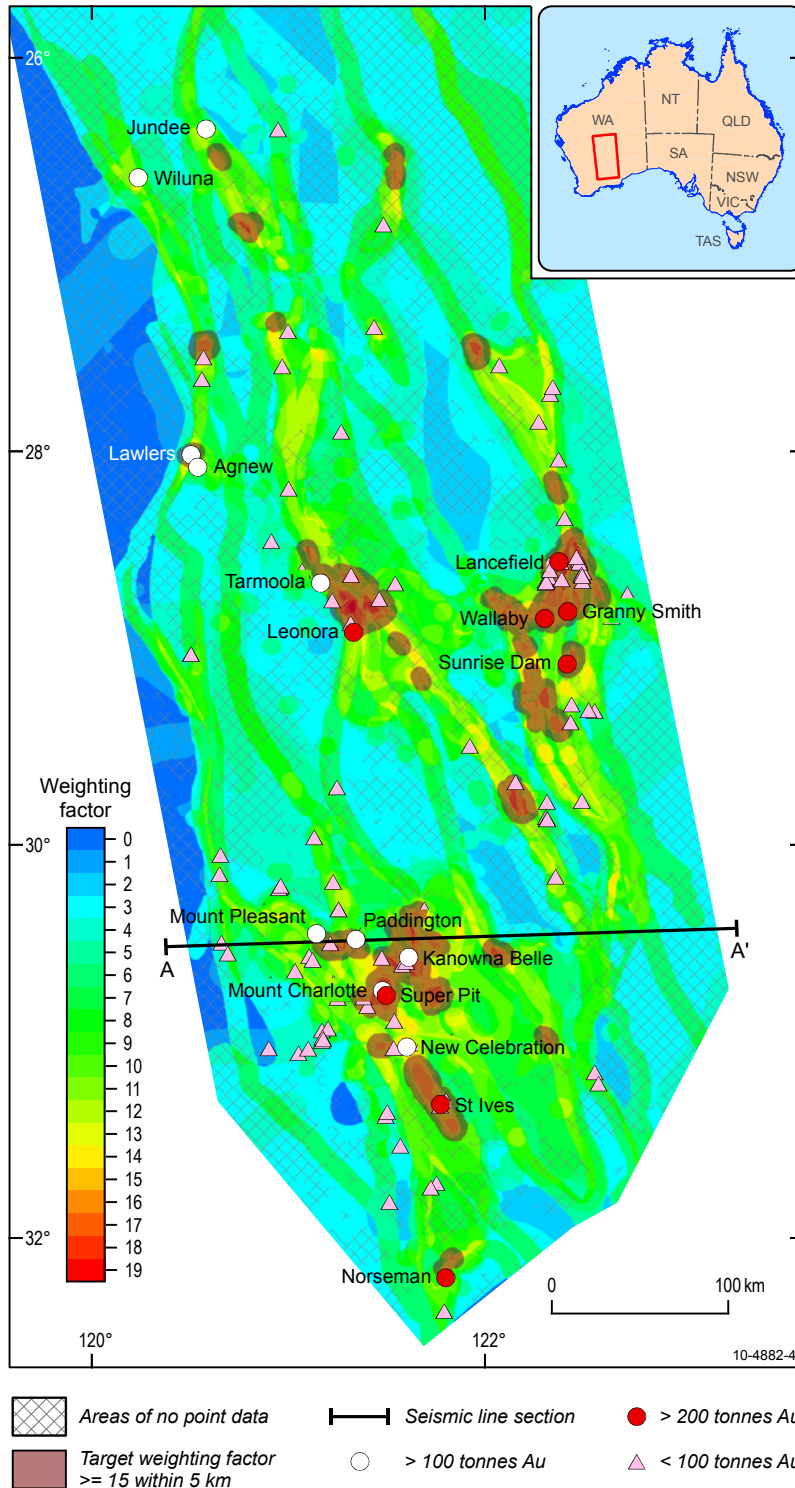


Figure 1. Map of the gold prospectivity of the eastern Yilgarn Craton overlain with known deposit locations (after Czarnota and others, 2010). The map has successfully predicted most of the known major gold deposits and is a positive test of the mineral systems understanding. High weighting factor areas (yellow to red colours) are most prospective for gold mineralisation. The brown areas represent a weighting factor score of 15 or more, with a five kilometre buffer. These areas contain 75 per cent of the known gold mineralisation in only 5 per cent of the study area. A number of new target areas with no known significant gold mineralisation are also identified – these represent new gold targets. The section line A–A’ is revealed in figure 4.

