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Focus Paper

Structural geometry of orogenic gold deposits: Implications for exploration of world-class and giant deposits

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A R T I C L E I N F O

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A B S T R A C T

With very few exceptions, orogenic gold deposits formed in subduction-related tectonic settings in accretionary to collisional orogenic belts from Archean to Tertiary times. Their genesis, including metal and fluid source, fluid pathways, depositional mechanisms, and timing relative to regional structural and metamorphic events, continues to be controversial. However, there is now general agreement that these deposits formed from metamorphic fluids, either from metamorphism of intra-basinal rock sequences or de-volatilization of a subducted sediment wedge, during a change from a compressional to transpressional, less commonly transtensional, stress regime, prior to orogenic collapse. In the case of Archean and Paleoproterozoic deposits, the formation of orogenic gold deposits was one of the last events prior to cratonization. The late timing of orogenic gold deposits within the structural evolution of the host orogen implies that any earlier structures may be mineralized and that the current structural geometry of the gold deposits is equivalent to that at the time of their formation provided that there has been no significant post-gold orogenic overprint. Within the host volcano-sedimentary sequences at the province scale, world-class orogenic gold deposits are most commonly located in second-order structures adjacent to crustal scale faults and shear zones, representing the first-order ore-forming fluid pathways, and whose deep lithospheric connection is marked by lamprophyre intrusions which, however, have no direct genetic association with gold deposition. More specifically, the gold deposits are located adjacent to $\sim 10^{\circ}-25^{\circ}$ district-scale jogs in these crustal-scale faults. These jogs are commonly the site of arrays of $\sim 70^{\circ}$ cross faults that accommodate the bending of the more rigid components, for example volcanic rocks and intrusive sills, of the host belts. Rotation of blocks between these accommodation faults causes failure of more competent units and/or reactivation and dilation of pre-existing structures, leading to deposit-scale focussing of ore-fluid and gold deposition. Anticlinal or antiformal fold hinges, particularly those of ‘locked-up’ folds with $\sim 30^{\circ}$ apical angles and overturned back limbs, represent sites of brittle-ductile rock failure and provide one of the more robust parameters for location of orogenic gold deposits.

In orogenic belts with abundant pre-gold granitic intrusions, particularly Precambrian granite-greenstone terranes, the boundaries between the rigid granitic bodies and more ductile greenstone sequences are commonly sites of heterogeneous stress and inhomogeneous strain. Thus, contacts between granitic intrusions and volcano-sedimentary sequences are common sites of ore-fluid infiltration and gold deposition. For orogenic gold deposits at deeper crustal levels, ore-forming fluids are commonly focused along strain gradients between more compressional zones where volcano-sedimentary sequences are thinned and relatively more extensional zones where they are thickened. World-class orogenic gold deposits are commonly located in the deformed volcano-sedimentary sequences in such strain gradients adjacent to triple-point junctions defined by the granitic intrusions, or along the zones of assembly of micro-blocks on a regional scale. These repetitive province to district-scale geometrical

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patterns of structures within the orogenic belts are clearly critical parameters in geology-based exploration targeting for orogenic gold deposits.

1. Introduction

The genesis of vein-type to disseminated gold deposits, broadly classified as orogenic gold deposits (Groves et al., 1998; Goldfarb et al., 2005) has remained controversial. The genetic models for these deposits were evaluated in a recent review by Goldfarb and Groves (2015). Much attention has been focused on the source of auriferous fluids. The majority of evidence favours a metamorphic source, either from fluids released during metamorphism of sequences deeper in the gold-hosting basins and oceanic rock sequences (see review in Goldfarb and Groves, 2015) or from de-volatilization of the sediment wedge above a down-going subduction slab (Groves and Santosh, 2015). From an exploration viewpoint, the source of the auriferous fluids is largely irrelevant because, with either of the more accepted models, the fluid is deeply sourced and widespread over the entire orogenic belt. This is demonstrated empirically by the widespread distribution of gold deposits, gold prospects and/or gold-related geochemical anomalies in many subduction-related tectonic environments with a moderate to steep geothermal gradient. Moderate to high pressure/low temperature blueschist belts represent the only parts of orogens without such gold favourability. The issue in terms of exploration is not where the gold came from but to where it was focussed to form mineable gold deposits (e.g., Hronsky and Groves, 2008). The most important aspects are crustal environments leading to enhanced fluid migration and focussing into sites favourable for gold deposition, both of which are intimately related to the structural evolution and structural geometry of gold-prospective orogens (e.g., Ridley, 1993; Cox et al., 2001; Sibson, 2004; Deng et al., 2015).

In order to use structural geology as an integral tool in gold exploration, the timing of gold mineralization within the structural history of the orogenic belt is a crucial constraint. As demonstrated in the seminal paper by Goldfarb et al. (1988) on the gold districts of the Juneau Gold Belt in south-eastern Alaska, studies on the timing of formation of gold deposits are most robust if they involve an understanding of tectonic and structural evolution within a geochronological framework which involves robust isotopic ages of the gold mineralization itself. Goldfarb et al. (1988) demonstrated that gold mineralization was essentially a single widespread event late in tectonic evolution, related to a shift in tectonic regime from compression to transpression during Pacific plate re-orientation (Goldfarb et al., 2005, fig. 9). Such late structural timing involving re-activation of pre-existing structures developed during previous deformation events has been verified in numerous studies worldwide that integrate structural analysis with textural information on the timing of gold within the deposits, within a robust geochronological framework (e.g., Goldfarb et al., 1991; Knight et al., 1993; Bloem et al., 1994; De Ronde and de Witt, 1994; Groves et al., 1995; Leader et al., 2010, 2013; Yang et al., 2016).

Despite these studies, there are still erroneous models that imply multiple gold mineralization events, commonly argued to have been separated by tens of millions of years, within individual gold provinces or districts. Although some of these reflect problematic issues with selected dating techniques or dating materials, most of these involve a scale problem where studies of the structural history of the individual deposits produce resultant deformation episodes that are then poorly correlated with those of the host terrane. This is perhaps best illustrated by a specific example, the Archean Eastern Goldfields of the Yilgarn Block of Western

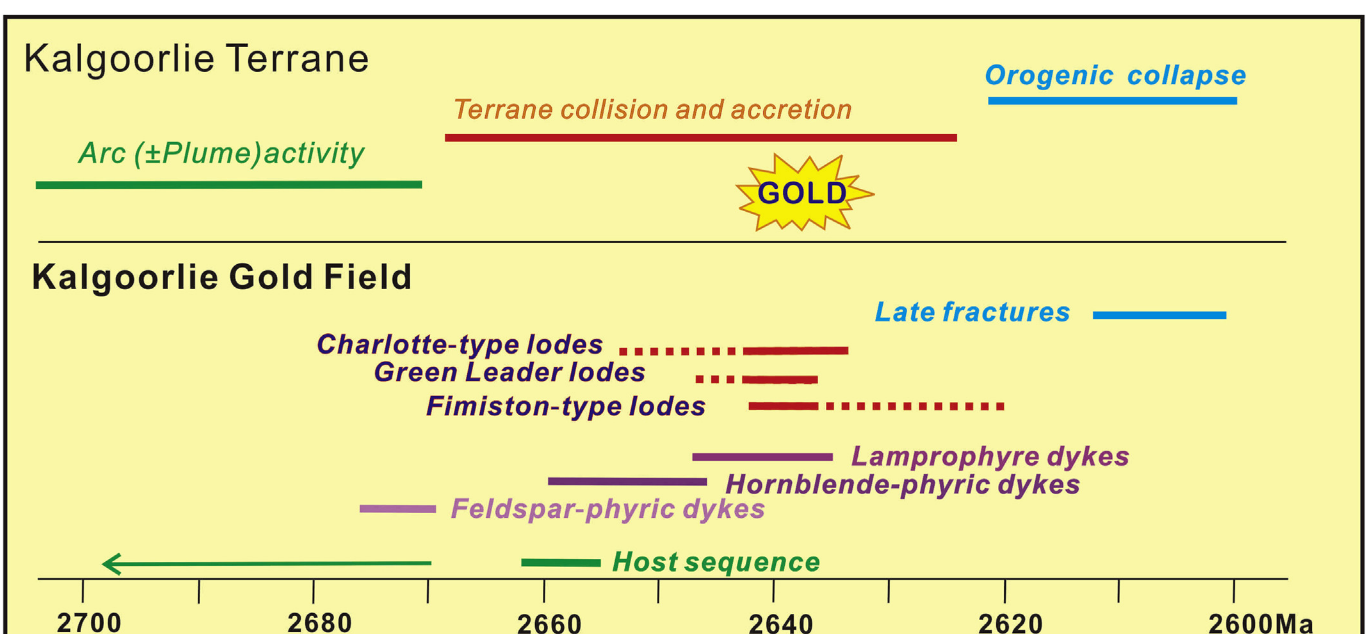

Figure 1. Figure demonstrating characteristic late kinematic timing of orogenic gold deposits. Timing of gold mineralization in the Kalgoorlie Gold Field and its host Kalgoorlie Terrane, Yilgarn Block, Western Australia (after Vielreicher et al., 2016).

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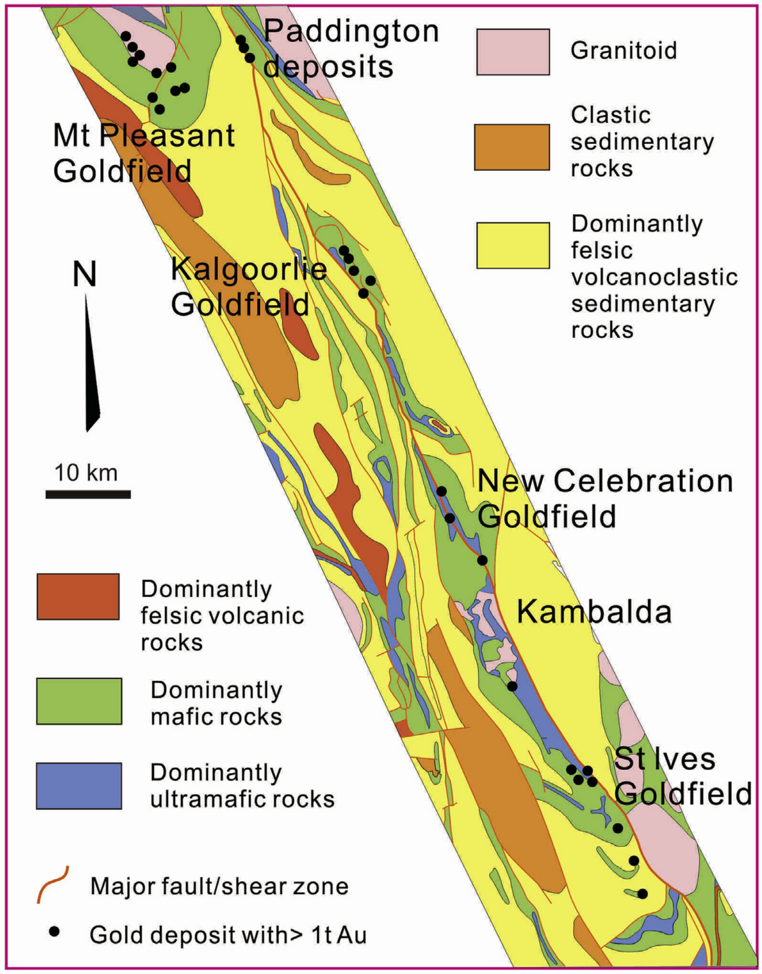

Figure 2. Regional geological map of the southern Kalgoorlie Terrane, Yilgarn Block, Western Australia showing major orogenic gold deposits spaced along the crustal-scale Boulder-Lefroy Fault. Map compiled from various sources.

