Gold mineral systems and exploration strategies for the Gawler Craton, South Australia

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SOUTH AUSTRALIA

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Acknowledgement of Country
The Department for Energy and Mining acknowledges Aboriginal people as the First Nations Peoples of South Australia. We recognise and respect the cultural connections as the traditional owners and occupants of the land and waters of South Australia, and that they continue to make a unique and irreplaceable contribution to the state.

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Gold in drill core, Challenger Gold Mine. (Courtesy of Kingsgate Consolidated; photo 414191).

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Gold mineral systems and exploration strategies for the Gawler Craton, South Australia

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ABSTRACT

Previous classification of gold deposits in the Gawler Craton grouped occurrences into either Archean orogenic deposits or Intrusion-related deposits associated with the Hiltaba Intrusive event (Central Gawler Gold Province). In this study, the gold deposits and occurrences of the Gawler Craton are classified using a mineral system methodology.

Four mineral systems are defined ranging in time from the Archean to the Mesoproterozoic. The regional extent of these mineral systems is shown to potentially extend significantly beyond the currently known distribution of mineralisation. In addition, at least two major magmatic events (St Peter Suite and Tunkillia Suite) are recognised as having potential to be associated with significant gold mineralisation.

Previous studies have shown the crust and lithospheric mantle below the Gawler Craton have either been progressively enriched and fertilised or maintained enrichment over extended periods of time. The implication is that any magmatic event with a component derived from this enriched lithospheric source has potential to result in significant mineralisation. Preliminary geochronological evidence from Barnes suggests gold mineralisation may be associated with the Tunkillia Suite and therefore supports a Tunkillia Suite-aged mineralisation event. This provides enticing evidence that prospective regions extend across large parts of the Gawler Craton and are yet to be explored.

Comparison of known deposits in the Gawler Craton are based mainly on alteration styles, vein morphology, elemental associations, host rocks, relationship to deformation and sulfur isotope data, and enabled the classification into orogenic or intrusion-related (oxidised or reduced) styles of mineralisation and the identification of seventeen different mineral fields.

Classification is difficult for many gold occurrences due to lack of consistent data, but has been attempted as best possible so that the extent of the various mineral systems can be defined.

An important factor not considered in most previous studies was the overprinting or incorporation of earlier mineralisation within subsequent mineralising events. Major, crustal-scale, fluid conduits have been reactivated repeatedly during deformation of the area and the passage of multiple mineralising events has the potential to explain much of the conflicting data seen in the Gawler Craton gold mineralisation.

Further work is required to refine the Mineral Field definitions by collecting a more consistent and wider data set. This could be done with spectral scanning of a wider selection of deposits to objectively define alteration styles and collection of more consistent geochemistry using pXRF methods. The methodology of this study should be used to define the gold mineral systems across the rest of South Australia initially, as well as the other economic minerals and commodities.

Suggestions for the most effect exploration strategies and techniques when looking for mineralisation within the various mineral systems are made.

INTRODUCTION

Historically there has only been a handful of evaluations of the state's gold mines and occurrences which either focussed on specific deposits or goldfields (e.g. Drew 1984; Budd and Skirrow 2007; Flintoft and Horn 1989; Hein et al. 1994; Morris 2011; Tomkins et al. 2004; Tomkins and Mavrogenes 2002) or were directed towards documenting goldfields for prospecting (Drew 2004). These reports usually focused on the historic workings, production figures, and geology of specific mines, but did not look at the gold occurrences with a mineral systems approach. With the development of understanding of mineral systems over the past 10–20 years, the need to classify the diverse mineralisation styles has increased with many areas of overlapping mineral systems causing confusion and limiting exploration. Sub-optimal methods of exploration and the use of pathfinder elements not appropriate to the style of mineralisation dominant in the target area, has led to poor exploration outcomes and the perception that areas have been thoroughly explored when in reality very little effective work has been done.

A significant motivation for this study was the persistent use of the 'Central Gawler Gold Province' (CGGP) as a term for any gold mineralisation occurring in an arc around the southern and western edge of the Gawler Range Volcanic Province outcrop (Fig. 1). Research on the deposits of the region since the CGGP was first recognised in the early 2000s (Budd 2002; Ferris and Schwarz 2003) has shown there to be a very complicated collection of deposit characteristics across a much wider region than that originally proposed. This variation is mainly due to the grouping of various genetically distinct mineral systems into the original single 'province'. In addition, the lack of discovery of 'gold only' systems outside of the CGGP is likely to be more a function of the depth of cover within the Western Gawler/Olympic domains and the difficulty of targeting this type of system through that cover. Areas of the Olympic Domain where the cover is thinner have either not been sampled for gold during regional exploration or have been sampled with calcrete which has proven to be a less than suitable method in many situations.

The main aim of this study is to subdivide the gold deposits and occurrences across the Gawler Craton into their genetically related mineral systems. This allows for mapping of the footprints of the various mineral systems more accurately and gives a clear indication of the potential prospectivity of large areas which may have previously been overlooked in exploration for gold deposits.

Previously, gold occurrences in the CGGP were generally considered to be part of the ~1590 Ma Hiltaba intrusive event (Ferris and Schwarz 2003; Fraser et al. 2007). The mineral system had been divided into two broad classifications: Olympic Domain IOCG Cu/Au and Central Gawler Au Domain (Fig. 2). Several attempts have been made to explain the reason for the different styles including the overall tectonic setting (Ferris and Schwarz 2003) and magma composition variation between the two main suites of Hiltaba intrusives (Budd 2002).

Classification of gold deposit types across the Gawler Craton has been attempted on several of the larger deposits across the Gawler Craton (Hein et al. 1994; Budd 2006). Varying levels of success has been achieved. The number of deformation events and the level of deformation has been a contributing factor.

What hasn't been considered previously is the possibility of earlier mineralisation being overprinted by subsequent mineralising events. Numerous studies have recognised the multiple reactivation of major, crustal-scale structures (e.g. Direen et al. 2005; Fraser and Lyons 2006; Swain et al. 2005b). It is possible that these structures represented fluid conduits repeatedly utilised during deformation of the area. The passage of multiple mineralising events has the potential to explain much of the conflicting data seen in the Gawler Craton gold mineralisation.

Classification has still proven difficult with many gold occurrences and smaller deposits with very little data available, other than gold assays and field geologist logs, to make a determination as to which system an occurrence belongs. However, outlying small gold occurrences are recognised as important in defining the overall extent of a mineral system's footprint.

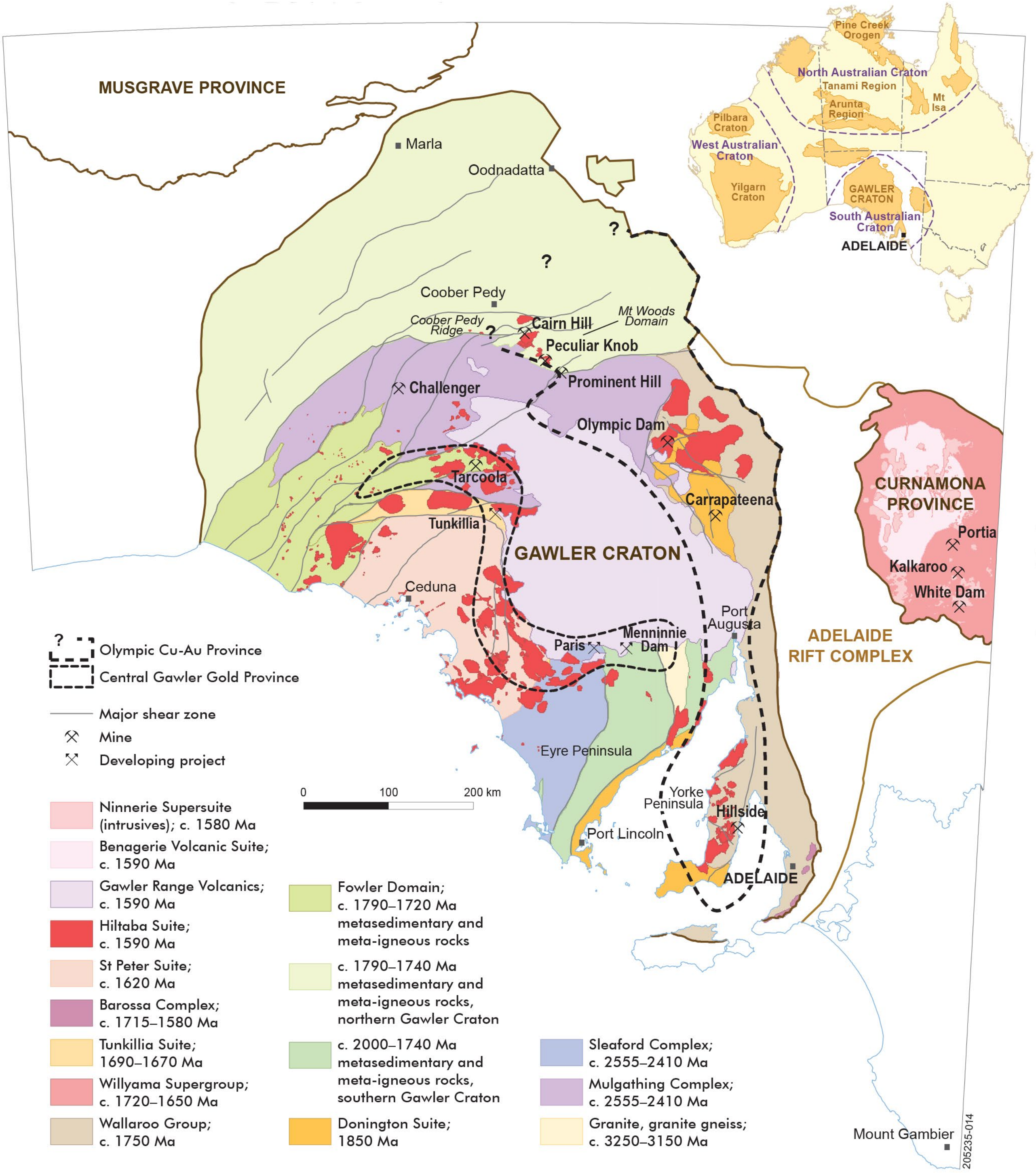
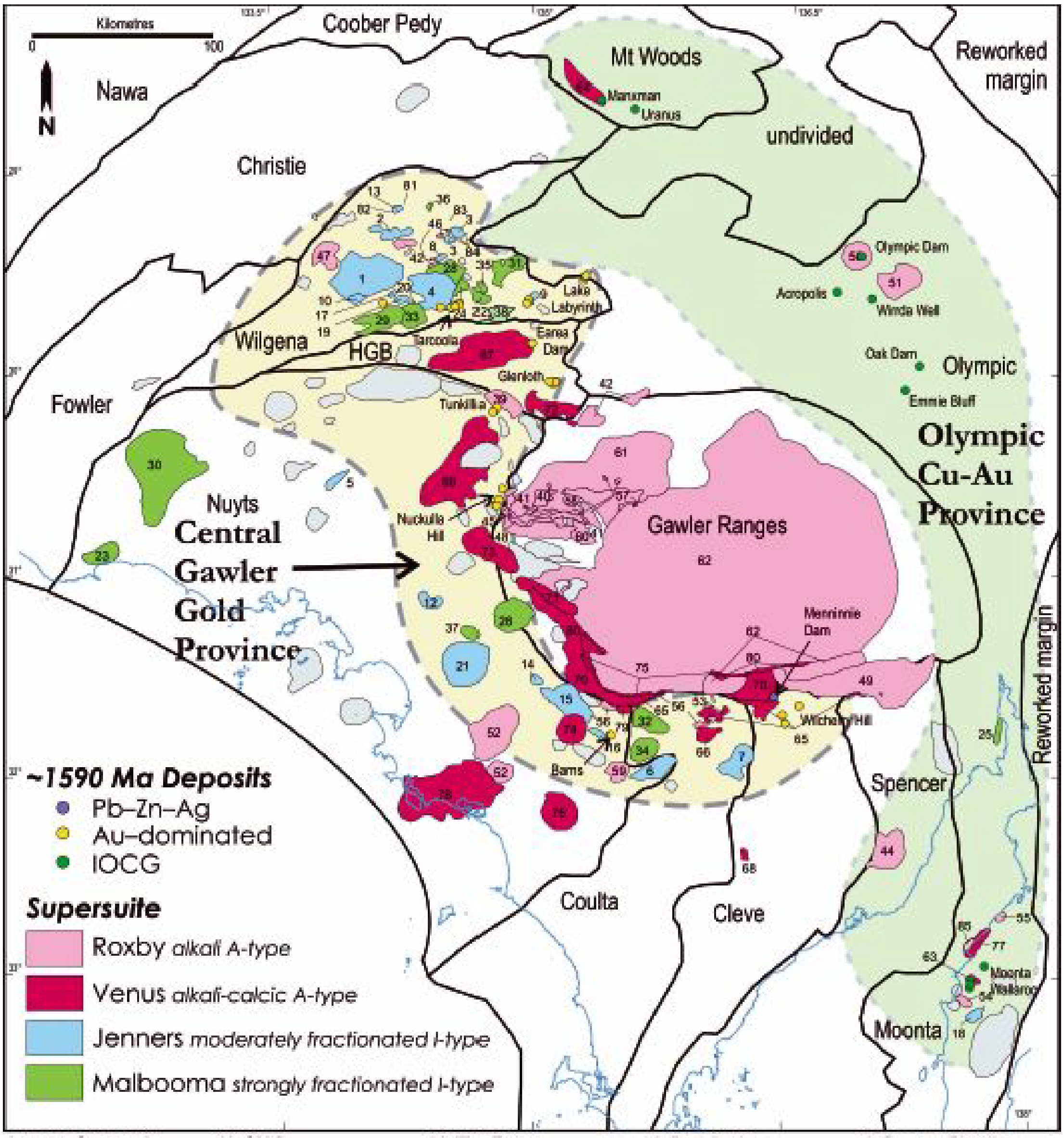


Figure 1. Location of the study area showing the originally defined Central Gawler Gold Province.



Jenners Supersuite
1 Ambrosia
2 Barry-Lepa
3 Birthday
4 Cooladding
5 Coppadurba
6 Corrobinnie
7 Cunyarie
8 Gibraltar
9 Labyrinth
10 Lyons
11 Nicholls
12 Nunnyah
13 Pegler
14 Pheasant
15 Podinna
16 Poondana
17 Rainbow
18 Ruins
19 SMIR
20 Soyuz
21 Wirrula

Malbooma Supersuite
22 Big Tank granite
23 Boree
24 Brown Hill
25 Cultana
26 Ilkina
27 Inila
28 Konkaby West
29 Kychering
30 Mitcherie
31 Partridge
32 Pennas
33 Pinding
34 Pinkawillinnie
35 Swamp
36 The Twins
37 Wallala
38 Welcome Well

Roxby Supersuite
39 Arcoordaby
40 Baldry Rhyolite
41 Bunburn Dacite
42 Carnding
43 Chandabooka Dacite
44 Charleston
45 Childera Dacite
46 Ealbara Rhyolite
47 Inglis
48 Mangaroongah Dacite
49 Nonning Rhyodacite
50 Olympic Dam Granite
51 Opal Fields
52 Parla
53 Peterlumbo
54 Rothmore
55 Vock
56 Waganny Dacite
57 Wheepool Rhyolite
58 Whyeela Dacite
59 Wudinna
60 Yandoolka Rhyolite
61 Yantea Dacite
62 Yardea Dacite

Venus Supersuite
63 Arthurton
64 Balta
65 Bittali Rhyolite
66 Buckleboo
67 Bulpara
68 Carappee
69 Childara
70 Eucarro Rhyolite
71 Hiltaba
72 Kokatha
73 Kondoolka
74 Minnipa
75 Paney Rhyolite
76 Pordia
77 Tickera
78 Tyringa
79 Waulkinna
80 Yannabie Rhyodacite

Unassigned
81 Bradman A
82 Bradman B
83 Came
84 Eileen Bore
85 Point Riley Tonalite

Figure 2. Hiltaba Intrusive Classification and Mineral Systems (Budd 2006).

METHODOLOGY

A selection of key gold deposits and occurrences for each area were evaluated in the first stage of the classification process. Deposits and occurrences were grouped by similar characteristics. Characteristics were selected to distinguish between mineralisation styles. The main characteristics focussed on were alteration, vein style, host lithologies, element associations and sulfur isotopic data, as these were the most commonly recorded information for prospects. These were supplemented with fluid chemistry and temperature data where available. These were all compiled into a spread sheet which is attached as Appendix 1. Generally, one or two main deposits in each area has seen the widest variety of exploration methods and research and these 'type deposits' were heavily used as the basis of classification.

Ideally all gold deposits and occurrences should be classified, and this could be part of an ongoing study. Several, previously overlooked gold occurrences were found during this study and have been added to the SA Geodata Mineral Deposit (MINDEP) database.

The selected deposits were compared to known styles of gold mineralisation. Robert et al. (2007) defined a system which broadly covers all styles of gold mineral systems. Numerous sub-classifications can be made under this system. Where possible, the broad classifications of Robert et al. (2007) were used, however some deposits/occurrences were better described using a more specific sub-classification (i.e. Groves et al. 2003).

The deposits can be subdivided into four broad mineral systems: Archean-Paleoproterozoic Sleaford, Paleoproterozoic Kimban, Mesoproterozoic Kararan Intrusive and Mesoproterozoic Kararan Volcanic Systems. These were further subdivided into nineteen mineral fields (MFs) which was based on clusters of mineral occurrences showing local similarities in host lithologies, deposit style and chemistry.

The Hiltaba system across the western and central Gawler Craton was very limited by the data available. Recent geochronology has determined that the Nankivel Intrusive complex is of St Peter Suite age (Blaschek 2017). The Barns and Baggy Green deposits have several characteristics which may suggest they belong to a separate mineral system. As further data becomes available, it is highly likely that the Hiltaba mineral system may be split further.

The interpreted spatial extent of each mineral system is shown below, along with known gold occurrences/deposits and their interpreted genetic classification. Only the reviewed and classified deposits are shown by their interpreted genetic style. Deposits not reviewed are shown as white circles. The bounding regions of the mineral systems were not limited to known occurrences but were extrapolated to encompass areas of similar host lithology/igneous influence within which further mineralisation of that type may reasonably be expected to occur. The maps include the key structures associated with the various mineral systems.

GOLD MINERAL SYSTEMS

The four gold mineral systems of the Gawler Craton are described in detail below from oldest to youngest.

SLEAFORDIAN GOLD MINERAL SYSTEM (C. 2555–2410 MA)

The Sleafordian gold mineral system is interpreted to have developed within Archean to early Paleoproterozoic (i.e. c. 2555–2440 Ma) lithologies that were deformed during the c. 2465–2410 Ma Sleafordian Orogeny (Reid et al. 2014; Halpin and Reid 2016). These rocks form an arcuate region that wraps around the northern and south-eastern side of the Gawler Craton (Figs 3 and 4). Belts of mineralised sedimentary/greenstone/banded iron formation (BIF) rocks within this arcuate region can be sub-divided into five mineral fields: Christie, Hilga, Harris Ultramafic, Kyancutta and Hall Bay (Figs 3 and 4). These mineral fields broadly follow distinct stratigraphic belts of mafic/ultramafic volcanic/intrusive rocks and associated BIF/carbonate/clastic sedimentary rocks. These belts may have been part of an originally contiguous zone which has been subsequently folded and dissected. Geophysical, geochronological and stratigraphic similarities between the northern and south-eastern extents of these belts suggests that similar rock packages could extend under the Gawler Range Volcanics, however to date, there is a lack of drilling to test this hypothesis. This mineral system is typified by deposits such as the Challenger mine, Golf Bore deposit and Aurora Tank deposits in the metasedimentary rocks of the Christie Gneiss and the Double Dutch prospect in the Lake Harris Greenstone Belt.

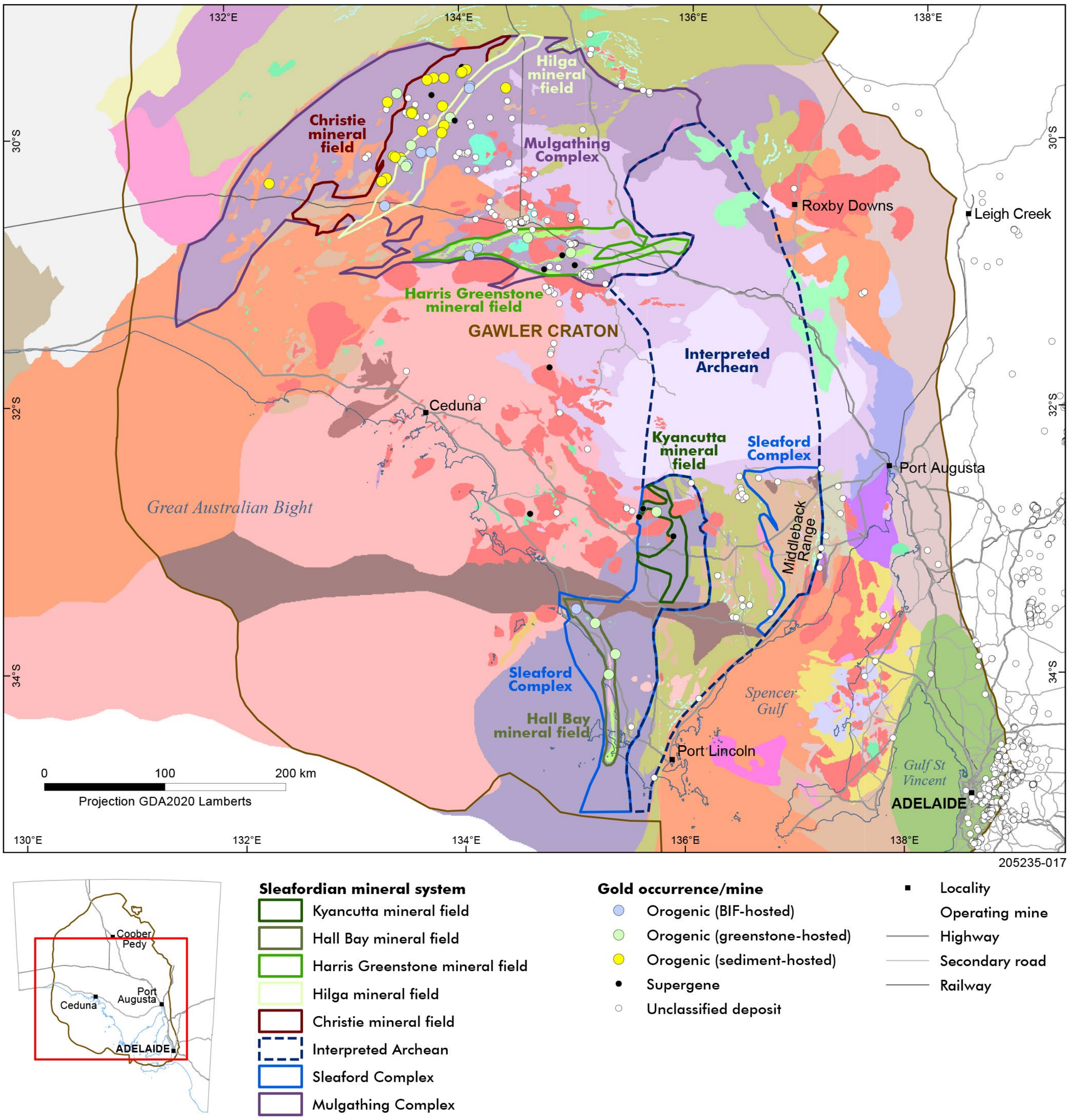


Figure 3. Sleafordian gold mineral systems and fields of the Gawler Craton.

