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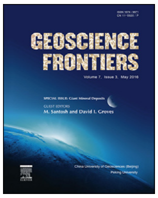

Focus paper

The conjunction of factors that lead to formation of giant gold provinces and deposits in non-arc settings

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ABSTRACT

It is quite evident that it is not anomalous metal transport, nor unique depositional conditions, nor any single factor at the deposit scale, that dictates whether a mineral deposit becomes a giant or not. A hierarchical approach thus is required to progressively examine controlling parameters at successively decreasing scales in the total mineral system to understand the location of giant gold deposits in non-arc environments. For giant orogenic, intrusion-related gold systems (IRGS) and Carlin-type gold deposits and iron oxide-copper-gold (IOCG) deposits, there are common factors among all of these at the lithospheric to crustal scale. All are sited in giant gold provinces controlled by complex fundamental fault or shear zones that follow craton margins or, in the case of most Phanerozoic orogenic giants, define the primary suture zones between tectonic terranes. Giant provinces of IRGS, IOCG, and Carlin-type deposits require melting of metasomatized lithosphere beneath craton margins with ascent of hybrid lamprophyric to granitic magmas and associated heat flux to generate the giant province. The IRGS and IOCG deposits require direct exsolution of volatile-rich magmatic-hydrothermal fluids, whereas the association of such melts with Carlin-type ores is more indirect and enigmatic. Giant orogenic gold provinces show no direct relationship to such magmatism, forming from metamorphic fluids, but show an indirect relationship to lamprophyres that reflect the mantle connectivity of controlling first-order structures.

In contrast to their province scale similarities, the different giant gold deposit styles show contrasting critical controls at the district to deposit scale. For orogenic gold deposits, the giants appear to have formed by conjunction of a greater number of parameters to those that control smaller deposits, with resultant geometrical and lithostratigraphic complexity as a guide to their location. There are few giant IRGS due to their inferior fluid-flux systems relative to orogenic gold deposits, and those few giants are essentially preservational exceptions. Many Carlin-type deposits are giants due to the exceptional conjunction of both structural and lithological parameters that caused reactive and permeable rocks, enriched in syngenetic gold, to be located below an impermeable cap along antiformal “trends”. Hydrocarbons probably played an important role in concentrating metal. The supergiant Post-Betze deposit has additional ore zones in strain heterogeneities surrounding the pre-gold Goldstrike stock. All unequivocal IOCG deposits are giant or near-giant deposits in terms of gold-equivalent resources, partly due to economic factors for this relatively poorly understood, low Cu-Au grade deposit type. The supergiant Olympic Dam deposit, the most shallowly formed deposit among the larger IOCGs, probably owes its origin to eruption of volatile-rich hybrid magma at surface, with formation of a large maar and intense and widespread brecciation, alteration and Cu-Au-U deposition in a huge rock volume.

1. Introduction

There has understandably been a fascination with giant mineral deposits, both from an economic viewpoint, in that they represent

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targets that can transform junior exploration companies into majors, particularly in the current exploration climate (Groves and Trench, 2014), and from an academic viewpoint in terms of their genesis. There has been considerable discussion on the precise definition of both the terms "world-class" and "giant" deposit (e.g., Laznicka, 2006). Most authors accept Singer's (1995) definition of world-class as those deposits in the top 10% of the deposit group in terms of metal endowment, but the definition of giant and supergiant is less clear. They are commonly much larger than the next-largest world-class deposit making them statistical anomalies (Fig. 1). Their anomalous size is primarily a geological feature, but is almost certainly enhanced by economies of scale during mining. In this paper, a world-class gold deposit is considered to have had a pre-production resource of >100 tonnes (>3 moz) gold and a giant deposit >250 tonnes (>7.5 moz) gold (or gold-equivalent for Au + Cu for the IOCG deposits).

Investigations on the giant mineral deposits themselves (e.g., Whiting et al., 1993; Kerrich et al., 2000; Cooke and Pongraz, 2002; Cooke et al., 2005; Leahy et al., 2005; Richards, 2013) and from reviews of major hydrothermal deposit types (e.g., papers in Hedenquist et al., 2005) reveal that giants of a given deposit type formed from similar ore fluids, via similar mechanisms, and under similar depositional conditions to smaller deposits of that type. Generally, fluid inclusion and stable isotope data are similar, as are alteration haloes, albeit with a much larger footprint for the giant deposits, a major factor in their early discovery in new mineral provinces (e.g., Hodgson, 1993; Hronsky and Groves, 2008). There have been suggestions that some individual giant deposits formed via special processes. For example, the giant Golden Mile orogenic gold system in the Yilgarn Block of Western Australia has been attributed to fluid mixing involving an anomalously oxidized fluid (Walshe et al., 2003; Neumayr et al., 2007), but other orogenic gold giants show no evidence of oxidized fluids. In fact, some giants such as Obuasi in the Ashanti Belt of Ghana, together with adjacent smaller deposits, were deposited from highly reduced fluids (e.g., Oberthuer et al., 1994). Furthermore, this anomalous oxidized fluid can simply be the consequence of a single reduced fluid interacting with more oxidized country rock (e.g., Evans, 2010).

It is evident that it is necessary to look beyond depositional thermodynamic conditions, to the physical environments of the deposits and to the mineral provinces that host the giant deposits, to search for the conjunction of factors that result in the anomalously large size of the giant deposits (e.g., Phillips et al., 1996; Kerrich et al., 2000). This paper takes this approach and is designed to provoke thought rather than provide an exhaustive review of all references and models for the gold deposit styles in non-arc environments that are used to illustrate the principles: for these see Goldfarb et al. (2001, 2005), Cline et al. (2005), Williams et al. (2005), and Groves et al. (2010). The global locations of giant gold deposits are shown in Fig. 2 and their size distribution in Fig. 3. Porphyry-high sulfidation Cu-Au-Mo systems are only briefly discussed in terms of their lithosphere scale controls because of analogies to IRGS, IOCGs and argumentatively Carlin-type deposits in terms of ore-related magmatic-hydrothermal processes. Other gold deposit types in volcanic arc settings, such as low sulfidation Au-Ag deposits and gold-rich volcanogenic massive sulfide (VMS) deposits, are not discussed, nor are paleoplacers such as the giant Witwatersrand deposits, nor modern placers.

2. Tectonic and lithospheric setting of giant gold provinces and deposits

2.1. Carlin-type deposits, IRGS, and IOCG deposits

Despite their obvious differences in terms of deposit-scale characteristics, metal associations and gold grades, Groves and Santosh (2015) in their review show that world-class to giant deposits of these three diverse gold deposit types share a common lithospheric setting. With rare exceptions, the deposits lie close to lithospheric boundaries, most commonly craton margins (Fig. 2), above metasomatized sub-continental lithospheric mantle (SCLM). Deep mantle-tapping fault or shear zones appear important, controlling the so-called trends in the Carlin districts (e.g., Grauch et al., 2003) and a structural corridor in the Carajas IOCG district (e.g., Grainger et al., 2008), for example. The key ingredient in deposit formation appears to be hybrid mantle-crustal volatile-rich magmas generated by emplacement of lamprophyric magmas into the base of the crust (e.g., Groves et al., 2010; Mair et al., 2011), with ascent controlled by the deep fault zones (see figures 3-6 in Groves and Santosh, 2015). These have a direct link to auriferous magmatic-hydrothermal fluids that deposited the IRGS and IOCG deposits, but have a more obscure relationship to the Carlin-type ores (Muntean et al., 2011), perhaps serving as the heat engine. Interestingly, the giant Bingham Canyon porphyry Cu-Au-Mo deposit to the east of the Carlin province, with its halo of disseminated gold deposits, is essentially the same age as the Carlin deposits and a similar magmatic history involving hybrid mantle-crustal melts has been postulated (Cunningham et al., 2004). In the case of the Carlin-type deposits and most IRGS (e.g., Lang et al., 2000), the conjunction of these tectonic and magmatic parameters with the occurrence of reactive shelf sequences, including permeable and reactive carbonate rocks, adjacent to the fragmented craton margins appears critical. In contrast, the IOCG deposits, which show a more direct link to metasomatized lithosphere, as for example defined by ore-related carbonatites (e.g., Vielreicher et al., 2000), may have formed in any hydrothermally brecciated host rocks.