Australia, with emphasis on the giant Kalgoorlie Goldfield. Robert et al. (2005) and Blewett et al. (2010) in their overviews of Yilgarn gold deposits interpreted multiple gold events in the gold province. Jones (2014) suggested multiple gold events in the Leonora District, and Bateman and Hagemann (2004) went further in suggesting up to 45 my of gold deposition hosted in the three main ore-deposit styles at Kalgoorlie alone. Vielreicher et al. (2010, 2016) provided an extensive review of all previous structural interpretations of gold timing in the Yilgarn generally and Kalgoorlie specifically. They carried out holistic research in which they combined structural studies with textural studies of the gold deposits and their wallrock alteration zones and combined these with robust SHRIMP U–Pb hydrothermal phosphate geochronology. Results show that there was a single late gold event in each Yilgarn terrane and that the ages of the three deposit styles at Kalgoorlie are indistinguishable (Fig. 1).

Similar interpretations of data from orogenic gold deposits worldwide indicate that they consistently formed late in the tectonic and structural evolution (D3–D4 in most structural sequences) of their host terranes, largely during a transition from compression to transpression related to a change in far-field stresses. Thus, any pre-existing structures, and not solely syn-gold structures, can be mineralized and it is structural geometry not structural history which is the important exploration parameter (Groves et al., 2000). In this paper, the repetitive structural geometries of orogenic gold deposits and their importance in gold exploration are examined. There is specific emphasis on Precambrian deposits, particularly those in Western Australia, due to the wealth of studies on Precambrian orogenic gold provinces, although some Phanerozoic examples are also presented.

2. Repetitive province-scale structural geometries

As noted by most authors (see summaries in Groves et al., 2000; Goldfarb et al., 2005; Robert et al., 2005), the first-order control on world-class orogenic gold districts is their location adjacent to crustal- to lithospheric-scale fault or shear zones at the province scale (Fig. 2). These structures are commonly marked by anomalous concentrations of lithosphere-sourced lamprophyre dykes that indicate a deep lithospheric connection for fluid conduits (Perring et al., 1989; Rock et al., 1989; Deng et al., 2017). However, these are not the source of the ore fluid itself as they lack intrinsically high gold and other noble-metal abundances (Wyman and Kerrich, 1989). Less-endowed orogenic gold provinces (e.g., Zimbabwe gold provinces; Klondike province; Seward Peninsula of Alaska) lack these first-order structures and associated deeply-sourced lamprophyres.

The giant gold districts, particularly those in Neoarchean terranes, are commonly located where late conglomerate basins are juxtaposed against lower volcanic sequences (e.g., Abitibi Belt, Canada: Colvine et al., 1984; Norseman-Wiluna Belt, Western Australia: Tripp, 2014). These are interpreted to signify sites of

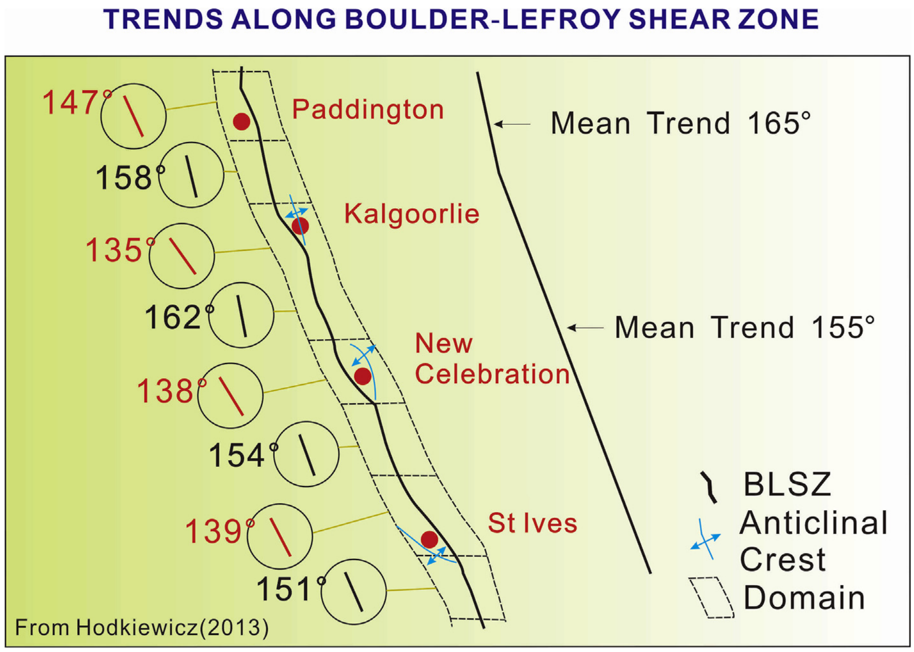

Figure 3. Map showing major orogenic gold districts, including the giant Kalgoorlie Goldfield, associated with distinctive jogs in the Boulder-Lefroy Fault, Kalgoorlie Terrane, Yilgarn Block, Western Australia (after Hodkiewicz et al., 2005).

anomalously rapid uplift rates along the first-order structures where lowering of lithostatic pressures in subsidiary second- and third-order interconnecting faults may have been important in enhancing hydrofracturing. This in turn, caused extreme pressure fluctuations and led to effective gold deposition through related chemical responses and fluid un-mixing episodes (e.g., Groves et al., 1987). The same appears to hold for younger terranes, such as for the Eocene gold deposits of the Chugach accretionary prism, southern Alaska. Here, gold deposition took place on the retrograde limb of a clockwise Barrovian metamorphic P-T path as host rocks were in the process of rapid uplift (Goldfarb et al., 1986).

Linear zones of the crustal- to lithospheric-scale faults and shear zones that have the mean structural trend generally lack economic gold deposits. It is along the curvilinear segments of the first-order structures, where segments of the structures jog into an anomalous orientation, normally 10°–25° to the mean trend, that the larger orogenic gold districts are located (e.g., Weinberg et al., 2004). These are normally spaced at intervals of tens of kilometres in mature gold provinces. For example, there is a spacing of ~30–35 km, broadly equivalent to depth to Moho, for world-class gold districts or camps along the Boulder-Lefroy fault system in the Eastern Goldfields of Western Australia (Fig. 3). It may be significant that the jog with the greatest angular discordance with respect to the mean trend of the Boulder-Lefroy Fault hosts the giant Kalgoorlie Goldfield. It is also significant that the jogs coincide with large-scale anticlinal structures (Fig. 3), one of the most robust associations with orogenic gold, as discussed below. Similar relationships are recorded for deposits in younger orogenic belts. For example, the largest known orogenic gold deposit, the giant late-Paleozoic Muruntau deposit is associated with a large-scale jog in the Turkestan suture/South Tien Shan fault system.

3. Repetitive district-scale structural geometries

3.1. Fault arrays

At the district to deposit scale, gold deposits may be hosted by a variety of faults or shear zones that pre-date gold mineralization: D1 and D2, less commonly D3, structures as evident in most published structural sequences (e.g., Vielreicher et al., 2016) typically defined by four or five distinct deformation episodes. However, it is the late fault arrays that are oblique to the belt-parallel structural trends that, in many instances, provide the most important structural geometries in terms of predictive exploration (Groves et al., 2000, Fig. 4). These faults tend to form subparallel arrays where there are flexures or jogs on the first-order faults (Fig. 4). Worldwide, such accommodation fault arrays tend to be at ~70° to the local trend of the first-order structures and rock sequences.

Most authors place these fault arrays as D3 to D4 in a D1-D4 structural sequence (e.g., for Kalgoorlie: Vielreicher et al., 2016: table 2) and consider them as post-gold structures (e.g, for Kalgoorlie: Boulter et al., 1987; Mueller et al., 1988; Bateman and Hagemann, 2004; Gauthier et al., 2004; Weinberg et al., 2006). However, there are a number of lines of evidence suggesting that these ubiquitous structures are the major structural controls on the location of gold mineralization. For example, gold mineralization may be hosted in earlier structures but may be totally confined between a pair of the oblique faults. Again, using Kalgoorlie as an example, the Mt Charlotte deposit is confined by two subparallel D3/D4 faults and the various lodes in the Golden Mile are hosted by D2 structures but the mineralization in the Golden Mile superpit is essentially confined between two D3/D4 faults: the Adelaide and Golden Pike Faults (Fig. 4). As shown by Vielreicher et al. (2010, 2016) all gold deposits are essentially the same age as these faults. The gold deposits at Kundana (Cooke et al., 2017) lie on a jog in the Zuleika Shear Zone, a crustal-scale fault that lies to the west of the Boulder-Lefroy Fault. As for the Boulder-Lefroy Fault at Kalgoorlie, the Zuleika Shear Zone jogs from its normally north-northwest trend to a roughly north-west trend with an array of broadly NE-trending cross faults coincident with this jog. The orogenic gold deposits are confined to this jog and are sited in a number of D2 shear zones at, or close to, their intersection with the cross-fault arrays (Fig. 5). Importantly, the lodes may be located on one side of a cross fault, but not consistently displaced to the other side of the fault.

In some gold districts, distinctive groups of subparallel gold lodes between pairs of cross faults may form a series of corridors

