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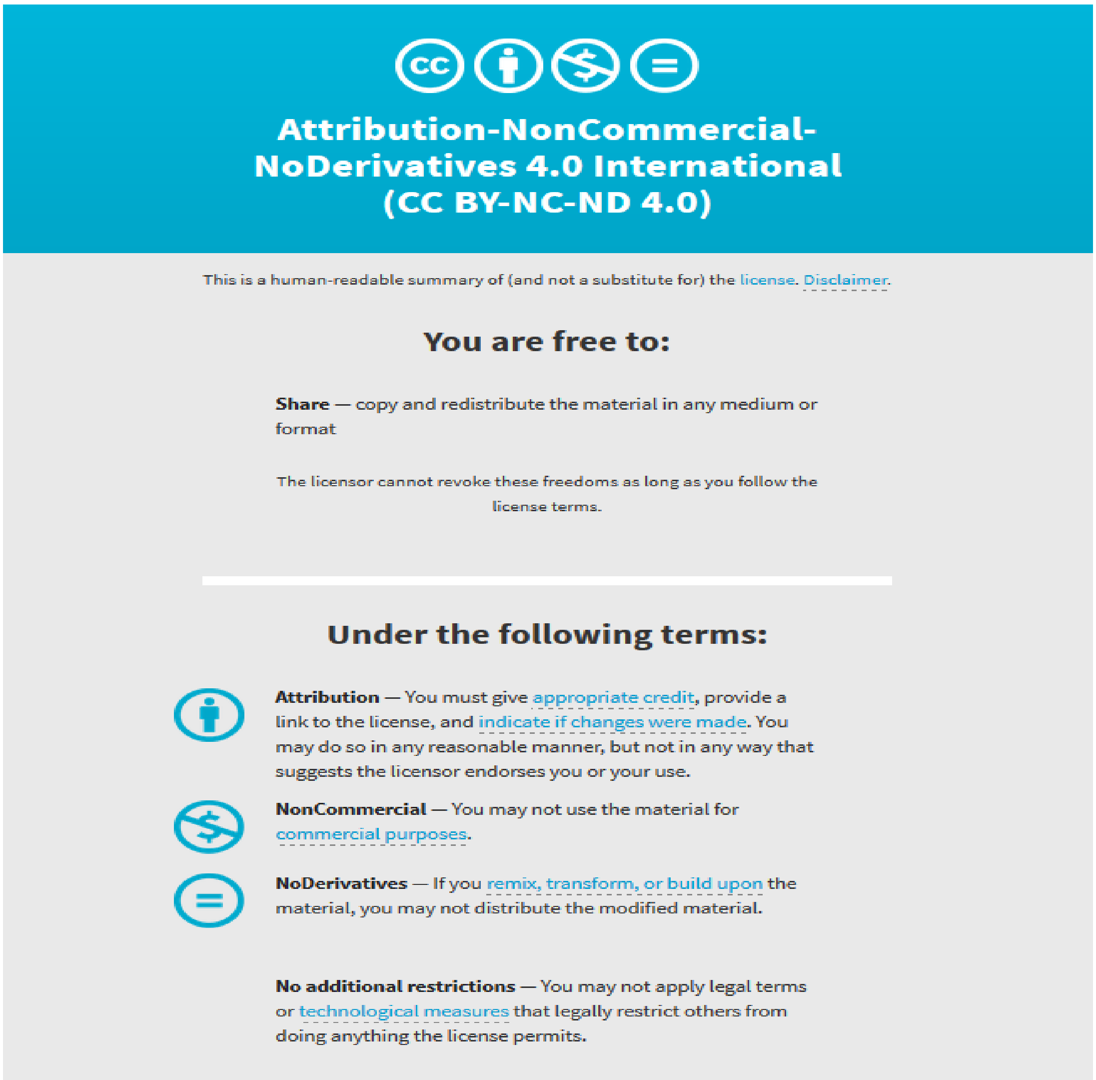

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Focus paper

Province-scale commonalities of some world-class gold deposits: Implications for mineral exploration

David I. Groves [a,b], M. Santosh [b,c,d,*]

[a] *Centre for Exploration Targeting, UWA, Crawley 6009, WA, Australia*
[b] *State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Beijing 100083, China*
[c] *Centre for Tectonics Resources and Exploration, Dept. of Earth Sciences, University of Adelaide, SA 5005, Australia*
[d] *Division of Interdisciplinary Science, Faculty of Science, Kochi University, Kochi 780-8520, Japan*

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ABSTRACT

Discovery rates for all metals, including gold, are declining, the cost per significant discovery is increasing sharply, and the economic situation of the industry is one of low base rate. The current hierarchical structure of the exploration and mining industry makes this situation difficult to redress. Economic geologists can do little to influence the required changes to the overall structure and philosophy of an industry driven by business rather than geological principles. However, it should be possible to follow the lead of the oil industry and improve the success rate of greenfield exploration, necessary for the next group of lower-exploration-spend significant mineral deposit discoveries.

Here we promote the concept that mineral explorers need to carefully consider the scale at which their exploration targets are viewed. It is necessary to carefully assess the potential of drill targets in terms of terrane to province to district scale, rather than deposit scale, where most current economic geology research and conceptual thinking is concentrated. If orogenic, IRGD, Carlin-style and IOCG gold-rich systems are viewed at the deposit scale, they appear quite different in terms of conventionally adopted research parameters. However, recent models for these deposit styles show increasingly similar source-region parameters when viewed at the lithosphere scale, suggesting common tectonic settings. It is only by assessing individual targets in their tectonic context that they can be more reliably ranked in terms of potential to provide a significant drill discovery. Targets adjacent to craton margins, other lithosphere boundaries, and suture zones are clearly favoured for all of these gold deposit styles, and such exploration could lead to incidental discovery of major deposits of other metals sited along the same tectonic boundaries.