all the major gold camps, thus confirming which critical processes are needed to form a giant gold deposit. The map revealed a number of areas that were not known for hosting large deposits, but had all the favourable ingredients – these represent new target area opportunities. The datasets used to map the critical process proxies are revealing in themselves; they inform on data requirements for successful prediction and exploration.

Tectonic setting and metamorphic evolution

The tectonic or geodynamic setting of most Archean terranes is controversial, with a number of competing hypotheses. For example, some researchers suggest that plate tectonics did not operate during early Earth history, or at least not in the way we understand it today. Nevertheless, first order constraints regarding the tectonics of the eastern Yilgarn Craton are provided by the following:

- 1) synthesising the main elements of the geodynamic system
- 2) mapping the fundamental boundaries
- 3) determining the metamorphic evolution.

Czarnota and others (2010b) have synthesised the main elements of the eastern Yilgarn Craton into a new integrated framework in time and space. The synthesised elements included the stratigraphy,

magmatic history, metamorphism, mineralisation, and structural geology, together with extensive geological and geophysical maps. The synthesis highlighted the interdependence of the system, where a change in one element is accompanied by a synchronous change in all other elements. This synthesis allows the key features of the gold mineral system to be placed in context, leading to better predictions (figure 1).

Fundamental map patterns are revealed by a new crustal age map (figure 2), which is based on measurements in granites of rare-earth isotopes of samarium and neodymium. The map shows that the eastern Yilgarn Craton consists of a series of NNW-striking belts of variable age, which developed on the edge of the Youanmi Terrane, an older continental block to the west (Cassidy and Champion 2004).