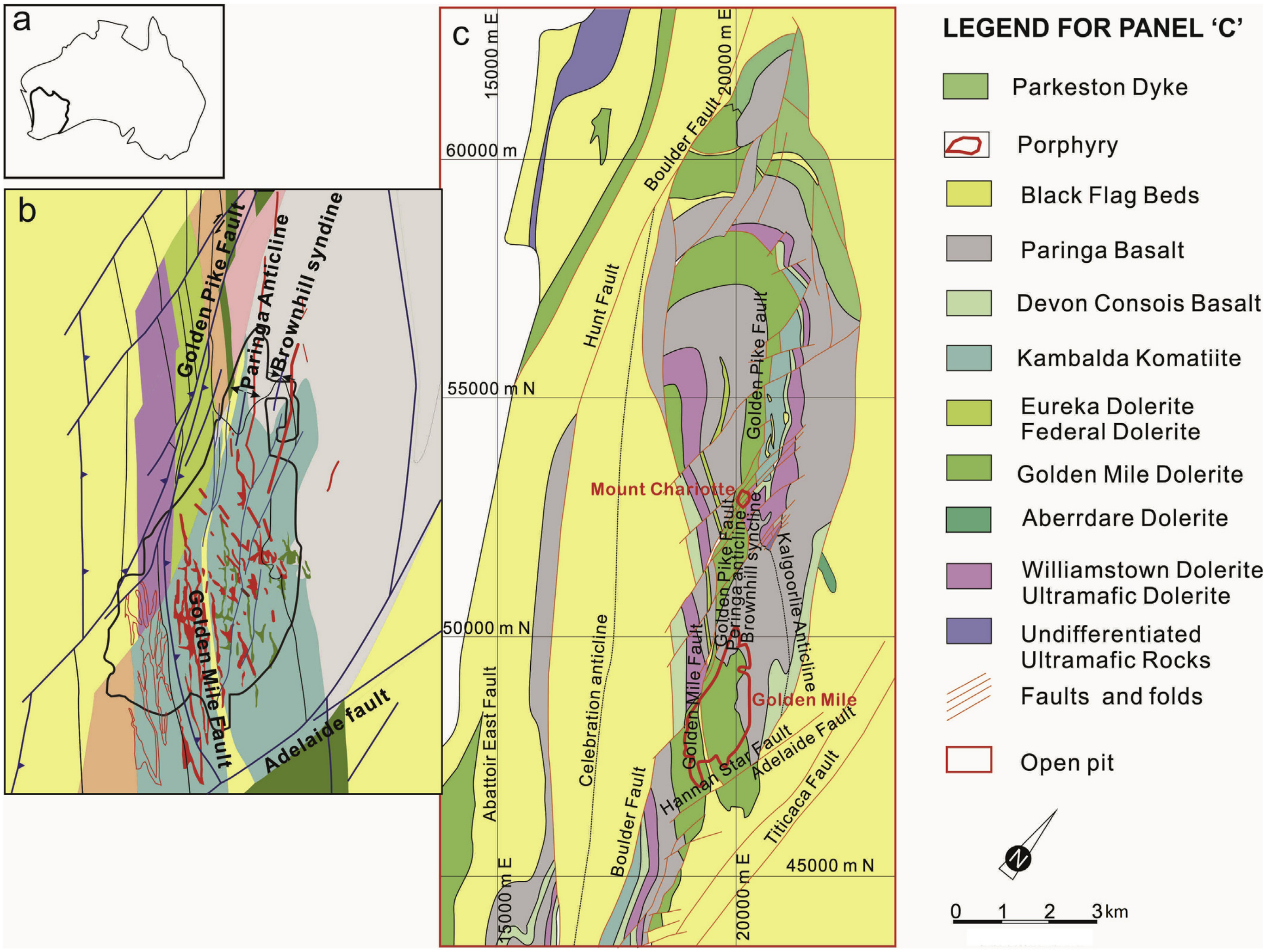

Figure 4. Geological map of the Kalgoorlie Goldfield showing arrays of NE-trending accommodation faults and the location of the Mt Charlotte and Golden Mile orogenic gold deposits. Inset in top left-hand corner shows Golden Mile lodes in early structures confined between the NE-trending Golden Pike and Adelaide Faults (after Vielreicher et al., 2010, 2015, 2016).

along the cross-fault trend. In the example from the Huangjindong District of Hunan Province of China (Fig. 6), it is evident that each corridor has a different number and spacing of lodes, such that they cannot be faulted equivalents but, instead, formed groups of lodes independently within each corridor defined by a specific pair of cross faults.

There are few publications that specifically discuss the controls of gold mineralization between such fault pairs. At Mt Charlotte (Fig. 4), the network of fracture and shear veins within the competent Unit 8 of the Golden Mile Dolerite has attracted two models. Bateman et al. (2001) suggested that the veins formed in response to movement on the bounding faults, whereas Ridley and Mengler (2000) suggested that the faults increased stresses in the competent Unit 8 leading to rock failure and vein formation. However, these models fail to explain the gold mineralization within pre-existing structures as at the Golden Mile, Kundana and Huangjindong. Insights can be gained from studies in non-mineralized terranes in California by Nicholson et al. (1986) and Jackson and Molnar (1990) and in east-central Alaska by Page et al. (1995). They describe rotation and torsional strain of the blocks between pairs of kinematically-compatible faults with the same sense of movement. This is shown somewhat schematically for the major bend in the Tintina-Denali Fault Systems with their localized oblique domino-like accommodation structures that facilitate the flexure of more rigid units in the sequences around the major bend (Fig. 7). Thus, it appears most likely that the rotation of fault blocks and their internal earlier structures, due to the opposite fault motion on either side of the bounding paired faults, causes reactivation of, and inhomogeneous strain within, those internal structures. In turn, this leads to focussed ore-fluid flux into dilation zones along suitably-aligned pre-existing structures and deposition of high-grade gold ores within those structures and more disseminated mineralization and alteration zones adjacent to them.

3.2. Anticlinal fold structures

As summarized by Groves et al. (2000) and Goldfarb et al. (2005), among others, anticlines, or antiforms, represent one of the most robust controls on the location of orogenic gold deposits at the district to deposit scale. In a series of seminal papers on the Victorian Goldfields of south-eastern Australia, Cox et al., (1991, 1995) demonstrated that deposits now termed orogenic gold formed when folds became 'locked up', with faulting and fracturing replacing flexural folding as the predominant deformation mechanism. As shown schematically in Groves et al. (2016, Fig. 5), the locked-up folds tend to be asymmetrical folds with overturned

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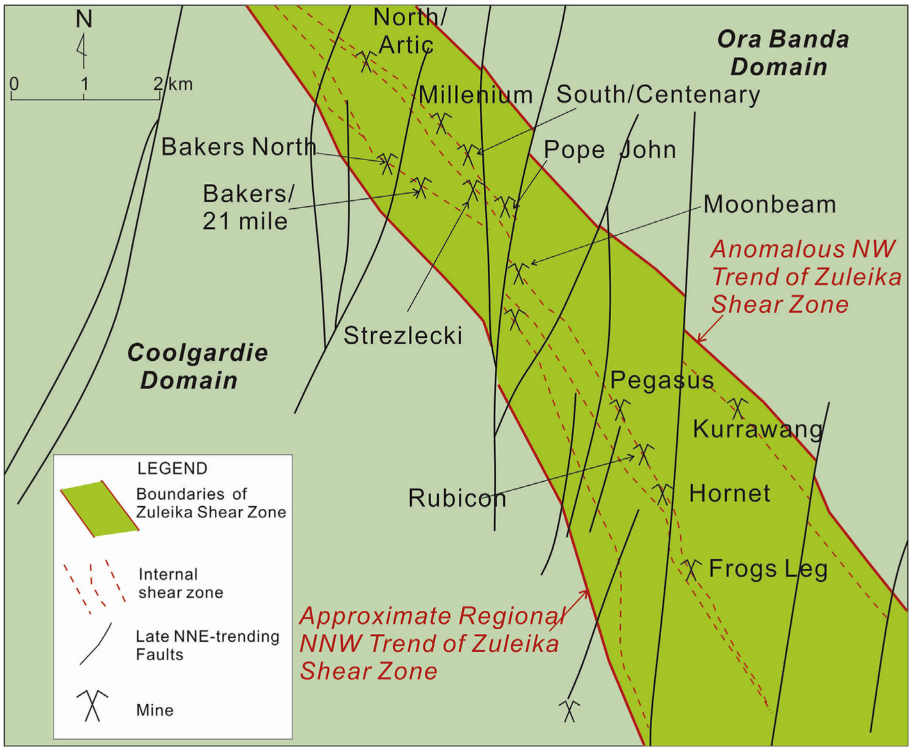

Figure 5. Structural map of Kundana Gold Field showing NE-trending cross faults interpreted to be accommodation faults related to a jog in the Zuleika Shear Zone from its regional NNW trend to a local NW trend. Orogenic gold deposits are sited close to the intersection of the cross faults in subsidiary shears within the Zuleika Shear Zone. Geology simplified, with lithostratigraphic units not shown for clarity (after Cooke et al., 2017).

back limbs, modified by thrusts and fracture arrays that promote focussed fluid flux and resultant gold deposition. For these locked-up anticlinal folds that host orogenic gold deposits, the apical angle is approximately 30° for a variety of gold districts and deposits worldwide. Fig. 8a shows a simplified schematic section through a locked-up fold with Fig. 8b–h illustrating global examples of sections and plan-view maps of gold-mineralized anticlines from the literature. It is also evident that anticlines with similar geometry were an important structural component of the controls on gold mineralization at Huangjindong (Fig. 6).

It is evident that district- to deposit-scale anticlinal or antiformal folds with ~30° apical angles, commonly with associated thrusts, are a predictable and repetitive characteristic of many orogenic gold deposits of all ages (Fig. 8a–h).

3.3. Complexities related to granitic intrusions

The discussion above deals exclusively with structures confined to the volcano-sedimentary sequences in gold provinces. Although absent in rare cases, granitic intrusions are normally a common component in orogenic gold provinces as a reflection of high thermal gradients related to subduction-related orogenesis (e.g., Goldfarb et al., 2005). They may be pre-gold, relatively rare syn-gold (e.g., Grass Valley, Taylor et al., 2015; Willow Creek, Alaska, Harlan et al., 2017) or post-gold intrusions, with no consistent spatial or genetic relationship to the orogenic gold deposits (Goldfarb and Santosh, 2014; Goldfarb and Groves, 2015). However, in some gold provinces, particularly in Archean and Paleoproterozoic terranes which are dominated by granitic intrusions, pre- to syn-gold intrusions may play an important structural role for the location of both gold districts or camps and individual gold deposits. This is discussed below, with emphasis on the district scale.

As shown somewhat schematically in Fig. 9a, individual rigid granitic intrusions, whether sheared against volcano-sedimentary sequences or with complex intrusive contacts against such sequences, can cause significant variations in the orientation of local principal maximum stress relative to the externally-imposed regional stress. These may cause anomalously-low minimum stress zones on a deposit scale related to variations in the geometry of the immediate contact zones (e.g., at Granny Smith in the Kurnalpi Terrane of Western Australia; Ojala et al., 1993, Fig. 9b) or on a district scale related to the regional geometry of the intrusion contact (Coolgardie Goldfield of the Kalgoorlie Terrane of Western Australia; Knight et al., 1993, Fig. 9c). Such principal stress variations at the deposit scale, relative to those of the province to district scale, explain the controversy overstudies on structural sequence that attempt to place deposit-scale observations into a regional structural-sequence scheme.

The structural geometry becomes more complex where two or more adjacent rigid granitic intrusions impinge on more ductile volcano-sedimentary sequences. The simplest case of interaction of two granitic bodies is well illustrated by the Barberton Goldfield of South Africa (Fig. 10). All significant gold deposits are located in complexly folded early thrust zones in the greenstone belt within the neck zone south of the Jamestown Schist Belt that sits between the two pre-gold granitic intrusions to the northwest. This inverted V-shaped neck zone represents a strain gradient between the compressional zone of thinning within the high-strain Schist Belt and the low strain greenstone belt of the Barberton Mountain Land with its perfectly preserved komatiite flows (Viljoen and Viljoen, 1969). Ore-fluid flux was directed to this zone of heterogeneous stress related to the structural geometry developed by the interaction of the two granitic intrusions.