1. Introduction

The most up-to-date available statistics on discovery and resource inventories for metals indicate that discovery rates are declining, the cost per discovery is rising steeply, and it takes an increasing amount of time to bring mines into production (Schodde, 2014; Zhang et al., 2015). This is particularly true for the gold exploration industry (Fig. 1; Schodde, 2013). The current exploration and mining industry structure, with largely acquisition-driven majors and poorly-resourced juniors and a historically low proportion of mid-tier companies, makes this situation difficult to redress (e.g., Groves and Trench, 2014). Several studies have shown that the industry as an entity is a low base-rate situation, with close to zero return. There is little economic geologists can do to influence the overall structure and philosophy of an industry driven by business principles. There is also little that can be done to influence an education system that, from anecdotal evidence, produces graduates less well equipped to deal with the more pragmatic aspects of mineral exploration (Groves and Trench, 2014). What can be done is influence the nature of greenfield exploration, necessary for the next group of significant discoveries required to replenish declining resources. As the oil industry has done over the past several decades, there is a need for the minerals industry to increase the percentage of discovery successes by

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* Corresponding author. State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Beijing 100083, China.
E-mail address: msantosh.gr@gmail.com (M. Santosh).

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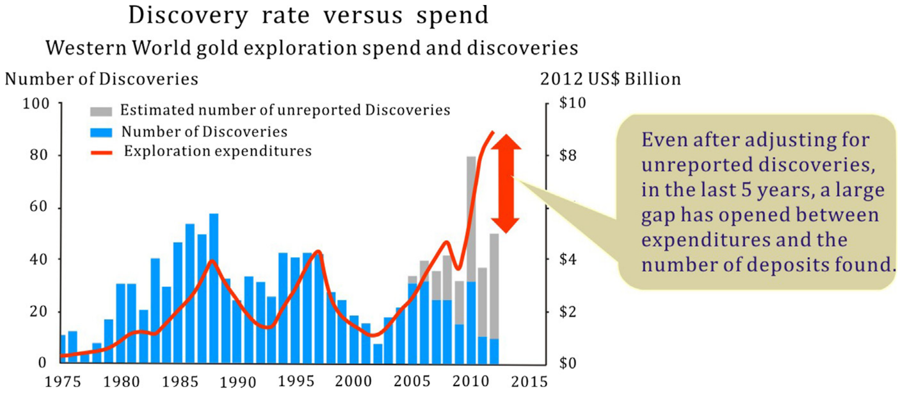


Figure 1. Rate of gold deposit discovery relative to exploration expenditure: number of reported discoveries and estimated unreported discoveries (after Schodde, 2013).

significantly decreasing the number of low-potential targets that are drilled, after careful consideration of their economic potential in terms of a regional geological framework. This paper examines the geological principles behind this type of regional assessment. It follows on from, although takes a more pragmatic approach than, previous studies by Hronsky and Groves (2008) and Hronsky et al. (2012).

2. Importance of scale

Most difficulties experienced in modern society are caused by an inability to view critical issues at an appropriately large scale: to “see the wood for the trees”. Arguably, economic geology also faces the same problem. As a profession, there is a tendency to view and classify mineral deposit types at the deposit scale, at least in part due to the more ready research funding from mining operations, than from regional exploration groups. Despite an increasing emphasis on a mineral systems approach at a variety of scales (e.g., McCuaig, 2013; McCuaig and Hronsky, 2014), a study of the major international economic geology journals of the past two years shows that about 90% of published papers concern district to deposit to intra-deposit scale research, with less than 5% having obvious global application. As highly anomalous metal concentrations, mineral deposits are not simply formed in specific locations at specific times due to deposit-scale processes, but due to tectonic processes in an evolving Earth (e.g. Groves et al., 2005). This is recognised when the exploration process is viewed theoretically as a logical temporally-staged process at increasingly smaller scales (Fig. 2). Each target, commonly acquired for reasons outside this rigorous framework, should thus be viewed in terms of its larger scale tectonic and temporal setting to access its true potential before an intensive exploration and drilling campaign is mounted.

3. Scale-dependant concepts for gold deposit styles

Orogenic gold, Intrusion-related gold (IRGD), Carlin-type gold, and Iron-oxide copper-gold (IOCG) deposits are classified as separate deposit types (e.g., Lang et al., 2000; Cline et al., 2005; Hedenquist et al., 2005; Williams et al., 2005; Goldfarb et al.,