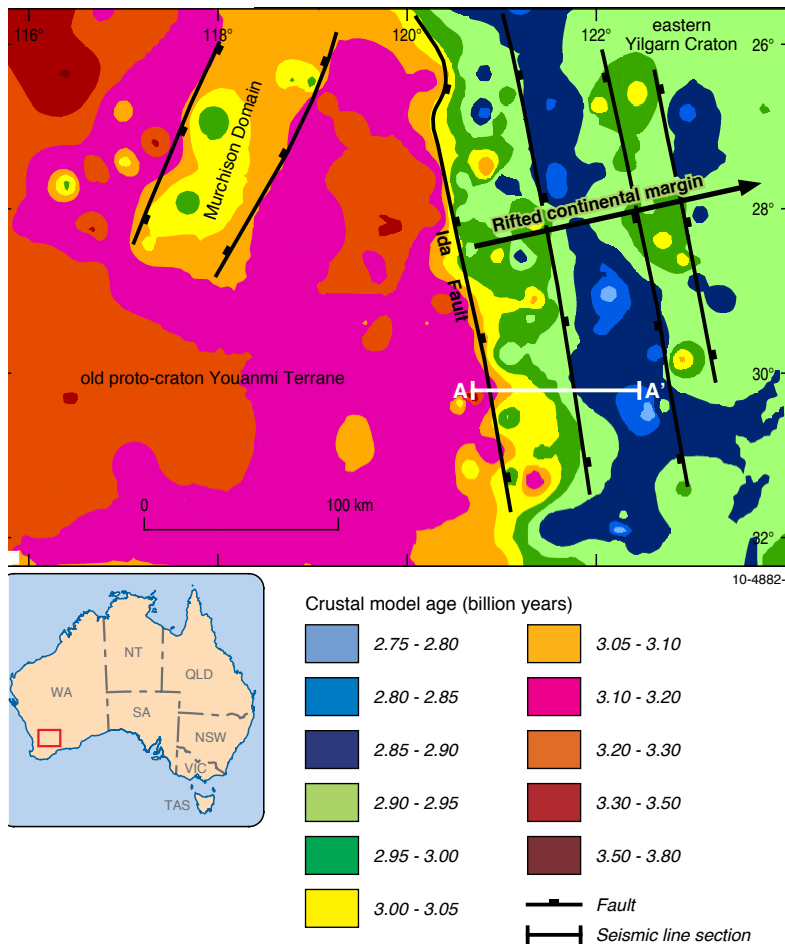


Figure 2. Crustal (model) age map of the Yilgarn Craton measured from samarium and neodymium isotopes in granites. The values are given in billions of years (or Ga), and are calculated as a two-stage depleted mantle isochron (after Cassidy & Champion 2004). The warm colours are the oldest crust. The cool colours are the youngest crust. The map shows the fundamental terranes and domains, and their boundaries, of the Yilgarn Craton. The eastern Yilgarn Craton, a zone of relatively young crust, developed on the extended margin of the old 'Youanmi' Terrane proto-craton. The section line A–A' is revealed in figure 4.

The patterns of change in crustal age are the result of variable degrees of crustal contamination caused by the variable thickness of the underlying extended basement and, as such, map the fundamental structures of the region. Areas of intermediate thinning and age (2.90 to 3.05 Ga or billion years) are the most endowed in gold and nickel.

The recent metamorphic work by Goscombe and others (2009) marks one of the most significant new advances in understanding the region's geodynamic evolution. This metamorphic study is probably the most comprehensive of any of the world's Archean terranes, and it provides new constraints on this poorly understood Eon. Previously, the eastern Yilgarn Craton was thought to record a single prograde metamorphic cycle as a consequence of crustal thickening from continent to continent collision. It has now been shown that five discrete metamorphic events occurred, with large variations in peak metamorphic crustal depths (12 to 31 kilometres). The metamorphic evolution can be viewed with stages of crustal growth, thermal priming of the crust, lithospheric extension, and finally inversion and reactivation. The work has major implications for metamorphic fluids and their role, or not, in gold transport and deposition.

The combined constraints challenge previous models involving exotic strike-slip terranes and obduction settings,

and support simpler rifting/back-arc extensional settings. They suggest that the eastern Yilgarn Craton developed on the rifted margin of an old continent, with the influence of a mantle plume.

Lithospheric architecture

The new understanding of the eastern Yilgarn Craton has benefited from a concerted effort to acquire high-quality geophysical data, and to integrate the architecture from the scale of the thin section (figure 3a), to drill core (figure 3b), to outcrop (figure 3c) to whole lithosphere (figure 4). Potential field data and limited seismic reflection data had been available up to the year 2000. Over the last decade there has been an increase in the availability of seismic reflection data, which has been augmented by passive seismic (tomographic) and magnetotelluric data (figure 4). Together, these geophysical datasets provide information on the architecture/structure of the crust and upper mantle, and they reveal anomalous features beneath the main gold camps (Blewett and others 2010). The development of the architecture can be linked to the geodynamic synthesis; together they provide a 4D understanding of the system, and improved predictive capacity (figure 1).

A Golden Corridor, stretching from St Ives to Wiluna (figure 1), is defined by a regional anticlinorium whose limbs are marked by outward dipping shears that connect to deep faults. Granite-cored domes are nested within this regional structure, providing a favourable focussing architecture for deep fluids.

The seismic character of the crust is interpreted to be dominated by extensional features—such as core complexes—contrasting earlier interpretations of contraction and thrust duplexes above a single detachment.

A fast shear-wave velocity body is mapped at a depth of 120 kilometres (figure 4), which is interpreted as delaminated lower crust. The process of delamination is interpreted to be a driver of the D_3 extensional event, which saw the start of major gold deposition and the development of the main dome-and-basin map patterns. Steps and changes in this velocity body are interpreted as mantle structures. The magnetotelluric data reveal anomalously enhanced conductivity beneath the Golden Corridor, which is interpreted to reflect large-scale fluid alteration (figure 4).