More complex structural geometries are developed at triple-point junctions between three granitic bodies that impinge on

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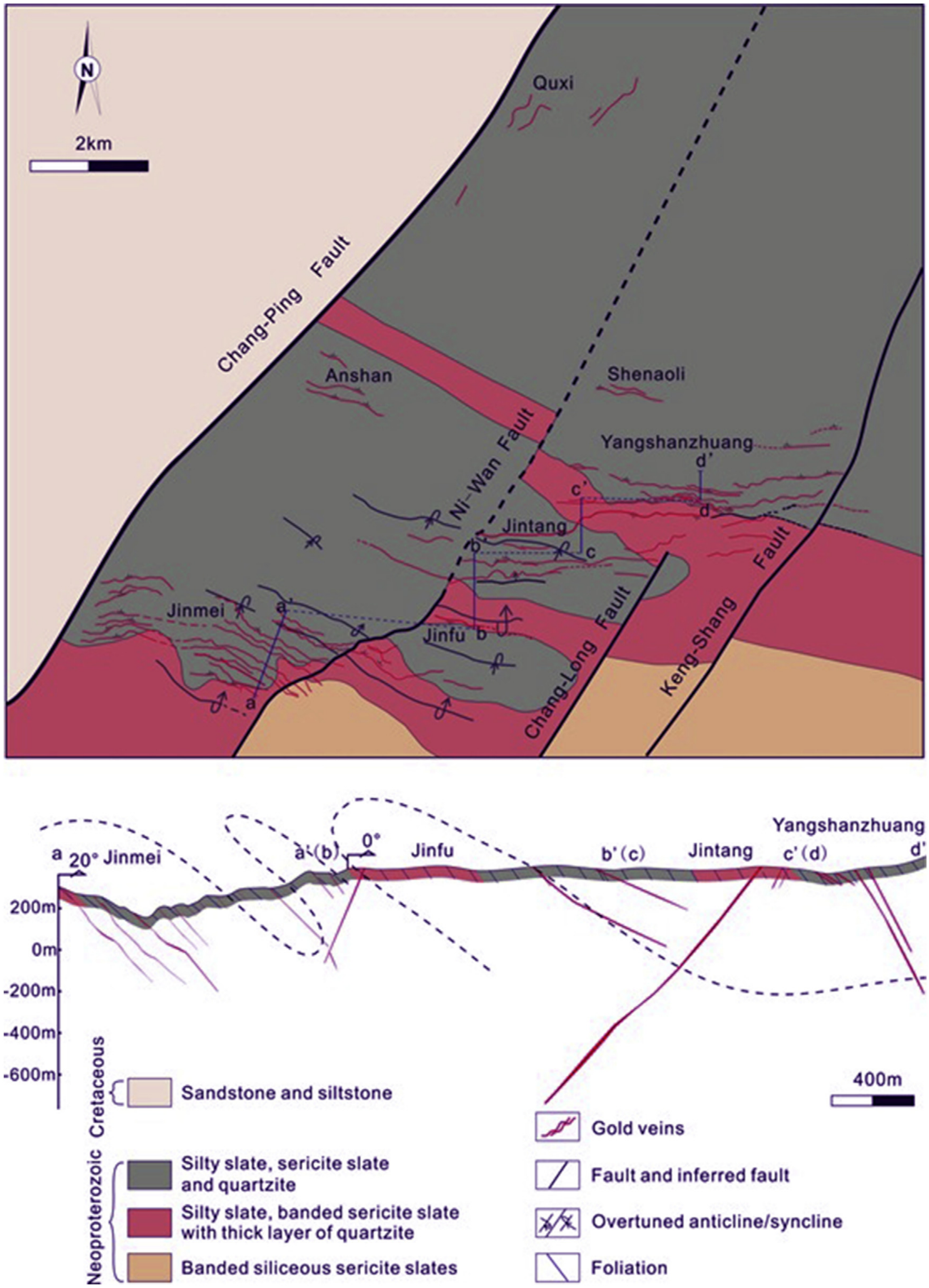

Figure 6. Geological map of the Huangjindong District, Hunan Province, China, showing controls on the location of multiple orogenic gold lodes by NNE-trending cross faults. Cross section shows deposits located in antiformal folds with ~30° apical angles. Adapted from P.H. Wang and others, Hunan HuangjindongGold Mining Co. Ltd., unpublished 2015 internal geological map.

the volcano-sedimentary sequences. Gold deposits are again located along strain gradients in heterogeneous stress zones within inverted V-shaped or cuspate volcano-sedimentary segments of belts. An example is shown from the Southern Cross Greenstone Belt in Western Australia, where the Frasers, Transvaal, Marvel Loch, Great Victoria, Nevoria, Yilgarn Star and Bounty gold deposits are all related to thickened segments of the greenstone belts along strain gradients in heterogeneous stress zones related to the

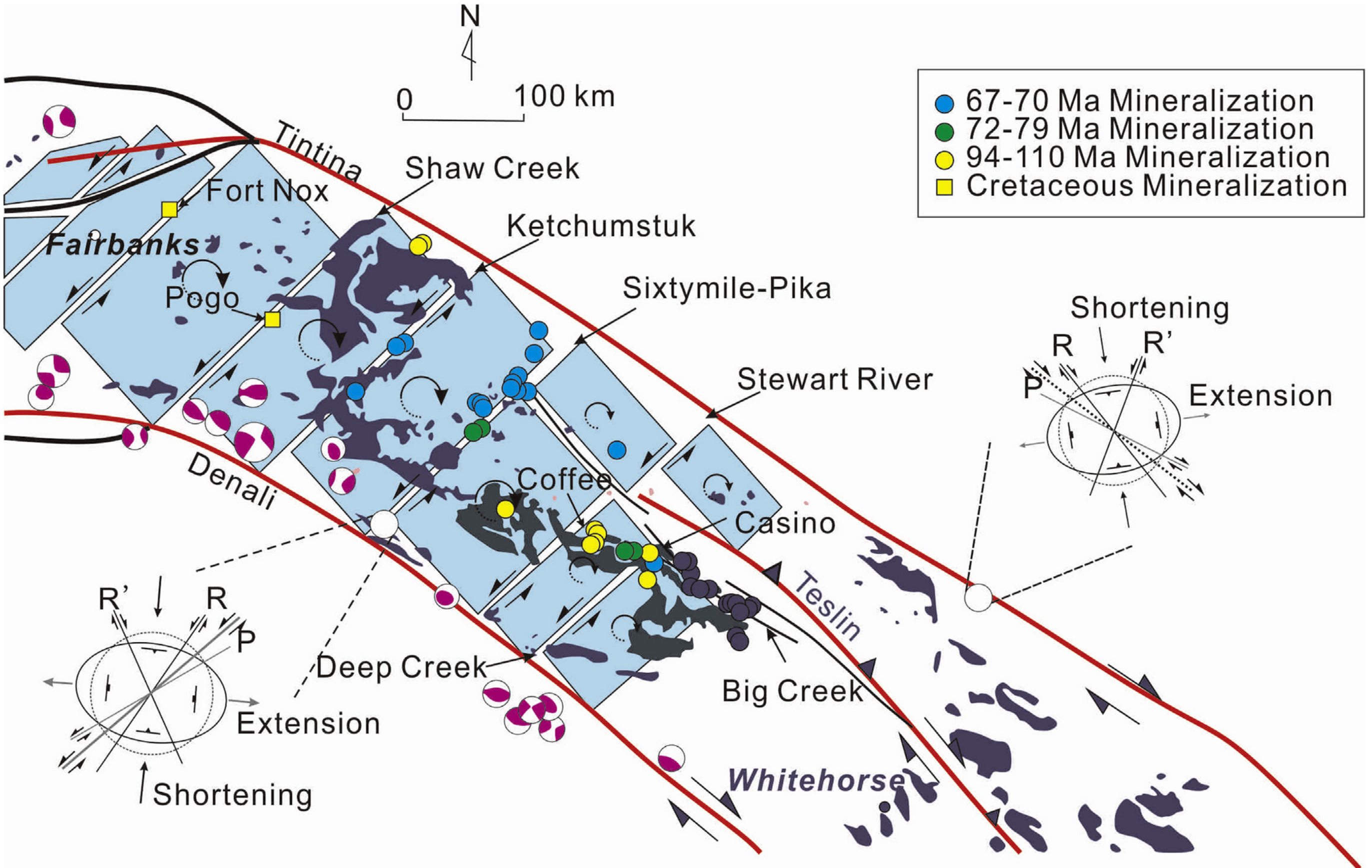

Figure 7. Map of the Denali-Tintina Fault Zone showing high-angle cross faults, in an array like a stack of dominoes, accommodating the bend in the Fault Zone. Note the rotation within blocks caused by opposite motion on either side of the blocks by faults with the same sense of motion (after Sanchez et al., 2014).

geometry of the granitic intrusions (Fig. 11). Most of such repetitive structural geometries are displayed in amphibolite-facies domains within Precambrian granite-greenstone belts and the individual deposits contain less than 5 moz gold (e.g., Musselwhite in Canada). However, some deposits, such as Red Lake and Eleonore in Canada are world-class deposits in amphibolite-facies domains, and world-class examples do occur in the greenstone belts of Barberton, Central Lapland, Finland, and Quadrilatero Ferrifrero, Brazil.

From an exploration viewpoint, these triple- and even quadruple-point junctions are evident on available aeromagnetic images (Fig. 12) and are commonly defined by gravity gradients due to the significantly higher magnetic susceptibilities and densities of greenstones relative to granitic intrusions.

Such 'triple points' have also been identified as potential locales for gold mineralization on a regional scale in recent studies such as those in the North China Craton (NCC). Recent studies proposed that the NCC is composed of a number of Archean microblocks which were assembled along zones of ocean closure as represented by major greenstone belts along the margins of these microblocks (Zhai and Santosh, 2011; Yang and Santosh, 2017). Li and Santosh (2017) identified that most of the major gold deposits associated with the Mesozoic giant metallogenic provinces in the NCC are located along the zones of amalgamation of two or three paleo microblocks. Where these gold deposits are located close to the margins of the craton, there is a clear correlation with sutures that bind two crustal fragments. Ore belts located within the interior of the craton are distributed along the "triple junction" of three micro-blocks. For example, world-class gold deposits of the Jiaodong-type (e.g., Yang et al., 2014) are located along the junction of the Xuhuai and Jiaoliao micro-blocks along the southern margin of the North China Craton. The Xiaoqinling-Xiong'ershan gold province is at the confluence of the Xuhuai and Xuchang micro-blocks at the southern margin of the craton, and the Zhang-Xuan ore province occurs along the zone of amalgamation of the Jining, Ordos and Fuping blocks. Similarly, the Jidong ore province is located at the junction of the Jining, Fuping and Jiaoliao blocks. The Fuping-Heshan ore province is confined to the confluence of the Fuping, Ordos and Xuchang blocks, and the Luxi ore province is situated along the join of the Fuping, Xuhuai and Jiaoliao blocks. Thus, Li and Santosh (2017) proposed that the "triple junctions" of Precambrian micro-continental blocks are potentially favourable locales for the exploration of giant gold deposits.

4. Discussion

This study shows that orogenic gold deposits as a group have a number of repetitive structural geometries that control ore-fluid flux and hence the sites of gold deposition. Not all deposits have the same conjunction of definitive structures, but many of the world-class to giant deposits possess these features.