2.2. Orogenic gold deposits

As with the other gold deposit types above, all world-class to giant orogenic gold deposits have a first-order tectonic control. They rarely occur along craton boundaries: important exceptions are the Neoarchean deposits of the Norseman-Wiluna Belt in the Yilgarn of Western Australia and the Cretaceous deposits of the Jiaodong Province on the margin of the North China Craton (Groves and Santosh, 2015, their fig. 10). More commonly, the large orogenic gold deposits are sited adjacent to lithospheric- to crustal-scale fault or shear systems that represent sutures between tectonic terranes. The giant deposits are commonly situated in second-order structures within geometrical complexities or major jogs along these sutures. These sutures almost invariably represent the sites of initial deformation in the assembly of the terranes, and late-kinematic deformation during reactivation processes at times of later translational motion between the terranes and final uplift; it is typically during this regional uplift that the gold provinces hosting giant orogenic gold deposits form in a retrograde P-T environment. Although, unlike the other gold deposit styles discussed above, the giant deposits have no direct genetic relationship to magmatism below craton margins, these margins may produce terrane-scale stress heterogeneities that cause the large-scale structural and geometrical complexities in which the giant orogenic gold deposits are located. For example, Central Asia incorporates large orogenic belts of the Altaid collage or Central Asian Orogenic Belt (CAOB), separating the East European and Siberian cratons to the north from the Tarim and North China cratons to the south (Xiao and Santosh, 2014; Xiao et al., 2015). The protracted tectonic evolution of the CAOB during Neoproterozoic to late Paleozoic—early Mesozoic involved accretion of multiple microcontinents, island arcs, seamounts, oceanic plateaus, ophiolites and accretionary complexes. This was followed by intracontinental tectonics in the Cenozoic related to far-field effects from collision of the Indian Plate with the Eurasian Plate (Xiao et al., 2015). Many

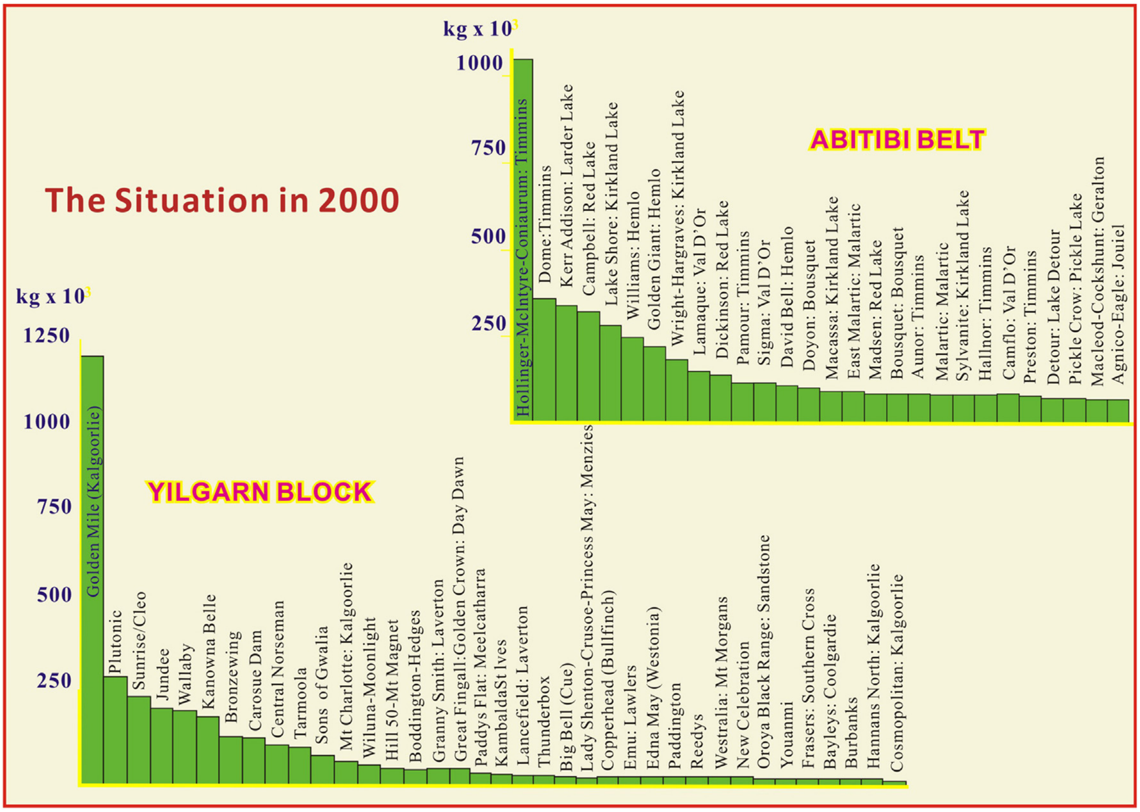

Figure 1. Cascade diagrams for total gold resources for orogenic gold deposits of the Abitibi Belt, Canada compared to those from the eastern Yilgarn, Western Australia at 2000, when both provinces had approached maturity. Note the anomalous size of the Hollinger-McIntire and Golden Mile deposits in each province.

world-class ore deposits were formed during the geodynamic evolution of the CAOB (Goldfarb et al., 2014), among which many of the giants are located in complex duplex zones in terrane-scale sutures that are associated with the multiple accretionary orogenesis of the CAOB, and that mimic the shape of exposed and covered craton margin as shown in Fig. 4.

Similarly, despite the lack of a direct genetic link between orogenic gold deposition and magmatism, there is commonly a spatial relationship with lamprophyric intrusions that ascended from the mantle along the deep fault zones in some locations, before gold deposition, broadly contemporaneous with it, and subsequent to it, indicating longevity of the deep structures.

2.3. *Common factors*

Despite the obvious differences in nature of the giant gold deposit styles at the deposit scale, they clearly share a number of common characteristics at the crustal to lithospheric scale. Major mantle-tapping fault zones that mimic craton margins or represent terrane sutures, complexities in fault geometry, and ascent along faults of hybrid mantle-crustal magmas that include lamprophyres are common to all these giant deposit types. This is irrespective of a direct (IRGS and IOCGs), indirect (Carlin-type deposits) or negligible (orogenic deposits) role in deposit genesis, all these deposit types have critical shared features (Hronsky et al., 2012; Groves and Santosh, 2015).

2.4. *Porphyry and high-sulfidation epithermal systems*

There is no intention to discuss giant porphyry-high-sulfidation epithermal systems (Sillitoe and Perello, 2005) in detail here, but, as mentioned above, there are some parallels at the crustal to lithospheric scale to other giant gold deposits discussed in this paper. For example, major arc-parallel fault zones appear to be important controls, particularly where they are cut by orthogonal trans-arc accommodation structures. The trans-arc faults divide the arc into domains that overlie segments of subducting oceanic crust, including underthrusted oceanic ridges, seamounts, and plateaus, with contrasting dip (Cooke et al., 2005). In addition, the larger deposits are restricted to more compressional segments of the arc, with resultant ponding of magmas in magma chambers at the crust-mantle boundary, prior to ascent to the surface (Loucks, 2012). Metasomatized mantle also appears to be involved in the magmatic-hydrothermal formation of some giant porphyry-epithermal systems (e.g., Grasberg, Ladolam, Porgera) associated with high-K calc-alkalic intrusions (Müller and Groves, 1993). Hence, there are some important common factors at the larger scale between these giant gold systems and giant Carlin-type deposits, IOCG deposits, and IRGS.

3. Giant orogenic gold mineral system parameters

3.1. *Age and source parameters*

Thorough reviews for the age and source of global orogenic gold deposits are given by Goldfarb et al. (2001) and Goldfarb and Groves (2015), respectively. The former shows that giant deposits can occur in any of the major orogenic periods of orogenic gold formation in the Neoarchean, Paleoproterozoic, late Neoproterozoic–Paleozoic, and Mesozoic–Tertiary. The source of orogenic gold is enigmatic, with two main competing models. The first, favored by one of us (RJG) as the most common scenario,

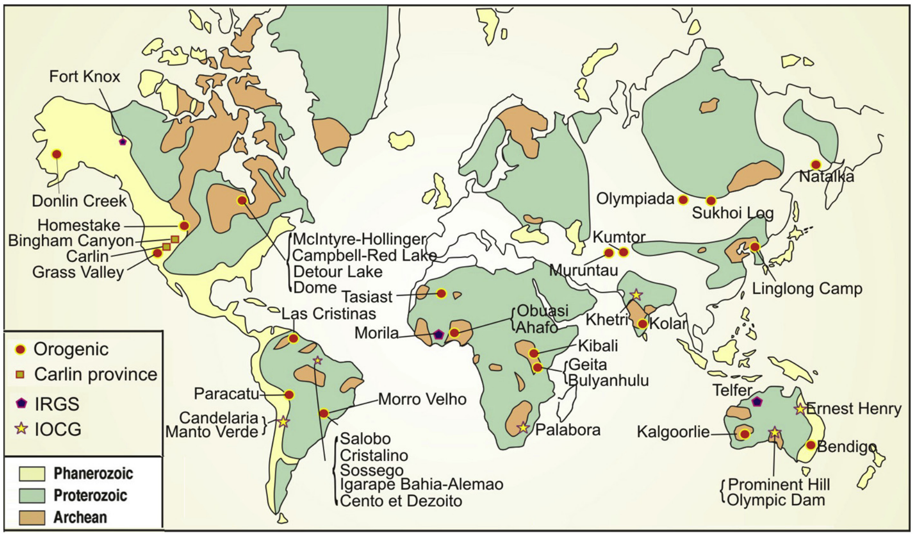

Figure 2. Schematic world map showing interpreted age of basement rocks and distribution of giant orogenic gold, Carlin-type, IRGD and IOCG deposits. Figure adapted from Goldfarb et al. (2005) and Groves et al. (2010).

considers that orogenic gold forms late in regional metamorphism from deep-crustal metamorphic fluids. Sulfur and gold would be released from pyrite-bound gold from largely sedimentary rocks in the Phanerozoic and perhaps largely volcanic rocks in the Precambrian. In this scenario, the source rocks have already been added to the older craton. The second, favored by another of us (DIG), uses the Mesozoic Jiaodong deposit model of Goldfarb and Santosh (2014), where gold is most likely sourced from devolatilization of pyritic sediments above a subducting slab of oceanic crust, to suggest that all deposits formed via this mechanism throughout geologic time. Thus, in this model, fluid and metal are always sourced from below the craton. This model, if correct, could partly explain why there are so many Neoarchean orogenic gold giants despite the antiquity of the host terranes. Some of this reflects preservation of mid-crustal levels in the cratons, which became highly gold mineralized because the early Earth heat engine was likely relatively strong (e.g., Groves et al., 2005). In addition, the associated plume activity, combined with hotter more magnesian basaltic oceanic crust, may have been essential for mobilizing metal from gold-rich pyrite nodules in overlying subducting oceanic sediments (e.g., Steadman et al., 2013). Irrespective of these models, giants do appear at all ages and hence neither age nor source is a critical factor.