New developments in software and hardware now permit realistic 3D inversions of potential field data, and the results can be visualised in 3D on a standard desktop computer. By integrating these geophysical datasets with geological maps, new 3D geological maps were constructed (figure 4). These maps delineate the granite-cored domes which dominate the regional architecture (Blewett and Hitchman 2006). Many domes nucleated about early growth

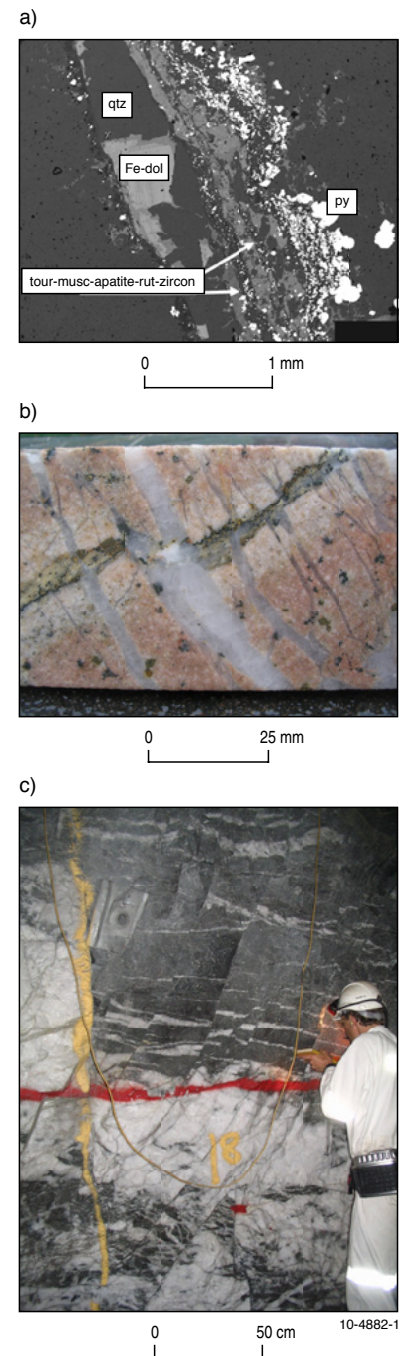


Figure 3. Illustration of the variety of scales mapped in the eastern Yilgarn Craton: a) thin section scale with contrasting fluid chemistry inferred from the mineralogy determined in this back-scattered SEM image of gold ore at Sunrise Dam; b) drill core scale with multiple generations of veins and alteration in mineralised quartz-feldspar porphyry from St Ives; c) outcrop scale mapping underground at Agnew.

faults, which also controlled the stratigraphy. Such faults, when inverted, became the location of major gold deposits, such as the Superpit at Kalgoorlie, at Wallaby and Kanowna Belle (figure 1).

Structural evolution

The eastern Yilgarn Craton gold deposits are structurally controlled, so knowledge of the structural evolution can lead to enhanced prediction (figure 1). Using an improved geochronological framework, a revised structural history was developed (Blewett and Czarnota 2007). The new history better integrates the stratigraphy and the 3D architecture, with six key Archean deformation events (D_1 to D_6). From this new understanding, a series of observations and interpretations are made:

- D_1 extension was E- to ENE-directed, reflecting the shape of the eastern continental margin, and dominated the period 2720–2670 Ma. This event established the fundamental NNW-trending architecture and the crustal age map patterns (figure 2); it also influenced all subsequent deformational events. Growth faults developed during this time were important for the early nickel and later gold mineralisation.
- The bulk crust was built during D_1 into three gravitationally unstable layers. The upper layer consisted of dense mafic rock-dominated greenstone. The middle layer consisted of less dense and thermally-weak granite. The lower layer consisted of a dense residue from the mid-layer granite melts.
- ENE-directed D_2 convergence commenced around 2665 Ma, perpendicular to the extensional margin. Folds and thrusts attest to some crustal thickening, but this rapidly led into major extension, as D_2 contraction triggered a reorganisation of the density distribution of the crust.
- The lower crust delaminated during D_3 , allowing mid- and upper-crustal core complexes and domes to develop, thus minimising the unstable potential energy. Late-stage clastic basin successions were deposited in the hangingwall of deep-penetrating extensional shear zones, together with intrusion of magmas from a metasomatised mantle source. These late-stage basin successions are a feature of many granite-greenstone belts (for example in Canada, Africa and India), and they are commonly synchronous with gold mineralisation. Both the D_1 and D_3 extensional events ruptured the crust. Together, they developed the deep-penetrating fault system (figure 4) that facilitated access to metasomatised mantle melts (as seen in deep seismic profiles and magnetotellurics).
- Convergence returned after 2655 Ma, with a series of far-field stress switches from an ENE (D_{4a}) to an ESE orientation (D_{4b}).