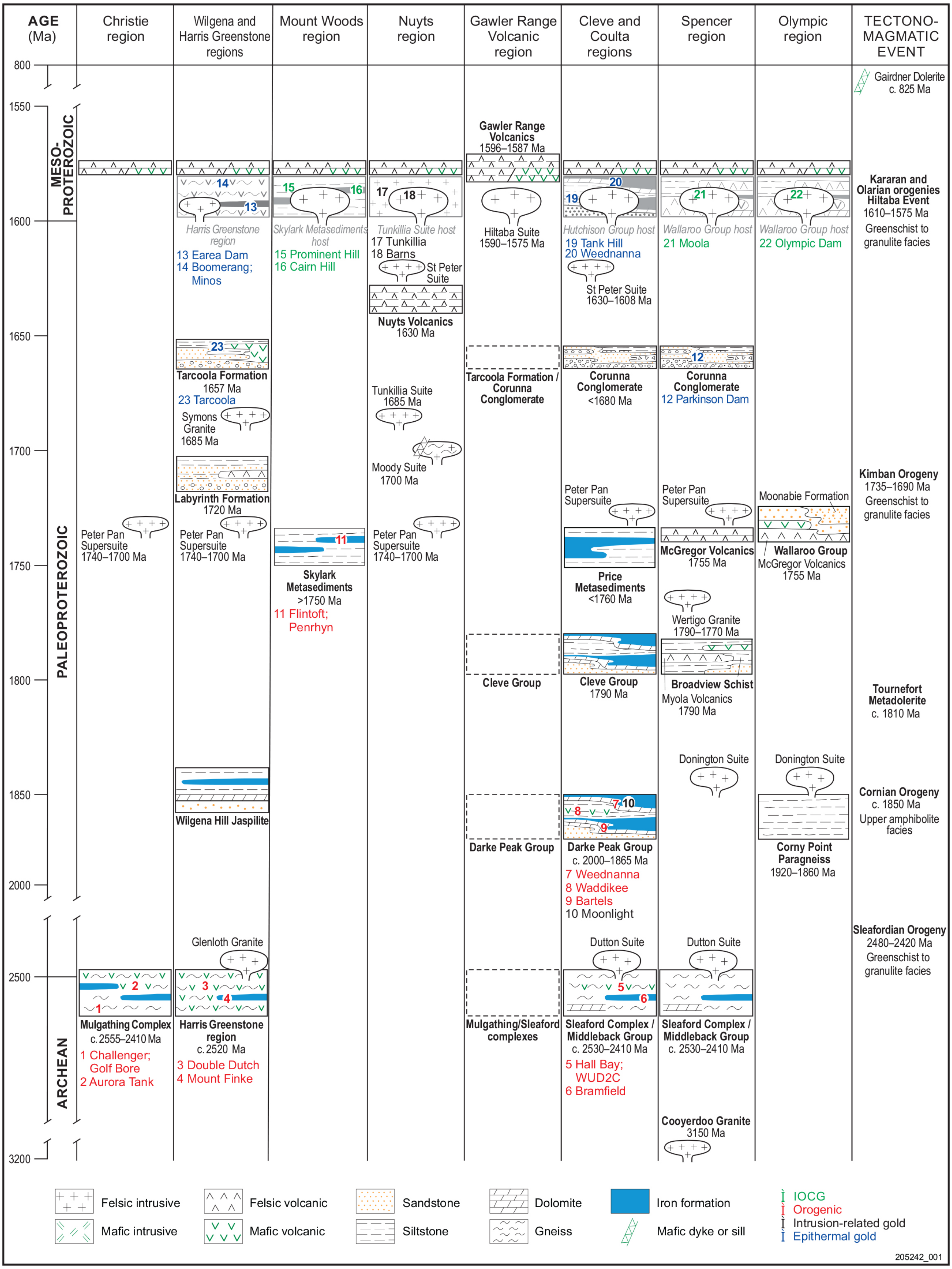


Figure 4. Time-space plot of the Gawler Craton mineral systems.

The majority of mineralisation in the Sleafordian gold mineral system is likely to be related to the c. 2465–2410 Ma Sleafordian Orogeny. The only dated deposit is the Challenger Mine, where pre-metamorphic alteration and mineralisation has been reported (McFarlane et al. 2007), however the extensive vertical extent and ore shoot association with shear zones supports either an orogenic model (Birt and Reid 2007) or significant mobilisation during metamorphism (Tomkins and Mavrogenes 2002). The relatively recent discovery of the Notrab gold occurrence (2005) and lack of systematic exploration in the region, highlights the potential for further discovery to the west and south of the Challenger mineral field.

It is noted that further Archean rocks have been intersected in the Nawa Domain in the northern Gawler Craton (Jagodzinski and Reid 2010). These areas have not been included as they are only known from several occurrences at the bottom of drillholes, at significant depths (generally greater than 200 m). It is possible that further orogenic gold MFs are present at depth under cover in this region, but these areas have not been included as part of the Archean Mineral System.

The region around the Middleback Ranges in the southern Gawler Craton (Fig. 3) has been highlighted although no confirmed Archean gold mineralisation has been located here. This region is particularly complex with structural interlayering of Archean (Sleaford Complex) and Paleoproterozoic (Hutchison Group) lithologies (e.g. Szpunar et al. 2011). This region has then been very strongly overprinted by the intrusion of the Mesoproterozoic Hiltaba Suite granites, which may have masked the presence of pre-existing Archean orogenic mineralisation. As this region includes the same lithologies that are present in the other Sleafordian MFs (Fig. 4), there is no reason why this area should not also be prospective for gold mineralisation. Previous exploration in this region has focused on iron resources and only minimal exploration has been conducted for gold systems.

Mineral system model

This mineral system is interpreted to be a typical Archean orogenic system (Fig. 5) although it is noted that there is considerable uncertainty regarding the orogen of particular occurrences in the Gawler Craton. All typical sub-types of orogenic gold mineral systems (sediment/greenstone/BIF-hosted) are represented in most of the mineral fields, with mineralisation variably associated with meta-sediments, iron-rich sediments and meta-volcanic lithologies. The Christie MF is currently unique in that mineralisation appears to be almost exclusively associated with clastic metasedimentary rocks. This poses an extra challenge to explorers, as there is almost no apparent geophysical signature to assist with targeting. The region hosting the gold mineralisation is generally characterised by uniform, low intensity magnetic response. Various electric methods have been trialed with mixed success.

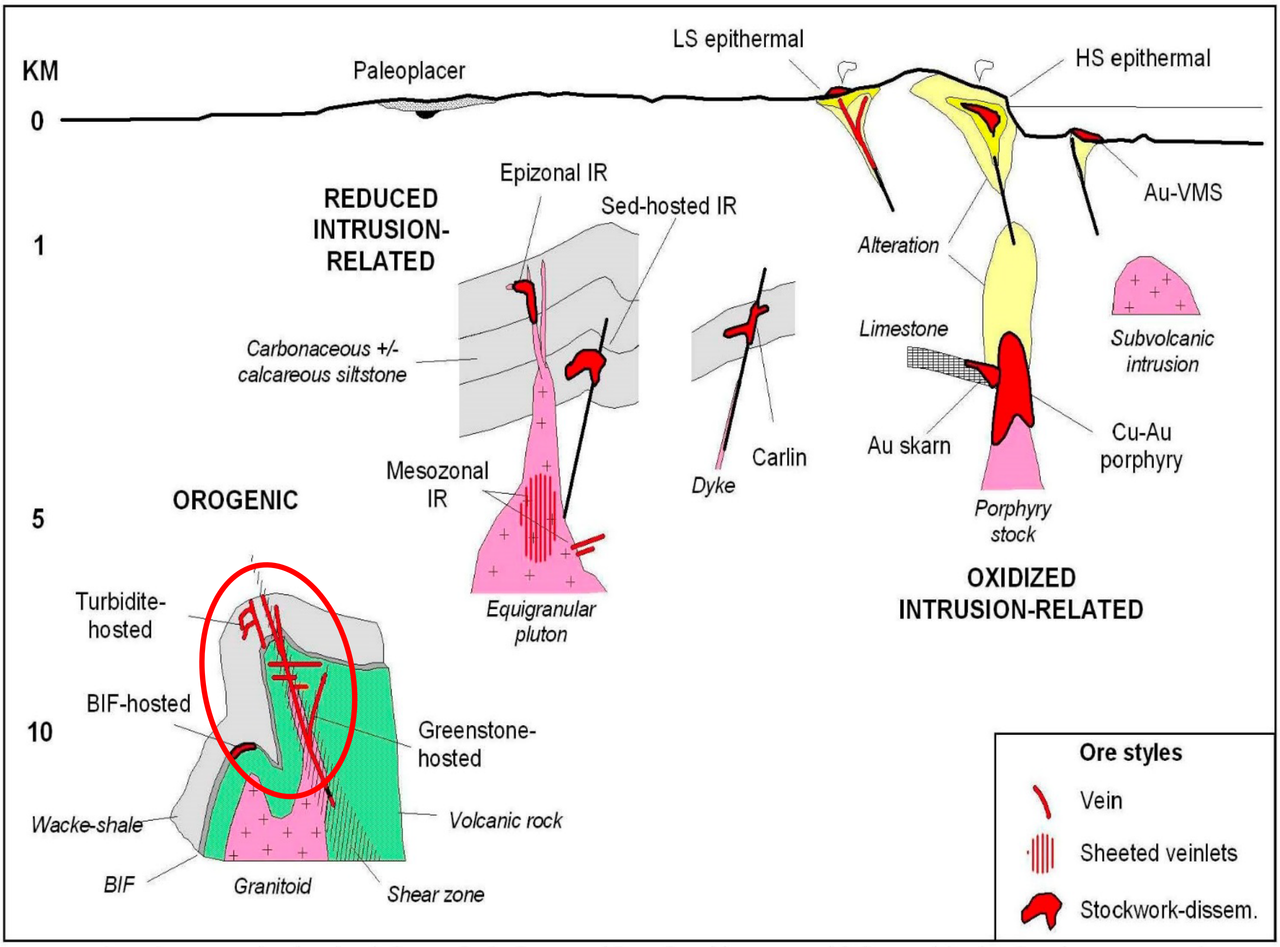


Figure 5. Gold mineral system classification scheme showing Sleafordian Mineral System (Robert et al. 2007).

ENERGY SOURCE

Although pre-existing mineralisation has been reported (Tomkins and Mavrogenes 2002), the energy source for the main economic mineralising event is interpreted to be the Sleafordian orogenic event (i.e. the 2465–2410 Ma Sleafordian Orogeny). The orogeny is broadly associated with syn-orogenic felsic magmas that intruded the volcano-sedimentary sequences. Several syn-orogenic granitoids have been defined in the Gawler Craton, including the 2507 Ma Glenloth Granite and 2488 Ma Mobella Tonalite (Reid et al. 2014). Ultimately, the energy drivers of mineralisation in these systems have not seen much research.

FLUID/METAL SOURCE

The mineralising fluid source for orogenic deposits is either metamorphosed basinal fluids, water released by metamorphic dehydration reactions, or a mixture of both (Goldfarb and Groves 2015). Regardless of the specific origin, the process generally involves a low salinity fluid which is mobilised through the surrounding volcano-sedimentary sequence during orogenesis and this can accumulate metals and sulfur from the regions it passes through. In higher temperature systems, magmatic fluids may play a significant role and in very shallow systems, meteoric waters may also contribute metals to the final mineralising fluids (Goldfarb and Groves 2015).

There has been no research on the ore fluids of the Archean systems in the Gawler Craton. This is primarily because the high-grade (granulite facies) deformation that has overprinted known mineralisation, would have destroyed any evidence of the original fluids. Therefore, there is no fluid inclusion data on these deposits. Sulfur isotope measurements should not have been affected or affected to a lesser extent and could provide valuable information on the origin of sulfur and metals in this mineral field.

MIGRATION PATH

The elemental associations in the deposits of this mineral system (primarily Au, As, Ag; Table 1, Appendix 1) suggest that the majority of the deposits were emplaced at or below the brittle-ductile transition (Fig. 6). In deposits such as the Challenger Mine, remobilisation under granulite facies metamorphism has resulted in local migration of the primary ore into leucosomes. The interpreted primary composition of the fluids, combined with the extensive vertical continuity of deposits such as Challenger Mine, is interpreted to be due to the ore zone being a fluid conduit for escape of large volumes of pressurised fluid across significant crustal volumes (Hronsky 2013). These observations indicate known gold occurrences in this mineral system are likely to have significant depth extensions and confirm an orogenic style of mineralisation.

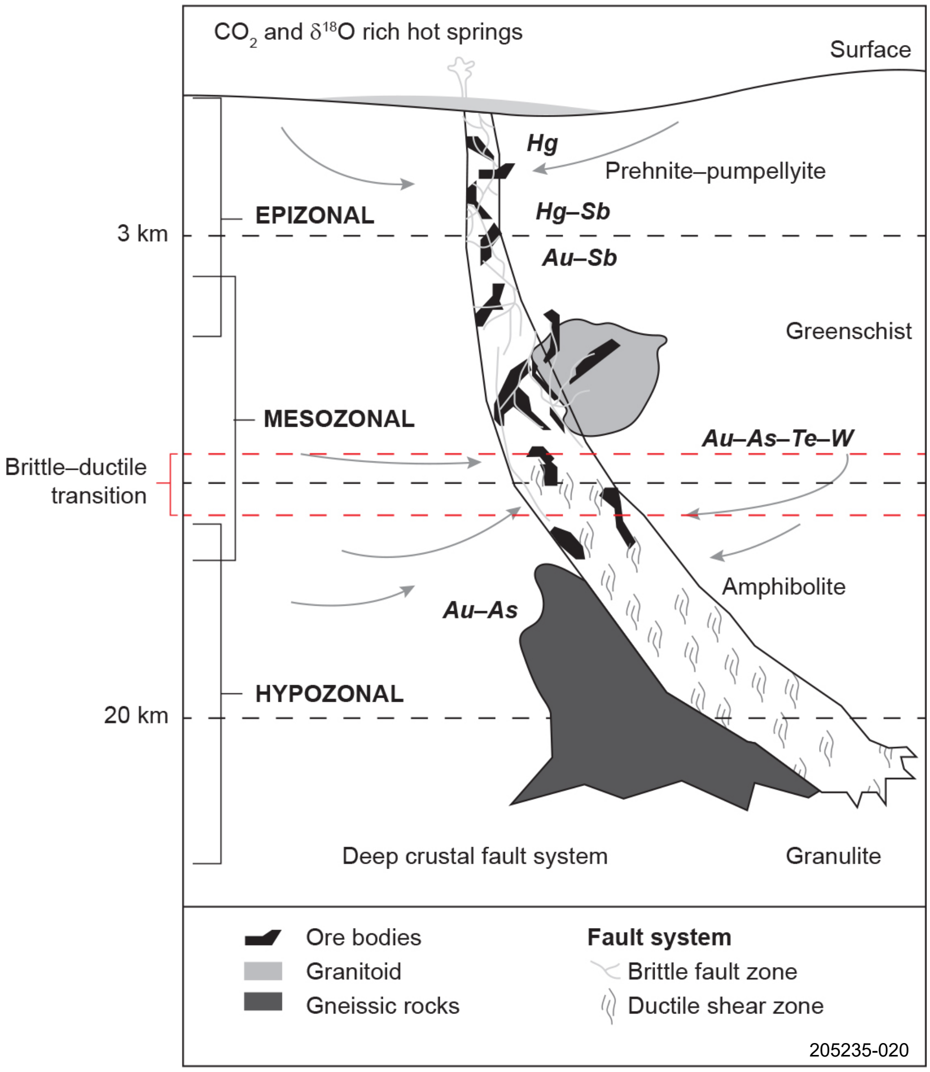


Figure 6. Orogenic gold mineral system showing elemental/metamorphic variation with depth (after Goldfarb and Groves 2015).

Orogenic fluids would have migrated along major, regional, crustal scale (1st order) structures. Due to the long, post-mineralisation, deformation history of these Archean sequences, it is very difficult to determine which structures may have been present and active at the time of mineralisation. Again, little research or interpretation has been completed on this area. Younger dolerite intrusives (undated) and lamprophyres (~1950 Ma, Rowett 2010) present in the vicinity of the gold mineralisation have likely exploited the same zone of weakness as the mineralisation and could possibly be used as a vector in exploration.

McFarlane et al. (2007) interpreted the pre-metamorphic alteration at the Challenger deposit to be sericite/chlorite/silica using lithogeochemistry. These principles could be used to define and locate alteration mineralogy associated with the passage of the mineralised fluids along structures. Furthermore, it is possible that the high-grade metamorphism in the area has enhanced rather than destroyed the alteration mineralogy and that these could be detected using hyperspectral spectral techniques.

DEPOSITION

Various triggers have been documented for the deposition of gold in these systems. Most commonly pressure/temperature variations or lithological composition variation are responsible for gold precipitation. Groves et al. (2016) summarised potential deposition zones (Fig. 7) and Hronsky (2013) outlined a three-level model of the factors controlling the deposition of mineralisation into high-grade ore shoots (Fig. 8).

Due to the subsequent high-grade deformation and mobilisation of the Challenger deposit, it is difficult to determine where and what might have triggered deposition of mineralisation at this position. Deposition of mineralisation in other types of orogenic deposits (greenstone-hosted/BIF-hosted) within this mineral system should be more obvious as they are likely to have a significant geochemical trigger rather than just a structural trap. Greenstones and BIFs are generally much less frequent in these belts and should be the focus of exploration. Mineralisation associated with BIF units is generally not found within the most magnetic silica facies but within iron-rich sediments and can be associated with fracture systems cutting across these lithologies.

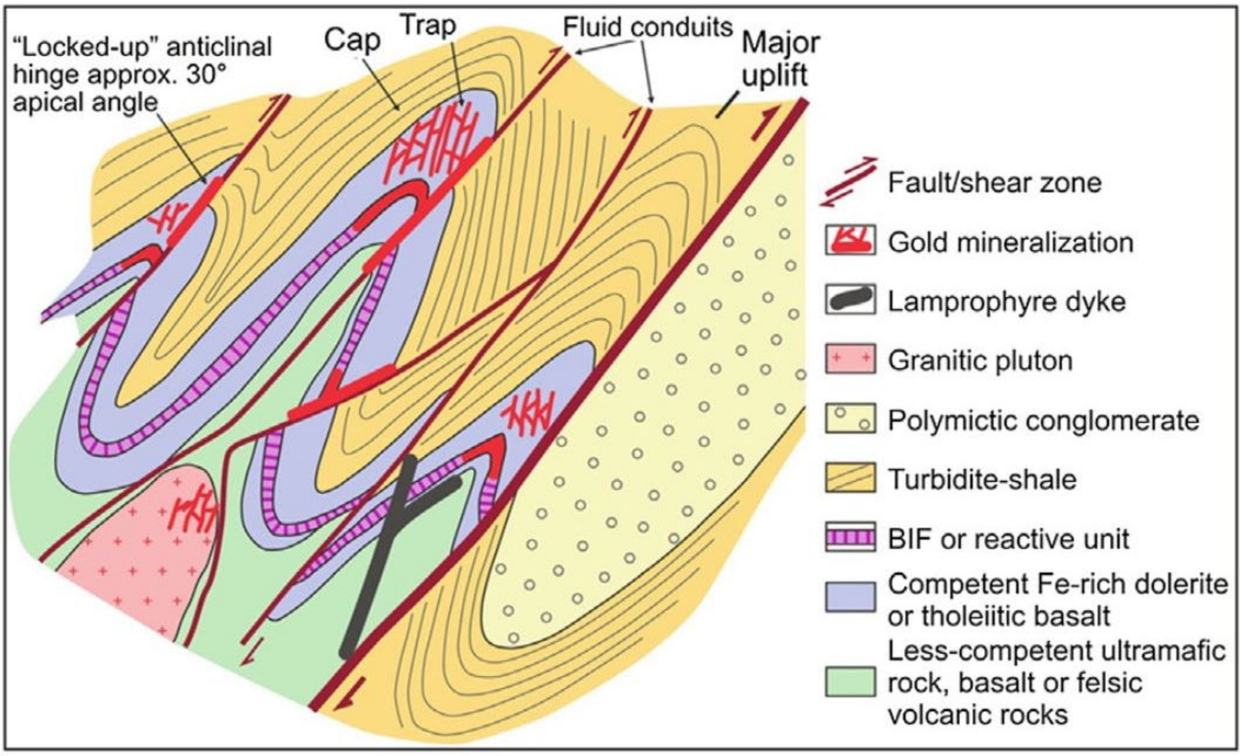


Figure 7. Orogenic gold mineral system traps (Groves et al. 2016).

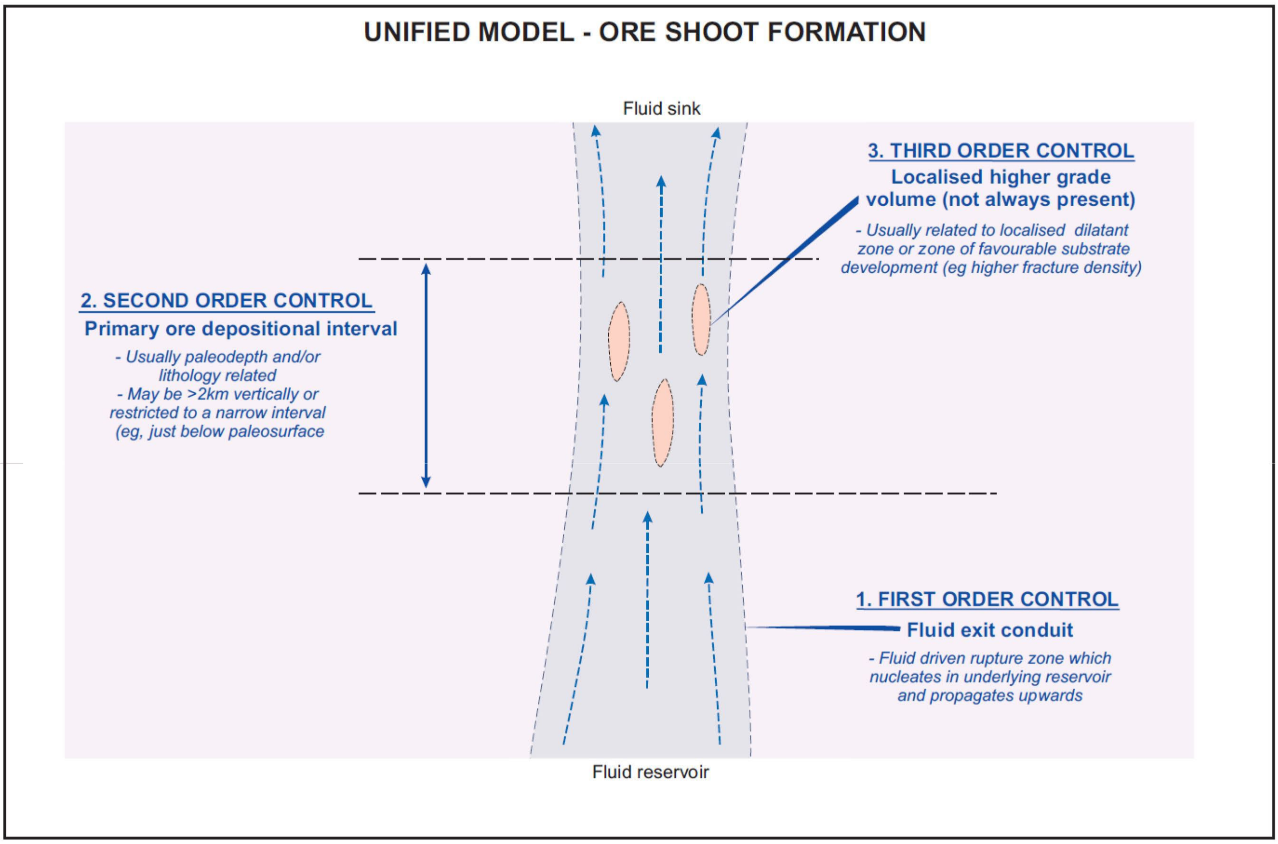


Figure 8. High-grade ore shoot model (Hronsky 2013).

OUTFLOW ZONE/FOOTPRINT

Generally, orogenic gold deposits do not leave wide alteration zones to mark the passage of the fluids forming the deposits. Recent work on several deposits in Western Australia has shown that alteration due to fluid flow can be mapped spectrally (Wang et al. 2017). In particular, systematic variations in white mica chemistry (muscovite, paragonite, phengite) can be mapped at various deposits across the Yilgarn Craton. This study outlined patterns of alteration associated with high-grade zones in systems with reduced/acid and oxidised/alkaline ore fluids which can be used as vectors towards these zones (Wang et al. 2017).

SUBSEQUENT MODIFICATION

Many questions remain about the origin of Archean mineralisation of the Christie MF due to granulite facies deformation. Mineralisation within the Harris UM, Hall Bay and Kyancutta MFs have also potentially been overprinted by subsequent deformation and mineralising events. The Harris UM MF in particular sits in a region heavily influenced by the subsequent Hiltaba Intrusive event. As a results, it has only recently been recognised that this region may host Sleafordian gold mineralisation. However, there are areas of the Sleaford and Mulgathing complexes that have been subjected to much lower deformation (Hoatson et al. 2005) and study of mineralisation in these areas (i.e. Double Dutch) may shed further light on the genesis of the Sleafordian mineral systems.

Mineral system distinguishing criteria

The key features of the deposits and occurrences examined as part of this review are presented for the various Mineral fields in Table 1.