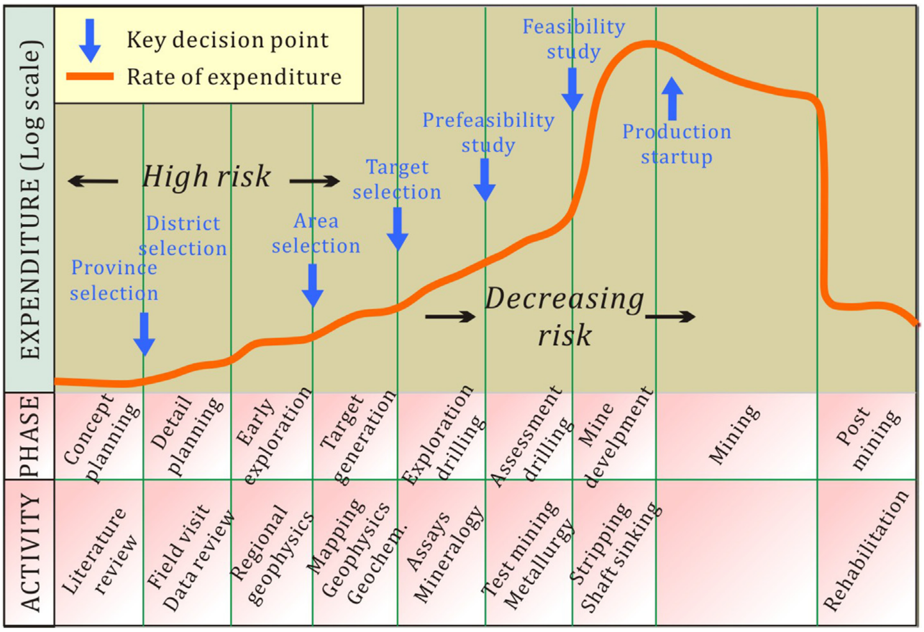
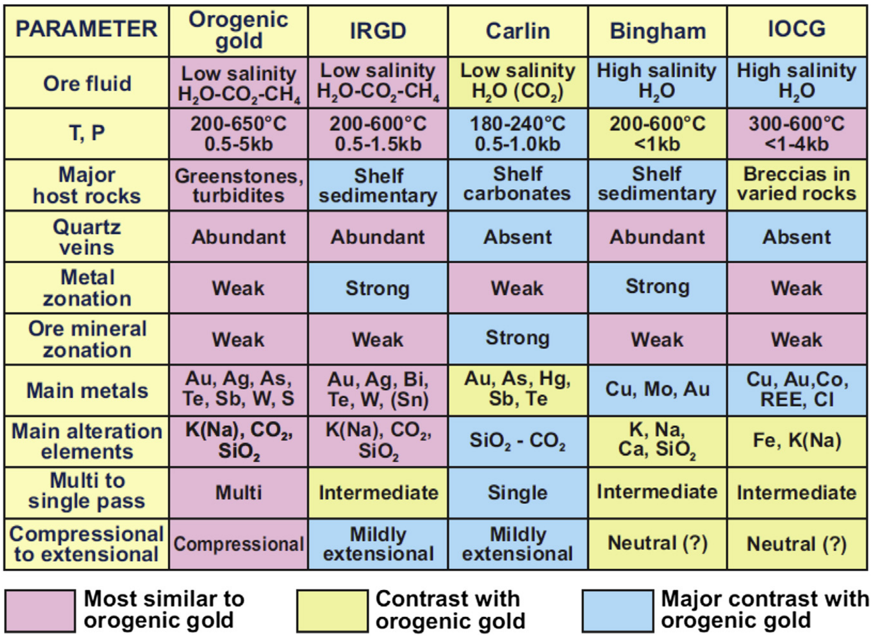


Figure 2. Key stages and decision points in a mineral exploration program. Province selection is a low cost but high geological risk phase. Poor decisions at the global to province scale mean that mineral exploration will never reach the feasibility stage.

Table 1
Deposit-scale mineral system models for orogenic, IRGD, Carlin-style, Bingham Canyon and IOCG gold (+/− Cu) deposits showing contrasts in many parameters at this scale.



PARAMETER	Orogenic gold	IRGD	Carlin	Bingham	IOCG
Ore fluid	Low salinity H_2O-CO_2-CH_4	Low salinity H_2O-CO_2-CH_4	Low salinity H_2O (CO_2)	High salinity H_2O	High salinity H_2O
T, P	200-650°C 0.5-5kb	200-600°C 0.5-1.5kb	180-240°C 0.5-1.0kb	200-600°C <1kb	300-600°C <1-4kb
Major host rocks	Greenstones, turbidites	Shelf sedimentary	Shelf carbonates	Shelf sedimentary	Breccias in varied rocks
Quartz veins	Abundant	Abundant	Absent	Abundant	Absent
Metal zonation	Weak	Strong	Weak	Strong	Weak
Ore mineral zonation	Weak	Weak	Strong	Weak	Weak
Main metals	Au, Ag, As, Te, Sb, W, S	Au, Ag, Bi, Te, W, (Sn)	Au, As, Hg, Sb, Te	Cu, Mo, Au	Cu, Au,Co, REE, Cl
Main alteration elements	K(Na), CO_2, SiO_2	K(Na), CO_2, SiO_2	SiO_2 - CO_2	K, Na, Ca, SiO_2	Fe, K(Na)
Multi to single pass	Multi	Intermediate	Single	Intermediate	Intermediate
Compressional to extensional	Compressional	Mildly extensional	Mildly extensional	Neutral (?)	Neutral (?)

🟪 Most similar to orogenic gold
🟨 Contrast with orogenic gold
🟦 Major contrast with orogenic gold