3.2. Magmatic associations

The literature abounds on suggestions of magmatic-hydrothermal associations between granitic intrusions and orogenic gold deposits, as reviewed by Goldfarb and Groves (2015). However, there is no consistent age relationship between granites and gold, with granites in the host orogenic belts being pre-, broadly syn- or post-gold deposition. Similarly, no studies have conclusively shown a consistent genetic relationship between the deposits and any specific type of broadly syn-gold granitic intrusion where this has been suggested. Robust geochronological research shows that in most cases there is a measurable age gap between granite intrusion and the subsequent major phase of gold deposition, with only low-grade (<0.5 g/t Au), economically insignificant gold related to intrusion emplacement and cooling (e.g., Vielreicher et al., 2015).

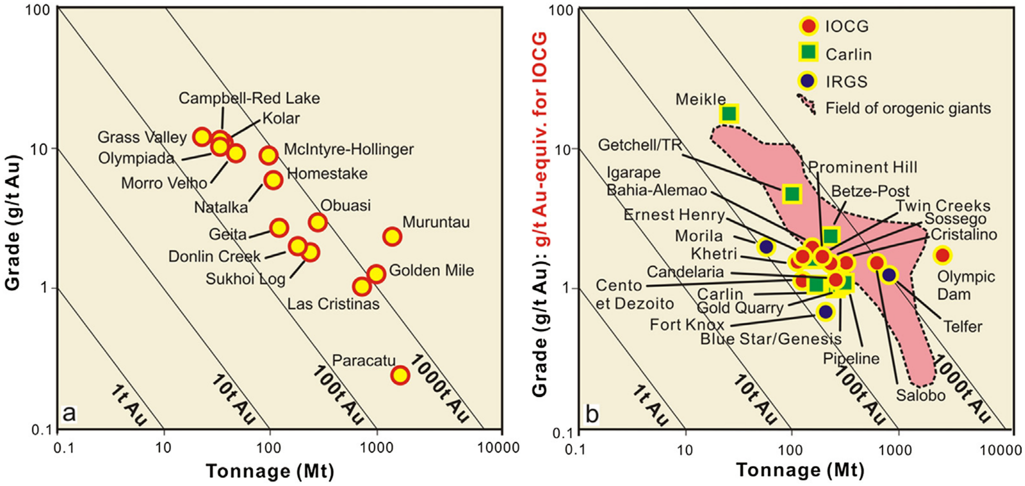

Figure 3. Ore grade in g/t gold versus metric tonnes of ore for giant deposits belonging to the orogenic, Carlin-type, IOCG and IRGD gold deposit groups. For IOCG deposits, grade is shown as g/t gold-equivalent, which utilizes current gold and copper prices to calculate copper value as gold equivalent value. Data from Cline et al. (2005), Goldfarb et al. (2005), Groves et al. (2010), and Goldfarb and Groves (2015).

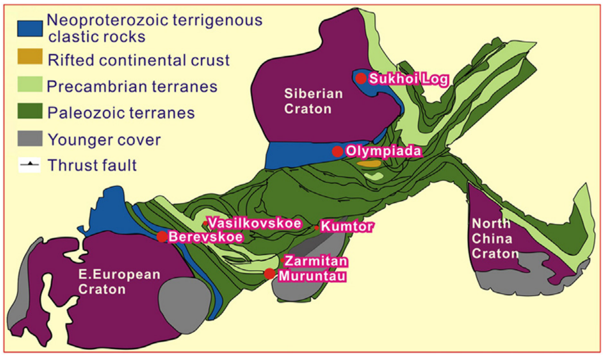

Figure 4. Tectonic map of Central Asian region showing position of giant orogenic gold deposits in complexities in suture zones in orogenic belts related to heterogeneous stresses developed around exposed and buried craton margins. Adapted from Sengor and Natal'in (1996).

Hence there can be no direct link between granites and giant gold deposits, although many of these deposits are spatially associated with lamprophyres, implicating the presence of mantle-tapping structures adjacent to the giant deposits.

3.3. *Fluid conduits*

The section above leads into the relative importance of major fault or shear zones as first-order fluid conduits for auriferous fluids. As discussed above, association with the most important first-order lithospheric-scale structures and major sutures is a factor common to all provinces that contain world-class to giant deposits, as confirmed by the common spatial association with lamprophyres. There is also some evidence to suggest that sites of anomalously high uplift rates along these structures, defined for example by juxtaposition of late conglomerate basins and lower volcanic sequences in the Neoarchean Abitibi Belt (e.g., Colvine et al., 1984) and Norseman-Wiluna Belt (e.g., Tripp, 2014), may be important in lowering lithostatic pressures and enhancing hydrofracturing, extreme pressure fluctuations, associated chemical changes and unmixing episodes, and gold deposition (e.g., Groves et al., 1987). Stacked thrust duplexes in the Ashanti Belt of Ghana may have had a similar effect in enhancing the size of the giant Obuasi deposit (e.g., Allibone et al., 2002). There are also commonly important second- and third-order faults that make up complex interconnecting fault networks around the larger orogenic gold deposits (e.g., Groves et al., 2000). These are commonly structures formed during early deformation events, typically termed D1 and D2, that are reworked during later D3 and D4 deformation, which is coincident with gold mineralization.

3.4. *Structural and lithological traps and caps*

Structural traps are a necessity for all orogenic gold deposits and anticlinal hinges are a robust feature of most deposits. These are particularly important for giant deposits that require large anticlinal hinges, commonly anticlinoria, to focus sufficient fluid to produce the large tonnage deposits. Good examples include the giant Neoarchean Golden Mile, Paleoproterozoic Homestake, and Paleozoic Bendigo deposits, which all show the classic geometry of "locked-up", commonly thrusted anticlines with an overturned back limb.

In terms of lithological traps, rheological contrasts between units that help establish strain gradients during deformation appear critical (Cox et al., 2001). For Precambrian deposits, most giants are hosted by rocks that are both competent and chemically reactive with the auriferous fluid. Volcanic rocks and mafic intrusions with high iron and high $Fe/Fe + Mg$ ratios or banded iron formations (BIFs) are commonly preferred host rocks, particularly where the sequences are duplicated by folding and/or thrusting (e.g., Golden Mile, Kalgoorlie). Many world-class to giant deposits are sited close to the regional contact between underlying volcanic and overlying sedimentary sequences, with the latter acting as a relatively impermeable cap on the hydrothermal systems. A schematic orogenic gold systems model, based on Archean examples, is presented in Fig. 5. This apparent lithostratigraphic control, as well as the stratabound nature of BIF-hosted deposits, led to proliferation of syn-sedimentary models for orogenic gold deposits by Hutchinson (1987) and others prior to research in the 1990s that clearly demonstrated an epigenetic origin. For some Phanerozoic giants, contrasts between competent granitic intrusions (Alaska-Juneau, Grass Valley) and turbidite sequences result in effective fluid focusing and resultant high fluid flux.

However, in most cases, controls are more subtle variations in competency related to thickness of turbidite units or the amount of reactive carbon within them. Thicker units tend to be the hosts whereas thinner, more shale-rich units tend to represent aquacludes. Anomalous rock units within the province, for example limestones on the northern side of Muruntau, may also play a role as important aquifers.

3.5. *Geometrical complexity*

Although most giant deposits have the parameters discussed above, there are exceptions, such that none of the parameters are unequivocally present. However, the giant deposits do appear to have a more complete combination of these parameters than the smaller deposits (e.g., Groves et al., 2000). This means that the giant deposits represent geometrical anomalies due to their complexity at scales from belt scale (Fig. 4) down to district scale (Fig. 6). This complexity results from the conjunction of factors such as the siting of giant deposits in misaligned jogs in first-order faults, progressive reworking of earlier structures during later deformational events, the anomalous size of reactive host units, and the presence of anomalous competent bodies such as small intrusions in shear zones.