This stress switch was also responsible for north-directed thrusts (previously called D_3), which developed along dome hinges as accommodation of regional sinistral strike-slip faulting within mostly inter-dome high-strain shear zones. Final NE–SW convergence (D_5) saw mostly dextral strike-slip faulting – much of it in the brittle domain. Weak extension (D_6) is the final Archean tectonic event.

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Gold mineralisation

The traditional orogenic gold or lode-gold model argues for gold to be deposited during contraction, from hydrothermal fluid derived from the metamorphism of mafic greenstones. New findings argue against the traditional view, including new knowledge of the structure, metamorphism, magmatism and chemistry. These insights lead to better predictive capacity (figure 1).

The metamorphic evolution does not support a late-stage metamorphic fluid hypothesis, at least for all the gold. The regional M2 metamorphic event was of moderate pressure and temperature, and was closely linked to the emplacement of voluminous granite batholiths, not major crustal thickening. This M2 event accounts for much of the available metamorphic fluid, and it was generated some 15 to 20 million years before the main gold deposition. Geochemical modelling shows that the devolatilisation of greenstones releases only short-duration, low-volume fluids. The resultant rock mass is left dry and unable to subsequently contribute significant fluid to any later event. Multiple gold events are observed, meaning that metamorphic fluids may have been involved in one of the gold events, but not all. Thus, metamorphic fluids derived from mafic greenstones were unlikely to be a major fluid source.

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Three end-member fluids are interpreted to account for the range of oxygen, sulphur and carbon stable isotopes, the range of redox conditions inferred from these, and from the chemistry of the alteration mineralogy (figure 3a). Within vein systems, fluid dominates over wall rock so that the chemistry reflects different sources of fluids and not necessarily the influence of reactions with local wall rocks (figure 3b). An emerging picture of the role of possible mantle fluid reservoirs is provided by studies of the noble gases, especially those at St Ives and Sunrise Dam. This is a significant finding.

Gold deposits are traditionally described from contractional settings, hence the name orogenic gold. However, gold with characteristics analogous to the classical orogenic type also occurs in extensional shear zones, with key examples found at Leonora, Lancefield, Lawlers and Kunanalling (figure 1). All these gold deposits developed in D_3 shear zones, as the large granite domes were exhumed as core complexes. The gold deposits are restricted to the shear planes of the extensional foliations, and they have very deep but narrow ore shoots developed parallel to the stretching direction. The largest of these deposits occur where the oldest

stratigraphy is exposed and/or high-pressure rocks are exhumed. They also nucleate from any outward projecting apophyses on the margin of the dome, especially where this apophysis comprises a mantle-derived pluton. The host rocks are the exhumed fragments of the old basement, with pressures up to 8.7 kilobar (around 30 kilometre depth). These core complexes indicate significant reordering of the crust across these extensional faults, and they are the largest structures in the eastern Yilgarn Craton, reaching the Moho in some places (figure 4). They are gold-bearing because of the dynamic permeability created during extension. These are a new and under-explored gold play, and they need to be targeted differently to the more common contractional settings.

The D_3 gold deposits developed synchronous with emplacement of gold-enriched magmas sourced from a metasomatised mantle and the deposition of late-stage basin successions. The magmas also provided a source of oxidised fluids. The late-stage basin successions are characterised by a high thermal gradient and unusual tight anticlockwise M3a pressure-temperature-time paths. Their contained fluids were reduced. Extension drives basin fluids downwards, providing contrasting fluids to the oxidised magmas. Chemical contrasts favour gold deposition, either as fluids mix (figure 3a), or where