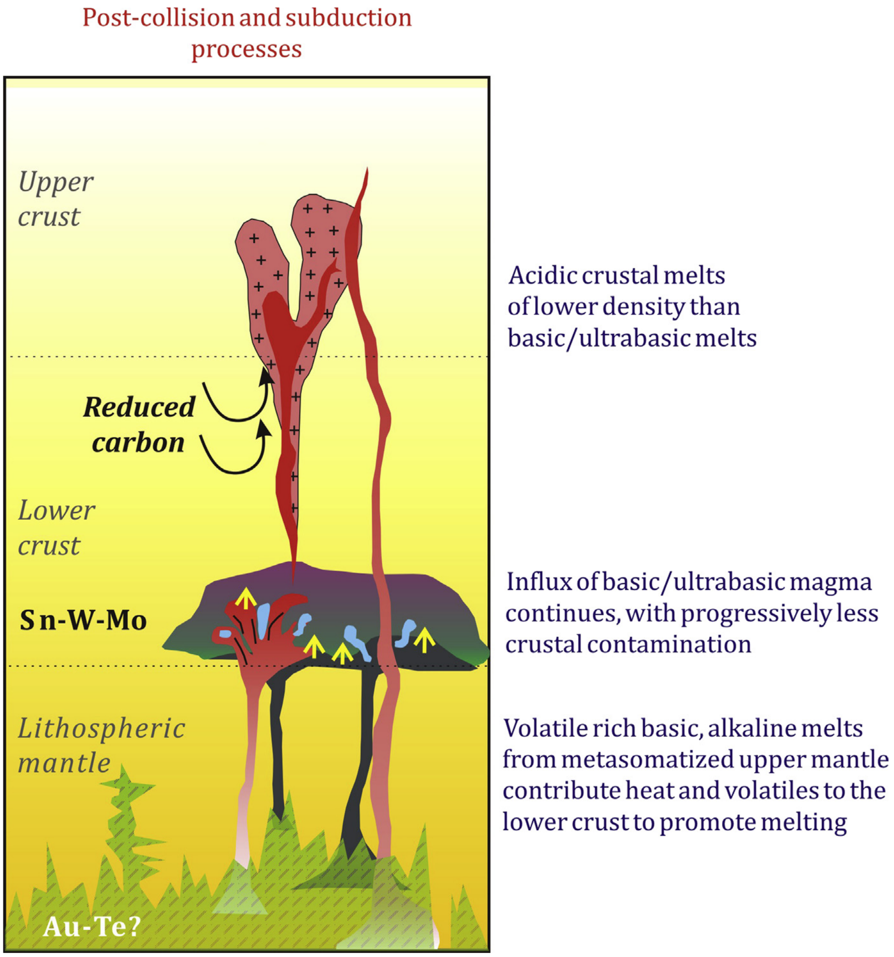


Figure 3. Magmatic-hydrothermal model for IRGD systems involving melting of metasomatised lithosphere on a craton margin (after Mair et al., 2011).

2007) on the basis of their deposit-scale geological and genetic characteristics: including, for example, structural style, host rocks, wall-rock alteration, metal associations, fluid characteristics, and P-T conditions of formation. At this scale, some deposits have shared characteristics but contrasts are more common than similarities (Table 1), and different deposit-scale genetic processes are invoked for their formation. When the deposit styles are viewed in terms of the supercontinent cycle, they again formed at different times, but, importantly, each formed at very specific times within that cycle (e.g., Goldfarb et al., 2001; Groves et al., 2010; Goldfarb et al., 2014), suggesting that each has a specific tectonic control.

When the driving forces for these deposits are viewed in terms of such a crustal to lithosphere to mantle scale, surprisingly they have many parameters in common. This was specifically highlighted at a recent FUTORES conference (Future Understanding of Tectonics, Ores, Resources, Environment and Sustainability—a conference run by Economic Geology Research Unit (EGRU) of James Cook University from 2 to 5 June 2013; see Chang et al., 2013) where these deposit styles were reviewed. The IRGDs (Mair et al., 2011; Fig. 3), Carlin deposits (Muntean et al., 2011; Fig. 4) and the broadly coeval zoned Bingham Canyon Cu-Au system (Cunningham et al., 2004; Fig. 5), and IOCG deposits (Groves et al., 2010, Fig. 6; Haywood, 2013) all are shown as forming above metasomatized lithosphere from fluid connected to mixed basic to felsic alkaline or sub-alkaline intrusions that formed in sub-MOHO magma chambers. Such systems provide strong chemical potential gradients between greatly contrasting magma geochemistry, allowing both metal and fluid migration from the hotter basic-ultrabasic melts to the less-dense overlying felsic melts which provide the source of ore fluid and metals to form the IRGD and IOCG deposits and the Bingham Canyon porphyry Cu-Au deposit. The source of ore fluid and metals is less clear for the Carlin deposits, with the hybrid intrusions providing at least the required heat (Cline et al., 2005; Muntean et al., 2011). Although in different settings, Loucks (2013) showed that arc-related economic porphyry Cu-Au deposits are connected to intrusions derived from magmas similarly ponded below the MOHO during arc compression.

Although the source of orogenic gold deposits is still hotly debated, magmas intruding hosting supracrustal sequences are considered highly unlikely as a direct source of major deposits (see summary in Goldfarb et al., 2007). However, Goldfarb and Santosh (2014) showed that, for at least the Jiaodong deposits of China, the