Hronsky (2011) proposed that most hydrothermal ore-forming systems, including orogenic gold systems, can be considered as forming in transient fluid-exit conduits associated with the episodic rupture of over-pressured fluid reservoirs at depth; that is,

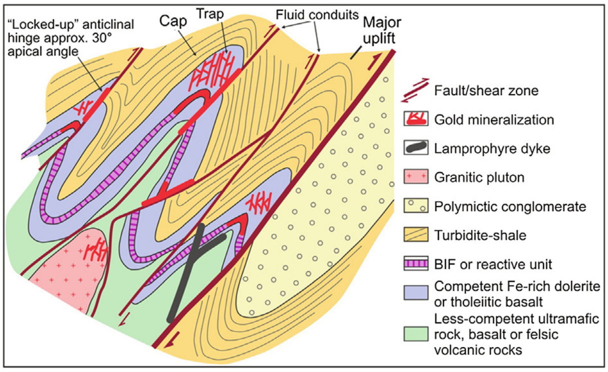

Figure 5. Schematic representation of the conjunction of parameters responsible for the formation of Archean orogenic gold deposits. Similar principles apply to younger deposits but host rocks are different and control potentially more subtle. As the sketch is a cross section, only the vertical components of transpressional faults are shown; there is clearly a strike-slip component. Oblique fault sets that represent accommodation structures are not shown for the same reason, but are an important additional parameter.

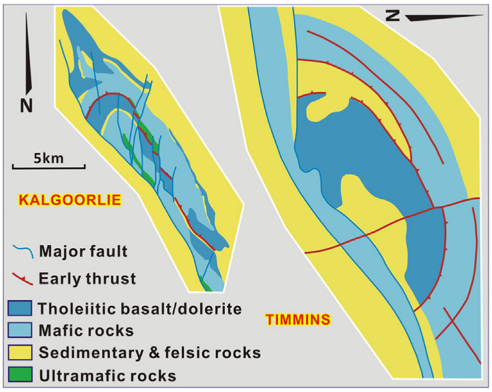

Figure 6. Comparison of the complex geometries of the two giant greenstone-hosted Neoarchean giant orogenic gold districts at Kalgoorlie, Western Australia, and Timmins, Canada. Timmins is rotated through 90°, such that stress fields at the time of gold mineralization, as shown on the figure, are broadly similar. Adapted from Groves et al. (2000).

they represent self-organized critical systems (SOCS). This explains why classical structural analyses commonly fail when applied in gold exploration when they are solely based on kinematic analysis of syn-gold deformation structures assuming conditions of homogeneous strain. However, the SOCS concept is entirely consistent with the concept of greater fluid flux through complex structures with related strain gradients caused by progressive heterogeneous deformation, including reactivation of pre-existing non-planar structures around local rigid bodies such as small intrusions or megaboudins.

3.6. *Critical conjunctions for giant orogenic gold deposits*

It appears that no one factor controls the location of giant orogenic gold deposits (e.g., Kalgoorlie: Phillips et al., 1996). The location of orogenic gold provinces that host multiple world-class and one or more giant deposits are clearly related to the most important of the first-order lithospheric structures and terrane-bounding sutures that may be marked by anomalous magmatism including emplacement of lamprophyre dikes. Anomalous zones of complex structural geometry along the length of these structures are particularly well gold-endowed, as are zones of high differential uplift marked by juxtaposed upper and lower lithostratigraphic units. The best criterion at the district to deposit scale is the overall geometric complexity of the geology caused by the conjunction of jogs in the first-order structures, arrays of accommodation structures, reactivated early structures including thrusts, large faulted anticlinoria in rheologically contrasting host rocks, and small rigid intrusive bodies in low-strength shear zones. The conjunction of a large number of parameters considered critical for formation of a large gold resource is clearly shown in GIS-based endowment/prospectivity analyses which highlight the giants whatever the number and nature of criteria are selected (e.g., Groves et al., 2000).

4. Comparison with IRGS

In contrast to orogenic gold systems where there are multiple fluid-flux pulses related to periodic seismic events during a single prolonged deformation episode, IRGS are related to a single prolonged pulse of magmatic-hydrothermal fluid related to emplacement of hybrid, reduced granitic intrusions. These systems include gold deposits mainly comprising sheeted vein networks in the intrusion cupola, and other deposits surrounding the causative pluton, which include skarns, and As-Au, Sb, and Ag-Pb-Zn magmatic-hydrothermal quartz vein deposits (Hart et al., 2002). Giant deposits are understandably rare in this rather uncommon magmatic-hydrothermal group of deposits or type of "system". The large low-grade Fort Knox deposit (e.g., Bakke et al., 1998) is arguably the only widely accepted giant deposit in this class, although Telfer in Western Australia (e.g., Rowins et al., 1997) and Morila in Mali (McFarlane et al., 2011) may be other examples. Why these deposits are larger than normal is unclear because of the low frequency of deposits in the group. Fort Knox and Telfer lie close to long-lived craton margins and Morila is arguably adjacent to the margin of a microcontinent, although this is far from certain. Fort Knox probably owes its size to the fortuitous exposure of the roof zone of the host intrusion at and just below the current land surface, preserving an intact deposit. Telfer lies in a thick carbonate-bearing stratigraphy with units contrasting in rheology in the roof zone of a regional anticlinorium, again with the first-mined, relatively flat-dipping ore zone fortuitously adjacent to the present land surface. Similarly, Morila was preserved in the hornfels within the contact aureole of the related complex granitic intrusion at the current land surface. So, these could be considered giants due to fortuitous preservational conditions.

5. Giant Carlin-type gold deposits

5.1. *Deposit style unique to Nevada, USA?*

The term Carlin-type deposit (e.g., Cline et al., 2005) has been widely employed in Nevada to differentiate the carbonate-hosted gold deposits from other deposit styles in the broad Carlin District. It has been used also by some authors to embrace any gold deposits hosted in sedimentary sequences that include carbonate rocks and by some mineral explorers to boost the potential of gold deposits in such rocks. However, all comparative studies between so-called Carlin-style deposits, for example in the West Qinling and Dian-Qian-Gui provinces of China, and the Carlin deposits themselves have shown important differences in deposit controls, the nature of the gold and its associated minor metals, and the fluids that deposited them (Cline et al., 2013). Most of these deposits are almost certainly sediment-hosted epizonal orogenic gold deposits in the sense of Groves et al. (1998). The recently discovered Osiris-Conrad deposit in the Selwyn Basin of the Yukon (www.atacresources.com) has characteristics similar to the Carlin-style deposits of Nevada, and is sited along the same western margin of the North American Craton as the Carlin District, making this a possible analog. However, to date it does not have the size of the Carlin-style deposits in Nevada. For the reasons outlined above, world-class to giant Carlin-style deposits are considered to be restricted to Nevada and the reasons for this are outlined below.

5.2. *Critical controls on the Carlin deposits*

As noted above, the first-order control on the Carlin deposits in Nevada (Fig. 2) is their position adjacent to the western margin of the North America Craton. Hybrid magmatism related to metasomatized SCLM at this margin arguably provided the heat engine for convection of the non-magmatic Carlin hydrothermal fluid system, although workers such as Cline et al. (2005, their fig. 12) suggest that high-level fluids may have migrated from the hybrid magmatism at depth The craton margin is clearly a fundamental metallogenic structure, as the Tintina IRGS province straddles it to the north, and the enigmatic Coeur d' Alene district, giant Homestake gold deposit and giant Bingham Canyon district all lie nearby (Fig. 2).

At the district scale, the conjunction of several important controlling parameters are summarized by Emsbo et al. (2006). The deposits lie along trends that appear to reflect the underlying crustal, and even lithospheric, architecture of the faulted craton margin (Grauch et al., 2003). The distinctive trends may reflect linear antiformal or horst-like zones created by rock-strength contrasts caused by step-like structures in the basement and overlying sedimentary sequences during pre-gold compressional deformation (Wijns et al., 2004). These host rock sequences comprise highly reactive platform sedimentary rocks with abundant carbonate units that were deposited above the fragmented and subsiding craton margin. A restricted middle Paleozoic basinal setting allowed a rare opportunity for anomalous levels of synegenetic gold and other metals, such as Ba and Zn, to accumulate in typically subeconomic quantities in specific rock units (Emsbo et al., 1999) prior to the main Tertiary hydrothermal event. This event either introduced additional gold to raise stratiform to stratabound deposits to economic levels or reconcentrated the Paleozoic metals into their present-day economic concentrations. Prior to this hydrothermal event, these permeable and reactive sequences with anomalous gold levels were capped by relatively impermeable oceanic rocks during eastwards-directed thrusting related to compressional deformation. Major thrusts, such as the Roberts Mountain Thrust, effectively capped and sealed the system in preparation for the later hydrothermal event that would result in formation of the Carlin-type gold ores via fluid infiltration along both faults, reactivated during onset of extension related to late-orogenic collapse, and permeable carbonate horizons.