At the province to district scale, the association of the larger orogenic gold deposits with second- and third-order faults or shear zones at 10°–25° jogs in first-order crustal- to lithospheric-scale faults of shear zones is ubiquitous. Such jogs are commonly the sites of oblique fault arrays that intersect the first-order structures in the jogs at approximately 70°. These are interpreted as transverse accommodation structures that formed in the jogs to allow more competent rock units in the gold-hosting sequences to

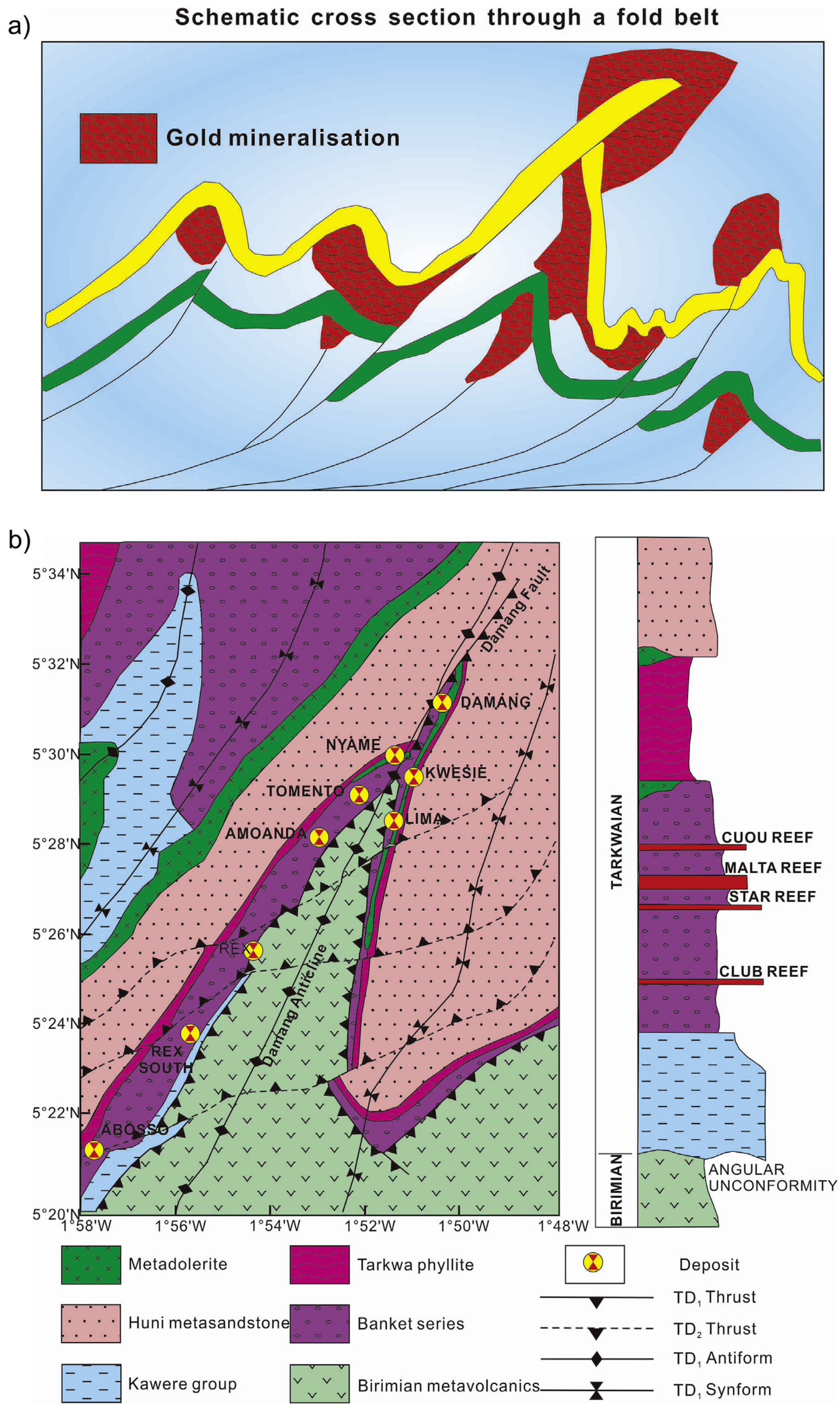

Figure 8. Collage of cross sections and plan views of anticlinal folds hosting orogenic gold deposits. Note repetitive ~30° apical angles of folds. Examples presented in order of decreasing age: (a) schematic figure showing locked-up fold and associated fractures; (b) geological map of Paleoproterozoic Damang Gold Field, Ghana, adapted from White et al. (2015); (c) simplified cross section of Paleoproterozoic Cosmo Howley deposit, Pine Creek Gold Field, N.T., Australia based on Alexander et al. (1990): more complex section in Edwards and Hitchman (2017, p.470); (d) open pit, Paleoproterozoic Big Howley deposit, Pine Creek Gold Field, N.T., Australia; (e) schematic cross section of Paleoproterozoic Homestake gold deposit, South Dakota, USA, based on Caddy et al. (1995); (f) schematic cross section of Paleozoic Bendigo Gold Field, Victoria, Australia, from Wilkinson et al. (1995); (g) Paleozoic Dolgellau Gold Belt, Wales, U.K., photo courtesy of R. J. Goldfarb; (h) cross section of Paleozoic Sukai Log deposit, Siberia, Russia, adapted from Large et al. (2011). All units are black shale and turbidite sequences.

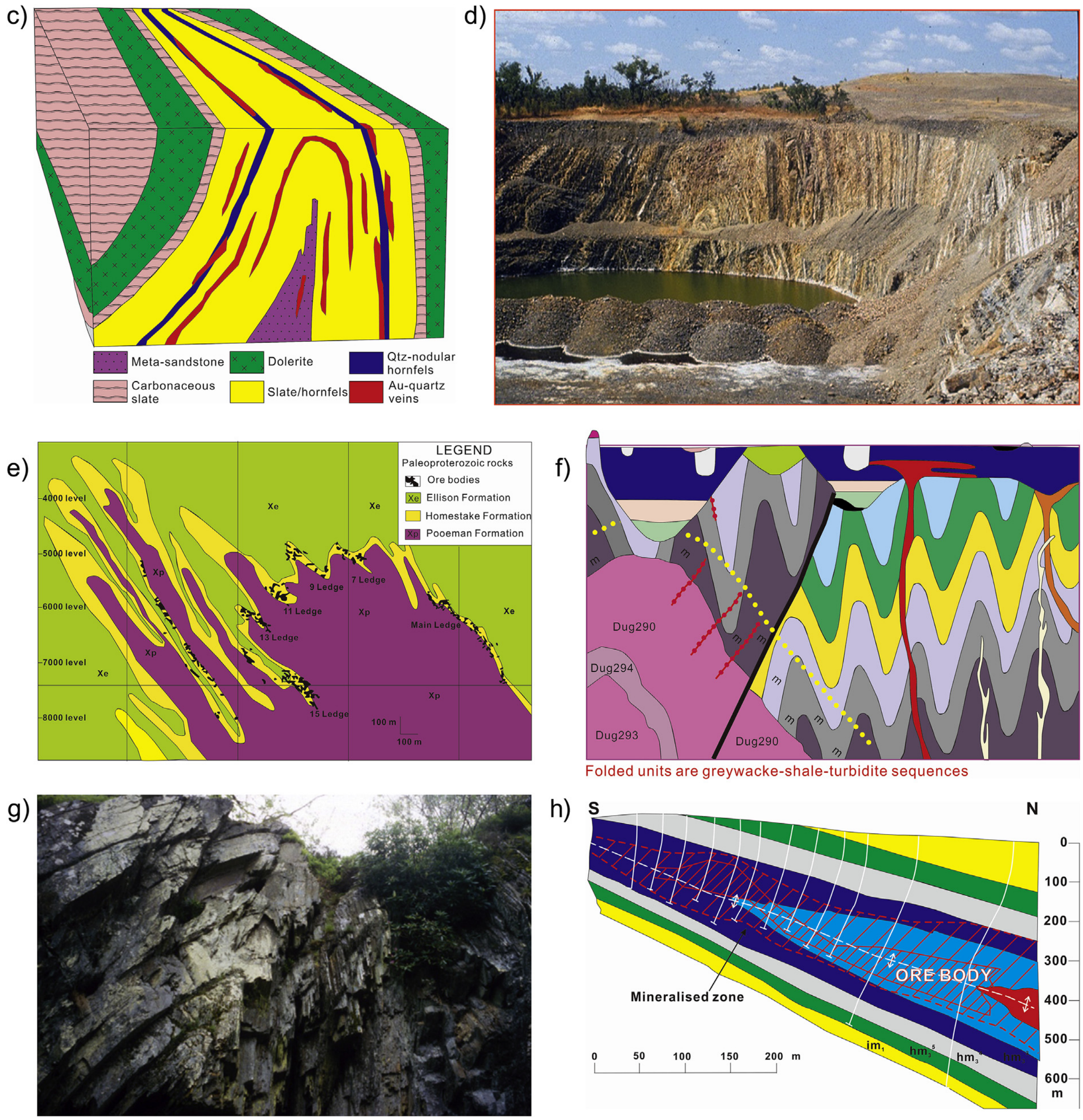

Figure 8. (*continued*).

accommodate the strike change around them. They play a similar, but smaller-scale, role to that of transfer faults on mid-ocean ridges.

As the accommodation faults have the same sense of motion, movement on paired faults causes rotation and induces torsional forces within the blocks between them due to opposite movement senses on each side of the blocks. Where competent rock units, such as granite, dolerite or gabbro sills of BIF units, lie between the fault pairs, brittle-ductile failure may result in auriferous fluid ingress and formation of quartz vein arrays and/or disseminated replacement deposits in very iron-rich rocks such as BIFs. Examples from over the world suggest that such deposits form between pairs of oblique faults that are ~200–500 m apart. Where the fault blocks host pre-existing faults and shear zones at a high angle to the oblique fault arrays, rotation of these structures during movement on the paired oblique faults is interpreted to lead to dilation along the earlier structures, ore-fluid flux into these sites and the formation of gold orebodies. Such orogenic gold deposits form on pairs of faults that may have several hundred metres to several kilometres spacing. This leads to a variety of deposit sizes from clusters of small high-grade deposits (e.g., Kundana: Fig. 5) to giant deposits with overall lower grade gold when considering the entire mineralized system of high-grade lodes and surrounding lower-grade wallrock alteration zones (e.g., Golden Mile, Kalgoorlie). The cross faults are normally obvious on aeromagnetic images from suitably-oriented surveys with 200 m line spacing or less.