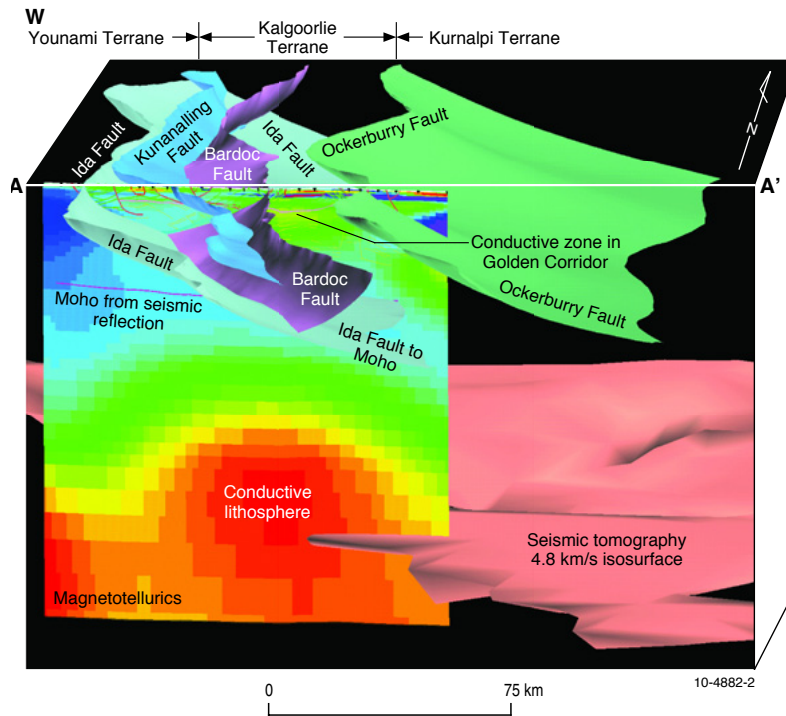


Figure 4. Lithospheric-scale section view across the eastern Yilgarn Craton at a latitude just north of Kalgoorlie’s Superpit (A–A’ in figures 1, 2). The brightly coloured image striking east–west is a conductivity map of the crust and upper mantle as measured by magnetotellurics. The warm colours are conductive regions – interpreted as alteration – such as within the Golden Corridor. The buff coloured feature in the lower right of the image is the fast seismic velocity body at around 120 kilometres depth. This is the interpreted delaminated lower crust. The green, blue and purple planes are the major faults of the region, some extend to the Moho. The location of the terranes are named.

one fluid encounters a host rock of contrasting redox or chemistry (figure 3b). Regional redox maps of alteration mineralogy illustrate the size of the footprint to these large-scale hydrothermal systems (Czarnota and others 2010a; Goscombe and others 2009).

Following lower crustal delamination during D_3 , a broad uplift of the eastern Yilgarn Craton occurred. This regional exhumation during D_4 – D_5 is recorded by widespread low-pressure M3b assemblages (~one kilobar) and was associated with regional retrogression and alteration. Shallow crustal levels favour mostly brittle deformation over ductile deformation. Brittle deformation favours dilation, especially in regions of structural complexity. A succession of stress switches (D_{4b} and D_5) were imparted onto this complexity, and resulted in a succession of gold depositional events (Czarnota and others 2010b).

Low-Calcium, or potassic, granites are high-temperature crustal melts that were emplaced at high levels across the entire

Yilgarn Craton. They mark the decompression and uplift of the exposed crust to high crustal levels (less than three kilometres), and their emplacement commenced some 10 to 15 million years after the inferred delamination of the lower crust. The time delay is consistent with the likely thermal diffusivity through the crust. The result was the effective transfer of heat and heat-producing elements into the upper crust, effectively cratonising the Yilgarn (Czarnota and others 2010b).

The 3D maps show that multi-phase granite-cored domes lie at varying depths beneath all the giant gold deposits. These vertically-zoned systems may have provided fluids from depth into the cores of the domes through the same pathways that earlier, small volume magmas had passed (Blewett and others 2010).

Conclusions

The project goal, to develop a mineral systems understanding for gold in the eastern Yilgarn Craton and to use the knowledge for predictive mineral discovery, was successfully met. Targets and recommendations from this work have resulted in new discoveries and extensions to known mineralisation, which extend mine life. There are generic learnings from this work that are applicable to other mineral systems in Australia.



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