Gold depositional processes to form exclusively "invisible" gold in As-rich rims to fine-grain hydrothermal pyrite and marcasite without associated quartz veins are also highly unusual for gold deposits worldwide. Studies at the Turquoise Ridge deposit in the Getchell District (Muntean et al., 2009) suggest that the fluid system was essentially a one-pass system producing unidirectional metal zoning in the gold-rich arsenian rims. This is totally dissimilar to the multi-pass fluid systems interpreted to form orogenic gold deposits at similar ore grades during numerous seismically related hydrofracturing events (e.g., Sibson et al., 1988). It implies a highly effective transporting ore fluid, a highly effective depositional mechanism, and (or) indeed a significant amount of synegenetic gold already within the favorable host strata. Abundant organic carbon in all the Carlin-type deposits also suggests the involvement of hydrocarbons in the ore system, although Cline et al. (2005) indicated it played no role in the ore-forming process. Geologic evidence suggests much of the petroleum migration occurred prior to the Jurassic (Emsbo et al., 2003), and could have helped further concentrate, on a local level, any Paleozoic gold. The rocks are anomalously black and carbon-rich (e.g., Hofstra and Cline, 2000); the widespread framboidal pyrite is similar to that in halos produced by sulfate-reducing bacteria around oil and gas reservoirs in the North Sea (e.g., Rosnes et al., 1991); the strong arsenic signature is consistent with fluid reduction; and there are known oilfields in adjacent parts of Nevada. However, the precise role played by the several generations of carbon described by Cline et al. (2005) is not clear.

5.3. A unique conjunction of parameters?

It is evident from the discussion above that a large number of critical parameters came into alignment in the Carlin province of Nevada. It lies along a fundamental long-lived margin underlain by possibly fertile, metasomatized SCLM (Muntean et al., 2011). The faulted margin controlled sedimentation and shallow basin hydrodynamics to produce gold-enriched permeable units and reactive carbonate-rich host rocks to later localize hydrothermal deposition. Post-sedimentation compressional deformation resulted in linear zones ("trends") of anticlinal to horst-like structures in these permeable units capped by thrusted relatively impermeable marine shales (Emsbo et al., 2006). This is the perfect scenario to precede later weak extension that reactivated compressional structures during orogenic collapse with contemporaneous asthenospheric uprising resulting in melting of metasomatized SCLM. The resulting hybrid magmatism and associated high heat flow could have driven auriferous fluid systems whose precise origin is still unclear, with most models (e.g., Large et al., 2011) having problems with mass balance considerations. Add in the role played by hydrocarbons and there is a "perfect storm" produced by the conjunction of numerous fundamentally inter-related parameters.

This clearly shows that Carlin-type deposits should be considered a fundamental part of province to district-scale tectonic evolution. The highly anomalous conjunction of factors in northeast Nevada explains why the Carlin province is probably unique and why consideration of individual sedimentary rock-hosted deposits as Carlin-like is counter-intuitive and almost inevitably incorrect.

5.4. Controls on giants

The Carlin province is a giant gold province, producing almost 10 percent of world's gold each year. It contains several giants, including Cortez Hills, Getchell, Gold Quarry, Meikle, Mike, Pipeline and Rabbit Creek, but the Post-Betze system with over 1000 t gold stands out as the supergiant (Cline et al., 2005, their fig. 2; Fig. 3). The most obvious potential reason for this is the presence of an additional factor to those combined sedimentological and structural parameters outlined above that are common to all the giants. This could be the presence of the pre-ore Jurassic Goldstrike stock that abuts the Post fault, which also controls the position of Meikle to the north (Cline et al., 2005, their fig. 4; Fig. 7). This was clearly recognized by Bettles (2002). A schematic cross section (Fig. 7) shows the main ore body at Betze confined to a horst with the Roberts Mountain Thrust above and the hornfels margin of the stock below. By analogy to orogenic gold systems involving pre-existing competent granite stocks, the competency contrast between the stock and country rocks would have induced heterogeneous stress that, in turn, would have resulted in strain gradients that localized fluid flux along the stock margins (e.g., Knight et al., 1993; Ojala et al., 1993). At Post-Betze, the rising hot, low density ore fluid would have been focused into low mean-stress zones within upper reactive carbonate layers around the stock, producing additional stratabound to discordant ore in addition to the normal stratabound deposits, controlled by a combination of structure and preferred gold-enriched host units along strike.

6. Giant IOCG deposits

6.1. How to define IOCG deposits

Following the recognition of IOCG deposits as a new class of mineral deposit by Hitzman et al. (1992), a large variety of deposits containing iron oxides with or without significant Cu and Au have traditionally been lumped into the IOCG deposit group (e.g., Williams et al., 2005). Groves et al. (2010) demonstrated that many of these that do have significant Cu and Au are skarns, whereas, in others (e.g., Tennant Creek deposits, Australia), the Cu sulfides and Au replaced pre-existing iron-oxide concentrations. Groves et al. (2010) provided a clear definition that IOCG deposits are magmatic-hydrothermal deposits that contain economic Cu ± Au ± U grades; are structurally controlled, commonly with breccias; have abundant low-Ti iron oxides or iron silicates intimately associated with Fe-Cu sulfides; have LREE enrichment and low-S sulfides (pyrrhotite, chalcopyrite, bornite, chalcocite); lack quartz veins or silicification; and show a clear temporal, but not

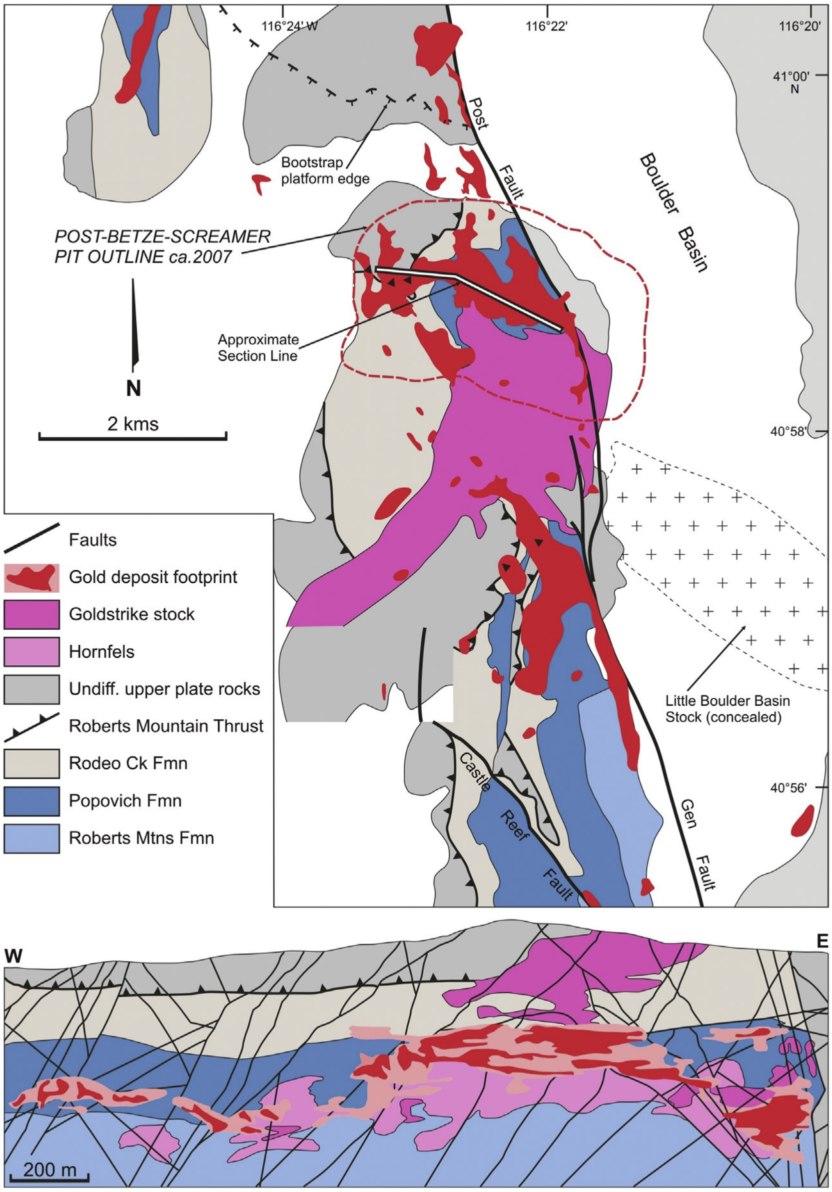

Figure 7. Giant gold deposits of the Blue Star-Goldstrike subdistrict of the Carlin trend, Nevada. Map shows ore bodies and Goldstrike stock projected to surface to illustrate complexity and close spatial relationship. West-east cross section across the open pit shows the strong development of Carlin-type ore in a horst with regionally most prospective stratigraphic units confined between hornfels, below, and the Roberts Mountain Thrust, above. The unusual geometry of the Jurassic intrusive rocks is due to the obliquity of the section. Adapted from Bettles (2002).

spatial, relationship to causative intrusions, which formed from hybrid mantle-crustal magmas sourced from metasomatized SCLM.

Using this definition, there are actually very few unequivocal IOCG deposits, with significant groups of deposits in the Gawler Craton (e.g., Olympic Dam, Prominent Hill) and Cloncurry (e.g., Ernest Henry) district of Australia, the Carajas (e.g., Salobo, Cristalino) region of Brazil, the Coastal Cordillera (e.g., Candelaria) of the Andes in Chile, and surrounding the Kaapvaal Craton of South Africa, assuming potential magmatic end-members at Palabora and O'okiep are included (Groves et al., 2010). For all these deposits, Cu and Au grades are normally below 1% and 1 g/t, respectively, similar to other magmatic-hydrothermal systems such as porphyry Cu-Au deposits, but tonnages for the IOCG deposits are >100 million tonnes, with as much as several thousand million tonnes at Olympic Dam.