Table 1. Sleafordian gold mineral system criteria

Criteria	Christie MF	Hilga MF	Harris UM MF	Hall Bay MF	Kyancutta MF
Type deposits	Challenger, Golf Bore	Hilga South, Birthday	Double Dutch, Boomerang	Bramfield, Mt Hope	WUD2C
Host	Christie Gneiss (sediment/felsic intrusive)	Christie Gneiss (sediment, mafic, ultramafic, BIF)	Lake Harris Komatiite, Hopeful Hill Basalt	Hall Bay Volcanics (BIF, gneiss)	Sleaford Complex (mafic and felsic, granulite)
Vein style	Quartz-pyrite	Quartz-feldspar-pyrite	Quartz-calcite-pyrite	Quartz-pyrite	–
Alteration	Biotite?	Biotite, chlorite	Carbonate, biotite, talc, chlorite	Biotite	Sericite, chlorite
Sulfides	Pyrite, pyrrhotite, arsenopyrite	Pyrite, arsenopyrite	Pyrite, galena, (chalcopyrite)	Pyrite, arsenopyrite, pyrrhotite	Pyrite
Elements (dominant elements in bold)	**Au, As, Bi**, (Ag, Co, Ni, Cu, Te)	**Au, As, Ag**	**Au, As, Ag**, Sb, Mo, Pb, Zn, Cu	**Au, Ag, As**, Cd, Pb, Zn	?
S Isotopes $\delta^{34}S$ ($^{0}/00$)	–	–	–	–	–
Style	Orogenic (sediment)	Orogenic (greenstone/BIF)	Orogenic (greenstone/BIF), oxidised intrusion related (low sulfidation epithermal alkalic	Orogenic (greenstone/BIF)	Orogenic (greenstone/BIF)
Mineralisation age	c. 2560–2500 Ma	c. 2560–2500 Ma	c. 2520 Ma	c. 2520 Ma	c. 2560–2500 Ma
Temperature	?	?	?	?	?
Depth of formation	Hypozonal (10–20 km)	Hypozonal (10–20 km)	Mesozonal (5–10 km)	Hypozonal (10–20 km)	?
Post-deposition modification	Regional granulite facies metamorphism to partial melting	Greenschist facies metamorphism	Greenschist facies metamorphism, deformation along regional shear zones	Regional granulite facies metamorphism	Regional granulite facies metamorphism

Lithologies are quite variable across the various mineral fields. The majority of the deposits in the Christie MF are associated with the metasedimentary rocks of the Christie Gneiss (biotite ± garnet gneiss), but some mafic gneisses are also present. Later mafic intrusives (dolerites) and lamprophyres are also present at these deposits, but these appear to be unrelated to mineralisation and probably exploited the same structural conduits as the earlier gold mineralisation.

The Hilga and Harris UM MFs are more strongly associated with the mafic (Hopeful Hill Basalt), ultramafic (Lake Harris Komatiite, Blackfellow Hill Pyroxenite) and banded iron formations within of the Mulgathing Complex.

The Hall Bay and Kyancutta MFs are hosted within the Sleaford Complex equivalents of the Mulgathing Complex. The Hall Bay MF is very similar to the Hilga and Harris UM lithologies while the Kyancutta MF resembles the Christie MF.

Questions for further research

ENERGY SOURCES

The Archean felsic intrusives that may have been involved in driving the orogenic system have seen very little investigation at all to date. The felsic intrusives associated with orogenic gold mineralisation in the Yilgarn Craton represent significant exploration targets in themselves. Some of the Archean felsic intrusives identified so far, for example the 3150 Ma Cooyerdoo Granite, and 2820 Ma Coolanie Gneiss (Fraser et al. 2010b; Fraser and Neumann 2010), are too old to have been associated with the orogenic mineralising event. Others, such as the 2507 Ma Glenloth Granite and ~2490 Ma Mobella Tonalite (Reid et al. 2014), are probably older than the orogenic event but appear to host subsequent mineralisation. The margins and brittle cores of these plutons and similar aged intrusives present significant targets.

MULGATHING/SLEAFORD STRATIGRAPHY

Some ambiguity remains about the overall stratigraphy of the Sleaford Complex (Swain et al. 2005; Reid et al. 2014) and how the various stratigraphic elements relate to each other. The main problem is that absolute age determination of most lithologies must be undertaken by geochronology. Expansion and compilation of this dataset may determine a preferential host sequence within the stratigraphy, but until this is undertaken all stratigraphic units must be seen as potential hosts.

SULFUR ISOTOPES

As can be seen from Table 1, no sulfur isotope data or any other stable isotope data could be found for the Archean deposits of South Australia. There is some suggestion of Mass Independent Fractionation (MIF) in the Paleo/Mesoproterozoic Weednanna deposit of the Southern GRV (Morrissey et al. 2018). This indicates an Archean component in the deposit, as MIF only occurred in the Archean due to the low levels of oxygen in the atmosphere. A key question is therefore to quantify the contribution of sulfur and gold to later deposits by pre-existing Archean mineralisation. An inference and subsequent question would be to test whether areas where Archean is present at shallow depths under younger lithologies are more prospective than where Archean lithologies are absent. Could the host lithologies at Weednanna include Archean lithologies and form an important contribution to the gold content of that deposit?

Further research in this area would allow a more rigorous classification of the origin and genetic relationships of many of the deposits and occurrences of the Gawler Craton.

KYANCUTTA MINERAL FIELD

The Kyancutta mineral field has been defined based on the mapped Archean geology. The WUD2C occurrence (Price 2005) is currently the only mineralised occurrence in the area, but as can be seen from Table 1, the area has not seen extensive exploration or study to date. Further work in this area could open up large sections of the southern Eyre Peninsula to gold exploration.

ALTERATION

McFarlane et al. (2007) investigated the alteration associated with mineralisation at Challenger Mine and concluded it was of phyllitic nature, leading them to propose that the mineralisation was originally an epithermal or porphyry style deposit. This is at odds however, with the elemental composition of the mineralisation (low Cu, containing significant As, Bi and Ag) and the apparent depth extent of the deposit which is more in keeping with an orogenic style (Goldfarb and Groves 2015). Further work on the nature of the alteration associated with several of the mineralised occurrences in the mineral fields may help to resolve this conflict. This would also assist in vectoring towards economic mineralisation in the area.

CONTROLLING STRUCTURES

As mentioned above, very little work has been done on the interpretation of structures which may have controlled the transport of mineralised fluids during the Sleafordian orogenic event. Many primary structures are obvious and have been reactivated subsequently across multiple deformational events before cratonisation (e.g. Direen et al. 2005; Fraser and Lyons 2006; Swain et al. 2005b). As mentioned above, McFarlane et al. (2007) interpreted the nature of pre-metamorphic alteration at the Challenger deposit using lithogeochemistry, and these principles could be used to locate signs of fluid migration along second and third order structures.

The newly acquired Gawler Craton Airborne Survey (GCAS) data has enabled an order of magnitude increase in the level of information obtainable in this area. An ongoing project within the Geological Survey of South Australia (GSSA) works to provide this pre-competitive data to industry (e.g. Pawley and Wilson 2019).

Exploration guidelines

LITHOLOGIES

The mineral fields defined in this study are broadly described by packages of greenstone/BIF lithologies in known Archean stratigraphy. As most of these areas are under cover, magnetic signatures are primarily used to determine underlying stratigraphy. In addition, Paleoproterozoic BIF packages sit on top of, and have been complexly folded within Archean gneissic lithologies, particularly in the Kyancutta mineral field (Lane et al. 2015) making exploration targeting difficult.

Mineralisation within the Christie and Kyancutta mineral fields are associated with lithologies which are difficult to distinguish with geophysical methods. Generally, these areas are described as ‘magnetically quiet’. There are also numerous such magnetically quiet regions associated with the Greenstone/BIF units in the Harris/Kyancutta and Hall Bay mineral fields which have seen little or no exploration, but which possibly host Challenger–style orogenic mineralisation. It may be possible to use the derivative datasets associated with GCAS (e.g. Foss et al. 2019) to understand the architecture of the magnetically quiet regions. However, it appears that mineralisation within these mineral fields may best be detected with geochemical methods which directly sample saprock.

VEIN SYSTEMS

In orogenic systems, the vein systems are commonly very continuous vertically over distances greater than a kilometre and show very little variation or zonation over this distance. Once a system has been located and its surface extent has been defined, it can be reasonably assumed that the system will extend to significant depth if it hasn’t been displaced or truncated by subsequent deformation. This is typified by the Challenger deposit which has currently been defined to depths of >1 km with little variation, despite, or possibly because, of subsequent high grade (granulite facies) metamorphism.

GEOCHEMICAL EXPLORATION

A large proportion of the areas defined by this mineral system have been covered with regional calcrete geochemical sampling, after the discovery of the Challenger deposit was falsely attributed to this sampling method (Edgecombe 1997). Extensive research by CRC LEME (http://crcleme.org.au/index.html) has shown the method to be very useful if conducted rigorously with a very good understanding of the regolith in the target area and descriptions of the sampled material. Unfortunately, many of the surveys undertaken have not proven effective in testing the geochemistry of the underlying basement. Consequently, many areas still require testing with a more effective geochemical survey method.

Biogeochemistry and UltraFine^{+} sampling are methods which have had some recent success as alternate surface sampling methods (Noble et al. 2020; Reid et al. 2008b). These also require a high level of understanding of the materials being samples along with the regolith landform in the target region. Extensive orientation sampling is strongly recommended.

PATHFINDER ELEMENTS

While many pathfinder elements have been determined to be associated with the known occurrences, many of these are only elevated by very low levels (< an order of magnitude). Au, As and Ag are the only robust pathfinder elements seen to be associated with the known mineralisation occurrences. The other elements have either been redistributed during subsequent metamorphism or are associated with the host lithologies to mineralisation. These can be very useful in the resource definition stage of exploration but have limited use in the greenfields regional exploration stage.

STRUCTURES

Detailed structural analysis is required to locate suitable conduits for mineralisation. These conduits are likely to be closely associated with major regional structures but not within them. Subsequent deformation may have also remobilised mineralisation away from its primary deposition site, but this is not likely to be very far (<100–200 m?).

ALTERATION GEOCHEMISTRY

Spectral mapping of the variation in white mica composition can be used to vector towards high grade zones within a wider alteration footprint. Mineralised zones associated with reduced/acid ore fluids tend to also be associated with carbonate, Fe-rich chlorite, pyrite and more paragonitic white mica and oxidised/alkaline ore fluids associated with phengitic white mica and a relative lack of carbonate, chlorite and common quartz and chalcopyrite.

Unfortunately, at a regional exploration stage, this requires a significant sub-crop exposure or means of transferring this chemistry through cover to the surface. Because of the relative lack of sub-crop in the Gawler Craton, this is not likely to be very useful as a regional exploration tool. It can be very useful in the resource definition stage of exploration to vector towards high-grade mineralisation. This method could also be much more useful if further sulfur isotope and fluid chemistry studies were undertaken across the region.

GEOPHYSICS

Unfortunately, aeromagnetic data is not very useful for locating this type of mineralisation directly. The most important use is in mapping structures which may have acted as conduits for the mineralising fluids (either first, second, or third order).

Electrical geophysical methods have not proven successful in defining high grade ore zones in this type of deposit.

KIMBAN MINERAL SYSTEM (C. 2000–1690 MA)

The Kimban gold mineral system is developed within the area of Paleoproterozoic basins that were deposited on the northern and south-eastern sides of the Gawler Craton (Figs 4 and 9). These basins consist of quartzite, dolomite, iron formation, schist and amphibolite which was deposited in a passive margin setting, possibly over several time periods (Hand et al. 2007; Parker et al. 1993; Szpunar et al. 2011). It is unclear whether this was one single basin margin or a series of basins as they have been folded and thrust between inliers of Archean basement, particularly on the Eyre Peninsula. There appears to be at least three separate periods of deposition, however the similarity of the sequences and the incomplete geochronological dataset makes correlations difficult in this area (Szpunar et al. 2011). The deposition of the sedimentary rocks was accompanied by bimodal magmatism (Hand et al. 2007; Parker et al. 1993). Four mineral fields have been defined within this system: Mt Woods, Waddikee, Cleve and Middleback (Fig. 9). These, to some extent, may represent separate basins within the region.

Archean and Paleoproterozoic rocks were deformed by the c. 1730–1690 Ma Kimban Orogeny (Hand et al. 2007; Parker et al. 1993), which was accompanied by felsic magmatism of the c. 1745–1700 Ma Peter Pan Supersuite (Wade and McAvaney 2017). Because of the level of deformation, it is often visually and geochemically hard to distinguish the Archean from the Paleoproterozoic rocks unless geochronological analysis is undertaken. This has also led to confusion in distinguishing between the Sleafordian and Kimban systems in the area. It is unlikely, but not impossible, that Kimban orogenic fluids have mineralised Sleaford Complex lithologies where they have provided suitable geochemical or structural depositional sites, as Archean Sleaford Complex has occasionally been thrust over the Paleoproterozoic Hutchison Group. This would have allowed the passage of Kimban orogenic fluids through packages of Sleaford Complex lithologies. The only distinction between Kimban and Sleafordian orogenic mineralisation would then be metamorphic, geochronological or isotopic in nature.

The extremely wide time extent for this mineral system reflects the lack of geochronology available to constrain the mineralisation potentially related to this system. The c. 2000–1865 Ma Darke Peak Group (Szpunar et al. 2011), and possibly the Wilgena Hill Jaspilite (undated), appear to be the oldest of the sedimentary basins. These could potentially have been mineralised during the c. 1850 Ma Cornian Orogeny, which was accompanied by intrusion of the Donington Suite (Reid et al. 2008b). However, this deformation event appears localised to the southern Yorke Peninsula near the eastern margin of the Gawler Craton. The remaining Paleoproterozoic sedimentary basin fill were deposited between c. 1790 Ma and 1750 Ma (Szpunar and Fraser 2010) and were likely mineralised during the c. 1730–1690 Ma Kimban Orogeny and the intrusion of the c. 1745–1700 Ma Peter Pan Supersuite. It is unlikely, but not impossible that this event influenced the mineralisation of the older Darke Peak Group. Also for consideration is the influence of the subsequent c. 1590–1560 Ma Kararan Orogeny (Hand et al. 2007) on orogenic style mineralisation, however, higher-grade deformation has been found to be localised into shear zones by strain partitioning such as in the Mt Allalone region (Fabris et al. 2017).

To complicate matters further, the majority of the Paleoproterozoic basins have been over-printed to a greater or lesser extent by the c. 1595–1575 Ma Hiltaba Suite and GRV magmatic event. (Flint et al. 1993). This has made it particularly difficult in places to distinguish between remobilised, primary sedimentary iron formation and overprinting skarn mineralisation. As orogenic mineralisation related to this system is only likely to be associated with primary BIFs, this is an important distinction to make.

Although no Au-only mineralisation has been identified in the Middleback Ranges region, there is high potential for BIF-hosted occurrences to be present. This region has historically been the focus of FeO exploration and a small amount of IOCG exploration. It has not seen a significant amount of Au exploration.

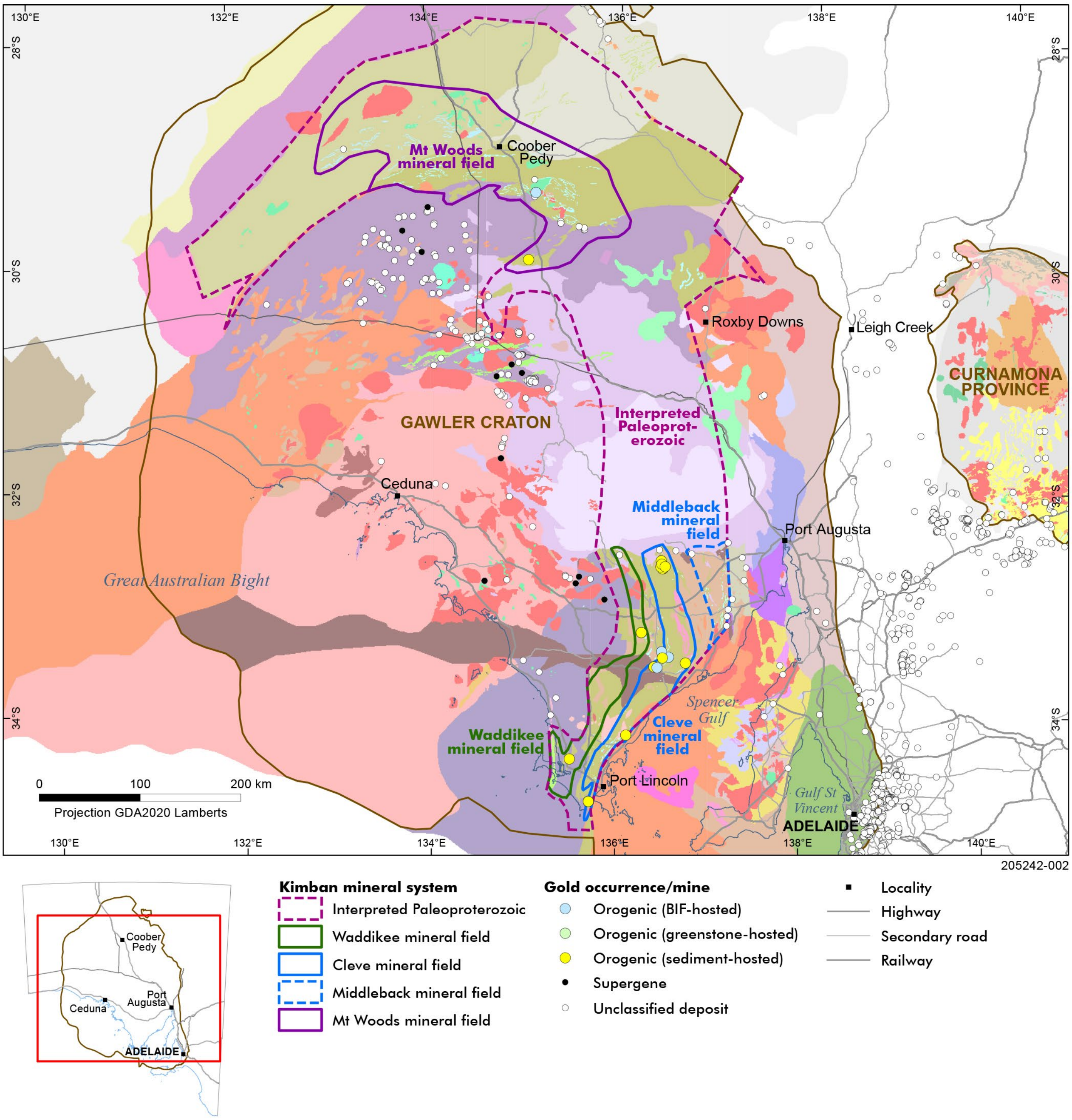


Figure 9. Kimban gold mineral system and fields of the Gawler Craton.

Mineral system model

This mineral system is also interpreted to primarily include orogenic, BIF or sediment-hosted gold style mineralisation (Fig. 10). The Hutchison Group mainly consists of clastic and chemical sediments deposited in a shallow marine, shelf environment (Szpunar et al. 2011). There are some intercalated volcanic units but these are of limited extent. Orogenic mineralisation is mainly confined to the sediment and BIF-hosted subgroups. The characteristics of the various mineral fields are outlined in Table 2.

ENERGY SOURCE

Orogenesis associated with the onset of the c. 1735–1690 Ma Kimban Orogeny is considered the thermal engine driving this mineral system. The intrusives of the Peter Pan Supersuite outline the primary extent of the Orogeny's influence which covers large parts of the Gawler Craton. However, the basins hosting potential mineralisation within this region have poor geochronological constraints allowing the possible influence of older events. Basin sediments in these mineral fields have been interpreted as being deposited over a 150 Ma time period (i.e. c. 1900–1750 Ma; Szpunar and Fraser 2010; Szpunar et al. 2011) and potentially include Archean age packages. As a result, the Cornian Orogeny and accompanying Donington Suite intrusion could also have been involved in these mineral fields.

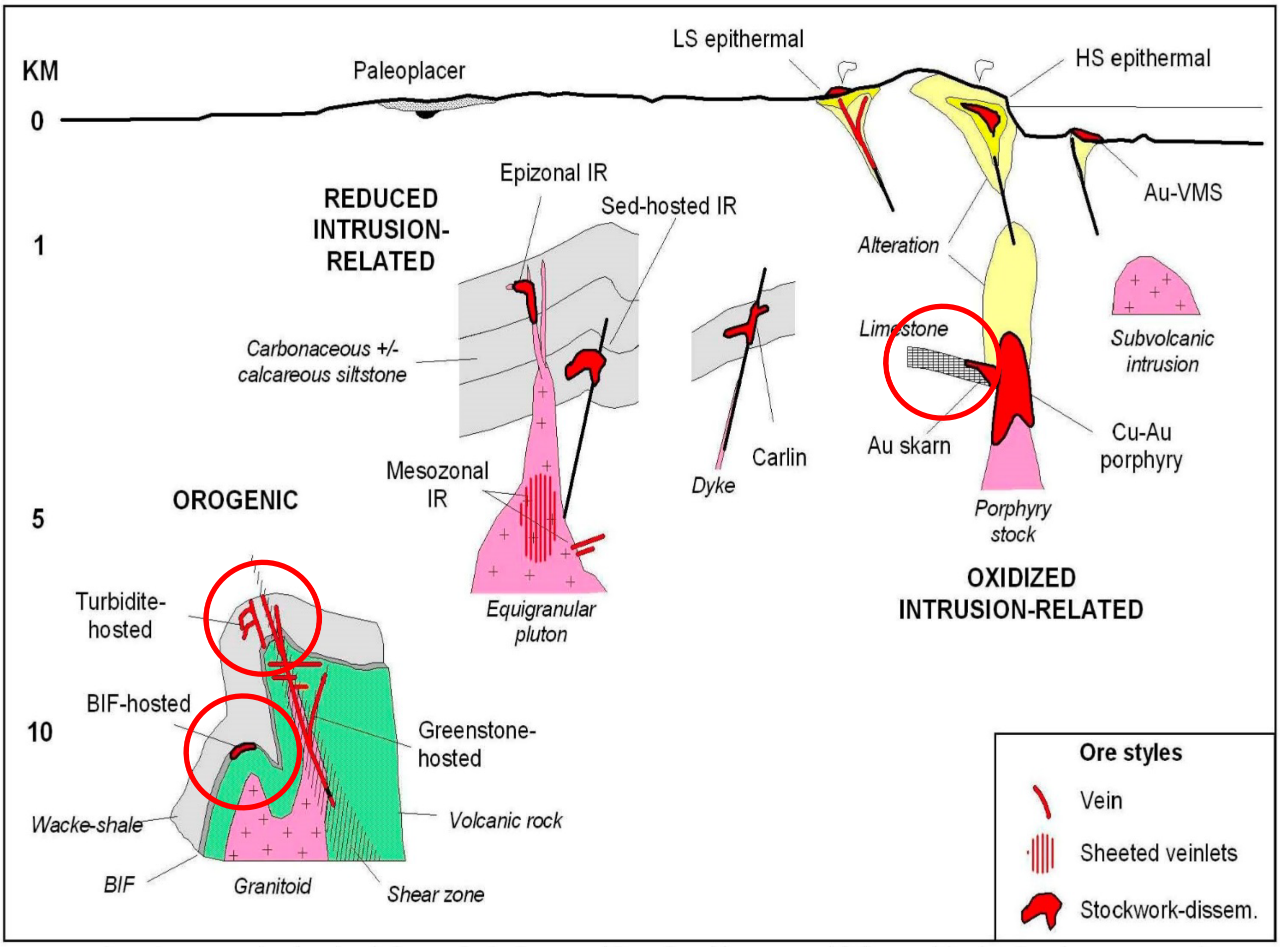


Figure 10. Gold mineral system classification scheme showing Kimban Mineral System (Robert et al. 2007).

FLUID/METAL SOURCE

The mineralising fluids are assumed to be mainly derived from basinal formation fluids although several sources are possible. There has been very little study of the deposits in this group apart from at the Weednanna Au deposit. Sulfur isotope studies at Weednanna (Morrisey et al. 2018) indicate the presence of Archean sulfur Mass Independent Fractionation (MIF) within the sulfides of this deposit (Fig. 11). The fluids depositing the primary mineralisation at Weednanna have therefore interacted with an Archean sulfur source. The positive $\Delta^{33}S$ value indicates a seawater sulfate origin. Elsewhere on the Eyre Peninsula, metasedimentary units assumed to be Paleoproterozoic in age have subsequently been geochronologically determined to be Archean (Szpunar et al. 2011). The results of this sulfur isotope study therefore suggests the local occurrence of Archean shallow marine packages (Middleback Group of Szpunar et al. 2011) at Weednanna and these units may well provide a source of metals in addition to sulfur.