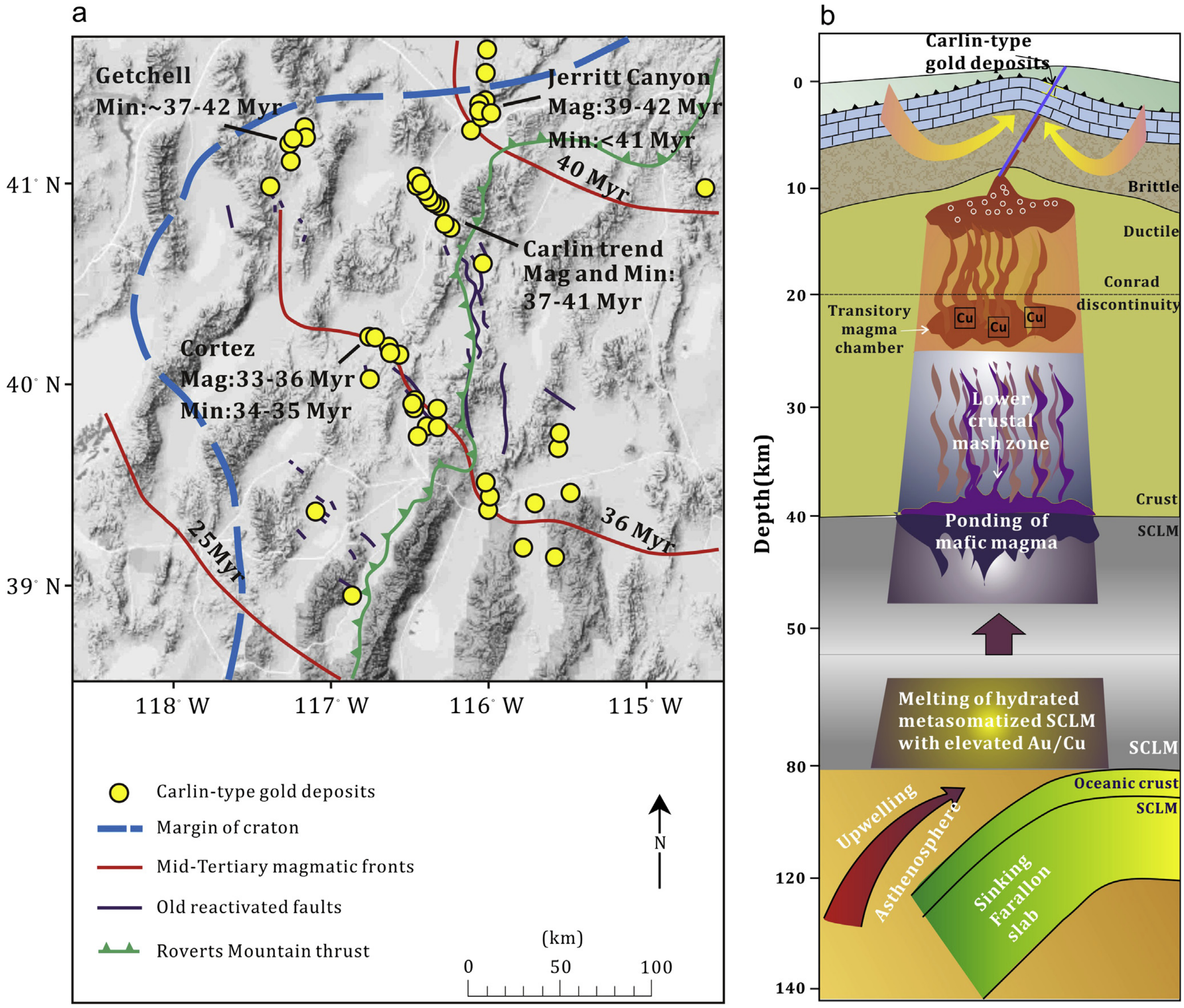
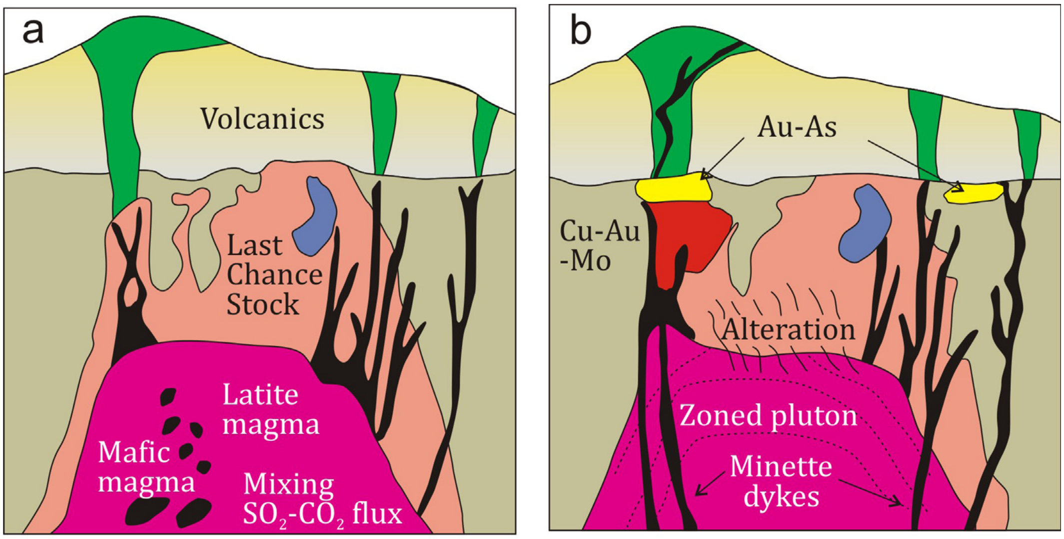


Figure 4. Genetic model for Carlin gold deposits based on spatially and temporarily coincident magmatism and mineralisation (after Muntean et al., 2011).



Minette and shoshonitic magmas add SO_2, H_2O, CO_2 and Cu to magma chamber. Crystallization of magma along walls provides aqueous fluid. Magma pressure decrease releases chalcophile metals and S gases to ore fluid.

After emplacement of silicic porphyries, minette dikes penetrate the batholith mostly along margins. Most Cu-Au-Mo mineralization is in adjacent porphyry. Fluids channeled through fractured intrusive rocks and Paleozoic country rocks to form late Au-As deposits.

Figure 5. Magmatic-hydrothermal model for Bingham Canyon porphyry Cu-Au-Mo deposit (after Cunningham et al., 2004).

source of ore fluids must be derived from below supracrustal rocks of the continental crust, the most commonly suggested fluid source for orogenic gold deposits (e.g., Phillips and Powell, 2010), from either the subducted slab, with overlying oceanic sediments, or the lithosphere below (Fig. 7). A deep source is also implied by the common spatial association of orogenic gold deposits with lamprophyre dykes (e.g., Rock and Groves, 1988; Wyman and Kerrich, 1988). Hence, the source region for orogenic gold deposits may be spatially adjacent to that of the other gold deposit types, but active at a different time in the orogenic cycle.