6.2. *Critical controls on IOCG deposits*

The primary controls on location of IOCGs at the global scale are long-lived craton margins with metasomatized SCLM and at least one period of hybrid mantle-crustal magmatism surrounding that margin (e.g., Grainger et al., 2008). Most deposits are Precambrian in age. The Carajas deposits have a similar Neoarchean age to the oldest giant orogenic gold provinces of the world, with an almost identical age to those deposits of the Kolar district of India (Sarma et al., 2011). The Mesoproterozoic IOCG deposits of Australia formed in broadly the same period as the giant SEDEX provinces in adjacent regions (Large et al., 2005). The deposits in the Coastal Cordillera have an anomalous tectonic setting, which Groves et al. (2010) attribute to Precambrian-like lithospheric structure in this unique part of the Andes.

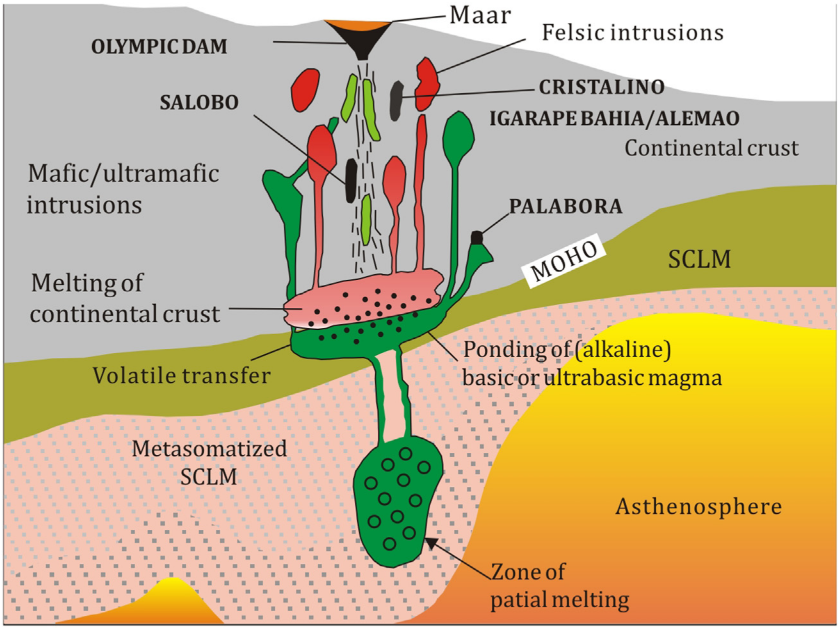

Figure 8. Schematic crustal-lithospheric section showing the known IOCG deposits in terms of interpreted depth of formation. The supergiant Olympic Dam deposit is the highest level deposit and is associated with a maar and giant pipe-like breccia zone. Adapted from Groves et al. (2010).

The deposits also have a close spatial relationship to crustal- to lithosphere-scale fault zones, which helped Western Mining Corp., led by Roy Woodall, target the Olympic Dam deposit under significant cover in 1975 (O'Driscoll, 1985). The deposits have no specific host rock control, with individual deposits hosted in metamorphic domains from near-granulite facies (Salobo to amphibolite facies (Ernest Henry) to greenschist or sub-greenschist facies (Olympic Dam)). They can be hosted in greenstones or other volcanic rocks (most Carajas deposits), at greenstone-sedimentary rock interfaces (Igarape-Bahia), in volcano-sedimentary rock sequences (Candelaria) or in granitic intrusions (Olympic Dam).

This lack of host rock control at crustal levels is almost certainly because of the deep derivation of anomalously volatile-rich magmas that ascend at similar rates to kimberlites, producing megabreccias at high crustal levels. The primary controls are lithospheric to crustal-scale fault zones, not crustal sequences, although these may control the shape of ore bodies, such as with the manto-like shape of Candelaria and similar deposits in the Andes (Marschik and Fontboté, 2001).

6.3. *Giants and supergiants*

If only the deposits recognized by Groves et al. (2010) are considered unequivocal IOCG deposits, they are all world class, most are giants, and at least one is a supergiant based on a classification that uses metric tonnes of gold equivalent for Au + Cu, based on the current or long-term metal prices (e.g., Trench and Groves, 2015). There are two reasons for this. First, the deep generation of high-energy, rapidly ascending, volatile-rich magmas will result in large, focused breccia-dominated ore bodies. Second, IOCG deposits have only been recognized as a viable exploration target for the past 20–30 years and are low grade, so bulk low-grade mining of large tonnages is the only viable mining method. Hence, historical workings of high-grade deposits, such as in orogenic gold provinces or similar workings of high-grade skarns surrounding porphyry Cu-Au systems, simply did not exist. So, the IOCG deposits must be giants in terms of tonnes of gold-equivalent resource, in the first place, to be mined. Explorers clearly recognize this, so unequivocal IOCG exploration projects that do not meet the requirement generally remain in the world of digital press releases and do not normally get into the published economic geology literature. Given the similarity between copper and gold grades of IOCG deposits and the more abundant, historically mined porphyry Cu-Au deposits (Fig. 3 in Williams et al., 2005), it may be more reasonable to view the IOCG deposits in light of the total group of low-grade Cu-Au deposits rather than on their own and in comparison to commonly higher grade orogenic and Carlin-type deposits.

If the top 10% of deposits classification is used, then, in this small group, Olympic Dam would be clearly recognized as not only a giant, but as a supergiant based on any classification that uses gold-equivalent metric tonnes for a multi-commodity resource. It is arguably the largest and most-valuable, current, single, metallic mineral deposit globally www.businesspectator.com.au.article/2011/5/16.

An explanation for its position as a supergiant can be postulated by the prior analogy to kimberlites and other deeply sourced alkaline rocks. The largest diamond deposit in the world in terms of contained carats of diamond, irrespective of quality, is Argyle in Western Australia (Boxer et al., 1989). It is a lamproite pipe that intruded so high into the crust that it erupted producing a maar. The analogy to Olympic Dam is obvious, with that IOCG being the highest-level of any of the giant IOCG deposits, and which also produced a maar (Fig. 8). In terms of a magmatic-hydrothermal analog, the Vergenoeg pipe in South Africa (Goff et al., 2004), one of the largest high-grade fluorite deposits globally, is also overlain by a maar containing bedded fluorite-Fe-oxide units. As the hybrid magmas rise towards the surface, lithostatic pressure decreases and transforms to hydrostatic pressure in water-saturated rocks close to the surface. Volatile release is then catastrophic, leading to eruption of tuffs and breccias, with fallback of diamonds from kimberlite eruption, or massive brecciation of host rocks with attendant virulent wallrock alteration and ore deposition on a massive scale for metal-rich magmatic-hydrothermal systems, leaving a supergiant footprint.

7. Discussion and conclusions

It is clear from prior literature on giant mineral deposits that the reason for their anomalous endowment is not to be elucidated on the deposit scale where much of economic geology research takes place to define metal transport and depositional conditions. It is, instead, to be deciphered by a hierarchical approach examining critical factors at the lithospheric to crustal to district scale. As stressed in the above deposit-type discussions, it is the conjunction of critical factors at the province scale that are the key to development of anomalously large gold resources. This is not only significant in the non-arc environment defined in this paper, but also for epithermal and porphyry ores in the arc environment, as summarized by Richards (2013).

For the gold deposit types in non-arc environments discussed here, there are clearly common factors at the largest scale for giant provinces of gold deposits that have major differences in metal ratios, ore mineralogy, wallrock alteration, implicated ore fluids and depositional conditions. Giant provinces of IRGS, IOCGs and Carlin-type deposits are all sited on fragmented long-lived craton margins. These are intruded by hybrid volatile-rich magmas, initiated by melting of metasomatized SCLM below the craton margin, that played a direct role in IRGS and IOCG deposit formation in contrast to an indirect and unresolved role for Carlin-type deposits. Reactive and high-permeability sedimentary rocks that were deposited on that margin played a key role for Carlin-type ores and probably IRGS, but host rocks appear to have been important in the location of giant IOCG provinces. Giant orogenic gold provinces may also be located on craton margins but are more commonly situated near geometrical complexities in first-order suture zones along which discrete terranes were accreted late in the history of the hosting orogenic belts. Granitic magmas may have played a minor role in some gold pre-concentration (<0.3 g/t Au) in some provinces (e.g., Malartic, Canada). However, there is no direct relationship to hybrid granitic intrusions as for the other giant gold provinces, although lamprophyres may occupy the same regional structures as orogenic gold deposits, implicating a deep lithospheric connection for those structures. Giant orogenic gold provinces occur at all times except the Mesoproterozoic, giant IOCG provinces appear to be mainly Precambrian phenomena, giant IRGS provinces range from Tertiary to possibly Paleoproterozoic, and the giant Carlin-type deposits, which formed at shallow crustal levels and hence could be easily eroded, appear to be restricted to the Tertiary giant Carlin province in Nevada.

At the district to deposit scale within the giant gold provinces, controls are more diverse than at the province scale with parameters determining the location of giant deposits varying markedly between deposit types.