Additional possible fluid and metal sources at Weednanna include intrusive units identified at the deposit. At least two intrusive suites have been described, but their relationship to mineralisation is yet to be determined. Undeformed granites in the footwall of the deposit have been dated at 1584 ± 5 Ma (Reid and Jagodzinski 2012). An older suite of deformed felsic intrusives have yet to be dated at Weednana but similar deformed granite has been dated elsewhere and form part of the Peter Pan Supersuite (Fabris et al. 2017; Jagodzinski et al. 2020). At Tin Hut Well prospect to the west of Weednanna, the Peter Pan Supersuite is associated with iron and magnesian skarn alteration and minor Pb-Zn mineralisation (Fabris et al. 2017). Similar to Weednanna, the Tin Hut Well prospect is located close to a Hiltaba Suite intrusion (Penna Granite) making a post-Kimban fluid and metal contribution permissible.

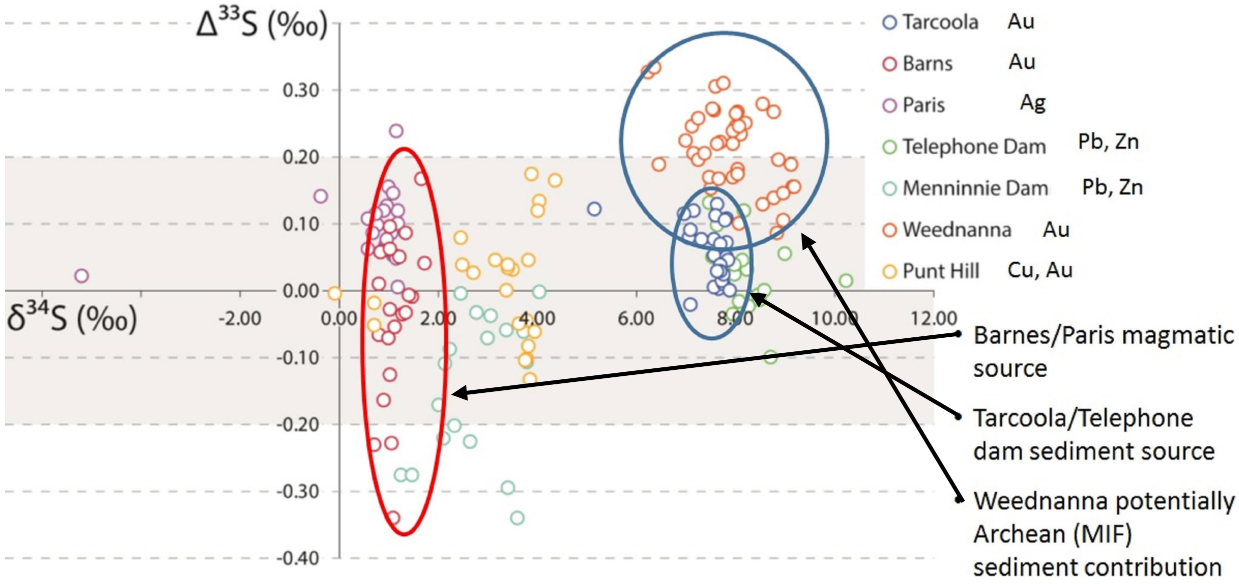


Figure 11. Summary plot of all sulfur isotope data from the Gawler Craton (modified after Morrissey et al. 2018).

A Zn skarn occurrence at No. 17 Bore, to the north of Tarcoola, which has been dated at 1710 ± 16 Ma provides further evidence for intrusive-related mineralisation (Reid et al. 2009). The skarn is closely associated with the intrusion of a Peter Pan Suite granite (1729 ± 13 Ma), which has itself been altered by the mineralising event. It was concluded that this mineralisation was a localised event, with fluids/metals derived from the late-stage crystallisation of the granite circulating through the surrounding sediments gathering further metals and causing the wider hydrothermal alteration and metasomatism (Reid et al. 2009).

The system at No. 17 Bore is similar to the W-Pb-Zn-Cu-(Au) skarn mineralisation at Telfer in Western Australia (Fig. 12; Rowins et al. 1998). The Telfer system is postulated to reflect magmatic fluids altering lithologies adjacent to the intrusion driving the mineral system. These fluids then mixed with formation fluids to scavenge Cu and Au from basinal sequences which are then deposited along major structural corridors where suitable chemical or physical traps occur (Fig. 12). At No. 17 Bore, the Bulgunnia Shear Zone may have acted as a primary conduit with secondary structures off the main shear zone hosting the mineralisation.

It is therefore possible that Kimban intrusive suites contributed fluids associated with Au mineralisation elsewhere within the Kimban mineral system and associated mineral fields.

Other magmatic events may also be contributing to some of the deposits in these mineral fields. Extensive intrusion of the c. 1850 Ma Donington Suite granites (Reid et al. 2008b) may have had a big influence on the Eyre and Yorke peninsulas but their association with mineralisation is unknown.

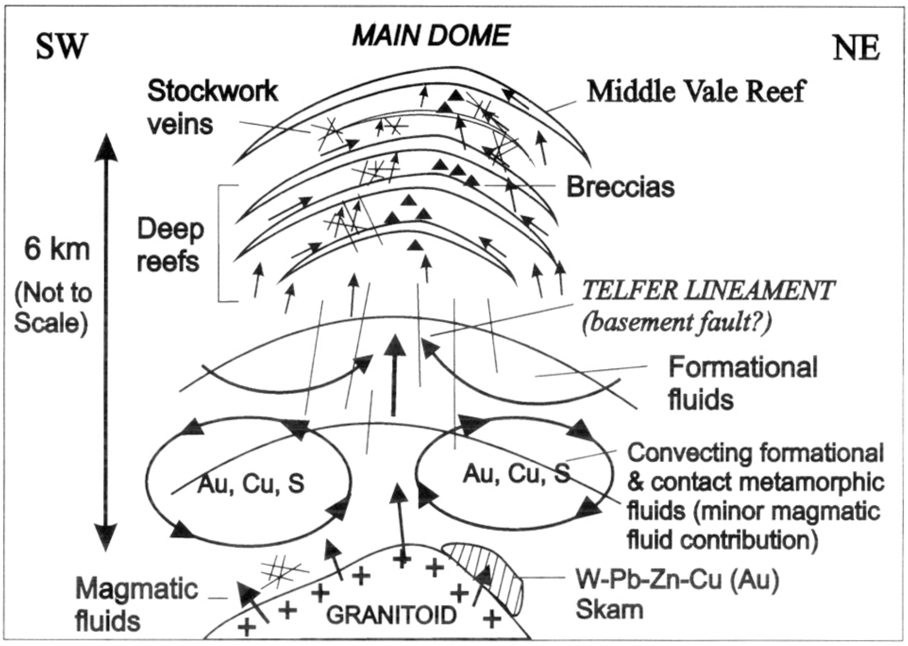


Figure 12. Schematic cross-section of the Telfer mineralisation model. Arrows represent the various fluid pathways (Rowins et al. 1998).

MIGRATION PATH

Fluids are likely to have migrated along major listric fault zones which formed during deposition within the basin. These would have been reactivated during the Kimban Orogeny into shear zones. These have been interpreted as east dipping structures, based on the OESP seismic line located along the southern margin of the GRV region (Fraser et al. 2010). Alternatively, these structures have been interpreted as west-dipping, based on a magnetotelluric profile and isotopic analysis (Curtis and Thiel 2019). Mineralisation is most likely to be associated with second and third order structures off these major crustal scale features.

Alteration along the fluid pathways can often be recognised by magnetite destruction in the host units. A good example of this is the Flintoft prospect (Fig. 13) in the Mt Woods mineral field (Davies et al. 1997). A single line of RC drillholes across a zone of lower magnetic response intersected gold mineralisation (4 m @ 4.58 g/t from 84–88 m) with several other anomalous gold zones as well. A limited follow-up program of calcrete sampling outlined significant gold anomalism. This was followed up with a limited program (49 holes) of shallow (<40 m, average depth 17.1 m) vertical aircore drilling, however this type of program is unlikely to adequately test this style of mineralisation.

Other alteration minerals may be visible with spectral methods, particularly in areas of lower grade metamorphism which is generally the case on the western side of this mineral system.

This raises questions about the gold potential of the BIF units in the Hutchison Group in the southern Gawler Craton. The BIF units have primarily been the focus of iron exploration, which targeted the more magnetic parts of the unit. It is possible that the areas of lower magnetic response, which have been avoided in previous exploration, could represent fluid pathways where magnetite was destroyed.

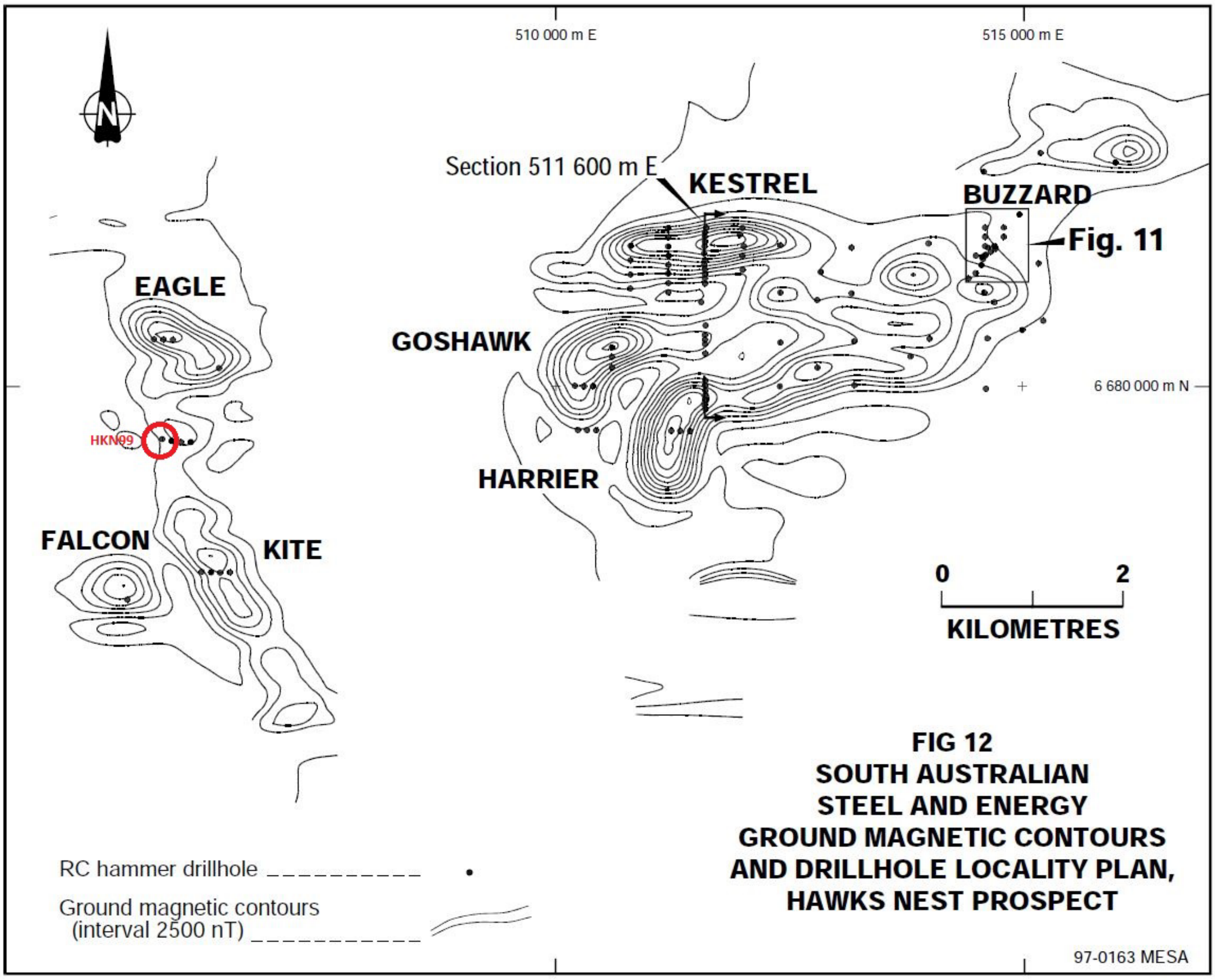


Figure 13. Ground magnetic contours showing magnetite destruction around Flintoft prospect (marked by drillhole HKN 99) (Davies et al. 1997).

DEPOSITION

Axial planar structures along major regional folding (Figs 14 and 15) are typically the hosts of this style of mineralisation (Steadman et al. 2014; Schmeider et al. 2017). BIF units within the stratigraphy acted as excellent reductants to Au-rich fluids migrating through the system. Often the most obviously magnetic BIF (magnetite/silica lithologies) are not the primary hosts. Iron-rich sediments higher or lower in the stratigraphy, which are usually seen as amphibole/magnetite-rich lithologies after metamorphism, are the best hosts.

Carbonates are also very common in the Hutchison Group sediments in close association with the BIFs. These could also potentially host Au-skarn mineralisation, although this is more likely to be an intrusion related system as described above.

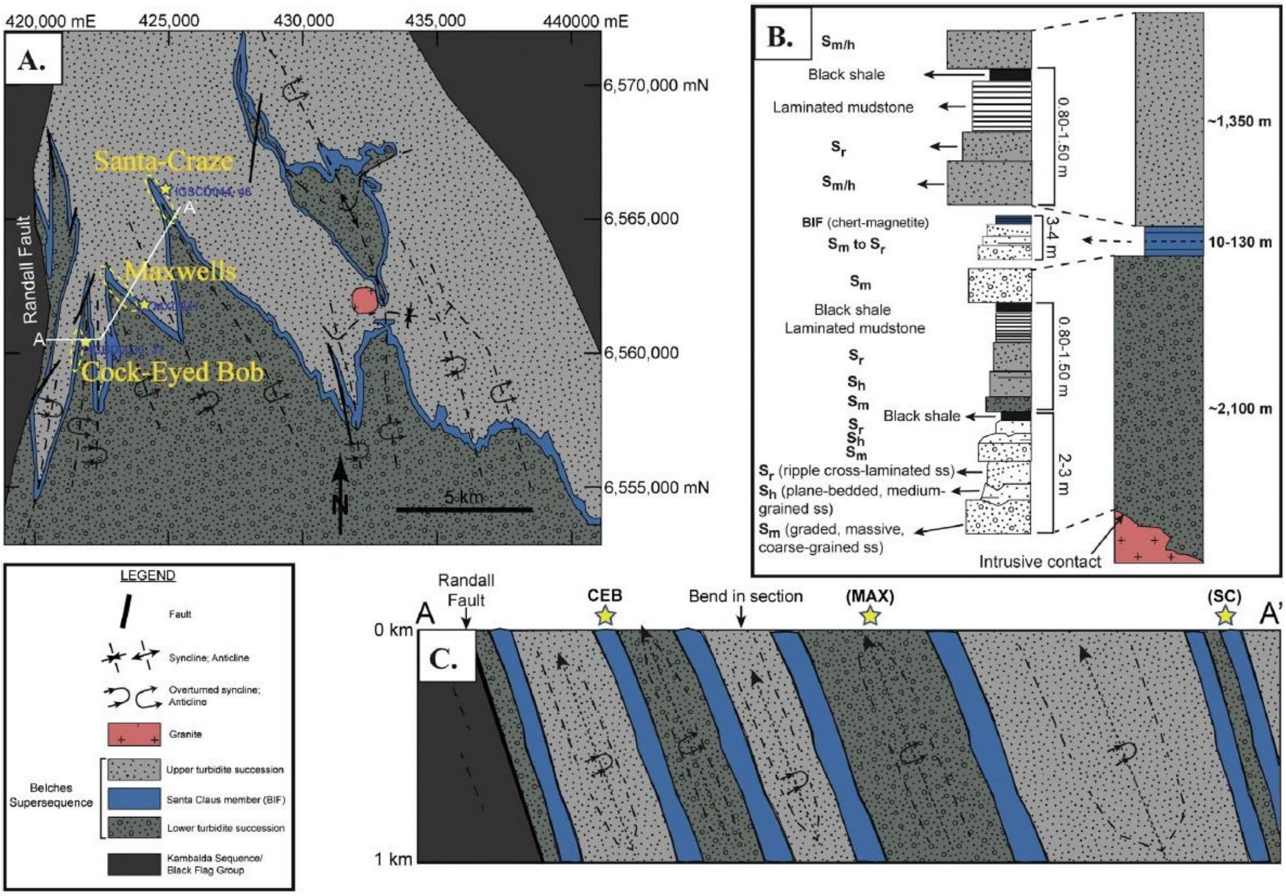


Figure 14. Example of BIF Hosted gold mineralisation stratigraphy, Belches Basin, Western Australia (Steadman et al. 2014).

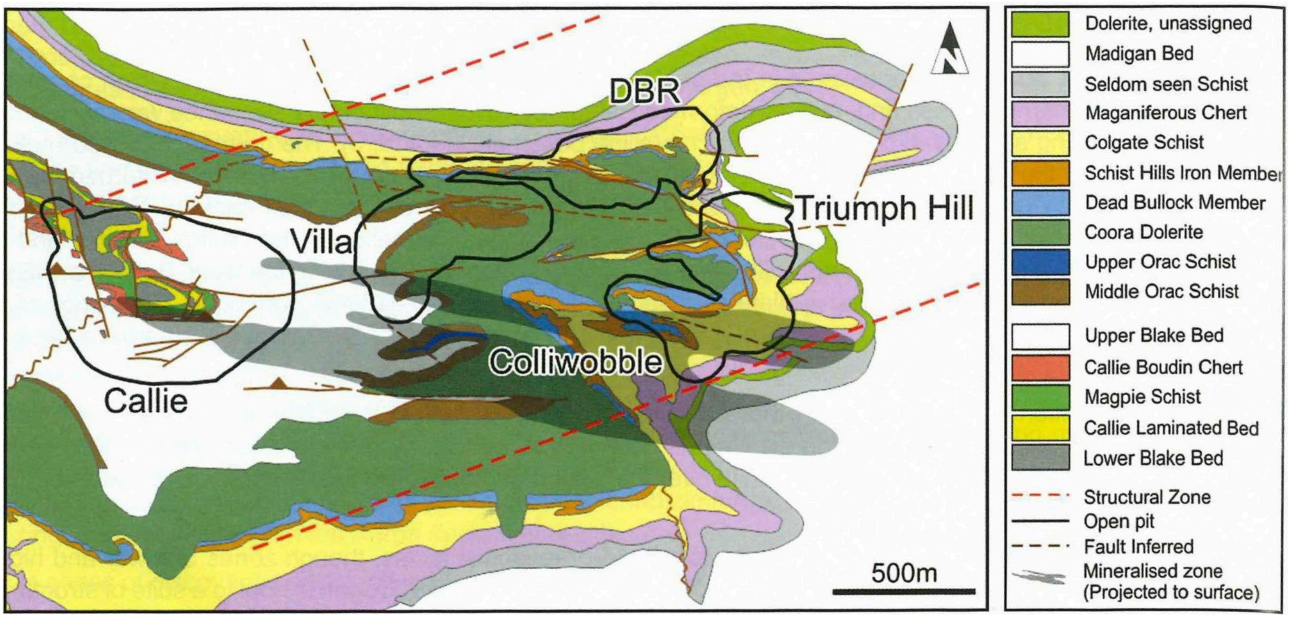


Figure 15. Example of BIF Hosted gold mineralisation stratigraphy, Dead Bullock Soak Deposits, Northern Territory (Schmeider et al. 2017).

OUTFLOW ZONE/FOOTPRINT

The outflow zones of orogenic Au deposits are generally not very distinct. Alteration systems for intrusion-related systems may be more easily detectable.

Selected drillholes from the Weednanna, Penrhyn and Flintoft occurrences were scanned with the HyLogger™ as part of the Central Gawler Workshop held in 2019. Preliminary analysis shows a distinct correlation between mineralised zones and various alteration styles (Weednanna – siderite; Penrhyn – Kaolinite). Further analysis may determine spectral signatures which could be used on a regional basis to locate further mineralisation. One difficulty in applying this exploration methodology is that the deposits within this mineral system have often been subsequently over-printed by Kararan intrusive and epithermal systems. Care needs to be taken that the alteration system being used in regional exploration is genetically related to the mineralising event that is being explored for.

Mineral system distinguishing criteria

The key features of the deposits and occurrences examined as part of this review are presented for the various mineral fields in Table 2.

Table 2. Kimban gold mineral system criteria

Criteria	Mt Woods MF	Waddikee MF	Cleve MF	Middleback MF
Type deposits	Flintoft, Penrhyn	Waddikee, Moonlight	Weednanna, Bartel	No discoveries yet
Host	Skylark Metasediments	Darke Peake Group (graphitic schist, amphibolite, marbles)	Cleve Group (schist, quartzite, carbonates)	Middleback Group, Broadview Schist
Vein style	Quartz-carbonate	Quartz	Quartz-pyrite	Quartz-pyrite?
Alteration	Chlorite, carbonate	Biotite	Silica, manganese, carbonate, (sericite, chlorite)	–
Sulfides	Pyrite, chalcopyrite	Pyrite, pyrrhotite, galena, chalcopyrite	Pyrite, argentite, chalcopyrite, galena, arsenopyrite	–
Elements (dominant elements in bold)	**Au, Fe, Zn**, Pb, Cu, Ag, As	**Au, Bi**, Pb, Zn, Ag, As, Cu	**Au, Pb, Cu, Ag, Zn**, Mo, As, Bi	**Au, Zn,** As, Cu?
S Isotopes $\delta^{34}S$ ($^{0}/00$)	–	–	3–7.5	–
Style	Orogenic (sediment/BIF)	Orogenic (greenstone)	Orogenic (sediment/BIF)	Orogenic?
Mineralisation age	c. <1730 Ma?	c. <1900 Ma?	c. <1730 Ma?	c. <1730 Ma?
Temperature	?	?	?	–
Depth of formation	Hypozonal (10–20 km)	Hypozonal (10–20 km)	Hypozonal (10–20 km)	–
Post-deposition modification	Greenschist to granulite metamorphism	Greenschist to granulite metamorphism	Greenschist metamorphism	Greenschist metamorphism

As with the Archean system, mineralisation is distributed across a wide variety of lithologies. Source rock region and host lithologies have probably had a large influence on the mineralising fluids and metals carried, contributing to the wide variety of chemistries associated with these deposits.

The elemental associations are not typical of the deeper orogenic systems as in the Archean Mineral System. Arsenic is often present and elevated but not as significantly as in the Archean deposits. (Fig. 5) Many of these systems appear to have been subsequently overprinted as mentioned above and this may explain the non-typical elemental associations.

Questions for further research

Further investigation is required on all aspects of this group of mineral occurrences.

SULFUR ISOTOPES

As with the Sleafordian mineral system, sulfur isotope analysis has been mostly ignored with only the Weednanna deposit having been investigated. Even so, only a few samples from several drillholes have been analysed at Weednanna (Morrisey et al. 2018). The Archean sulfur component in the Weednanna deposit is, so far, an isolated occurrence. How similar are other deposits/occurrences to Weednanna? Extension of the sulfur isotope data to examine sulfur sources in different areas of the Weednanna deposit may also shed further light on the origin of the mineralisation. Further data from other deposits in the Kimban MS will allow a more rigorous classification of the origin and genetic relationships of many of the deposits and occurrences of the Gawler Craton.

AGE DETERMINATION

The majority of this type of mineralisation has been assumed to be skarn Fe-alteration related to Hiltaba IOCG systems. Only Weednanna has had any direct geochronology conducted (Reid and Jagodzinski 2012). The Weednanna deposit has obviously been overprinted by subsequent Hiltaba mineralisation, probably both epithermal and oxidised intrusion-related (OIR) styles, but the majority of the deposit is centered around primary Paleoproterozoic banded iron formations and carbonates and it has distinct gold only zones. The relative proportions of mineralisation related to each event is indeterminate at this stage, but the bulk of the gold may have been introduced in the second mineralising event.

Further geochronology is also required to determine if there are, in fact, two Paleoproterozoic mineral systems present (c. 1850 Ma and c. 1730 Ma), corresponding to the Cornian and Kimban orogenies.

FLUID SOURCES

There are many questions regarding the sources of the fluids. Did the Hutchison Group basinal fluids interact with the Archean basement? Can we distinguish the Archean fluids from the Paleoproterozoic fluids and are there demonstrated relationships between Kimban-aged intrusions and mineralisation at deposits other than No.17 Bore and Tin Hut Well?