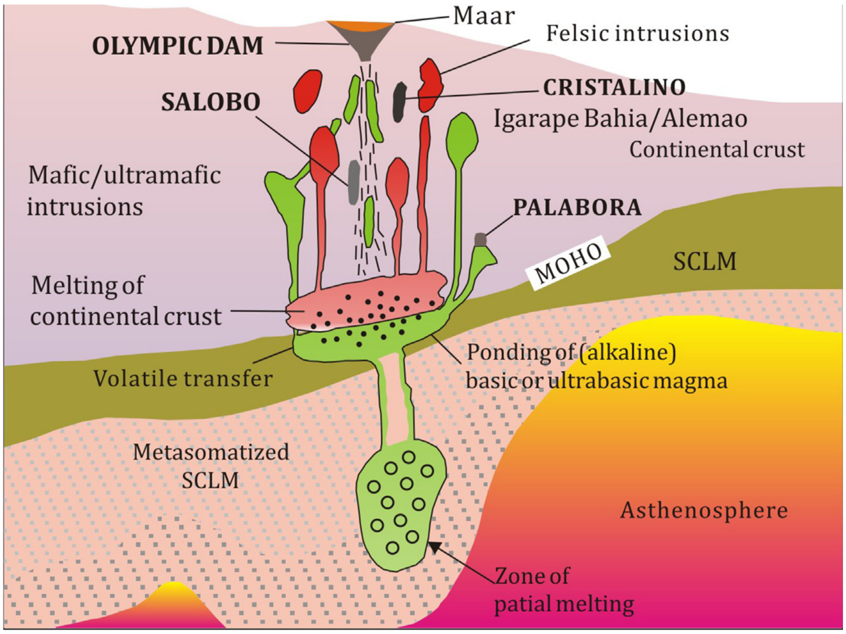


Figure 6. Magmatic-hydrothermal model for IOCG deposits associated with alkaline magmatism derived from metasomatised lithosphere on craton margins (after Groves et al., 2010).

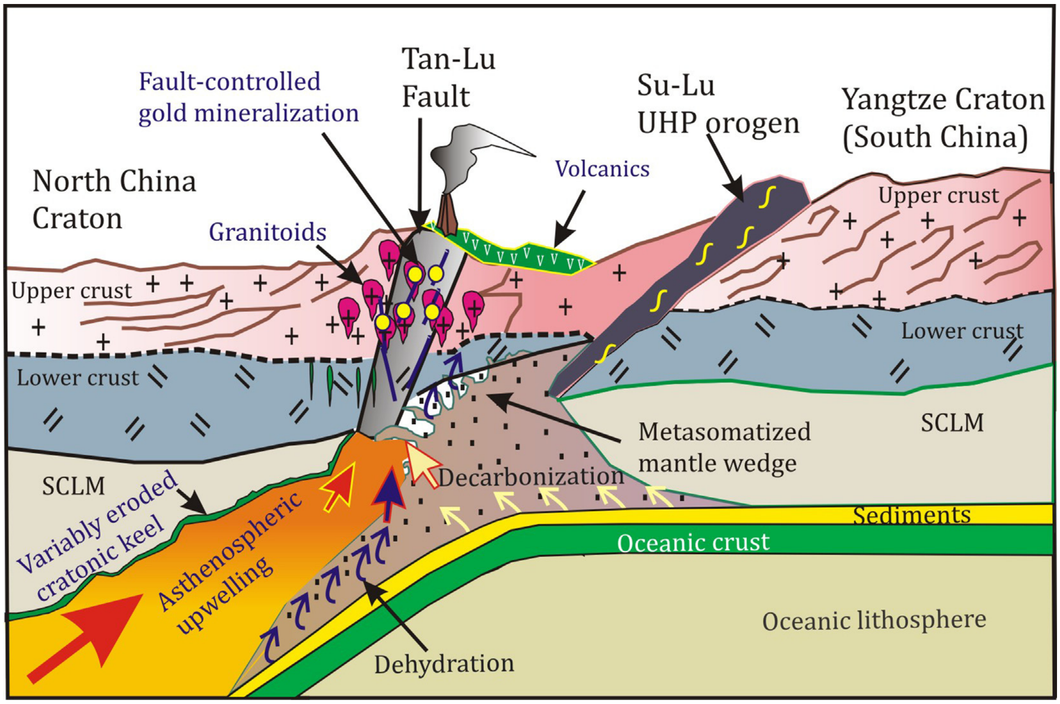


Figure 7. Ore fluid derived from subducted oceanic crust and overlying sedimentary wedge or metasomatised lithosphere for the orogenic gold deposits of the Jiaodong province, China (after Goldfarb and Santosh, 2014 and Yang and Santosh, 2015).

These lithospheric-scale genetic commonalities suggest that the deposits may have similarities in tectonic settings despite their deposit-scale contrasts.

4. Tectonic settings of gold deposit types

As expected from their similar lithospheric-scale genetic models, IRGDs, Carlin-type (and Bingham Canyon), and IOCG deposits all show spatial associations with near-vertical, partly fault-disrupted craton margins, defined by a combination of geological, isotopic and geophysical parameters. At these long-lived margins, previous subduction events have enriched the lithosphere with incompatible elements and metals during metasomatism. The universally accepted IRGDs of the Tintina Province of Alaska and the Yukon are related to hybrid granite intrusions into shelf sedimentary sequences adjacent to, and overlying, the western margin of the North America Craton (Fig. 8). A combination of geological, geophysical and radiogenic isotopic data firmly places the Carlin deposits on the same, partly fragmented margin of the North America Craton (Fig. 9). As shown by Groves et al. (2010), one of the