For orogenic gold deposits, the giants are formed due to a more comprehensive conjunction of the factors than those that control orogenic gold deposits as a whole. They are most commonly located close to the most fundamental first-order fault and shear zones in the province; are in mainly faulted, but in places duplexed, antiformal structures; are associated with abundant oblique second- and third-order faults; and are in brittle-ductile zones commonly in reactive iron-rich or carbonaceous host rocks. In other words, they are formed in the most highly efficient structural systems in the province. The conjunction of these controlling parameters produces a complex geometry, visible in geological maps and other data sets, that is most conducive to the activation of self-organizing critical fluid-flux systems. Leahy et al. (2005) further suggested that the orogenic gold giants, as well as arc-related gold giants, may additionally reflect longevity of subduction, such that long-lived subduction will enhance the opportunity for significant fluid and metal volumes.

The contrast between the multi-pass orogenic gold systems and essentially single-pass IRGS systems dictates that large IRGS are generally low grade, as is recorded for other magmatic-hydrothermal gold (plus Cu) systems. Therefore, giant IRGS, or provinces of such systems, are rare. Giant gold resources within this type of magmatic-hydrothermal system appear to be large because of their almost complete preservation at the present land surface.

Giant Carlin-type deposits are presently restricted to the giant Carlin province of northern Nevada, where a unique conjunction of critical parameters evolved on the faulted western margin of the long-lived North American Craton. Here, structurally induced early compressional antiformal “trends” controlled efficient fluid flux into reactive carbonate units in gold-anomalous sedimentary rocks, which were deposited in restricted shallow water environments over the fractured craton margin. Hydrocarbons probably played a role in formation of framboidal pyrite cores to gold-mineralized arsenian rims and in efficient transport and/or deposition of gold. The Post-Betze deposit is arguably a supergiant because of the additional, but still mainly stratabound, gold resources developed in strain heterogeneities adjacent to the pre-existing Goldstrike stock.

Most unequivocal IOCG ores are large-tonnage, low-grade, world-class to giant deposits with no historical high-grade deposits in contrast to the other gold deposit types. Olympic Dam is arguably the supergiant of the group because of ascent of fertile, volatile-rich hybrid magma to the surface with explosive exsolution of volatiles, formation of a maar, widespread brecciation and alteration, and Cu, Au and U deposition over an enormous brecciated rock mass.

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References

Allibone, A.H., McCuaig, T.C., Harris, D., Etheridge, M., Munroe, S., Byrne, D., Amanor, J., Gyapong, W., 2002. Structural controls on gold mineralization at the Ashanti deposit, Obuasi, Ghana. Society of Economic Geologists Special Publication 9, 65–93.

Bakke, A.A., Morrell, R., Odden, J., 1998. The Fort Knox porphyry gold deposit, Eastern Central Alaska: an overview and update. In: Porter, T.M. (Ed.), Porphyry and Hydrothermal Copper and Gold Deposits: A Global Perspective, Porter Consultancy, pp. 89–98.

Bettles, K., 2002. Exploration and geology, 1962-2002, at the Goldstrike property, Carlin trend, Nevada. Society of Economic Geologists Special Publications 9, 275–298.

Boxer, G.L., Lorenz, V., Smith, C.B., 1989. The geology and volcanology of the Argyle (AK1) lamproite diatreme, Western Australia. Geological Society of Australia Special Publication 14, 140–152.

Cline, J.S., Hofstra, A.H., Muntean, J.L., Tosdal, R.M., Hickey, K., 2005. Carlin-type Deposits in Nevada: Critical Geological Characteristics and Viable Models. In: Economic Geology 100th Anniversary Volume, pp. 371–405.

Cline, J.S., Muntean, J.L., Gu, X.-X., Xia, Y., 2013. A comparison of Carlin-type gold deposits—Guizhou province, Golden Triangle, southwest China, and northern Nevada, USA. Earth Science Frontiers 20, 1–18.

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. An Integrated Model for the Origin of Archean Lode-gold Deposits. In: Ontario Geological Survey Open-file Report, 5524, 98 pp.

Cooke, D., Pongraz, J. (Eds.), 2002. Giant Ore Deposits: Characteristics, Genesis and Exploration. CODES Special Publication, 4, p. 269.

Cooke, D., Hollings, P., Walshe, J.L., 2005. Giant porphyry deposits, characteristics, distribution and tectonic controls. Economic Geology 100, 801–818.

Cox, S.F., Knackstedt, M.A., Braun, J., 2001. Principles of structural control on permeability and fluid flow in hydrothermal systems. Society of Economic Geologists Reviews 14, 1–24.

Cunningham, C.G., Austin, G.W., Naeser, C.V.V., 2004. Formation of a paleothermal anomaly and disseminated gold deposits associated with the Bingham Canyon porphyry Cu-Au-Mo system, Utah. Economic Geology 99, 789–906.

Emsbo, P., Hutchinson, R.W., Hofstra, A.H., Volk, J.A., Bettles, K.H., Baschuk, G.J., Johnson, C.A., 1999. Syngenetic Au on the Carlin trend: Implications for Carlin-type deposits. Geology 27, 59–62.

Emsbo, P., Hofstra, A.H., Lauha, E.A., Griffin, G.L., Hutchinson, R.W., 2003. Origin of high-grade gold ore, source of ore fluid components, and genesis of the Meikle and neighboring Carlin-type deposits, northern Carlin trend, Nevada. Economic Geology 98, 1069–1100.

Emsbo, P., Groves, D.I., Hofstra, A.H., Bierlein, F.P., 2006. The giant Carlin gold province: a protracted interplay of orogenic, basinal and hydrothermal processes above a lithospheric boundary. Mineralium Deposita 41, 517–525.

Evans, K.A., 2010. A test of the viability of fluid–wall rock interaction mechanisms for changes in opaque phase assemblage in metasedimentary rocks in the Kambalda-St. Ives goldfield, Western Australia. Mineralium Deposita 45, 207–213.

Goff, B.H., Weinberg, R., Groves, D.I., Vielreicher, N.M., Fourie, P.J., 2004. The giant Vergenoeg fluorite deposit in a magnetite-fluorite-fayalite-REE pipe: a hydrothermally altered carbonatite-related pegmatoid? Mineralogy and Petrology 80, 173–199.

Goldfarb, R.J., Groves, D.I., 2015. Orogenic gold: common or evolving fluid and metal sources through time. Lithos http://dx.doi.org/10.1016/j.lithos.2015.07.011.

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

Goldfarb, R.F., Groves, D.I., Gardoll, S., 2001. Orogenic gold and geologic time: a global synthesis. Ore Geology Reviews 18, 1–75.

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. In: Economic Geology 100th Anniversary Volume, pp. 407–450.

Goldfarb, R.J., Taylor, R.D., Collins, G.S., Goryachev, N.A., Orlandini, O.F., 2014. Phanerozoic continental growth and gold metallogeny of Asia. Gondwana Research 25, 48–102.

Grainger, C.J., Groves, D.I., Fletcher, I.R., Tallarico, F.M.B., 2008. Metallogenesis of the Carajas Mineral Province, Southern Amazon Craton, Brazil: Varying Styles of Archean through Paleoproterozoic to Neoproterozoic base- and precious- metal mineralisation. Ore Geology Reviews 33, pp. 451–489.

Grauch, V.J.S., Rodrigues, B.D., Wooden, J.L., 2003. Geophysical and isotopic constraints on crustal structure related to mineral trends in north-central Nevada and implications for tectonic history. Economic Geology 98, 269–286.

Groves, D.I., Santosh, M., 2015. Province-scale commonalities of some world-class gold deposits: implications for mineral exploration. Geoscience Frontiers 6, 389–399.

Groves, D.I., Trench, A., 2014. A looming crisis for the mineral exploration industry: a geological perspective. SEG Newsletter 98, 10–12.

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., 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., 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., Condie, K.C., Goldfarb, R.J., Hronsky, J.M.A., Vielreicher, R.M., 2005. Secular changes in global tectonic processes and their influence on the temporal distribution of gold-bearing mineral deposits. Economic Geology 100, 203–224.

Groves, D.I., Bierlein, F.P., Meinert, L.D., Hitzman, M.W., 2010. Iron-oxide copper-gold (IOCG) deposits through Earth history. Implications for origin, lithospheric setting, and distinction from other epigenetic iron oxide deposits. Economic Geology 105, 641–654.

Hart, C.J.R., McCoy, D., Goldfarb, R.J., Smith, M., Roberts, P., Hulstein, R., Blake, A.A., Bundtzen, T.K., 2002. Geology, exploration and discovery in the Tintina gold province, Alaska and Yukon. Society of Economic Geologists Special Publication 9, 241–274.

Hedenquist, J.W., Thompson, J.F.H., Goldfarb, R.J., Richards, J.P. (Eds.), 2005. Economic Geology 100th Anniversary Volume. Society of Economic Geologists.

Hitzman, M.W., Oreskes, N., Einaudi, M.T., 1992. Geological characteristics and tectonic setting of Proterozoic iron oxide (Cu-U-Au-REE) deposits. Precambrian Research 58, 241–287.

Hodgson, C.J., 1993. Introduction to giant ore deposits. Society of Economic Geologists Special Publication 2, 1–12.