CARBONATES/Pb–Zn INFLUENCE

How much of an effect do carbonate lithologies and the presence of base metal mineralisation, such as at Menninnie Dam, have on gold mineralisation? Gold is commonly associated with these deposits, but the details of the relationship hasn't been widely investigated in this study.

CONTROLLING STRUCTURES

Can we recognise the structures that controlled fluid flow? The Weednanna deposit appears to be hosted in a tight to isoclinal synclinal structure. This style of folding could cause the structures and associated mineralisation to be repeated across the area. Due to the properties of the mineralisation, electrical and magnetic geophysical methods may be useful in chasing this style of mineralisation deeper under cover. The antiformal structures associated with the syncline are likely to be better hosts to mineralisation but are also likely to have been sheared very strongly. Furthermore, the gold mineralisation at Weednanna appears to be influenced by a NW-trending shear zone (Fig. 16) along which a large quartz vein has intruded (Anthony Gray - Alliance Resources pers. comm.). This is interpreted as a third order structure in the region which appears to be relatively late and more brittle in character. This structure is at a low-angle to the NNW-trending fold axes and primary metamorphic fabric in this area.

To the south of Weednanna, the majority of mineral occurrences occur on the northern side of the east-trending, Mesoproterozoic to Permian Polda Trough. Structures with similar orientations to those in the Weednanna area can be seen here as well (Fig. 17). No investigations have been undertaken to determine the relationship of these structures to mineralisation. The primary metamorphic fabric in this region has been deflected adjacent to the Polda trough and there is an apparent dextral offset of the Archean and Paleoproterozoic stratigraphy by up to 30 km. The amount of offset diminishes to the east, with the Kalinjala Shear Zone deflected but not offset.

These observations indicate the presence of a major crustal structure in this region, with the diminishing offset suggesting it may have a rotational component. Very little exploration has been undertaken to the south of the Polda Trough.

Furthermore, more detailed, aeromagnetic surveys may help to better understand the structures controlling the mineralisation in this area.

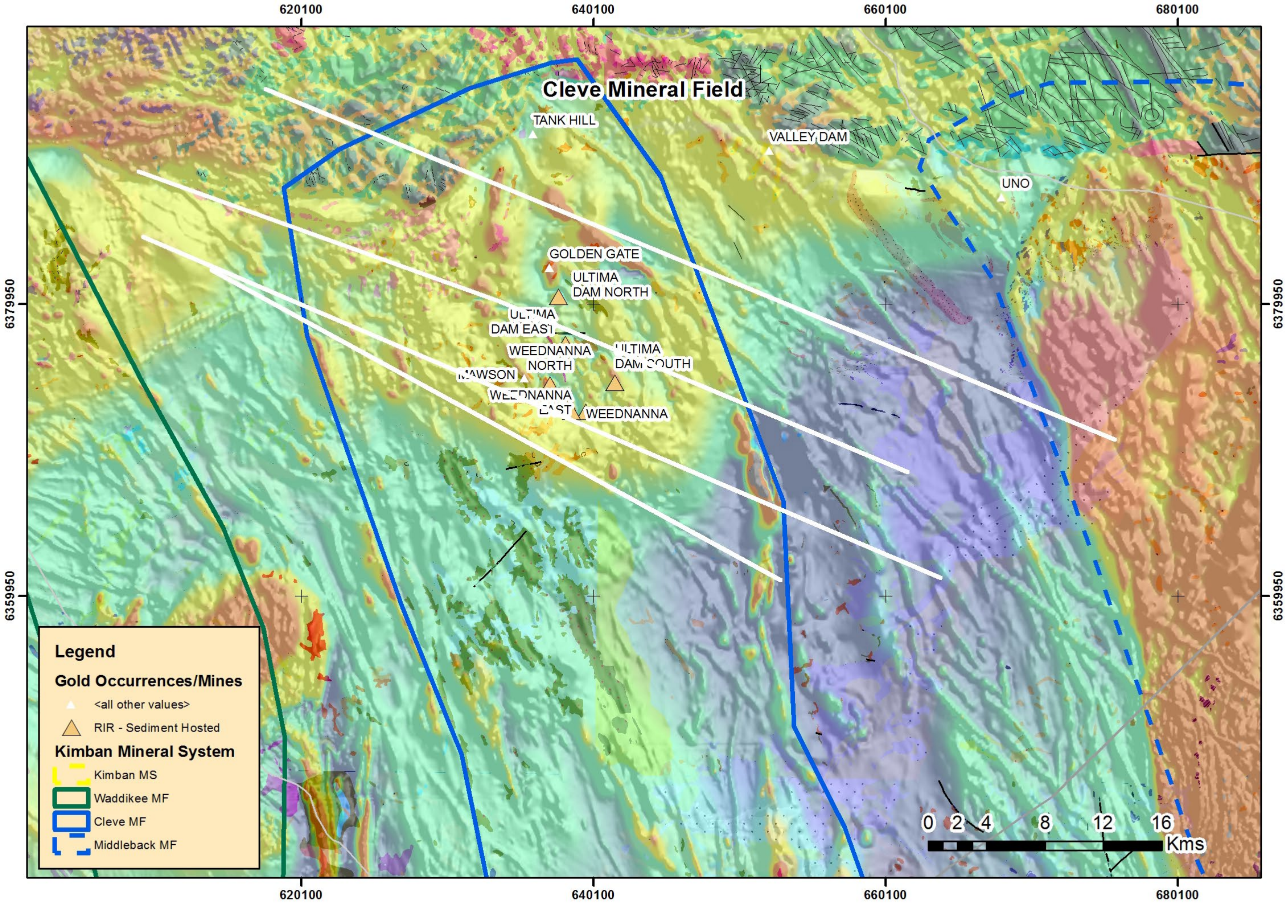


Figure 16. TMI RTP aeromagnetic image with 100k geology superimposed, northern Cleve MF. The white lines show northwest orientated trend lines and inferred structures.

HUTCHISON BASINS EXTENT AND ARCHITECTURE

Many questions still remain around exactly what the Hutchison Group consists of and how far the basin/s extended to the north and west (e.g. Szpunar et al. 2011). Detailed stratigraphic section logging, in conjunction with geochemistry, petrology and detrital zircon analysis may answer some of these questions and help define the number and the extent of these mineral systems/fields.

MIDDLEBACK MINERAL FIELD

Although no Au-only mineralisation has been identified in the Middleback Ranges region, there is high potential for BIF-hosted occurrences based on the amount of iron formation present in the area. This region has historically been the focus of iron ore exploration and a small amount of Iron Oxide Copper Gold deposit (IOCG) exploration and has been subject to very little gold-focused exploration

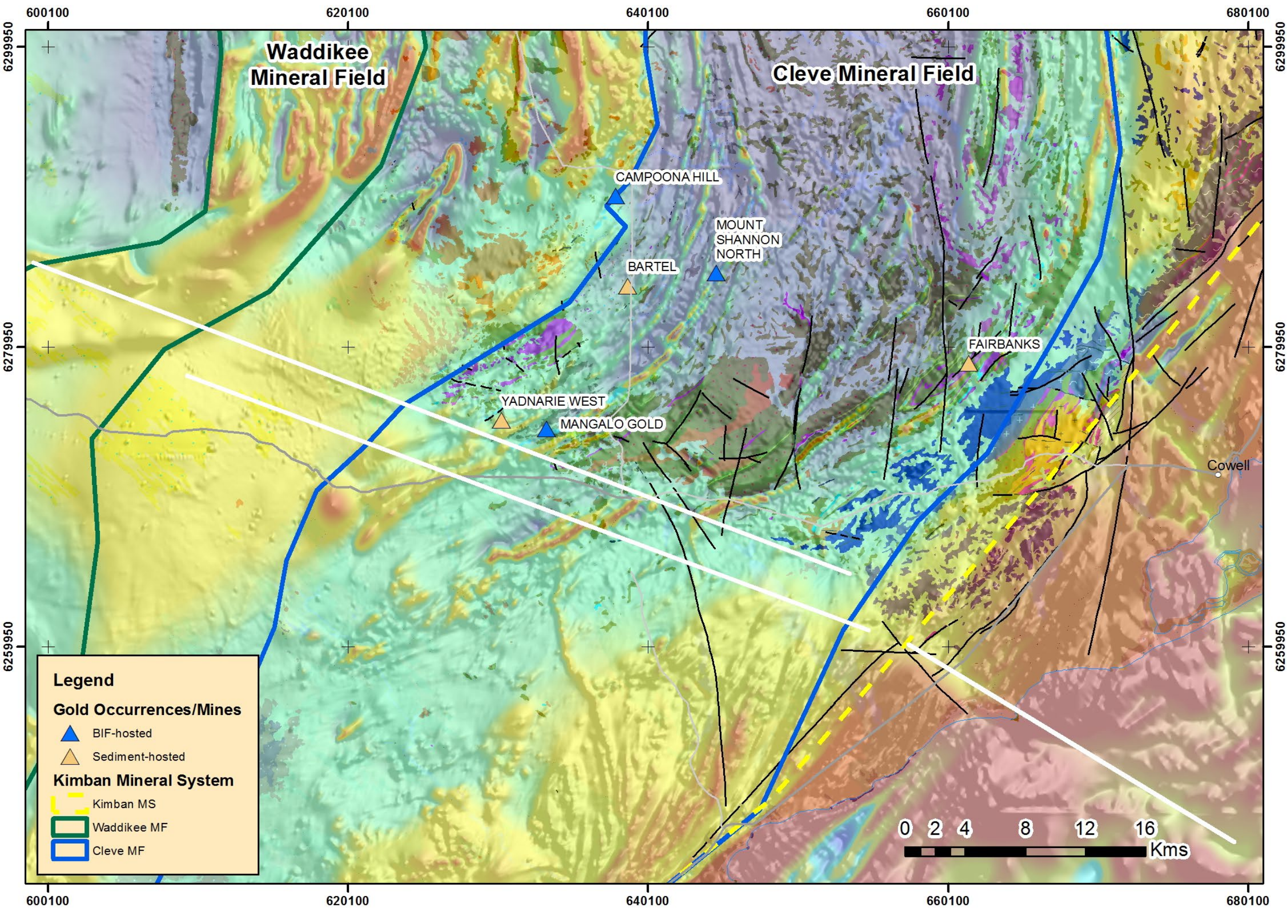


Figure 17. TMI RTP aeromagnetic image with 100k geology superimposed, southern Cleve MF. The white lines show northwest orientated trend lines and inferred structures.

Exploration guidelines

LITHOLOGIES

The gold mineral systems associated with BIF do not generally occur in the most magnetic portions of the lithologies. The alteration associated with these systems is generally magnetite destructive. In addition, quite often the mineralisation is associated with banded, iron-rich sediments rather than the massive silica/magnetite zones. These are quite often seen as banded amphibole/carbonate lithologies. Therefore, mineralisation can often be located in zones of lower or no magnetic response.

Since skarn-type mineralisation is recognised proximal to Peter Pan Supersuite, carbonaceous silt/mudstones and carbonates are likely to be good hosts for this style of mineralisation.

VEIN SYSTEMS

The Kimban MS generally do not have a large amount of associated quartz veining, and it is often the smaller veins which host the higher grade mineralisation. Subsequent deformation of the vein systems during the later Kararan Orogeny may add another layer of complexity to interpretation of the relative significance of the veining systems. Due to the association with fold axial zones there is likely to be stacked vein zones forming at multiple stratigraphic levels (Fig. 12). What seems to be a minor vein system, may in fact be proximal to very high-grade gold mineralisation.

The alteration haloes associated with this style of mineralisation are generally very narrow (0.1–1 m wide). This makes vectoring towards high-grade zones using alteration or pathfinder geochemistry very difficult.

PATHFINDER ELEMENTS

Gold is still the most useful element to use in exploration for this type of mineral system due to the narrow extent of the alteration haloes. Arsenic is the most common, and often the only associated element, whereas Bi can be present but generally the elevation is very subtle except where Au grades are also high.

Ag, Pb, Zn and Cu are often associated with the deposits and occurrences within the Cleve and Waddikee mineral fields. This may be a coincidental relationship formed from the stratigraphic association of exhalative base metal with the iron formations of the Hutchison Group. There are no consistent relationships of these elements with Au mineralisation and all four vary as the dominant element associated with Au (Appendix 1).

STRUCTURES

Folds are the key structural component to this type of mineralisation, with many isoclinal fold structures evident in all the mineral fields defined within this mineral system. The Weednanna deposit appears to occur within and around the axial zone of a synclinal structure so it seems any axial structural zone is prospective within this mineral system. Elsewhere, it has been demonstrated that shear/fault zones aligned sub-parallel to the axial planes of regional scale antiforms, focused fluid flow and mineralisation (Figs 14 and 15). However, many of the antiforms in the Gawler Craton have been the focus of shearing during the Kimban Orogeny, consequently, mineralisation in the antiforms may have been disrupted during subsequent deformation or possibly localised into high-grade zones.

Furthermore, there is a high possibility of multiple stacked ore zones where suitable host lithologies are repeated within the stratigraphy.

GEOCHEMISTRY

An advantage of the majority of the areas within this mineral system is that there is relatively little cover. This means that surface geochemistry is an ideal first-pass exploration tool. Depletion within the upper saprolite is still likely to be an issue, but methods such as ultrafine fraction sampling (<2 µm fraction), may be very useful as the majority of the metals adsorb onto the clay fraction so that weak signals of mineralisation are amplified, highlighting anomalous zones (e.g. Noble et al. 2020).

Other methods such as calcrete and partial leaches may work, so long as suitable, detailed, orientation surveys are conducted over known nearby mineralisation, and the nature and origin of the sample media is well understood.

GEOPHYSICS

Detailed magnetic data is likely to be the most useful geophysical exploration technique as it will 1) reveal the axial fold zones potentially hosting mineralisation and 2) highlight zones of magnetite destruction that will indicate the path of potentially mineralising fluids.

Due to the generally weakly conductive nature of the mineralisation and the common presence of highly conductive lithologies within the host sequence, electrical geophysical methods are often very hard to interpret and produce very subjective results. Careful use in combination with drillhole data to constrain local responses may work in some areas. Methods such as Controlled Source Audio-frequency Magneto-tellurics (CSAMT) have not been used in the region and may be useful in defining alteration/mineralisation in structures.

KARARAN GAWLER RANGE VOLCANIC (GRV) MINERAL SYSTEM

This mineral system is defined by the original extent of the shallow, sub-volcanic, hydrothermal systems of the Gawler Range Volcanic event (Figs 4 and 18). This system is typified by the Tarcoola and Glenloth mining areas as well as the Minos and Parkinson Dam prospects. Five mineral fields are defined within this system (Tarcoola, Labyrinth, Glenloth and Southern GRV mineral fields) and these are based mainly on local criteria that affected the migration of mineralising fluids and emplacement of the mineralisation in the areas. Other mineral fields are likely to be able to be defined with further work.

The mineral system is postulated to extend across the original extent of the GRV outcrop and associated sub-volcanic hydrothermal systems. While this original extent is hard to define due to subsequent erosion, the distribution of GRV felsic dykes gives some indication and has been used to define the extent of the system in this study.

Key components of this mineral system are the sedimentary basins immediately underlying the GRV (outlined in dark blue, Fig. 18). The original extent of these basins is also difficult to determine and may be wider than currently known. An example being the Blue Range Beds which are associated with the Corunna Conglomerate and is known along the margins of the GRV Province and south in the Polda Trough on the southern Eyre Peninsula, but is likely to also have been deposited within the Kararan (GRV) MS.

Mineral system model

This mineral system is interpreted to be a typical low sulfidation, subalkalic epithermal system associated with oxidised intrusions (Figs 19 and 20). The key distinction between the deposits included in this system and associated intrusion related Epizonal to Mesozonal mineralisation of the Kararan (Hiltaba) Intrusive suite MS, is the metals associated with the deposits. Epithermal deposits are generally much richer in Ag, strongly anomalous in Pb Zn, and while As is present and can be used as a pathfinder, it is not a dominant component. The current level of exhumation of the various occurrences of mineralisation varies dramatically. Deposits such as Parkinson Dam and Telephone Dam are quite shallow with common banded, vuggy veining, whereas deposits such as Tarcoola are much more strongly gold mineralised. Tarcoola is interpreted to have been exhumed to a much greater degree and reflect a deeper level of the mineral system as there is only minor evidence of classic banded and vuggy, shallow, epithermal textures (Hein et al. 1994). The primary distinguishing characteristics of the various mineral fields within this system are outlined in Table 3.

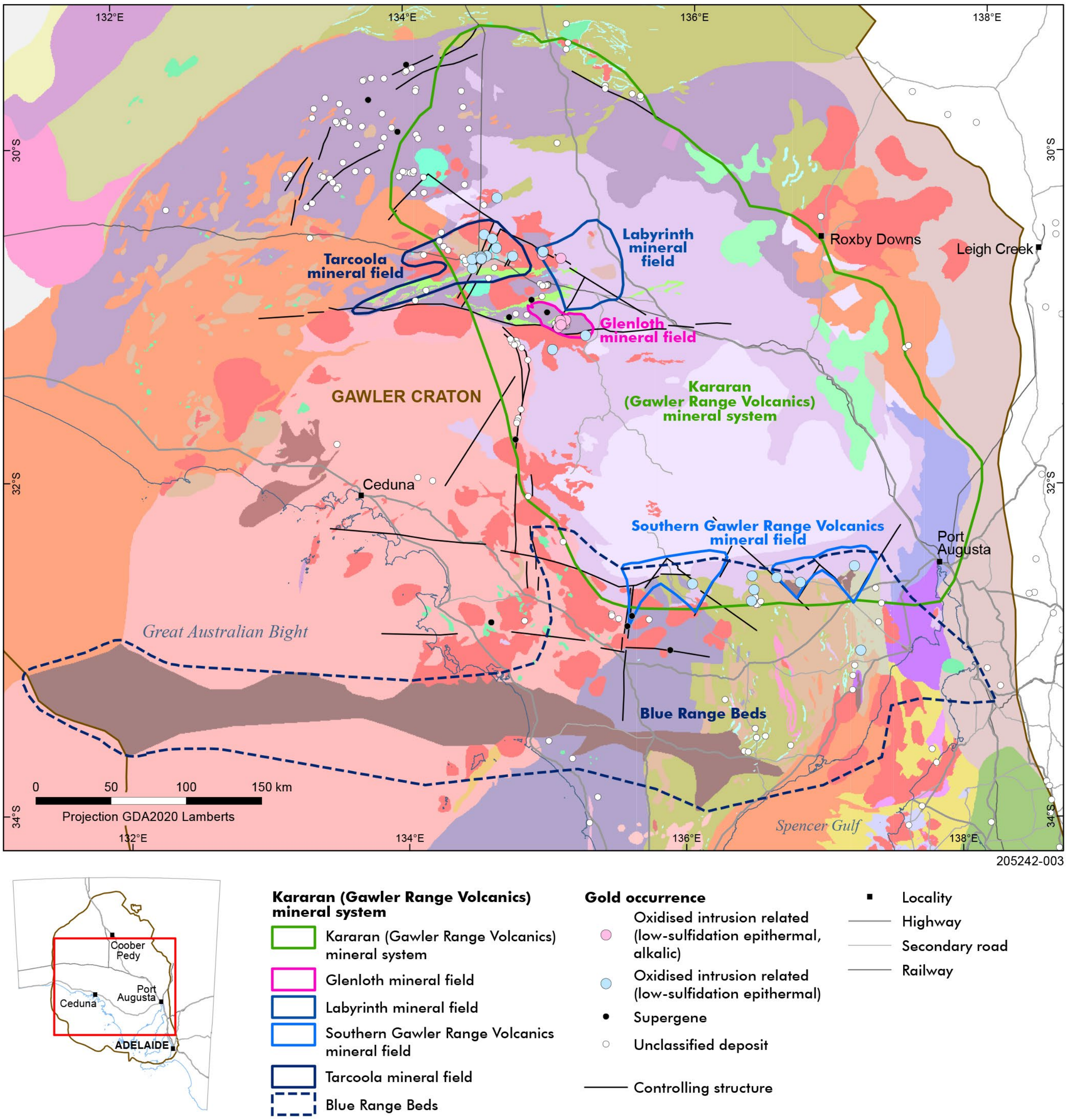


Figure 18. Kararan GRV epithermal mineral system of the Gawler Craton.

Research in the Tarcoola district using sulfur isotopes indicates that sulfur and probably metals were derived from the underlying Tarcoola Formation sediments. (Hein et al. 1994). There are no obvious indications of widespread alteration of the Tarcoola Formation, which also supports the interpretation that this deposit formed at deeper level than the other deposits in this MS. In the southern GRV, basement lithologies sitting below the base of the GRV have generally undergone extensive argillic alteration associated with the mixing of hydrothermal fluids and shallow groundwater (Wade et al. 2014; Curtis et al. 2018). This is consistent with fluid flow modelling by the PMD CRC (Potma and Bastrakov 2006; Fig. 21). This work has shown that a thick blanket of GRV would act as an aquitard, promoting hydrothermal alteration of the underlying lithologies and focusing fluid flow through any fault/fracture zones penetrating the GRV.

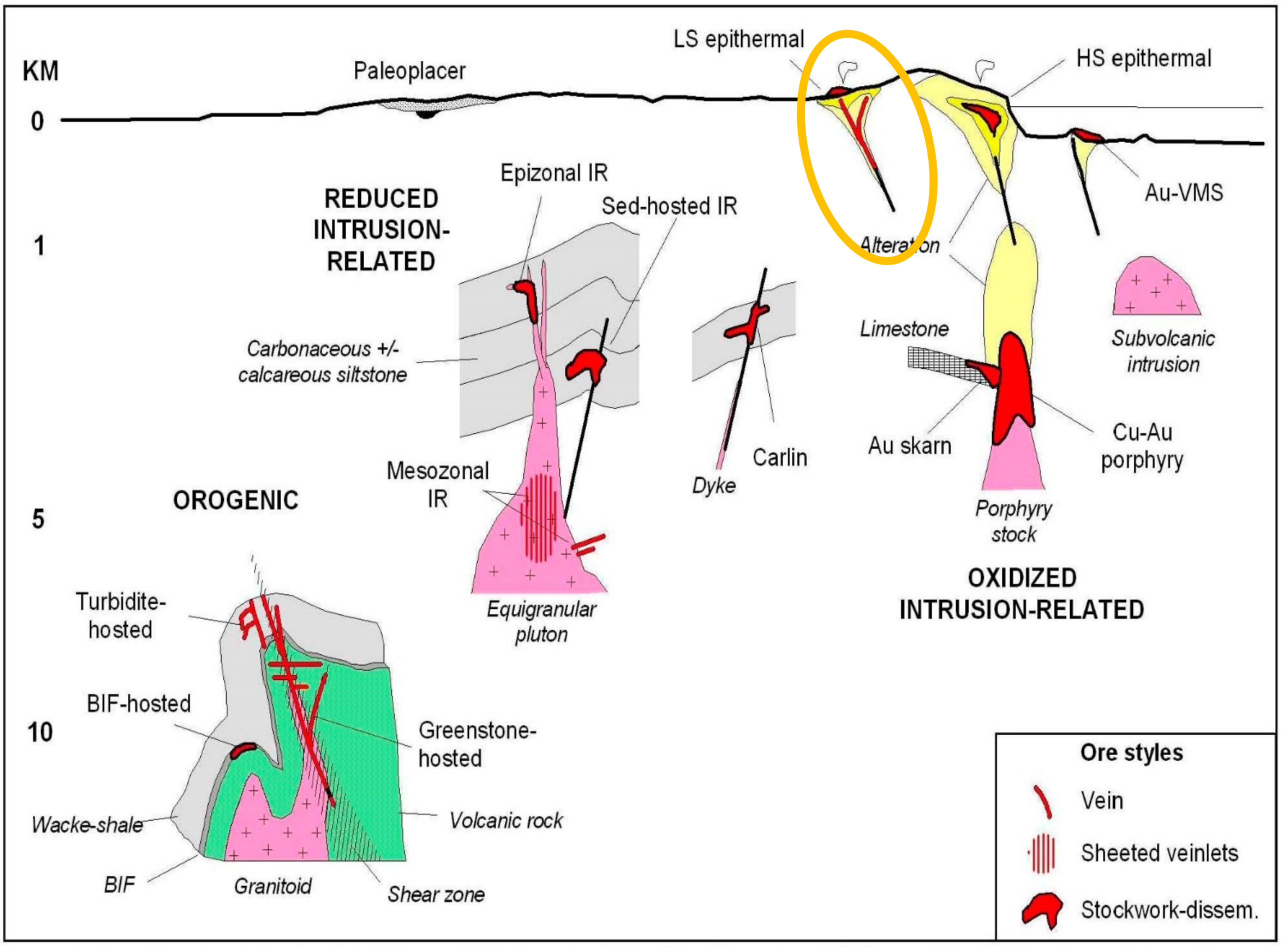


Figure 19. Gold mineral system classification scheme showing the Gawler Range Volcanic Epithermal Mineral system (Robert et al. 2007).