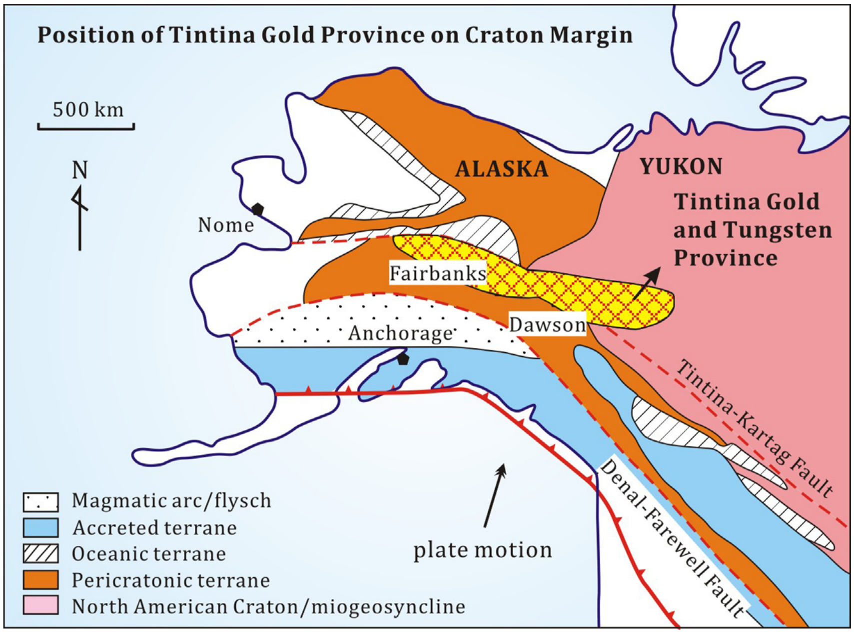


Figure 8. Schematic tectonic map showing the situation of the Tintina IRGD province on the margin of the North America Craton: derived from several compilations provided by Craig Hart of MDRU.

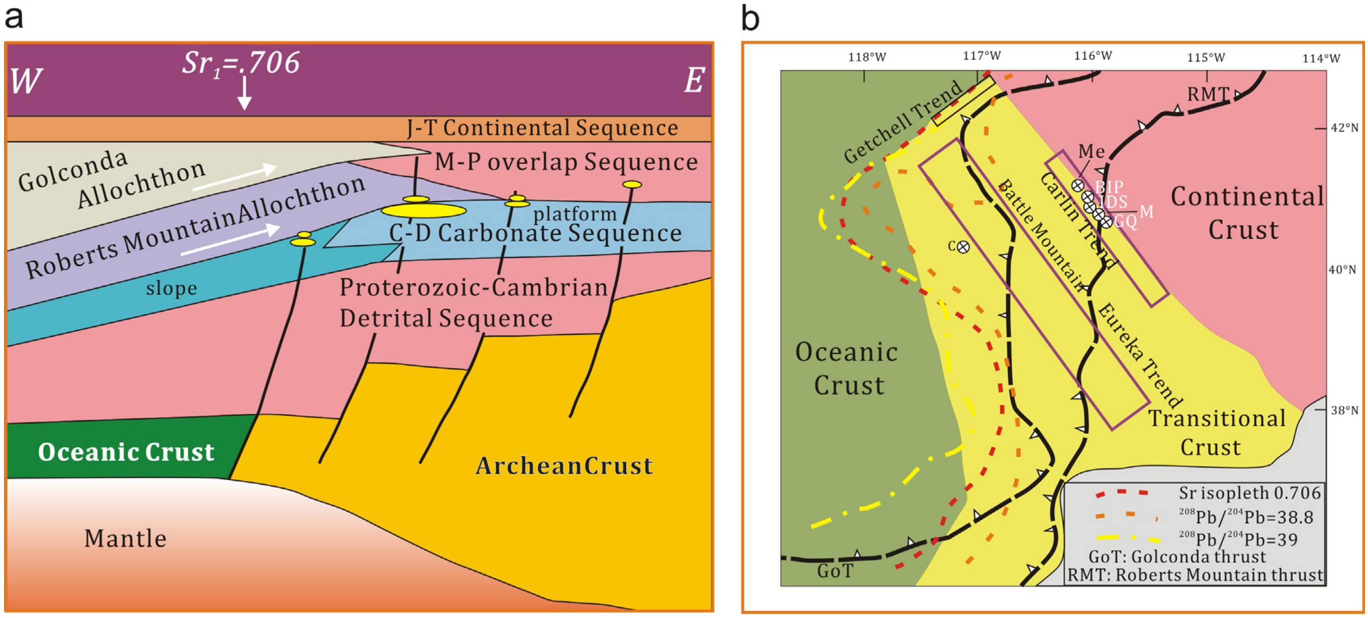


Figure 9. Tectonic setting of Carlin trends, Nevada, situated on the faulted North American Craton margin (after Emsbo et al., 2006, based on data from Crafford and Grauch, 2003 and Grauch et al., 2003).

key parameters that distinguish true IOCG deposits from those deposits misclassified as such, many of them skarns or oxidized porphyry Cu-Au deposits (Williams et al., 2005), is their tectonic position on craton margins. Fig. 10 shows an example from the Gawler Craton of South Australia, where several deposits, including the supergiant Olympic Dam deposit, lie within 100 km of its eastern margin. The giant Carajas IOCG province of Brasil is another classic example (Grainger et al., 2008).

More sophisticated analysis of combined geological, geophysical and isotopic data at the lithospheric scale (e.g., Begg et al., 2010) shows the importance of these margins, and other discontinuities not so readily discerned by traditional analysis, as lithosphere boundaries that control many ore deposits, including these gold deposit types. For example, the giant Bingham Canyon porphyry Cu-Au-Mo deposit clearly lies at a lithospheric triple-point junction in their analysis.