Jogs in first-order faults may also be the sites of anticlinal folds that control the location of orogenic gold deposits (Fig. 3), but anticlinal or antiformal folds outside these jogs are a robust ubiquitous control of these deposits. These anticlines are tight locked-up folds with overturned back limb and apical angles of ~30°. In the folds, flexural bedding-plane slip is replaced by thrust faulting and the generation of arrays of brittle-ductile fractures as the structure locks up. These thrust faults and fracture arrays promote focussed high auriferous ore-fluid flux and deposition of gold, most

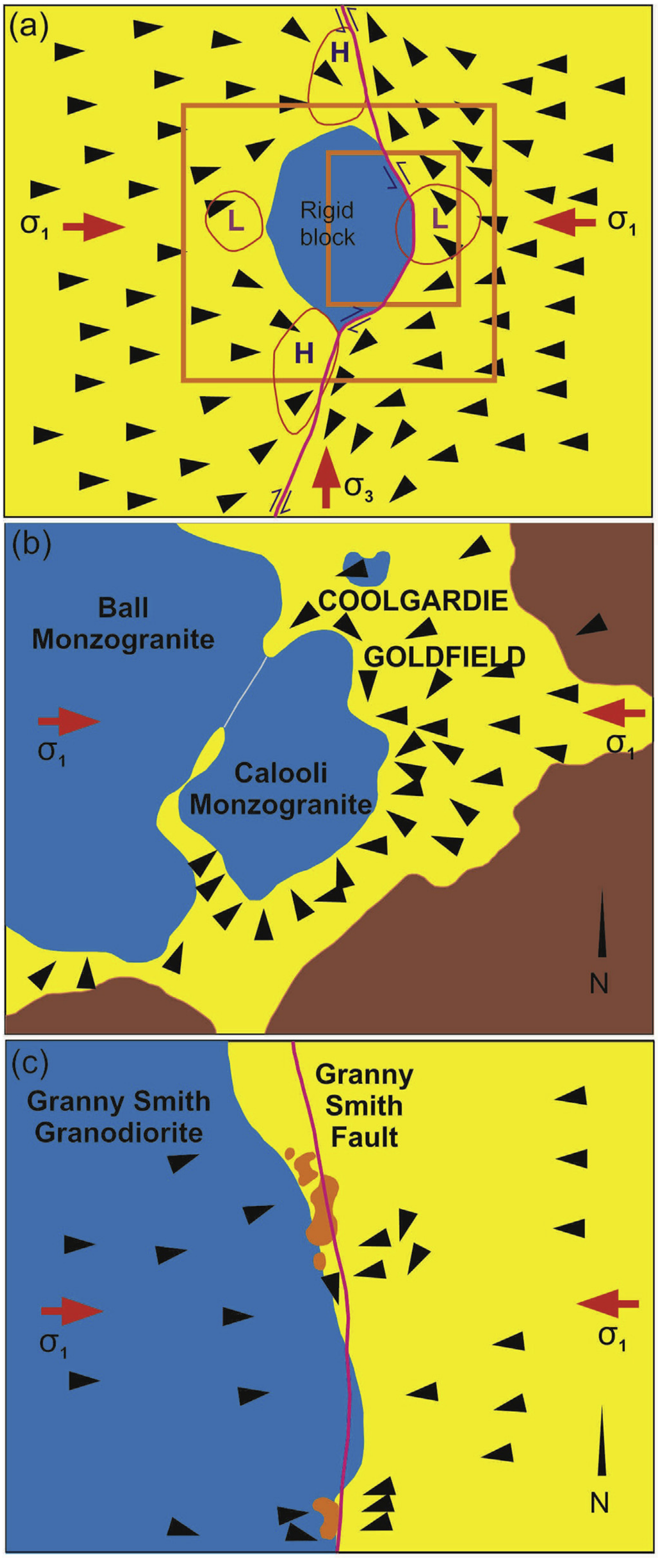

Figure 9. Schematic diagrams showing: (a) theoretical stress model at a faulted contact between a rigid granite and more ductile greenstones; (b) variation of maximum principal stress interpreted from field measurements of critical structures around the gold-mineralized Granny Smith diorite intrusion, Laverton region, Yilgarn Block; (c) similarly determined variation in maximum principal stress in the Coolgardie Gold Field, Yilgarn Block (after Knight et al., 1993; Ojala et al., 1993).

commonly in the hinge zones and back limbs of the anticlines. Such fold controls are independent of the nature and age of hosting rock sequences.

In provinces where the geometry of volcano-sedimentary belts is dominated by impingements of rigid granitic intrusions, particularly at deeper crustal levels, repetitive structural geometries relate to the shape of the contacts between the intrusions and the volcano-sedimentary sequences. In the case of contacts between single intrusions and volcano-sedimentary rocks, heterogeneous stresses related to complexities in the contact geometry determine the sites of high ore-fluid flux and hence location of gold mineralization (Fig. 9a). Where there is convergence to coalescence of several intrusions, gold deposits tend to be located along strain gradients close to triple-point or quadruple-point junctions related to impingement of the intrusions on the volcano-sedimentary sequences (Figs. 10–12). The anomalous gross shape of the Quadrilatero Ferrifero in Brazil is formed by a conjunction of several triple-point junctions which also control the location of world-class orogenic gold deposits such as Cuiaba, Morro Velho and Sao Bento (Lobato et al., 2001, fig. 2). Similarly, giant gold deposits may be located at the conjunctions of micro-blocks in similar geometric configurations at a larger tectonic scale.

The discussion above concerns only the repetitive structural geometry of orogenic gold provinces and districts. Although not dealt with specifically here, the nature of the hosting sequences plays important roles in structural and/or geochemical traps and caps to the hydrothermal systems (e.g., reviews by Groves et al., 2000, 2016; Goldfarb et al., 2005; Robert et al., 2005). Due to a combination of low mean stress, limited fault displacement and over-pressured auriferous ore-fluid during deposit formation (e.g., Cox, 2005), only the most competent units in the rock sequence fail above the brittle-ductile transition, providing enhanced permeability for fluid flow and gold deposition. The specific rock units that fracture and are therefore gold mineralized vary in different orogenic belts because the litho-stratigraphic successions in these belts are distinct from one to the other. In general, more iron-rich competent rocks, such as BIFs, dolerites, tholeiitic basalts and mafic granitic plutons, are selectively mineralized in Archean to Paleoproterozoic greenstone belts, whereas thicker more-competent turbidite units or mafic to granitic sills and plutons may be selectively mineralized in Phanerozoic turbidite belts. In the latter case, carbonaceous shales may also host gold deposits as they play an important geochemical role in gold-deposition.

5. Conclusion: relevance to exploration

As initially pointed out by Phillips et al. (1996) for the Kalgoorlie Goldfield, followed by Groves et al. (2016) for orogenic gold deposits generally, it is the conjunction of the above repetitive factors that determines the efficiency of ore-fluid infiltration in orogenic gold systems and the quality of the gold ores deposited. For example, at the regional scale, the giant Golden Mile deposit is sited in a ~25° jog in the crustal to lithosphere- scale Boulder-Lefroy Fault, which is marked in areas of outcrop by swarms of deeply-sourced lamprophyre and associated felsic porphyry dykes. The deposit is hosted in mainly early D2 structures between two D3–D4 cross (accommodation) faults with similar kinematics which are ~4 km apart. The Golden Mile represents a thrusted locked-up anticline-thrust pair in which the thrust has duplicated the competent and iron-rich deposit hosting Golden Mile Dolerite. The relatively high crustal-level of exposure does not allow the relationship of the Kalgoorlie Gold Field to the geometry of surrounding and underlying granitic batholiths to be deciphered. However, other world-class gold deposits in the Laverton, Leonora,

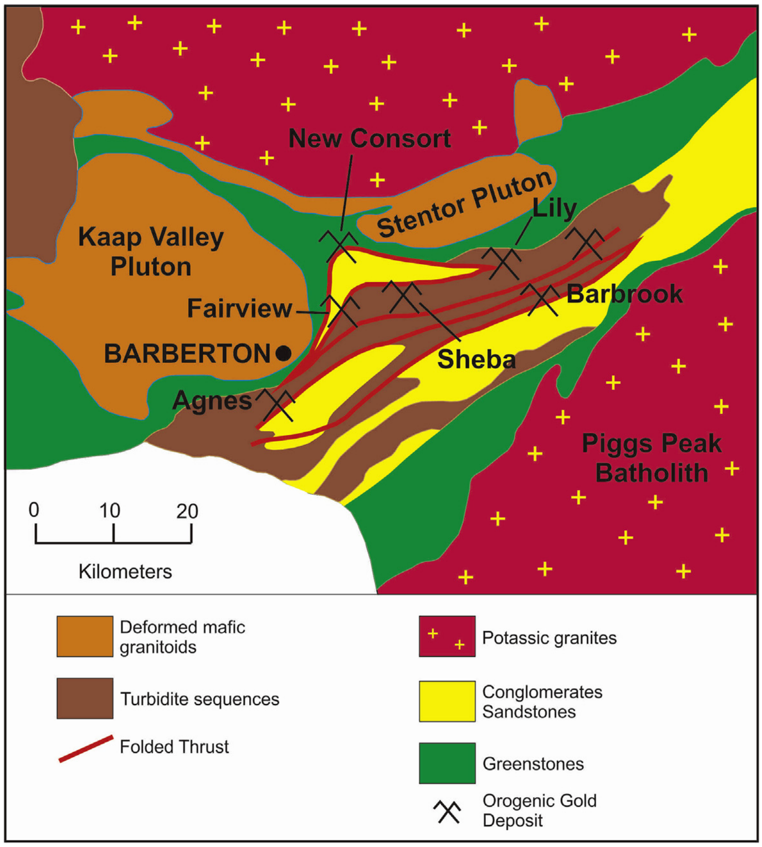

Figure 10. Simplified map of Barberton Gold Field, South Africa, showing orogenic gold deposits located adjacent to folded thrust faults within an inverted V-shaped domain of volcano-sedimentary rocks between two impinging mafic granitic plutons. Map simplified from several geological maps of the Barberton Mountain Land.

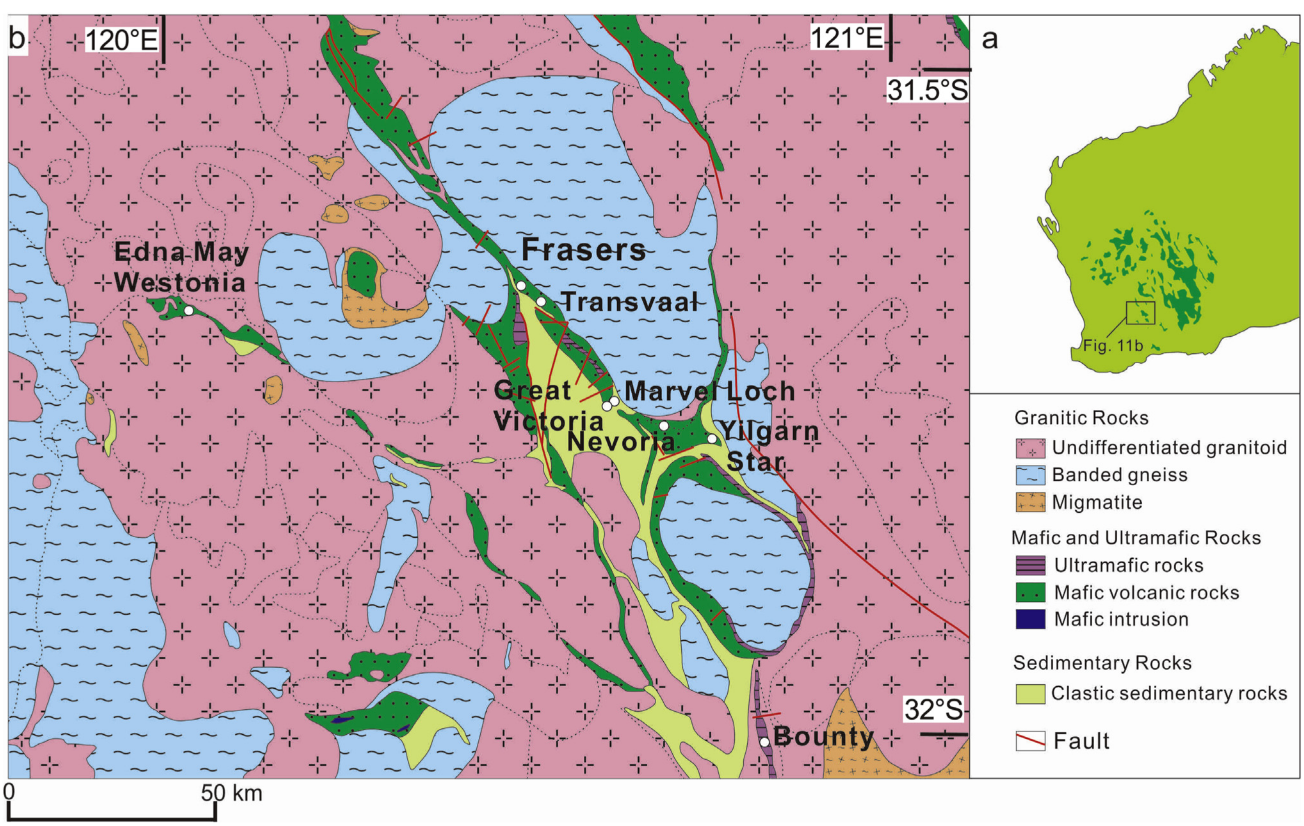

Figure 11. Simplified map of the Southern Cross Greenstone Belt showing several orogenic gold deposits clustered in volcano-sedimentary sequences at impingement zones and triple-point junctions of granitic batholiths. Map simplified from a variety of map sources.