This type of mineral system is also likely to be strongly affected by the local lithologies underlying the individual hydrothermal cells. The fluid flow is also likely to migrate along long-lived fracture systems, which could potentially have been mineralised by previous orogenic events. Thus, confusion arises with hybrid systems showing characteristics of multiple styles of mineralisation (i.e. Boomerang, Weednanna).

ENERGY SOURCE

The energy source for this system is postulated as being the sub-volcanic hydrothermal systems of the GRV. The distribution of the deposits reflects the original distribution of the GRV, which was much greater than the current exposed outcrop. Exploration and research drilling over the past 10-15 years has expanded the known occurrence of the GRV greatly. However, the original maximum distribution of the extrusive lavas and more particularly the original distribution of the eruptive centers is still open to debate.

FLUID/METAL SOURCE

The sulfur isotopes of both the Tarcoola and Weednanna deposits indicate a significant input of sulfur and most likely metals from a sedimentary rather than a magmatic source (Fig. 11; Hein et al. 1994). This is probably due to interaction of the epithermal systems with the Tarcoola Formation and the Hutchison Group sediments respectively (Morrissey et al. 2018). Interestingly, the distribution of values is quite different in the two deposits. This may reflect the varying sulfur content of the sources, but unfortunately little data is available on the background values of the Hutchison Group. If it is not related to the background sulfur sources, then is it possible it reflects different origins for the two deposits, with the Weednanna deposit being an earlier phase of mineralisation (see above) which was subsequently overprinted with the epithermal mineralisation event.

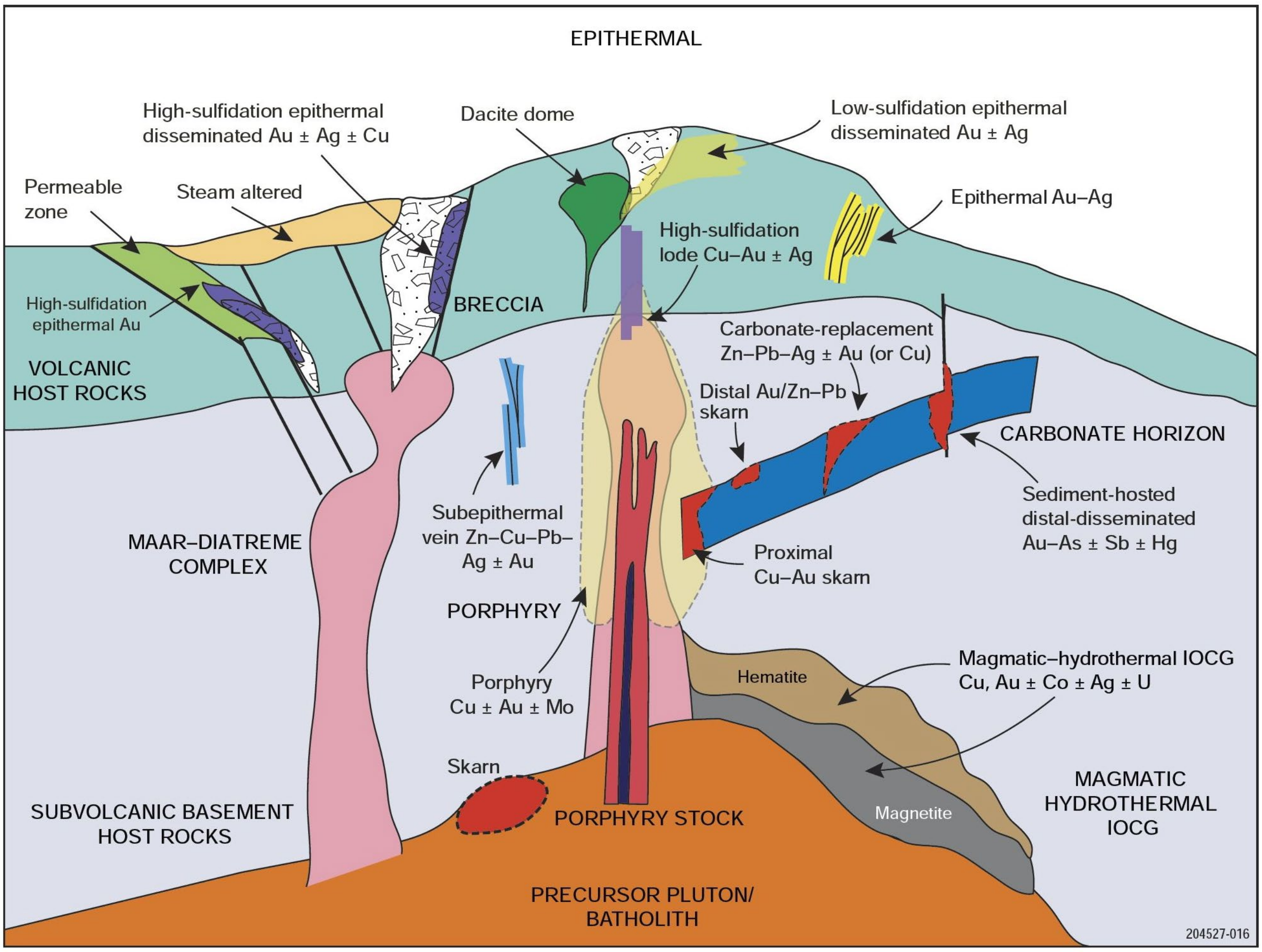


Figure 20. Epithermal mineralisation styles of the southern GRV mineral field and their relationship to Hiltaba Suite intrusives (Wade et al. 2014 after Corbett and Leach 1998; Sillitoe 2010; Richards and Mumin 2013).

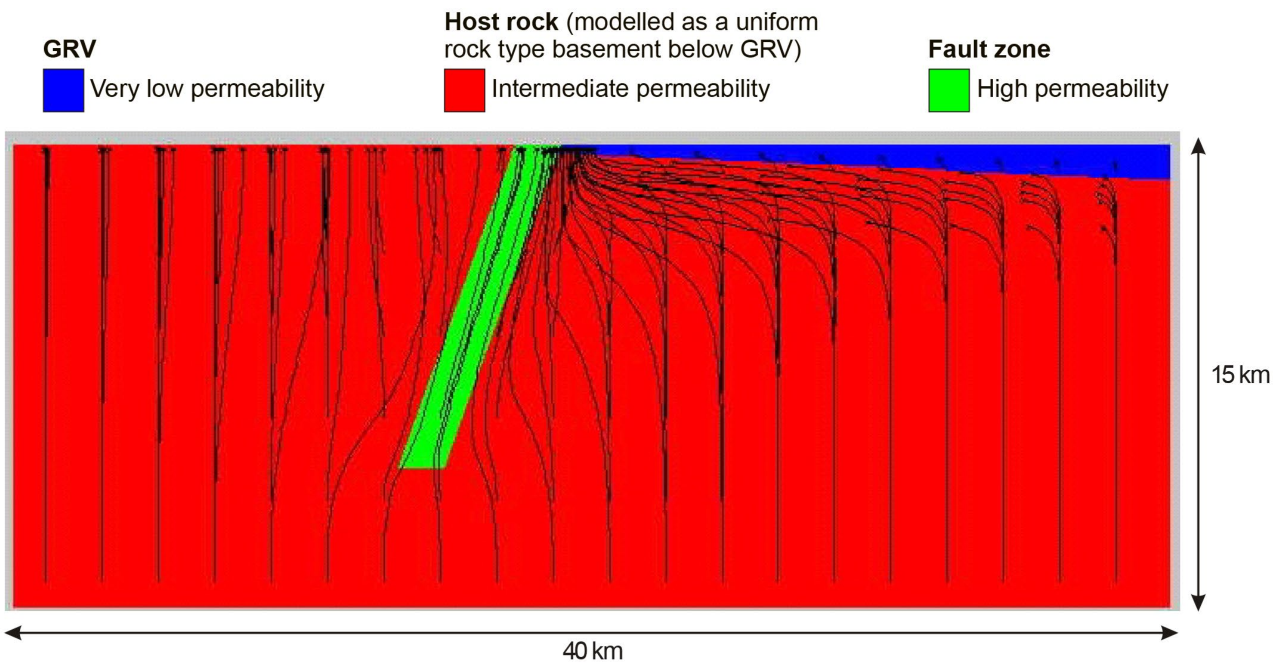


Figure 21. Fluid flow modelling showing increased flow along the basal contact of the GRV (Potma and Bastrakov 2006).

MIGRATION PATH

Many of the mineral fields defined in this system show a very strong association with a conjugate set of NW- and NE-trending structures (Fig. 18). The age of first development of these structures has not been determined, but must be post-Sleafordian as they have not been affected by early high-grade deformation. Many of these structures cut plutons of the Hiltaba Suite, suggesting these structures are younger than, or were reactivated after c. 1585 Ma (Pawley and Wilson 2019), and form part of the Kararan Orogeny. The apparent kinematics of the structures indicate they formed during north-south-directed shortening (Wilson et al. 2018). However, these structures influence the current extent of the pre-GRV sediments such as the Tarcoola Formation and Corunna Conglomerate, supporting an origin that is pre-Kararan Orogeny. Nevertheless, these structures are thought to provide a primary control and fluid conduits for mineralisation in this mineral system as is evidenced by their vein-hosted nature and proximity to NW- and NE-trending structures.

At Tarcoola, the main mineralising structure is the NNE-trending Perseverance Shear Zone, where mineralisation is dated at 1564 Ma, late in the Kararan Orogeny (Bockmann et al. 2019). The mineralising fluids would have migrated along the NNE-trending structure, which would have been in a suitable orientation for dilation during N-S-directed compression (Budd and Skirrow 2007; Wilson et al. 2018).

The Labyrinth mineral field has NW-trending structures that contain mineralisation. However, these structures are unlikely to have been dilational under N-S-shortening, and may be the result of several processes. First, they may reflect an earlier stage of mineralisation under a different deformational regime. Second, they may represent dilational zones along the Lake Labyrinth Fault, which has common stepovers that could form dilational jogs. Third, the sites of mineralisation may represent low pressure sites where minor NE-trending structures intersect with the NW-trending Lake Labyrinth Fault. Short structures in this orientation can be seen in the aeromagnetic images.

An additional structural element may be the relatively competent GRV which could have acted as a cap that prevented the upward migration of fluids (Potma and Bastrakov 2006). This could potentially have caused the fluids to spread laterally along this boundary.

DEPOSITION

Deposition of mineralisation within this system is strongly controlled by the physio-chemical environments around the mineralised fluids as they pass through. The Tarcoola Blocks and Perseverance deposits have had the most study in this respect, but unfortunately most is anecdotal and has not been published. Gold in the Perseverance open pit at Tarcoola occurs in two main styles, which are both restricted to near the Perseverance Shear Zone. Gold occurs in suphide-bearing quartz veins within the metasedimentary rocks adjacent to the dykes of lady Jane Diorite, and along the sheared margins of the dykes. Disseminated gold occurs in alteration zones along two main sites. First, in bedding-parallel fractures, and the non-conformity at the top of the Paxton granite. Second, at the intersection of conjugate faults that were subsequently intersected by the Perseverance Shear Zone. All these features are generally E-W-striking, and therefore at a high-angle to the NNE-trending Perseverance Shear Zone. It was proposed that fluid flow was largely along the dilational Perseverance Shear Zone, with the intersection with E-W-striking structures forming sites of fluid ponding and mineralisation (Wilson et al. 2018).

BIF units within the stratigraphy are regarded as excellent reductants to Au-rich fluids migrating through the system.

The fluid flow model of Potma and Bastrakov (2006), suggests periods of fluid and pressure accumulation below the GRV would be sporadically released in high, flow-rate ‘escapes’ of fluids to the surface. Systems where this could be demonstrated as happening repeatedly over time are likely to be more strongly mineralised. The Tarcoola deposits appear to be simple systems with only one or two releases of fluids. The Southern GRV systems appear to be more complex. Mineralisation in the Southern GRV MF is located very close to the Uno Fault, which forms a growth fault along the southern margin of the GRV (Werner et al. 2019), and the structures hosting mineralisation may only be locally significant. Alternatively, as the deposits are often associated with tightly folded and dissected stratigraphy, mineralisation could have exploited the reactivation of older structures.

OUTFLOW ZONE/FOOTPRINT

The outflow zones of these mineral systems are not likely to have been preserved. Alteration related to the passage of fluids could be found along structural corridors which would also host mineralisation. The surface alteration of these systems is strongly argillitic and siliceous. This combination is highly prone to weathering and thus is rarely preserved. Paris Ag deposit represents one such system and potential exists for a Au-rich system at depth below the Ag mineralisation. Many places also show alteration due to fluid ponding below the base of the GRV (Tank Hill prospect).

Mineral system distinguishing criteria

HOSTS

The host does not help find gold of the GRV mineralising system, as these deposits have been recognised in a range of rock types and ages, from Archean meta-igneous and metasedimentary rocks of the Mulgathing and Sleaford Complex, to Mesoproterozoic igneous and sedimentary rocks. However, it is likely that the deposits within this mineral system would be spatially related to subvolcanic feeders and high-level intrusions. They may also be hosted with fault zones which cut-across different rock types.

SULFIDES

Gold is largely associated with pyrite and sphalerite. Pyrrhotite, arsenopyrite, galena, and chalcopyrite are less common.

ELEMENTAL ASSOCIATIONS

Gold is commonly associated with Cu, Au, Ag, As, Mo, REE in this type of deposit.

MINERALISATION FORM (VEINS, DISSEMINATIONS ETC.)

Colloform quartz has been recognised at Tarcoola. The nature and frequency of the veins varies strongly between deposits indicating that the deposits in this mineral system form across a wide range of paleodepths. The veins are commonly composed of quartz and carbonate.

ALTERATION

Common alteration minerals include sericite, chlorite, epidote, hematite, silica and carbonate, suggesting argillic and propylitic alteration around these deposits. Unfortunately, the footprint may not be very wide.

SUBSEQUENT DEFORMATION

It is unlikely that the deposits experienced significant post deposition modification. The only recognised younger deformation in the study area is the Coorabie Orogeny, which resulted in local reactivation of existing structures, with no pervasive deformation (Fraser and Lyons 2006).

The key features of the deposits and occurrences examined as part of this review are tabulated for the various mineral fields in Table 3.

Questions for further research

ENERGY SOURCES

Very little work has been done on the energy source for this mineral system, however it is likely that they are related to high-level intrusions and sub-volcanic feeders. Is a certain sized sub-volcanic body necessary to generate and sustain the heat of the mineralising system?

Table 3. Kararan GRV mineral system criteria

Criteria	Tarcoola MF	Labyrinth MF	Southern GRV MF	Glenloth MF
Type deposits	Perseverance, Tarcoola Blocks, Daly's Dream	Minos, North Hicks, Arcoordaby	Weednanna, Parkinson Dam, Uno	Fabian, Royal Tiger, Glen Markie, Kingfisher
Host	Paxton Granite, Tarcoola Formation, Gawler Range Volcanics, Kenella Gneiss	Kenella Gneiss, Glenloth Granite, Lake Harris Komatiite, Hopeful Hill Basalt.	Hutchison Group (carbonates, BIF, gneiss), Corunna Conglomerate, Broadview Schist	Glenloth Granite (Archean)
Vein style	Colloform quartz, Quartz-(calcite-pyrite)	Quartz-pyrite-(carbonate)	Quartz-sulfide, pyrite-chlorite	Quartz-(ironstone/ pyrite?)
Alteration	Sericite, chlorite	Sericite, chlorite, epidote, carbonate, silica	Sericite, chlorite, biotite, silica	–
Sulfides	Pyrite, galena, sphalerite, chalcopyrite, (arsenopyrite)	Pyrite, ?	Pyrite, pyrrhotite, arsenopyrite, galena	Pyrite, ?
Elements (dominant elements in bold)	**Au, Ag**, **Pb, Zn**, Cu, As, Te	**Au, Pb, Zn,** As, ?	**Au, Pb, Zn**, Cu, As, Bi, Sn	**Au**
S Isotopes $\delta^{34}S$ ($^0/00$)	+7.45	–	+7.5, MIF present	–
Style	Oxidised intrusion related (low-sulfidation epithermal)	Oxidised intrusion related (low-sulfidation epithermal)	Oxidised intrusion related (low-sulfidation epithermal)	Oxidised intrusion related (low-sulfidation epithermal, alkalic?)
Mineralisation age	1582 ± 5 Ma	c.1580 Ma	1580 ± 10 Ma (reset?)	1580 ± 10 Ma (reset?)
Temperature	~150-340°	–	~300–400°	–
Depth of formation	<1 km	<1 km	<1 km	<1 km
Post-deposition modification	Negligible	Brittle faulting	Negligible	Negligible

FLUID SOURCES

Little work has been done on the source of fluid. The current data suggests mainly basinal fluids, but it is unclear if there is a magmatic component related to the intrusions. What was the original distribution/thickness of these sediments, and did this affect the migration of the fluids and their composition? Do the compositions of the sediments at Tarcoola, Eba and Corunna influence variations in mineralisation?

Basement lithologies

There is a wide variety of basement lithologies hosting the occurrences attributed to this mineral system. The Tarcoola Formation and Corunna Conglomerate appear to be the hosts which produce the best mineralisation, but the slightly older Labyrinth Formation may also prove to be a suitable source. The known mineralisation along the Lake Labyrinth shear zone does not sit within this formation but below it in the basement. The known outcrop of the labyrinth Formation is to the north of the Lake Labyrinth shear zone. Detailed mapping of outcrop and drill holes in the area may provide some answers as to the proximity and relationship of the Labyrinth Formation to the mineralisation in the area.

The Lake Labyrinth shear zone mineralisation is some of the strongest mineralisation of this type located so far, but it has had almost no research directed towards its origin and potential.

Occurrences

What was the original extent of the GRV, and did this control the distribution of mineralisation? Are there epithermal zones distal to the present GRV outcrop?

Controlling structures

As mentioned above, it has been shown that the Perseverance fault zone at Tarcoola which is parallel to the major 'basement' fault of Daly et al. (1990) is the main fluid conduit for the mineralisation in the area (Pawley and Wilson 2019; Wilson et al. 2018). As this orientation of structure is relatively rare in this area (Fig. 22), are the more common, NNW structures also suitable conduits and hosts for this style of mineralisation?

For deposits associated with high-level intrusion and sub-volcanic feeders, do the structures reflect local stresses associated with the magmatic system, or are the structures controlled by regional stresses? Furthermore, do the magmatic systems have a regional structural control? Are the structures new, or were they reactivated? Is the contact between the Upper and Lower GRV contact a prime site for epithermal mineralisation?

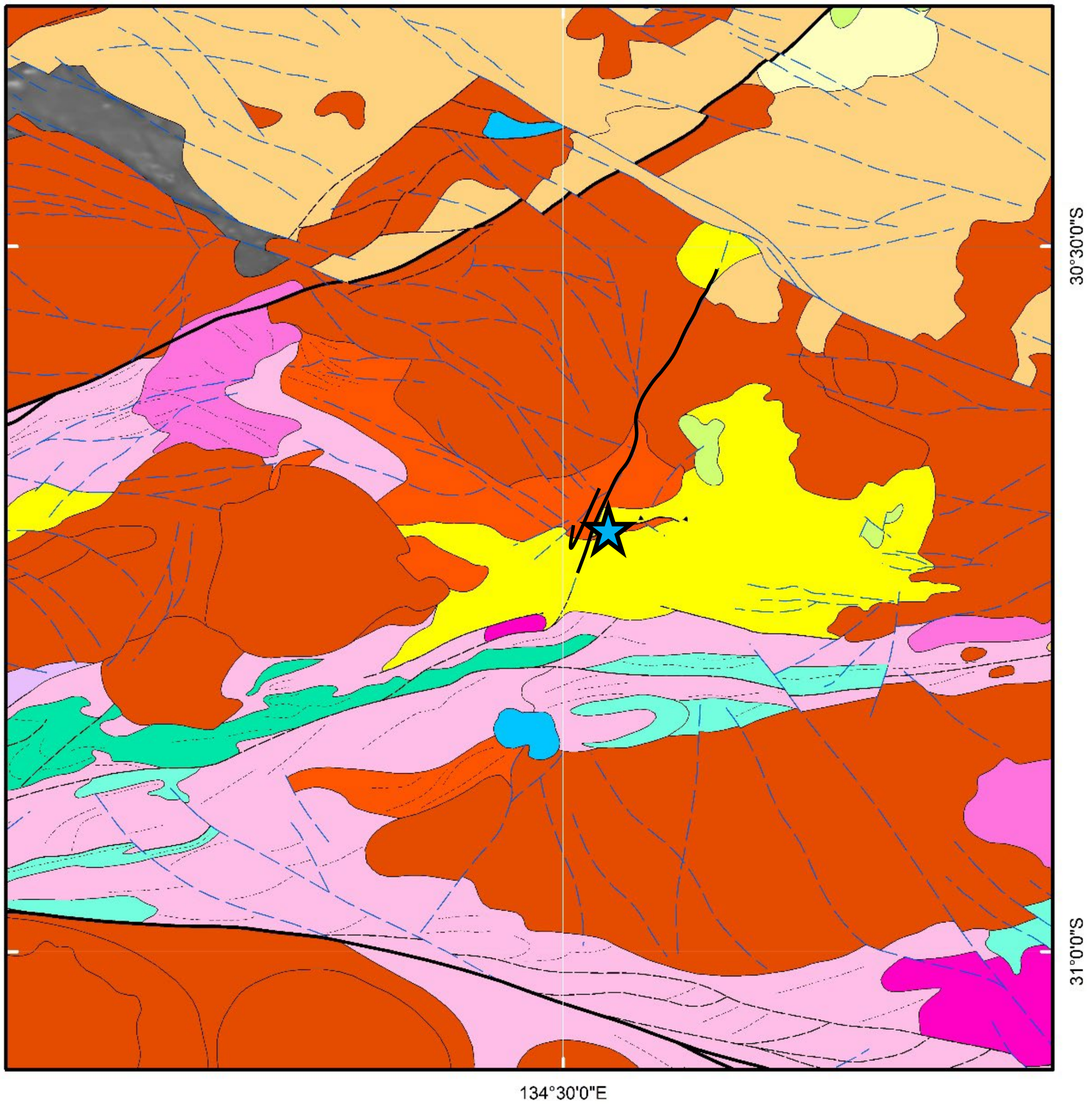


Figure 22. Structural interpretation for the Tarcoola region showing the relationship of the Tarcoola mineralisation (blue star) to the 'basement' fault of Daly et al. 1990 (Pawley and Wilson 2019).

PALEO-DEPTH

The paleo-depth of the various occurrences in this mineral system appear to vary a great deal across the Gawler Craton. Mineral precipitation in epithermal systems is very sensitive to the pressure and temperature variations within the system and areas which appear to be barren can be sitting just above or adjacent to very strongly mineralised regions.

Very little work has been undertaken to determine the variations of paleo-depth across the Gawler Craton. This could be very critical in determining if large gold or base metal systems are located at deeper levels below weaker mineralisation or unmineralised alteration zones across this region.

SULFUR ISOTOPES

Sulfur isotopic data has potential to answer many questions surrounding these mineral systems. The Tarcoola deposit has a reasonable quantity of data but only from a couple of selected locations on the surface and underground.

A broader regional data set would determine how similar other deposits/occurrences are to the Tarcoola system.

Extension of the sulfur isotope data to examine sulfur sources in different areas of the Weednanna deposit may also shed further light on the origin of this complex system.

Another question that can potentially be answered by the isotopic data would be the relative contribution of metals to the deposits from magmatic versus basement sources. A comprehensive data set from basement lithologies distal to known mineralisation would be very helpful in understanding this contribution to the mineral systems.

AGES

Further geochronology is required to confirm that the mineralisation in the Labyrinth mineral field does belong in this system. There are several other occurrences of mineralisation in the area which do not have enough information to classify (e.g. Glenloth / Earea Dam). Targeted geochronology would help with assigning these deposits to a mineral system.

Initial $^{40}Ar/^{39}Ar$ dating suggests an age of 1590–1570 Ma for mineralisation at Tarcoola, Tunkillia, Barns, Weednanna and Nuckulla Hill, but this may have been reset (Fraser 2004). Recently, mineralisation at Tarcoola has been constrained at 1564 ± 15 Ma (Bockmann et al. 2019). This is significantly younger than the age of the c. 1582 Ma for the lady Jane Diorite (Budd 2006), which hosts mineralisation. Are there multiple events within this mineral system? Can they be divided based on whether there is exclusively a structural control (e.g. Tarcoola), or whether there is a strong input from the volcanic system?