Hofstra, A.H., Cline, J.S., 2000. Characteristics and models for Carlin-type gold deposits. Reviews in Economic Geology 13, 163–220.

Hronsky, J.M.A., 2011. Self-organised critical systems and ore formation. SEG Newsletter 84, 14–16.

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.

Hronsky, J.M.A., Groves, D.I., Loucks, R.R., Begg, G.C., 2012. A unified model for gold mineralisation in accretionary orogens and implications for regional scale targeting methods. Mineralium Deposita 47, 339–358.

Hutchinson, R.W., 1987. Metallogeny of Precambrian gold deposits: space and time relationships. Economic Geology 90, 1918–1933.

Kerrich, R., Goldfarb, R., Groves, D., Garwin, S., 2000. The geodynamics of world-class gold deposits: characteristics, space-time distributions, and origins. Reviews in Economic Geology 13, 501–551.

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.

Lang, J.R., Baker, T., Hart, C.J.R., Mortensen, J.K., 2000. An exploration model for intrusion-related gold systems. SEG Newsletter 40.

Large, R.R., Bull, S.W., McGoldrick, P.J., Walters, S., Derrick, G.M., Carr, G.R., 2005. Stratiform and Strata-bound Zn-Pb-Ag Deposits in Proterozoic Sedimentary Basins, Northern Australia. In: 100th Anniversary Volume, Economic Geology, pp. 931–964.

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

Laznicka, P., 2006. Giant Metallic Deposits: Future Sources of Industrial Metals. Springer, Heidelberg, 732 pp.

Leahy, K., Barnicoat, A.C., Foster, R.P., Lawrence, S.R., Napier, R.W., 2005. Geodynamic processes that control the global distribution of giant gold deposits. Geological Society of London Special Publication 248, 119–132.

Loucks, R., 2012. Chemical characteristics, geodynamic settings, and petrogenesis of copper- ore-forming arc magmas. Centre for Exploration Targeting UWA Quarterly Newsletter 19, 1–10.

Mair, J.L., Farmer, G.L., Groves, D.I., Hart, C.J.R., Goldfarb, R.J., 2011. Petrogenesis of mid-Cretaceous post-collisional magmatism at Scheelite Dome, Yukon, Canada: evidence for a lithospheric mantle source for intrusion-related gold systems. Economic Geology 106, 451–480.

Marschik, R., Fontboté, L., 2001. The Candelaria – Punta del Cobre iron oxide Cu-Au (-Zn-Ag) deposits, Chile. Economic Geology 96, 1766–1826.

McFarlane, C.R.M., Mavrogenes, J., Lentz, D., King, K., Alibone, A., Holcombe, R., 2011. Geology and intrusion-related affinity of the Morila gold mine, southeast Mali. Economic Geology 106, 727–750.

Müller, D., Groves, D.I., 1993. Direct and indirect associations between potassic igneous rocks, shoshonites and gold-copper deposits. Ore Geology Reviews 8, 386–406.

Muntean, J.L., Cassinerio, M.D., Arehart, G.B., Cline, J.S., Longo, A.A., 2009. Fluid pathways at the Turquoise Ridge Carlin-type gold deposit, Getchell District, Nevada. In: Williams, P.J. (Ed.), Smart Science for Exploration and Mining, Proceedings of the Tenth Biennial Meeting of the Society of Geology Applied to Mineral Deposits, Townsville, Australia, pp. 251–252.

Muntean, J.L., Cline, J.S., Simon, A.C., Longo, A.A., 2011. Magmatic-hydrothermal origin of Nevada's Carlin-type gold deposits. Nature Geoscience 4, 122–127.

Neumayr, P., Walshe, J., Hagemann, S., Ptersen, K., Roache, A., Fricken, P., Horn, L., Halley, S., 2007. Oxidised and reduced mineral assemblages in greenstone belt rocks of the St Ives gold camp, Western Australia-vectors to high-grade ore bodies in Archean gold deposits. Mineralium Deposita 43, 363–371.

O'Driscoll, E.S.T., 1985. The application of lineament tectonics in the discovery of the Olympic Dam Cu-U deposit at Roxby Downns, South Australia. Global Tectonics and Metallogeny 3, 43–57.

Oberthuer, T., Mumm, A.S., Vetter, U., Simon, J., Amanor, J.A., 1994. Gold mineralization in the Ashanti Belt of Ghana: genetic constraints on the stable isotope geochemistry. Economic Geology 91, 289–301.

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.

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.

Richards, J., 2013. Giant ore deposits formed by optimal alignments and combinations of geological processes. Nature Geoscience 911–916.

Rosnes, J.T., Torsvik, T., Lien, T., 1991. Spore-forming thermophylic sulphate-reducing bacteria isolated from North Sea oil field waters. Applied and Environmental Microbiology 578, 2302–2307.

Rowins, S.M., Groves, D.I., McNaughton, N.J., Palmer, M.R., Eldridge, C.S., 1997. A reinterpretation of the role of granitoids in the genesis of Neoproterozoic gold mineralization in the Telfer Dome, Western Australia. Economic Geology 92, 133–160.

Sarma, D.S., Fletcher, I.R., Rasmussen, B., McNaughton, N.J., Mohan, M.R., Groves, D.I., 2011. Archaean gold mineralization synchronous with late cratonization of the Western Dharwar Craton, India: 2.52 Ga U-Pb ages of hydrothermal monazite and xenotime in gold deposits. Mineralium Deposita 46, 273–288.

Sengor, A.M.C., Natal'in, B.A., 1996. Palaeotectonics of Asia-fragments of a synthesis. In: Yin, A., Harrison, T.A. (Eds.), The Tectonic Evolution of Asia. Cambridge University Press, Cambridge, pp. 486–640.

Sibson, R.H., Robert, F., Poulsen, K.H., 1988. High-angle reverse faults, fluid pressure cycling, and mesothermal gold–quartz deposits. Geology 16, 551–555.

Sillitoe, R.H., Perello, J., 2005. Andean Copper Province: Tectonomagmatic Settings, Deposit Types, Metallogeny, Exploration and Discovery. In: 100th Anniversary Volume Economic Geology, pp. 845–890.

Singer, D.A., 1995. World class base and precious metal deposits: a quantitative analysis. Economic Geology 90, 88–104.

Steadman, J.A., Large, R.R., Meffre, S., Bull, S.W., 2013. Age, origin and significance of nodular sulphides in 2680 Ma carbonaceous black shale of the Eastern Goldfields Superterrane, Yilgarn Craton, Western Australia. Precambrian Research 230, 227–247.

Trench, A., Groves, D., April 2015. The western Arabian-Nubian Shield: a rapidly emerging gold province. SEG Newsletter 1, 13–15.

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 124–128.

Vielreicher, N.M., Groves, D.I., McNaughton, N.J., Fletcher, I., 2015. The timing of gold mineralization across the eastern Yilgarn using U-Pb geochronology of hydrothermal phosphate minerals. Mineralium Deposita http://dx.doi.org/10.1007/s00126-015-0589-9.

Vielreicher, N.M., Groves, D.I., Vielreicher, R.M., 2000. The Phalabowra (Palabora) deposit and its potential connection to iron-oxide-copper-gold deposits. In: Porter, T.M. (Ed.), Hydrothermal Iron-Oxide Copper-Gold and Related Deposits: A Global Perspective. Australian Mineral Foundation, Adelaide, pp. 321–330.

Walshe, J.L., Halley, S.W., Hall, G.A., Kitto, P., 2003. Contrasting Fluid Systems, Chemical Gradients, and Controls on Large-tonnage High-grade Gold Deposits, Eastern Goldfields Province, Yilgarn Block, Western Australia. Mineral Exploration and Sustainable Development, 7th Biennial DGA Meeting, Athens, pp. 827–830.

Whiting, B.H., Hodgson, C.J., Mason, R. (Eds.), 1993. Giant Ore Deposits. Society of Economic Geologists Special Publication 2, p. 349.

Wijns, C., Hall, G., Groves, D.I., Muntean, J., 2004. Compressional tectonics of the Carlin gold trend. In: Muhling, J.R., et al. (Eds.), SEG 2004 Predictive Mineral Discovery Under Cover, Extended Abstracts, Centre for Global Metallogeny, The University of Western Australia Publication 33, pp. 292–295.

Williams, P.J., Barton, M.D., Johnson, D.A., Fontbote, L., De Haller, A., Mark, G., Oliver, N.H.S., 2005. Iron Oxide Copper Gold Deposits: Geology, Space-time Relationships and Possible Modes of Origin. In: Economic Geology 100th Anniversary Volume, pp. 371–405.

Xiao, W.J., Santosh, M., 2014. The western Central Asian Orogenic Belt: a window to accretionary orogenesis and continental growth. Gondwana Research 25, 1429–1444.

Xiao, W.J., Sun, M., Santosh, M., 2015. Continental reconstruction and metallogeny of the Circum-Junggar areas and termination of the southern Central Asian Orogenic Belt. Geoscience Frontiers 6, 137–140.

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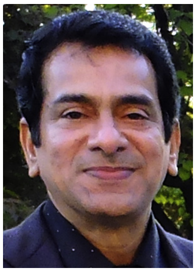

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