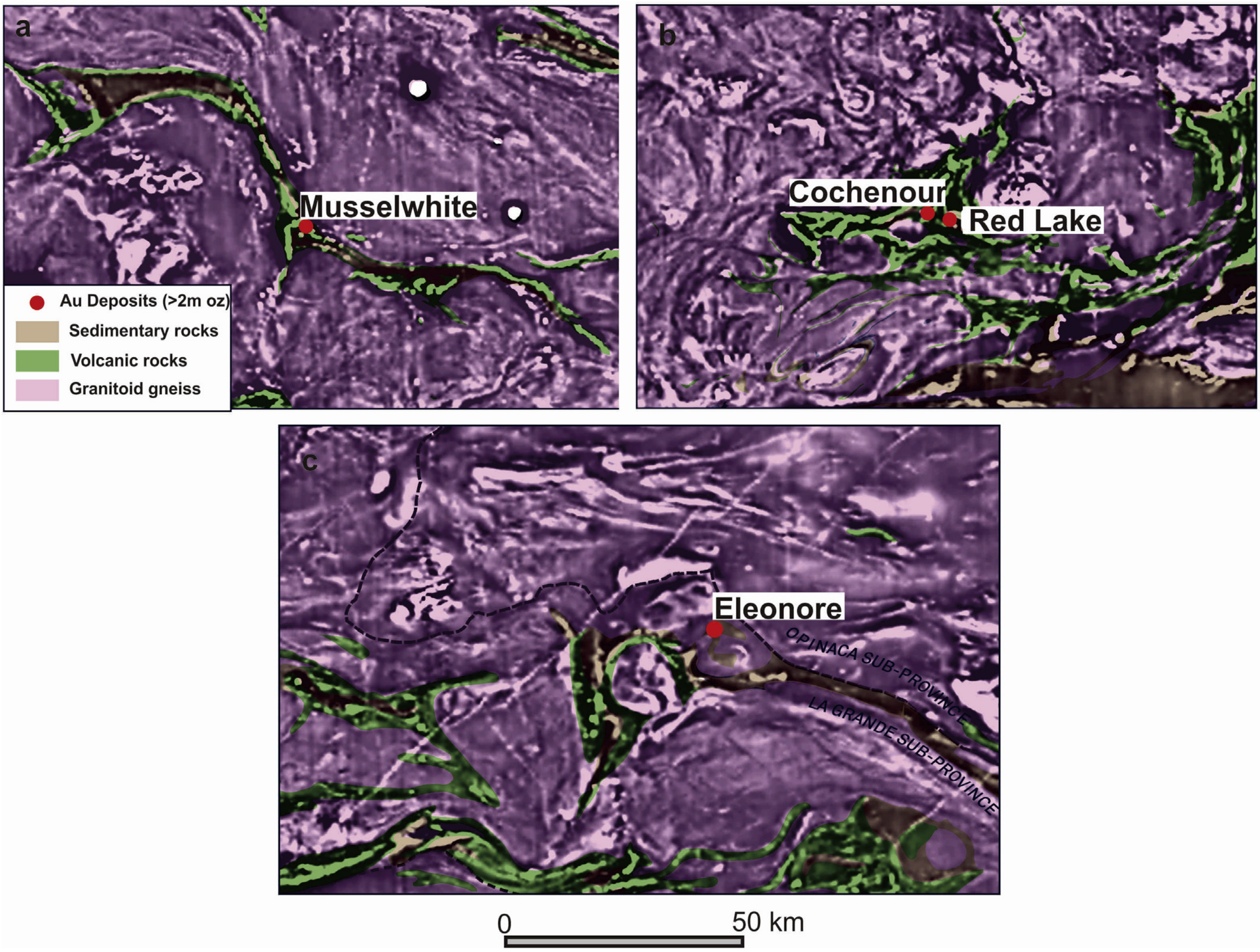

Figure 12. Aeromagnetic images showing gold deposits or districts located at triple-point and quadruple-point junctions of granitic batholiths: (a) Musselwhite; (b) Red Lake; (c) Eleonore: all in the Superior Province of Canada. Images courtesy of Francis Macdonald of Kenorland Minerals.

Agnew, and Ora Banda orogenic gold districts clearly lie at triple-point junctions at the province scale.

As the majority of world-class orogenic gold deposits are late in the kinematic history of their hosting orogens, their geometry is commonly preserved to the present time, making geological maps and derived cross sections essential exploration tools (Groves et al., 2000). The critical data in these maps can be digitally interrogated in increasingly sophisticated ways (e.g., Yousefi and Nykanen, 2016 and references therein) to produce gold prospectivity or endowment maps for conceptual geological targeting.

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References

Alexander, K.R., Kavanagh, M.E., Rolfe, G.I., 1990. The Cosmopoliton Howley mine, 14. Australasian Institute of Mining and Metallurgy Monograph, pp. 751–753.

Bateman, R.J., Hagemann, S.G., 2004. Gold mineralisation throughout about 45 Ma of Archaean orogenesis: protracted flux of gold in the Golden Mile, Yilgarn craton, Western Australia. Mineralium Deposita 39, 536–559.

Bateman, R.J., Hagemann, S.G., McCuaig, T.C., Swager, C.P., 2001. Protracted gold mineralization throughout Archean orogenesis in the Kalgoorlie camp, Yilgarn craton, Western Australia: structural, mineralogical, and geochemical evolution. Geological Survey of Western Australia Record 2001/17 63–98.

Blewett, R.S., Czarnota, K., Henson, P.A., 2010. Structural-event framework for the eastern Yilgarn Craton, Western Australia, and its implications for orogenic gold. Precambrian Research 183, 203–229.

Bloem, E.J.M., Dalstra, H., Groves, D.I., Ridley, J.R., 1994. Metamorphic and structural setting of Archaean amphibolite-hosted gold deposits near Southern Cross, Southern Cross Province, Yilgarn Block, Western Australia. Ore Geology Reviews 9, 183–208.

Boulter, C.A., Fotios, M.G., Phillips, G.N., 1987. The Golden Mile, Kalgoorlie: a giant gold deposit localized in ductile shear zones by structurally induced infiltration of auriferous metamorphic fluids. Economic Geology 82, 1661–1678.

Caddy, S.W., Bachman, R.L., Campbell, J.J., Reid, R.R., Otto, R.P., 1995. The Homestake gold mine, an early Proterozoic iron-formation-hosted gold deposit, Lawrence County, South Dakota. United States Geological Survey Bulletin 1857 J.

Colvine, A.C., Andrews, A.J., Cherry, M.E., Durocher, M.E., Fyon, J.A., Lavigne, M.J., MacDonald, A.J., Marmont, S., et al., 1984. Ontario Geological Survey Open-File Report. An Integrated Model for for the Origin of Archean Lode-gold Deposits, vol. 5524, 98p.

Cooke, D.P., Ramsey, T., Miller, J.M., Bath, A.B., 2017. Kundana Goldfield. In: Phillips, G.N. (Ed.), Australian Ore Deposits, vol. 32. Australian Institute of Mining and Metallurgy Monograph, pp. 199–206.

Cox, S.F., 2005. Coupling between Deformation, Fluid Pressures, and Fluid Flow in Ore-producing Hydrothermal Systems at Depth in the Crust. Economic Geology 100th Anniversary Volume, pp. 39–75.

Cox, S.F., Knackstedt, M.A., Braun, J., 2001. Principles of Structural Control on Permeability and Fluid Flow in Hydrothermal Systems, vol. 14. Society of Economic Geologists Reviews, pp. 1–24.

Cox, S.F., Sun, S.S., Etheridge, M.A., Wall, V.J., 1995. Structural and geochemical controls on the development of turbidite-hosted gold quartz vein deposits, Wattle Gully mine, central Victoria, Australia. Economic Geology 90, 1722–1786.

Cox, S.F., Wall, V.J., Etheridge, M.A., Potter, T.F., 1991. Deformational and metamorphic processes in the formation of mesothermal vein-hosted gold deposits — examples from the Lachlan Fold Belt in central Victoria, Australia. Ore Geology Reviews 6, 391–423.

Deng, J., Liu, X.F., Wang, Q.F., Dilek, Y., Liang, Y.Y., 2017. Isotopic characterization and petrogenetic modelling of early Cretaceous mafic diking-lithospheric extension in the North China Craton, eastern Asia. The Geological Society of America Bulletin 129, 1379–1407.

Deng, J., Wang, C.M., Bagas, L., Carranza, E.J.M., Lu, Y.j., 2015. Cretaceous-Cenozoic tectonic history of the Jiaojia Fault and gold mineralization in the Jiaodong Peninsula, China: constraints from zircon U-Pb, illite K-Ar, and apatite fission track thermochronometry. Mineralium Deposita 50, 987–1006.

De Ronde, C.E.J., de Wit, M.J., 1994. The tectonothermal evolution of the Barberton Greenstone Belt, South Africa: 490 million years of crustal evolution. Tectonics 13, 983–1005.

Edwards, M.J., Hitchman, S.P., 2017. Pine Creek gold province including Cosmo and Maud Creek. In: Phillips, G.N. (Ed.), Australian Ore Deposits, vol. 32. Australasian Institute of Mining and Metallurgy Monograph, pp. 467–472.

Gauthier, L., Hagemann, S.G., Robert, F., Pickens, G., 2004. New constraints on the architecture and timing of the giant Golden Mile gold deposit, Kalgoorlie, Western Australia. In: Groves, D.I. (Ed.), SEG2004: Predictive Mineral Discovery under Cover, Extended Abstracts. Society of Economic Geologists, Conference Series, pp. 353–356.

Goldfarb, R.J., Groves, D.I., 2015. Orogenic gold: common or evolving fluid and metal sources through time. Lithos 233, 2–26.

Goldfarb, R.J., Baker, T., Dube, B., Groves, D.I., Hart, C.J.R., Gosselin, P., 2005. Distribution, Character, and Genesis of Gold Deposits in Metamorphic Belts. Economic Geology 100th Anniversary Volume, pp. 407–450.

Goldfarb, R.J., Leach, D.I., Miller, M.L., Pickthorn, W.A., 1986. Geology, metamorphic setting, and genetic constraints of epigenetic lode-gold mineralization within the Cretaceous Valdez Group, South-central Alaska. Geological Association of Canada Special Paper 32, 87–105.

Goldfarb, R.J., Leach, D.I., Pickthorn, W.A., Paterson, C.J., 1988. Origin of lode-gold deposits of the Juneau gold deposit, southeast Alaska. Geology 16, 440–443.