Exploration guidelines

LITHOLOGIES

Previous work has shown the importance of certain basement lithologies in sourcing and hosting mineralisation in the Kararan (GRV) mineral system (i.e. Tarcoola Formation and Corunna Conglomerate). Further research and exploration is likely to determine the relative importance of other basement lithologies as well. Some lithologies (i.e. Glenloth Granite, Labyrinth Formation) have a vague or spatial relationship with mineralisation which has yet to be clearly defined. All these lithologies are prime exploration targets, particularly where they are cut or bounded by regional structures.

The western side of the GRV appears to have generally thinner flow thicknesses which may have been related to this region being an upland during eruption of the volcanics. Potential exists for mineral systems to be preserved under these outcrops adjacent to major structures.

VEIN SYSTEMS

A common feature of many of the deposits within this mineral system is the presence of epithermal textures within the veins. The nature and frequency of the veins varies strongly between deposits indicating that the deposits in this mineral system display a wide range of paleodepths. Unfortunately, in many of the deposits, there is a lack of investigation to determine whether the epithermal veins are genetically associated with the mineralisation or are just overprinting at a later stage and further research is required.

Epithermal systems are also generally very sensitive to variations in pressure and temperature controlling the deposition of metals. Once epithermal veining has been located, detailed examination of the alteration mineralogy and vein textures may be required to vector into the portions of the vein system which are economically mineralised (Corbett 2002).

The vein textures can also provide a quick guide as to the style of mineral system present as shown in Figure 23.

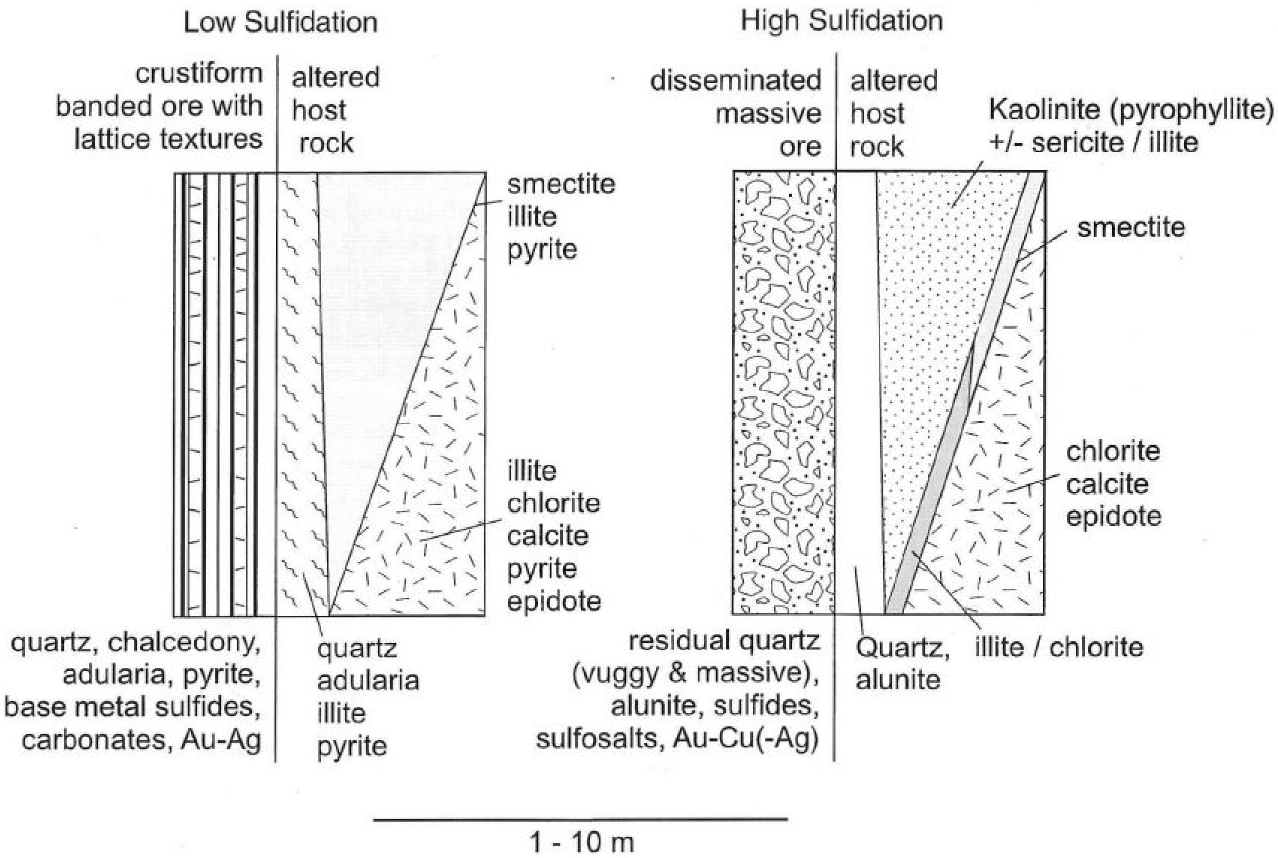


Figure 23. Schematic diagram showing mineralogic zoning in low- and high-sulfidation epithermal deposits (Cooke and Simmons 2000 after Sillitoe 1993).

PATHFINDER ELEMENTS

There are many pathfinder elements which can be used to determine where a particular sample comes from in an epithermal system. Unfortunately, epithermal system are some of the most complex and 'messy' mineral systems with complex overprinting relationships derived from multiple pulses of volcanic activity. Several principles can be broadly applied to assist with unraveling where the highest grade mineralisation might be concealed.

In low sulfidation systems (Fig. 20), which are the majority of GRV hosted systems, Ag, Zn and Pb are major components of the mineralisation. The ratio of Au:Ag increases towards the surface with the Paris Ag deposit (Investigator Resources 2017) being an example of a Ag-rich system now found very close to the surface. Other minor elements present in these systems include As, Te, and Cu, with anomalous Bi and Ce in some cases (Weednanna and Minos), which are generally more typical of high sulfidation systems.

Generally low sulfidation systems are associated with Au, Ag, Zn, Pb (anomalous Sb, As, Hg, Se, K), high Ag/Au, low Cu, low Te/Se and high sulfidation systems are associated with Cu, Au, Ag, As (anomalous Pb, Hg, Sb, Te, Sn, Mo, Bi), high Te/Se, low K, Zn, Ag/Au. These metal associations have not been well defined in many of the deposits investigated during this study, mainly as assay results for many of these elements are not publicly available. Re-analysis of existing core/pulps may be the best method to develop a deposit scale map of elemental variations which could then allow vectoring towards high-grade zones as yet undiscovered in these systems.

STRUCTURES

Several of the deposits exhibit a strong regional structural control on mineralisation. Tarcoola is associated with secondary structures (i.e. the Perseverance Shear Zone) that are sub-parallel to a major NNE-trending structure. This trend would be dilational and therefore optimally oriented for fluid flow during the NS-directed shortening that prevailed at this time. As structural intersections on the mesoscale in the Perseverance pit and Tarcoola Block underground are seen to be sites of higher grade mineralisation, regional scale junctions could host major deposits. Many of these have not yet been explored.

The mineralisation in the Labyrinth MF is generally located along the NW-trending Lake Labyrinth Fault, often at the intersections with minor NE-trending structures. This suggests that structures that are nearly north-trending, and intersection of conjugate structures may be worthwhile targets.

ALTERATION MINERALOGY

As alteration mineralogy is the key to locating the high-grade portions of epithermal systems (Fig. 23), spectral mapping of the variation in alteration within these deposits may be the best method for defining the overall deposit alteration.

Currently very little spectral mapping has been undertaken across the deposit within these mineral systems. As part of a recent core workshop, example holes from within as many deposit styles as possible was undertaken. This has provided clear evidence of the usefulness of this method with alteration halos being recognised for the first time in many deposits (e.g. siderite in Minos).

Further scanning of core and chips from various deposits will provide an excellent vectoring tool to use in the location of high-grade mineralisation.

GEOPHYSICS

These systems are particularly hard to target with geophysical exploration methods. Systems which detect conductive targets could detect various parts of the alteration system but not necessarily the mineralised portions. Graphitic units in the Proterozoic basement provide further challenges to applying electrical techniques. If the basement geology is well understood, methods such as IP have been used with a reasonable level of success however it is recommended that a highly experienced geophysicist familiar with the area be used for interpretation of results.

The most reliable geophysical method would be the use of detailed (<100 m line spacing, <50 m height) aeromagnetic data to define potential mineralising structures and alteration zones. Intersections of sub-ordinate structures and geochemically reactive lithologies with these primary fluid conduits are likely to present the best targets.

The recently acquired GCAS data (Katona 2019, Pawley and Wilson 2019), which is publicly available, provides an excellent tool for reanalysis of many parts of the Gawler Craton for suitable targets (Fig. 24).

Electrical methods such as CSAMT have been used to great effect in locating zones of conductivity associated with alteration and mineralisation within shear zones. This would be an ideal method to locate structural targets to test below moderate cover. This type of system has not previously been used in the Gawler Craton and presents an excellent opportunity for extending exploration coverage across the region. There are also several other related electrical methods which may be of use in this area.

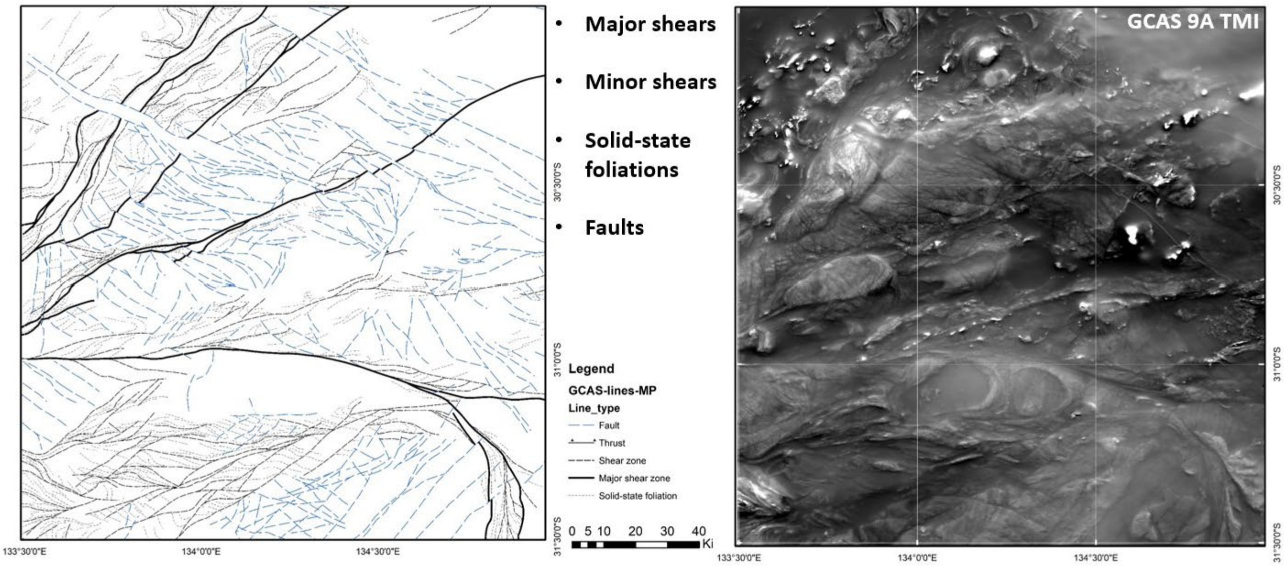


Figure 24. Example of new GCAS TMI data around Tarcoola region (Pawley and Wilson 2019).

KARARAN (HILTABA) INTRUSIVE SUITE MINERAL SYSTEM

The Kararan (Hiltaba) Intrusive Suite mineral system is defined as all the mineral systems related to Hiltaba Suite intrusive magmas. The Olympic Cu-Au Province has been included as a mineral field, although this has previously been described in its own right (Skirrow 2010; Skirrow et al. 2018). The Western Gawler MF covers the rest of the Gawler Craton, with two subdivisions: the Tunkillia and Wudinna mineral fields which cover specific regions (Figs 4 and 25).

The Western Gawler MF is very broadly defined and covers the known outcrop/subcrop of the Hiltaba Suite intrusives to the west of the Olympic MF. Only a handful of gold occurrences have been attributed to this system and most are very poorly defined (e.g. the Pureba prospect; Emslie and Taylor 2000). Many of the attributes linking these occurrences to Hiltaba intrusives may be wishful thinking on the part of the over enthusiastic geologist logging the chips on the rig. Much more analysis is required to confirm the extent and nature of this system.

The Tunkillia and Wudinna mineral fields have tentatively been included in this mineral system, as the mineralisation has much more in common with intrusive-related gold systems than epithermal gold systems, but these deposits may represent a continuum with the epithermal systems. However, recent geochronology (Justin Payne pers. comm.) has suggested that mineralisation at Barnes may be of similar age to the Tunkillia Suite, indicating an older phase of mineralisation. It is noted that aspects of the occurrences within the Wudinna mineral field share many similarities with intrusion related or intrusion-hosted systems in the Tanana-Yukon Domain (e.g. Donlin Creek, Pogo, Hart 2005a).

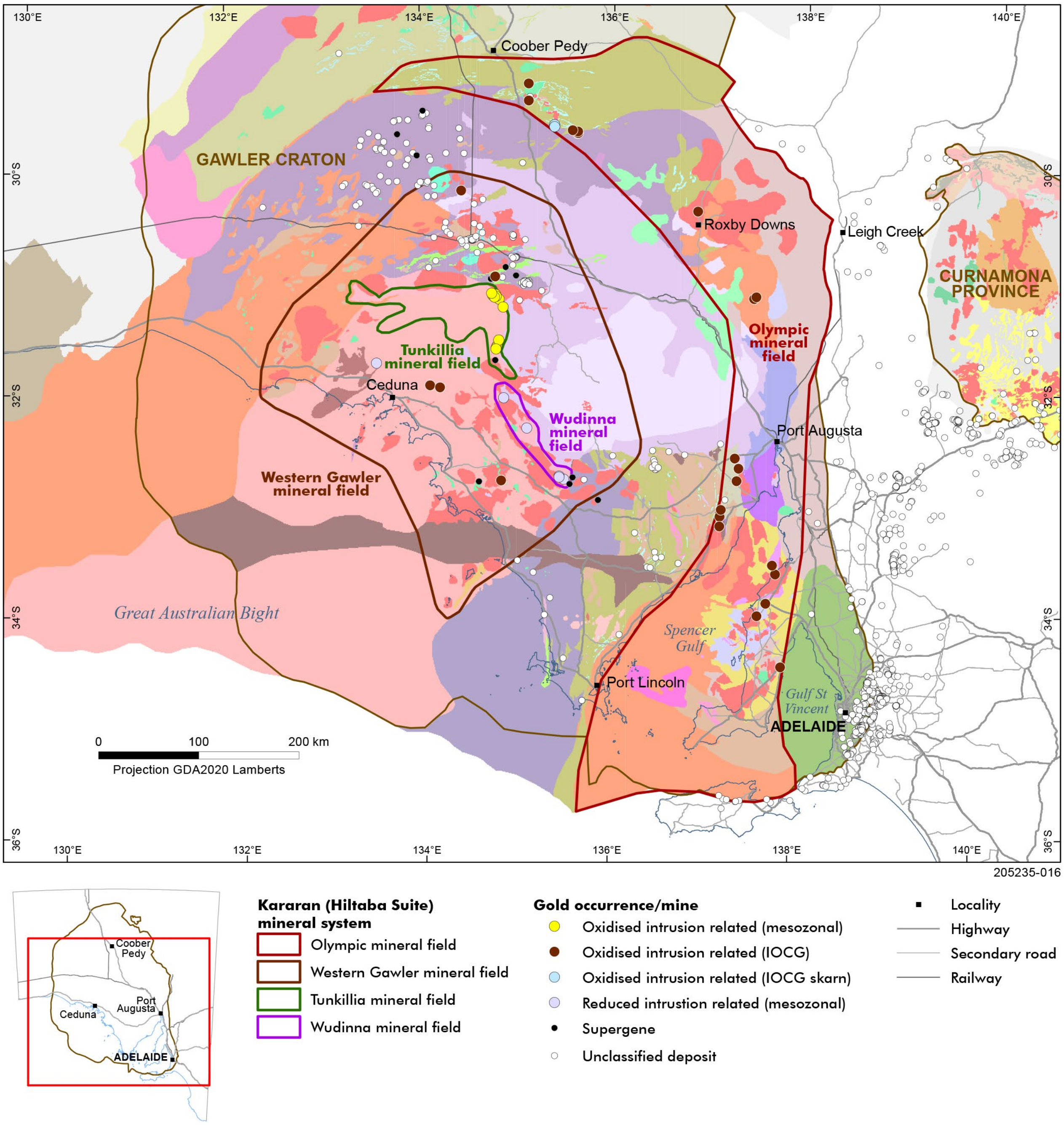


Figure 25. Hiltaba gold mineral system and fields of the Gawler Craton.

Mineral system model

The mineralisation grouped into this system generally has the character of a reduced intrusion-related system (RIR). This style of mineralisation is associated with equigranular, multiphase, moderately reduced granodiorite-granite stocks and batholiths (Figs 26 and 27; Robert 2007). The gold mineralisation is commonly associated with sericite-carbonate alteration and pathfinder elements include Bi, W, As, Mo, Te and in some cases Sb.

Mineralisation is hosted by a range of rock types, including ultramafic to felsic intrusive and extrusive igneous rocks, and sedimentary rocks. The host rocks range in age from Archean to Mesoproterozoic.

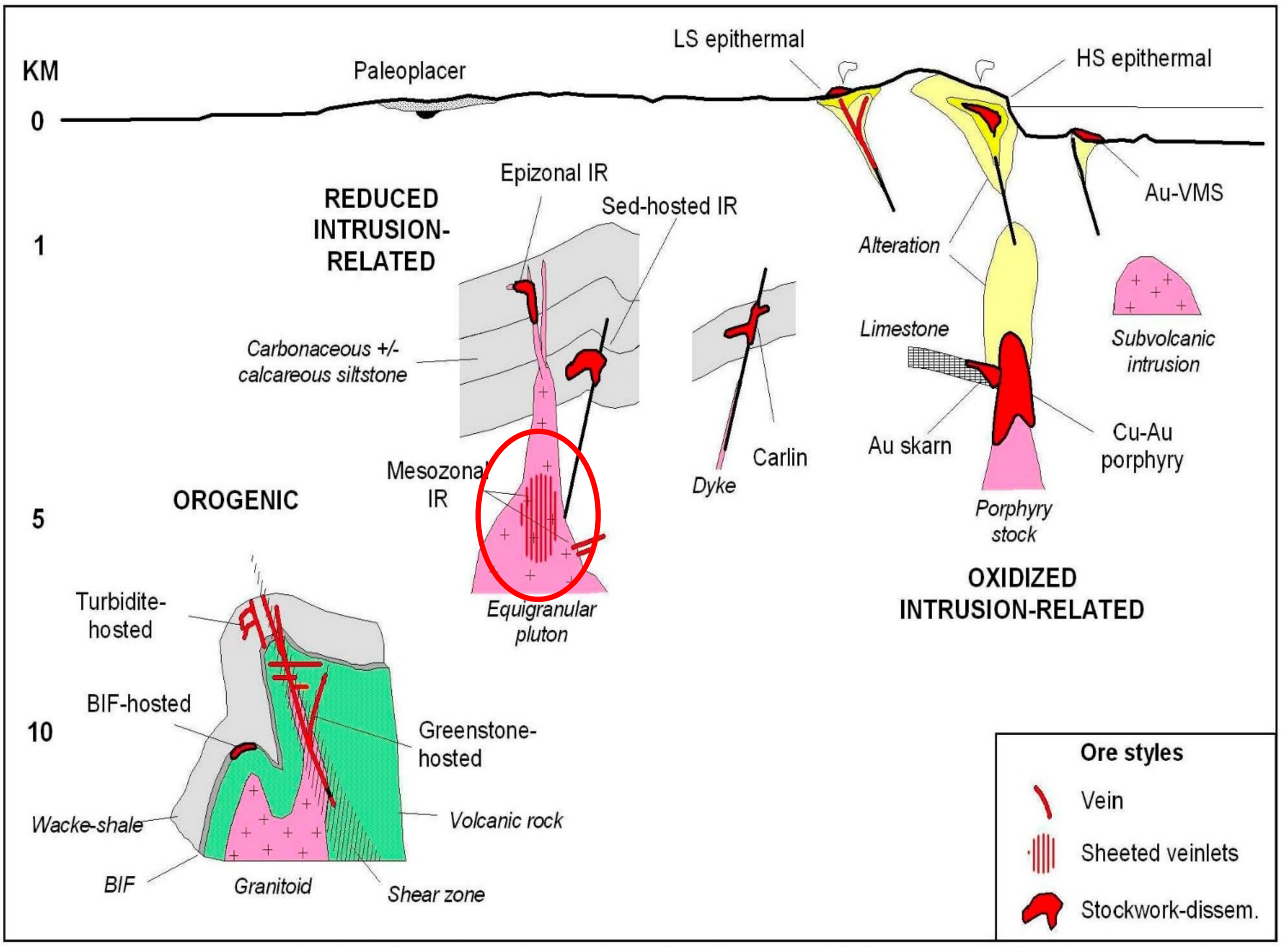


Figure 26. Gold mineral system classification scheme showing the Hiltaba Mineral system (Robert et al. 2007).

ENERGY SOURCE

The energy source is considered to be the intrusive bodies themselves, as the mineralisation is spatially associated with the intrusions and either occurs within the magmatic body or within 1-2 km of the intrusion's margins. The majority of the mineralisation seen in this system occurs outside of intrusions and in most cases, the source intrusion is difficult to determine. However, no specific research has been conducted into which intrusive bodies may be the source of the fluids forming the occurrences in this mineral system. As mentioned above, Tunkillia Suite intrusives may be associated with mineralisation within the Tunkillia and Wudinna mineral fields.

FLUID/METAL SOURCE

The mantle below the Gawler Craton has become increasingly more evolved and enriched in metals during the approximately one and a half billion years of magmatic record that is preserved across the region (Wade 2012). This provides the proposed source of metals for the formation of both the world class IOCG mineral systems of the Olympic mineral field as well as the Hiltaba-aged gold systems.

Sulfur isotope analysis at Tunkillia and Barns (Fig. 11) suggest a magmatic source for the sulfur and presumably also the metals supporting the intrusion-related model. This is supported by fluid inclusion data which shows only a magmatic input (Ferris and Wilson 2004).

Unlike sulfur isotope values from IOCG systems where complex mineralisation histories down both oxidizing and reducing pathways have evolved very complex and diverse distributions of sulfur isotope values (Schlegel et al. 2016), the sulfur isotope distributions from the gold deposits so far studied show very homogeneous population with relatively simple mineralisation histories, indicating the primary source of the sulfur is magmatic.