Goldfarb, R.J., Snee, L.W., Miller, L.D., Newberry, R.J., 1991. Rapid dewatering of the crust deduced from ages of mesothermal gold deposits. Nature 354, 296–298.

Goldfarb, R.J., Santosh, M., 2014. The dilemma of the Jiaodong gold deposits: are they unique? Geoscience Frontiers 5, 139–153.

Groves, D.I., Santosh, M., 2015. The giant Jiaodong gold province: the key to a unified model for orogenic gold deposits. Geoscience Frontiers 7, 409–417.

Groves, D.I., Goldfarb, R.J., Gebre-Mariam, M., Hagemann, S.G., Robert, F., 1998. Orogenic gold deposits-a proposed classification in the context of their crustal distribution and relationship to other gold deposit types. Ore Geology Reviews 13, 7–27.

Groves, D.I., Goldfarb, R.J., Knox-Robinson, C.M., Ojala, J., Gardoll, S., Yun, G.Y., Holyland, P., 2000. Late-kinematic timing of orogenic gold deposits and significance for computer- based exploration techniques with emphasis on the Yilgarn Block, Western Australia. Ore Geology Reviews 17, 1–38.

Groves, D.I., Goldfarb, R.J., Santosh, M., 2016. The conjunction of factors that lead to formation of giant gold provinces and deposits in non-arc settings. Geoscience Frontiers 7, 303–314.

Groves, D.I., Phillips, G.N., Ho, S.E., Houstoun, S.M., Standing, C.A., 1987. Craton-scale distribution of Archaean greenstone gold deposits: predictive capacity of the metamorphic model. Economic Geology 82, 2045–2058.

Groves, D.I., Ridley, J.R., Bloem, E.J.M., Gebre-Mariam, M., Hronsky, J.M.A., Knight, J.T., McNaughton, N.J., Ojala, V.J., Vielreicher, R.M., Holyland, P.W., McCuaig, T.C., 1995. Lode-gold deposits of the Yilgarn Block: products of late-Archaean crustal-scale overpressured hydrothermal systems. In: Coward, M.P., Ries, A.C. (Eds.), Early Precambrian Processes, Journal of the Geological Society of London, Special Publication, vol. 95, pp. 155–172.

Harlan, S.S., Vielreicher, R.M., Mortensen, J.M., Bradley, D.C., Goldfarb, R.J., Snee, L.W., Till, A.B., 2017. Geology and timing of ore formation in the Willow Creek gold district, Talkeetna Mountains, southern Alaska. Economic Geology 112.

Hronsky, J.M.A., Groves, D.I., 2008. Science of targeting. Definition, strategies, targeting and performance measurement. Australian Journal of Earth Sciences 55, 3–12.

Hodkiewiecz, P.F., Weinberg, R.F., Gardoll, S.J., Groves, D.I., 2005. Complexity gradients in the Yilgarn Craton: fundamental controls on crustal-scale fluid flow and formation of world-class orogenic gold deposits. Australian Journal of Earth Sciences 52, 831–841.

Jackson, J., Molnar, P., 1990. Active faulting and block rotations in the western Transverse Ranges, California. Tectonics 5, 629–648.

Jones, S.A., 2014. Contrasting structural style of gold deposits in the Leonora Domain: evidence for early gold deposition, Eastern Goldfields, Western Australia. Australian Journal of Earth Sciences 61, 881–917.

Knight, J.T., Groves, D.I., Ridley, J.R., 1993. District-scale structural and metamorphic controls on Archaean lode-gold mineralization in the amphibolites facies Coolgardie Goldfield, Western Australia. Mineralium Deposita 28, 436–456.

Large, R.R., Bull, S.W., Maslennikov, V.V., 2011. A carbonaceous sedimentary source-rock model for Carlin-type and orogenic gold deposits. Economic Geology 106, 331–358.

Leader, L.D., Robinson, J.A., Wilson, C.J.L., 2010. Role of faults and folding in controlling gold mineralization at Fosterville, Victoria. Australian Journal of Earth Sciences 57, 259–277.

Leader, L.D., Wilson, C.J.L., Robinson, J.A., 2013. Structural constraints and numerical simulation of strain localization in the Bendigo Goldfield, Victoria, Australia. Economic Geology 108, 279–307.

Li, S.R., Santosh, M., 2017. Geodynamics of heterogeneous gold mineralization in the North China Craton and its relationship to lithospheric destruction. Gondwana Research 50, 267–292.

Lobato, L.M., Ribeiro-Rodrigues, L.C., Zuccheyi, M., Noce, C.M., Baltazar, O.F., da Silva, L.C., Pinto, C.P., 2001. Brazil's premier gold province. Part 1: the tectonic, magmatic, and structural setting of the Archean Rio das Velhas greenstone belt, Quadrilatero Ferrifero. Mineralium Deposita 36, 228–248.

Mueller, A.G., Harris, L.B., Lungan, A., 1988. Structural control on greenstone-hosted gold mineralization by transcurrent shearing: a new interpretation of the Kalgoorlie mining district, Western Australia. Ore Geology Reviews 3, 359–387.

Nicholson, C., Seeber, L., Williams, P., Sykes, L.R., 1986. Seismic evidence for conjugate slip and block rotation within the San Andreas Fault system, California. Tectonics 5, 629–648.

Ojala, V.J., Ridley, J.R., Groves, D.I., Hall, G.C., 1993. The Granny Smith gold deposit: the role of heterogeneous stress distribution at an irregular granitoid contact in a greenschist facies terrane. Mineralium Deposita 28, 409–419.

Page, R.A., Plafker, G., Pulpan, H., 1995. Block rotations in east-central Alaska: a framework for evaluating earthquake potential? Geology 23, 629–632.

Perring, C.S., Barley, M.E., Cassidy, K.F., Groves, D.I., McNaughton, N.J., Rock, N.M.S., Bettenay, L.F., Golding, S.D., Hallberg, J.A., 1989. The association of linear mobilebelts, mantle-crustal magmatism and Archean gold mineralization in the eastern Yilgarn Block of Western Australia. Economic Geology Monograph 6, 571–584.

Phillips, G.N., Groves, D.I., Kerrich, R., 1996. Factors in the formation of the giant Kalgoorlie gold deposit. Ore Geology Reviews 10, 295–317.

Ridley, J.R., 1993. The relations between mean rock stress and fluid flow in the crust: with reference to vein- and lode-style gold deposits. Ore Geology Reviews 8, 23–37.

Ridley, J.R., Mengler, F., 2000. Lithological and structural controls on the form and setting of vein stockwork ore bodies at the Mt Charlotte gold deposit, Kalgoorlie. Economic Geology 95, 85–98.

Robert, F., Poulson, H.K., Cassidy, K.F., Hodgson, J.C., 2005. Gold Metallogeny of the Superior and Yilgarn Cratons. Economic Geology 100th Anniversary Volume, pp. 1001–1033.

Rock, N.M.S., Groves, D.I., Perring, C.S., Golding, S.D., 1989. Gold, lamprophyres, and porphyries: what does their association mean? Economic Geology Monograph 6, 609–625.

Sanchez, M.G., Allan, M.M., Hart, C.J.R., Mortensen, J.K., 2014. Structural and tectonic control on mineralization by magnetite-destructive faults in western Yukon and eastern Alaska. Geological Society of America Abstracts with Programs 46 (6), 462.

Sibson, R.H., 2004. Controls on maximum fluid overpressure defining conditions for mezozonal mineralization. Journal of Structural Geology 26, 1127–1136.

Taylor, R.D., Goldfarb, R.J., Monecke, T., Fletcher, I.R., Cosca, M.A., Kelly, N.M., 2015. Application of U-Th-Pb phosphate dating to young orogenic gold deposits: new age constraints on the formation of the Grass Valley gold district, Sierra Foothills province, California. Economic Geology 110, 1313–1337.

Tripp, G., 2014. How Neoarchean Stratigraphy and Structural Geology Determine the Timing and Controls of World-class Greenstone Gold Camps in the Eastern Goldfields Province: Key Factors for Gold Exploration. Gold'14 Extended Abstracts, AIG Bulletin 59-2014, pp. 124–128.

Vielreicher, N.M., Groves, D.I., Snee, L.W., Fletcher, I.R., McNaughton, N.J., 2010. Broad synchroneity of three gold mineralization styles in the Kalgoorlie Gold Field: SHRIMP U-Pb and Ar/Ar geochronological evidence. Economic Geology 105, 187–227.

Vielreicher, N.M., Groves, D.I., McNaughton, N.J., 2015. The timing of gold mineralization across the eastern Yilgarn craton using U–Pb geochronology of hydrothermal phosphate minerals. Mineralium Deposita 50, 391–428.

Vielreicher, N.M., Groves, D.I., McNaughton, N.J., 2016. The giant Kalgoorlie Goldfield revisited. Geoscience Frontiers 7, 359–374.

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Viljoen, M.J., Viljoen, R.P., 1969. An introduction to the geology of the Barberton Granite-Greenstone terrain. Geological Society of South Africa Special Publication 2, 9–28.
Weinberg, R.F., Hodkiewitcz, P.F., Groves, D.I., 2004. What controls gold distribution in Archean terranes? Geology 32, 545–548.
Weinberg, R.F., van der Borgh, P., Bateman, R.J., Groves, D.I., 2006. Kinematic history of the Boulder-Lefroy Shear Zone system and controls on associated gold mineralization, Yilgarn Craton, Western Australia. Economic Geology 100, 1407–1426.
White, A.J.R., Waters, D.J., Robb, L.J., 2015. Exhumation-driven devolatilization as a fluid source for orogenic gold mineralization at the Damang deposit, Ghana. Economic Geology 110, 1009–1025.
Wilkinson, H.E., Cherry, D.P., King, R.L., Malone, M.P., Williams, C.E., Byrne, D.R., 1995. Bendigo, and Part of Mitiamo. 1–100,000 Geological Map. Geological Survey of Victoria.
Wyman, D., Kerrich, R., 1989. Archaean shoshonitic lamprophyres associated with Superior Province gold deposits: distribution, tectonic setting, nobel metal abundances and significance to gold mineralization. Economic Geology Monograph 6, 651–667 x and implications for gold mineralization: a case study of th.
Yang, L.Q., Deng, J., Wang, Z.l., Zhang, l., Goldfarb, R.j., Yuan, W.M., Weinberg, R.F., Zhang, R.Z., 2016. Thermochronologic constraints on evolution of the Linglong metamorphic core Complex: a case study from the Xiadian gold deposit, Jiaodong Peninsula, eastern China. Ore Geology Reviews 72, 165–178.
Yang, L.Q., Deng, J., Wang, Z.l., Zhang, L., Guo, L.N., Song, M.C., Zheng, X.L., 2014. Mesozoic gold metallogenic system of the Jiaodong gold province, Mesozoic gold metallogenic system of the Jiaodong gold province, eastern China. Acta Petrologica Sinica 30, 2447–2467 (in Chinese with English abstract).
Yang, Q.Y., Santosh, M., 2017. The building of an Archean microcontinent: evidence from the North China Craton. Gondwana Research 50, 3–37.
Yousefi, M., Nykanen, V., 2016. Data-driven logistic-based weighting of geochemical and geological evidence layers in mineral prospectivity mapping. Journal of Geochemical Exploration 164, 94–106.
Zhai, M.G., Santosh, M., 2011. The early Precambrian odyssey of the North China Craton: a synoptic overview. Gondwana Research 20, 6–25.

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