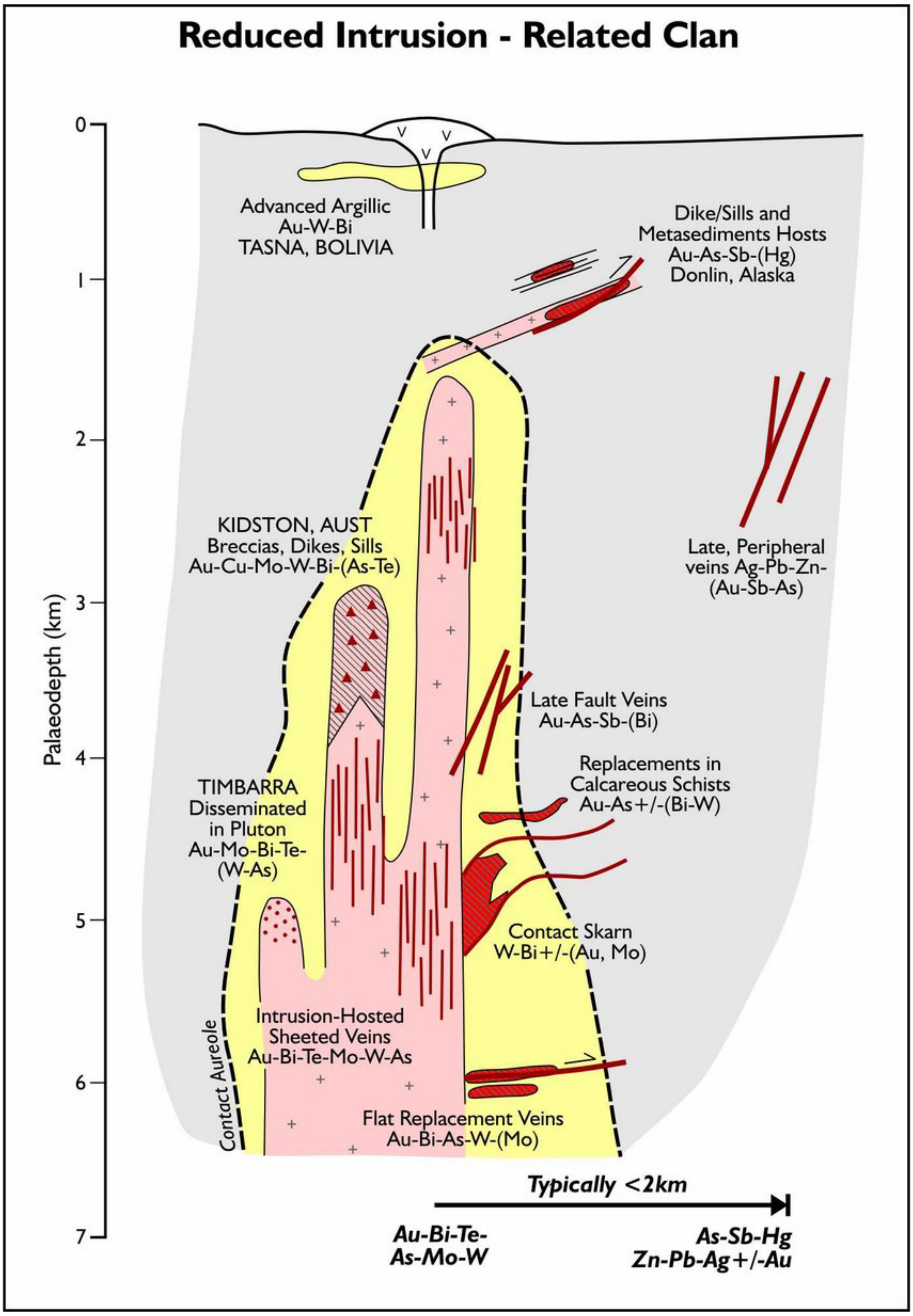


Figure 27. Reduced Intrusion related mineral system model (Robert et al. 2007).

MIGRATION PATH

This type of mineral system does not specifically require large scale structural conduits for fluid migration from the source to the deposition site, as they can exploit volcanic centres, magmatic plumbing and structures. However, there may be a connection between these paths, as the intrusion of Hiltaba Suite magma, although widespread across the Gawler Craton, is commonly focussed on major regional structures. These structures were frequently reactivated and would have made excellent conduits for migrating mineralising fluid and may explain why there is no close association between intrusions and mineralisation. The Tunkillia MF is an example of this relationship, with the deposits focussed along the Yarlbrinda Shear Zone (Ferris and Wilson 2004).

Globally, there are numerous examples of this type of mineralisation where the host intrusive bodies have been localised along structural corridors (e.g. Tintina Belt, Alaska; Hart et al. 2000).

DEPOSITION

Deposition of mineralisation within the Intrusion Related/Hosted systems is much less energetic than other gold systems and is generally controlled by cooling paths and subtle pressure changes. Metals and volatiles are concentrated in the roof zone of the cooling felsic intrusive. Systems of sheeted vein sets form within the cupola of the parent intrusion or within structural traps in country rock within two kilometers of the parent intrusion (Figs 27 and 28). These systems develop a wide range of mineralisation styles and geochemical associations depending on emplacement depth of the parent intrusion which makes the system difficult classify.

Mineralisation in the Tunkillia and Wudinna mineral fields are mesozonal, suggesting they formed at, or just above the brittle-ductile transition (Fig. 26). In contrast, mineralisation at Olympic Dam occurred under brittle conditions at 2–4 km depth (Courtney-Davies et al. 2020).

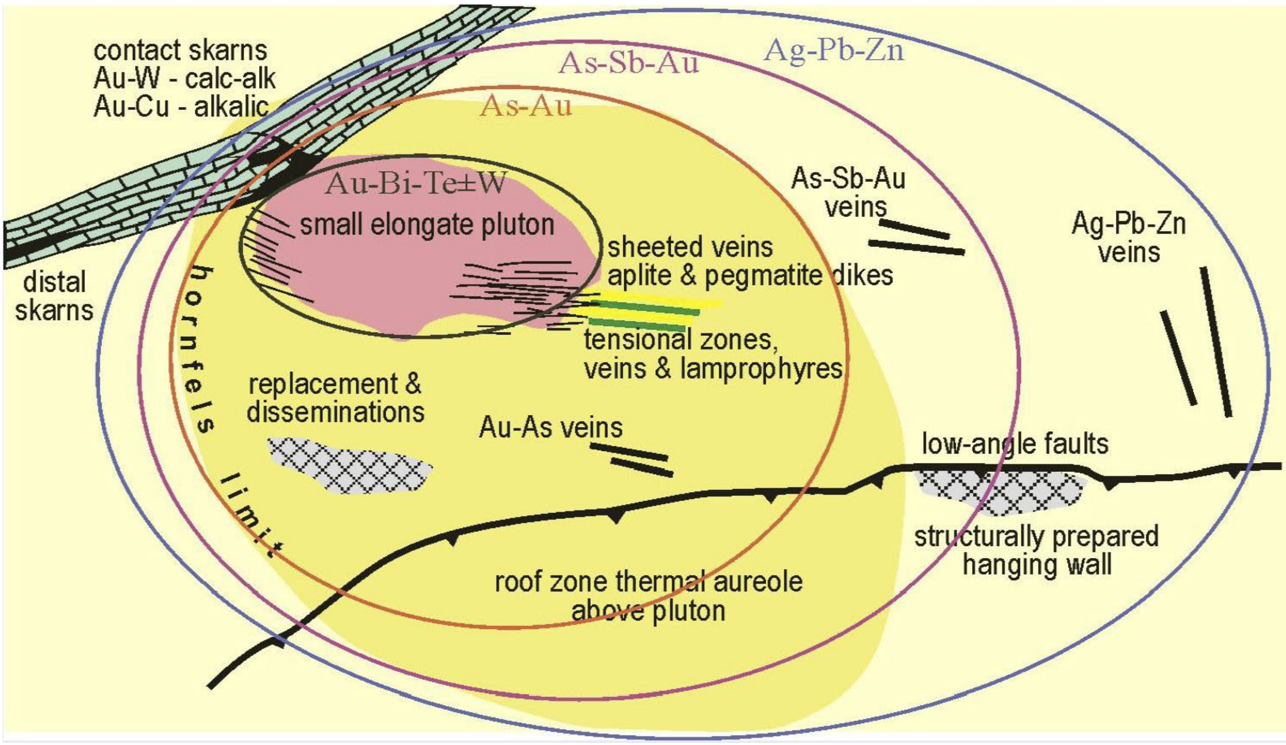


Figure 28. General plan model of intrusion-related gold systems (Hart 2005a).

There is commonly evidence of fractionation and fluid exsolution (pegmatites, unidirectional solidifying textures and miarolites) associated with the mineralising event. The strong structural control on these deposits means they are often situated within regional scale shear zones (Fig. 29).

The mineralisation associated with this system generally has very low sulfide contents (<5 volume %).

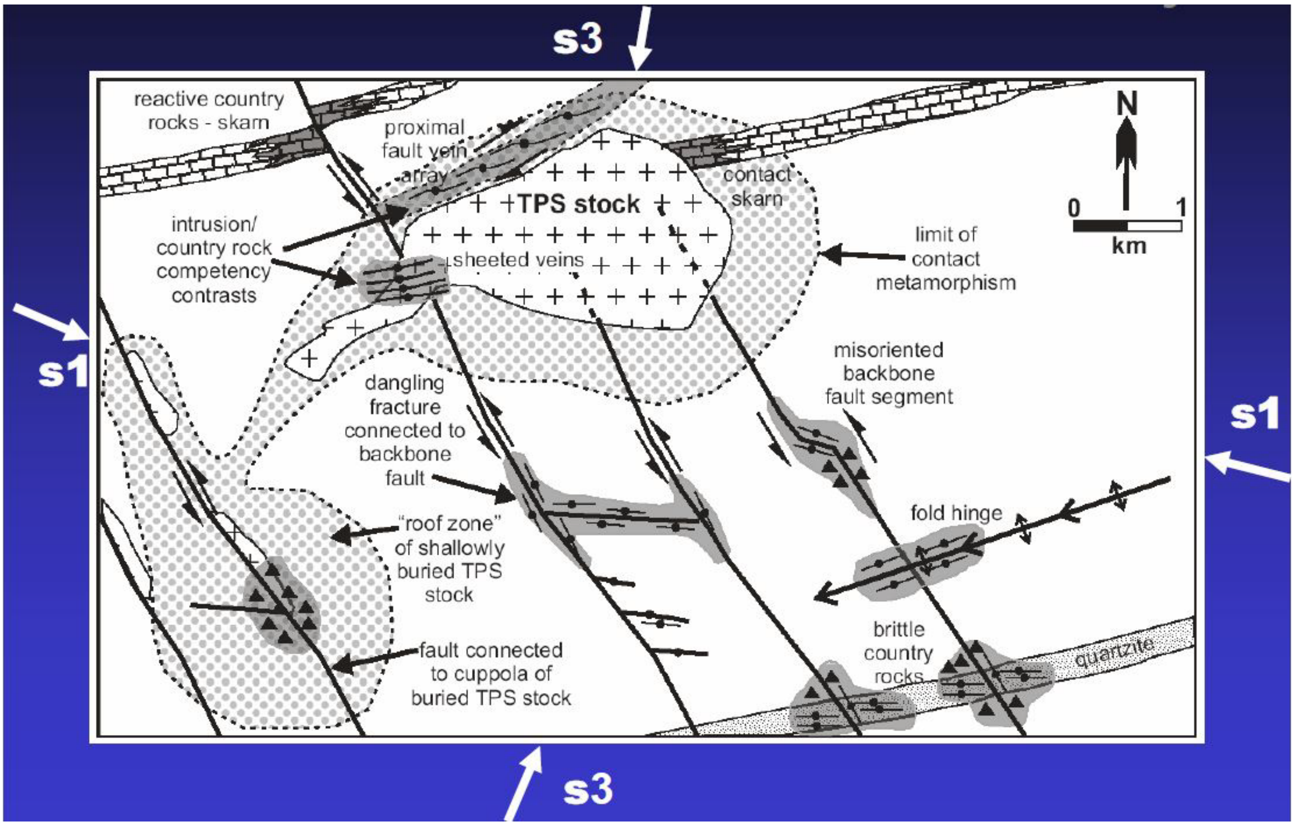


Figure 29. General plan model of structural controls on deposition of intrusion-related gold systems (Hart 2005b).

OUTFLOW ZONE/FOOTPRINT

This type of mineralisation can have reasonably wide alteration halos of typically carbonate/sericite alteration which can be used as a vector towards mineralisation. The mineralisation within the Tunkillia mineral field is typically associated with wide zones of alteration within the shear zone (Ferris and Wilson 2004).

Mineralisation in the Western Gawler MF is much more poorly constrained. It is generally reported as associated with hematite alteration however the preliminary stage of exploration around these occurrences suggests that this needs to be confirmed.

SUBSEQUENT MODIFICATION

An interesting feature of the Tunkillia mineral field is the mylonitic deformation that has overprinted mineralisation (Ferris and Wilson 2004). Generally, Kararan deformation is much lower grade, however the Mineral Systems Drilling Program intersected mylonitic deformation of sediments associated with the Corunna Conglomerate within a NS-trending structure around Mt Allalone (Fabris et al. 2017). This was attributed to strain partitioning which could explain the high strain in the Tunkillia MF. The alternative interpretation is that the mineralisation is actually older (Justin Payne pers. comm.) and may represent an Intrusive Related system associated with the Tunkillia Suite (~1685 Ma). The deformation could be associated with the waning stages of the Kimban deformational event and it may have downgraded the mineralisation by shearing out the orebody. It may have also been deformed during the Kararan Orogeny further downgrading the system. Again, further research is required to determine exact origin of the mineralisation within this particular mineral field.

Mineral system distinguishing criteria

The mineralisation grouped into this system have the character of intrusion-related deposits and include both reduced and oxidised systems. The mineralisation is commonly associated with equigranular, multiphase, moderately reduced granodiorite-granite stocks and batholiths (Robert

2007). Gold mineralisation is commonly associated with sericite-carbonate alteration and pathfinder elements include Ag, Cu, Bi, Mo, and in some cases REE.

The key features of the deposits and occurrences examined as part of this review are tabulated for the various mineral fields in Table 4.

Table 4. Hiltaba gold mineral system criteria.

Criteria	Western Gawler MF	Wudinna MF	Tunkillia MF	Olympic MF
Type deposits	Yumbarra, Pureba, Yerda West	Barnes, Baggy Green, Toondulya	Tunkillia Area 191, Tomahawk, Myall, Sheoak	Olympic Dam, Carrapateena, Prominent Hill
Host	Hiltaba Suite, Nuyts Volcanics, St Peter Suite, Kenella Gneiss	Tunkillia Suite (felsics), Hiltaba Suite (mafics, ultramafics), Broadview Schist.	Tunkillia Suite felsics and minor mafics (Hiltaba Suite?)	Hiltaba Suite, Donington Suite, Wallaroo Group, Gawler Range Volcanics, Broadview Schist
Vein style	Quartz-(pyrite), ?	Quartz-pyrite	Quartz-pyrite-(galena-sphalerite)	Calcite-barite-fluorite-haematite-chalcopyrite veins
Alteration	Hematite, sericite, chlorite, silica	Sericite, chlorite, biotite	Sericite, chlorite, hematite, silica, (epidote)	Hematite, chlorite, sericite, carbonate
Sulfides	Pyrite, ?	Pyrite, chalcopyrite, galena	Pyrite, galena, sphalerite	Chalcopyrite, pyrite, bornite
Elements (dominant minerals in bold)	**Au**, Ag, Zn, Pb, ?	**Au**, Ag, Cu, Pb, Bi, Mo	**Au, Ag**, Pb, Zn, Sb, La	**Cu, Fe, Au, U**, Ag, La, Ce, Te
S Isotopes $\delta^{34}S$ ($^{0}/00$)	–	+1.15	+0.09	-8 to +12
Style	Oxidised intrusion related (mesozonal? IOCG?)	Reduced intrusion related (mesozonal?)	Oxidised intrusion related (mesozonal?)	Oxidised intrusion related (IOCG)
Mineralisation age	c. 1590 Ma?	c. 1590 Ma?	1580 ± 10 Ma (reset?)	c. 1590 Ma?
Temperature	–	–	~300–400°	Mixing >400° / <100°
Depth of formation	–	>1 km	>1 km	0.5–2 km
Post-deposition modification	Fault brecciation, none?	Greenschist to granulite metamorphism	Mylonitic shearing	Fault brecciation, groundwater infiltration

Questions for further research

TIMING

What is the age of deformation and mineralisation at Tunkillia? Previous work has shown that there is evidence of Kararan age sericite alteration associated with the deposit, but this seems to be present on the majority of mineral deposits across the Gawler Craton. In many cases this is likely to be a subsequent overprint. Recent high-precision TIMS geochronology (Justin Payne pers. comm.) has suggested that the mafic dykes within the shear at Tunkillia which intrude the mineralisation are latest Kimban age. If this is the case, how many other deposits have been incorrectly assumed to be associated with the Hiltaba Suite magmatic event?

MINERALISATION STYLE

Although the Tunkillia and Barnes/Baggy Green mineralisation has been assigned as mesozonal intrusion related, questions remain as to the timing and style of mineralisation, with Kimban (Peter Pan Supersuite related) or post-Kimban (Tunkillia Suite related) ages possible. It is likely that further work would enable additional subdivision.

FLUID SOURCES

Ferris and Wilson (2004) studied the fluids associated with the Tunkillia deposit and concluded that only magmatic fluids were present. However, mineralisation in this system could be derived from several possible magmatic events (Peter Pan Supersuite, Tunkillia Suite, St Peter Suite or Hiltaba Suite). Are there any differences in the magmatic fluids derived from these magmatic suites which could be used to determine their origin?

Further work looking at variations in sulfur isotope values across some of the larger mineralisation occurrences (i.e. Tunkillia and Barnes) in addition to extending the coverage to other mineral occurrences would potentially help to determine the origin of the magmatic fluids associated with these deposits.

OCCURRENCES

The Western Gawler MF is primarily defined on five very early stage exploration targets. Are there any other occurrences in this region which could help to define the mineral system? Further exploration on these known targets or discovery of a new system could significantly aid the definition of this mineral field or even split it into several mineral fields.

CONTROLLING STRUCTURES

The Yarlbrinda Shear Zone has a clear association with the Tunkillia and Nuckalla Hill deposits, however it is unclear as to whether the shear zone controlled primary mineralisation or resulted in subsequent downgrading. Gold mineralisation at the Barnes deposit is associated with shears evident in drill core however at a macro-scale, shear zones are not seen in regional magnetic data so it is hard to determine their significance in a regional context. Further work in this area may define particular orientations of structure that are more likely to host mineralisation. Figure 29 shows the significance of the structural regime in intrusion related systems elsewhere, underlining their importance to this style of mineralisation.

Exploration guidelines

LITHOLOGIES

This mineral system is primarily hosted in felsic intrusive bodies. There is a great diversity of ages of felsic intrusives within the Gawler Craton. To ensure the optimal exploration strategy is being used to discover mineralisation, it is essential to understand the host intrusive that is being explored. There have been many recent publications on the geochemical and isotopic characteristics of the various intrusive suites across the Gawler Craton (e.g. Reid et al. 2020; Wade 2012; Payne et al. 2010; Budd 2006). These provide valuable reference material in determining the origin of host intrusives. Geochronology can also assist with this process so long as representative samples are analysed.

The broad belt of Tunkillia Suite intrusives which hosts the Tunkillia and Wudinna MF is a key characteristic in defining the boundaries of those mineral fields. The Tunkillia Suite extends much further to the west and there are probably many more intrusive bodies which have not yet been positively identified. This is a key host to mineralisation and should be ranked very highly in regional target generation.

Intrusion related systems elsewhere in the world commonly develop skarn and carbonate replacement mineralisation where the parent magmatic bodies have intruded carbonate-rich lithologies. The Weednanna deposit has been described as this type of mineralisation, but the causative magmatic event introducing the mineralisation is yet to be determined. The frequency of carbonate-rich lithologies within the Hutchison Group in particular means that skarn mineralisation should be common close to intrusive bodies and may provide an indication of additional mineralisation styles associated with the same intrusion.

VEIN SYSTEMS

These systems generally do not have a large amount of quartz veining associated with them and consist of sheeted sets of narrow veins (<10 cm). It is often the smaller veins which host higher grade mineralisation. Vein intersections also host higher grades however these are difficult to target in an exploration environment.

ALTERATION

Alteration haloes to vein systems are typically narrow and primarily consists of sericite, although broader zones of weak sericite alteration have been defined at the larger deposits. The degree of post-mineralisation overprinting alteration is uncertain.

PATHFINDER ELEMENTS

Pyrite is the main ore mineral in these systems. The pathfinder element suite recorded to date is typically restricted to Ag, Pb, Zn and Cu. Some deposits show correlation of Sb (Tunkillia) or Bi (Barnes) with Au mineralisation and these are key elements to use for these specific mineralisation styles.

Arsenic does not show a strong association with mineralisation and it is unclear as to why this might be the case.

Tellurium and W are often associated with the very proximal, intrusion-hosted systems. These have not been extensively assayed for in these mineral fields and may be a useful indicator of mineralisation that has been overlooked

STRUCTURES

The Yarlbrinda Shear Zone hosts several mineral systems and sections of this structure have been prospected intensively during the 1990s. Much of the structure's length has only seen geochemical exploration, with no exploration along its southern extent.

No other structures have been positively identified as being significant hosts to Au mineralisation. It appears that deposits such as Barnes are closely associated with small scale shears, suggesting that small scale dilational traps (Fig. 29) are the best targets for this style of mineralisation. Detailed structural interpretation and a good understanding of the compressional stresses at the time of mineralisation are essential for successful targeting. However, it is essential to know the correct timing of mineralisation so that the correct stress regime for the mineral system is chosen.

GEOPHYSICS

As with the other Au mineral systems, the low sulfide contents and lack of strong alteration associated with these systems makes targeting with geophysical methods difficult. Where alteration is more broadly developed, there is a strong suggestion that this is due to later overprinting which may have downgraded the mineralisation.

Airborne magnetic data combined with detailed gravity is excellent at mapping the regional geology including intrusive bodies which may potentially be mineralised. Electrical methods such as IP or CSAMT could then be used to select structures with conductive zones which may represent either sulfide or alteration. Unfortunately, the very weak response from the mineralisation typically developed in this type of system means that it is very difficult to distinguish from other weak conductors such as saline groundwaters.

CONCLUSIONS

This project has completed a regional investigation into the gold mineralisation of the Gawler Craton. It is the most comprehensive project to compare the various styles and ages of mineralisation across the craton undertaken to date.

A significant goal of this investigation was to determine if the preliminary classification of the Central Gawler Gold Province (Budd 2002) was still applicable. This investigation has shown that this model was an oversimplification of the combination of several different mineral systems. The various mineral systems cover the majority of the Gawler Craton and rather than a narrow band around the edge of the GRV outcrop, the entire area of the Craton has strong potential to host gold-dominant mineralisation. This includes the Olympic MF which is the focus of IOCG exploration that are major gold systems in their own right. IOCG-style mineralisation has not specifically been included in this investigation as it has been the focus of many other more in-depth studies elsewhere. The depth of cover is a significant obstacle for exploration in the Olympic MF for Au-dominant mineralisation, but it does not exclude the possibility of these deposits existing in this region.

Despite the attempt to cover the entire spectrum of mineralisation styles across the Gawler Craton, the lack of data in many areas has meant that this classification of mineral systems can only be regarded as preliminary. Current research by the University of South Australia indicate that an additional period of mineralisation associated with the Tunkillia Suite is possible and could potentially be added to future iterations of this mineral system classification.

This investigation has shown that many mineral systems in the Gawler Craton have undergone complex histories with some being overprinted with multiple mineralising events over wide time intervals. This appears to be due to major, regional-scale structures being reactivated multiple times throughout the cratons history as well as being due to the lower crust and upper mantle beneath the craton being a strongly enriched source for mineralising fluids (Wade 2012; Skirrow et al. 2018). Wade (2012) demonstrated the crust and lithospheric mantle below the Gawler Craton has either been progressively enriched and fertilised or maintained its enrichment over extended periods of time. If this is the case, then any magmatic event with a component derived from this enriched lithospheric source is likely to have potential to be mineralised. Evidence is building that the Tunkillia Suite may also be associated with a significant mineral system, similar to the Tanana-Yukon Belt in North America. The Tunkillia and Barnes/Baggy deposits have many similarities with Intrusion Related/Hosted deposits of this belt (e.g. Donlin Creek and Pogo).

Base metal skarn mineralisation has been discovered that is associated with the Peter Pan Suite (Reid et al. 2009; Fabris et al. 2017). This is a significant step in defining a separate mineral system associated with this intrusive event, although no gold mineralisation has been located.

No mineralisation has been conclusively assigned to the St Peter Suite, possibly due to the level of exposure of the plutons, but the potential exists for this magmatic event to also host Au mineralisation. Porphyry systems mainly sit just above or within the top of the source intrusives. Many of the St Peter Suite intrusives appear to be exposed to quite a deep level, particularly along the west coast of South Australia where most of the known outcrops occur. This deep level of exposure down-grades the chances of preserved mineral resources. The Nankivel Intrusive complex was not recognised as St Peter Suite until recently and represents the most eastern occurrence of this intrusive suite. Given that it is likely that additional St Peter Suite intrusives are yet to be found and that different levels of the intrusive system may be preserved elsewhere, the mineral potential of this suite is yet to be adequately determined. Because of the very poor outcrop of the majority of this suite and lack of distinct visual characteristics, it is difficult to define the potential extent of the system.

The mineral systems defined in this report cover many areas that have, to date, been poorly or unexplored for gold mineralisation. This report highlights the many exploration opportunities that the Gawler Craton still presents to the modern explorationist. Many of these require the collection of diverse datasets and an understanding of the complex geological history of the Gawler Craton and its Au mineral systems.

Numerous knowledge gaps and opportunities highlighted in this report provide future avenues for research and ideas for improved Au exploration in the Gawler Craton.

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APPENDIX

INDIVIDUAL OCCURRENCE SUMMARY TABLE

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