The Jiaodong orogenic gold deposits show clear spatial relationships to such lithosphere boundaries around the margins of the North China Craton (Goldfarb and Santosh, 2014). The regional distribution of gold deposits of various scales in this craton (Fig. 11) shows that these are located along the three major Paleoproterozoic suture zones that amalgamated the crustal blocks, within reactivated lithospheric-scale fault zone such as the Tanlu Fault, or along craton margins. Recent studies in the North China Craton establish a close link between metallogeny and craton destruction (e.g., Li and Santosh, 2014; Yang et al., 2014). The boundaries of the micro-blocks and the margins of the craton, as well as the reactivated paleo-sutures, served as weak zones and were the principal

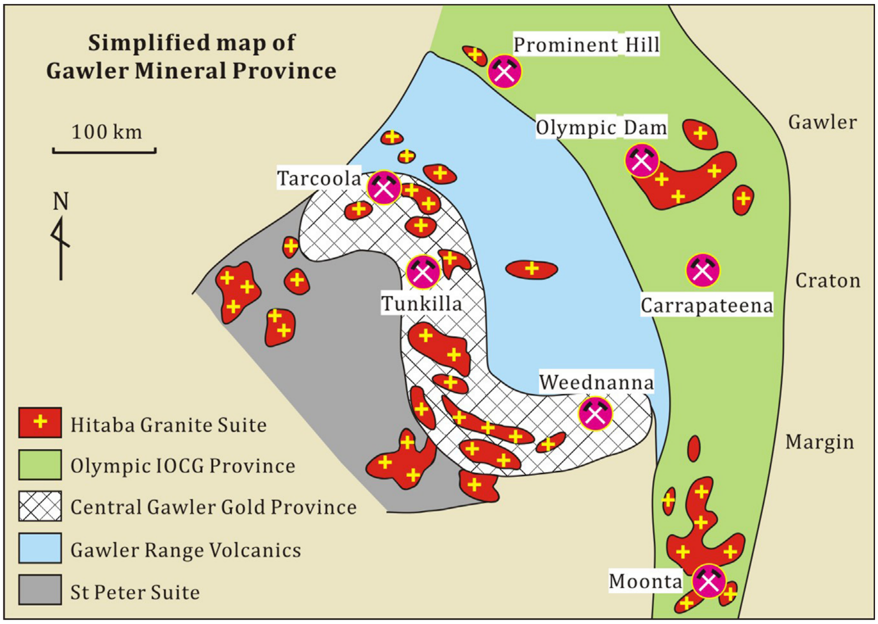


Figure 10. Tectonic setting of IOCG deposits, including the supergiant Olympic Dam deposit, on the eastern margin of the Gawler Craton, South Australia (from Hand et al., 2007).

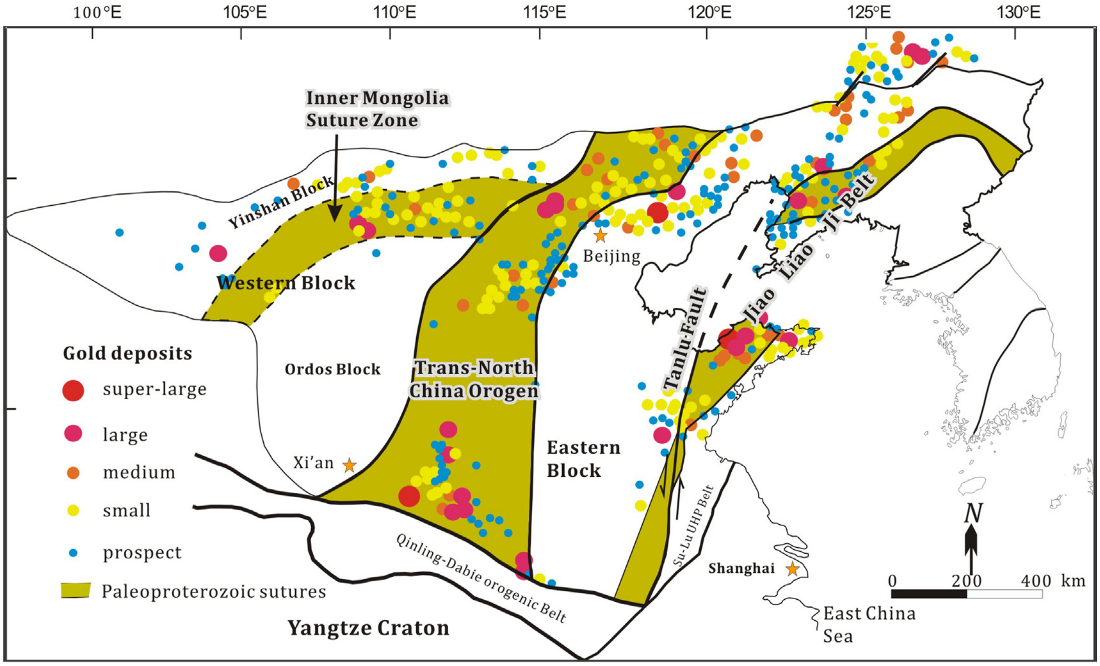


Figure 11. Tectonic framework of the North China Craton (after Zhao et al., 2005; Santosh, 2010; Yang and Santosh, 2014) showing the distribution of gold deposits (after Li and Santosh, 2014). The three major Paleoproterozoic sutures (Inner Mongolia Suture Zone, Trans-North China Orogen and Jiao-Liao-Ji Belt) along which the crustal blocks amalgamated at the final stage of cratonization during late Paleoproterozoic are also shown.

locales along which inhomogeneous lithospheric thinning and destruction of the craton occurred during later tectonothermal events. The voluminous Jurassic granitoids and Cretaceous intrusions carrying gold, molybdenum, copper, lead and zinc deposits are mostly localized along the reactivated paleo-sutures, weak zones, and block margins (Li and Santosh, 2014). Suture zones or mobile belts, representing fossil subduction zones associated with the amalgamation of continents, and eventual assembly of supercontinents, although distal from the present plate boundaries, are known to play a key role in intra-continental deformation (Gorczyk and Vogt, 2015). These regions mark zones of metasomatized mantle lithosphere and their reworking during intra-continental orogeny can lead to concentration of mineral deposits.

There is emerging evidence that other world-class orogenic gold provinces extend along or adjacent to such boundaries (e.g., Champion and Cassidy, 2007 for the Yilgarn craton). This is,

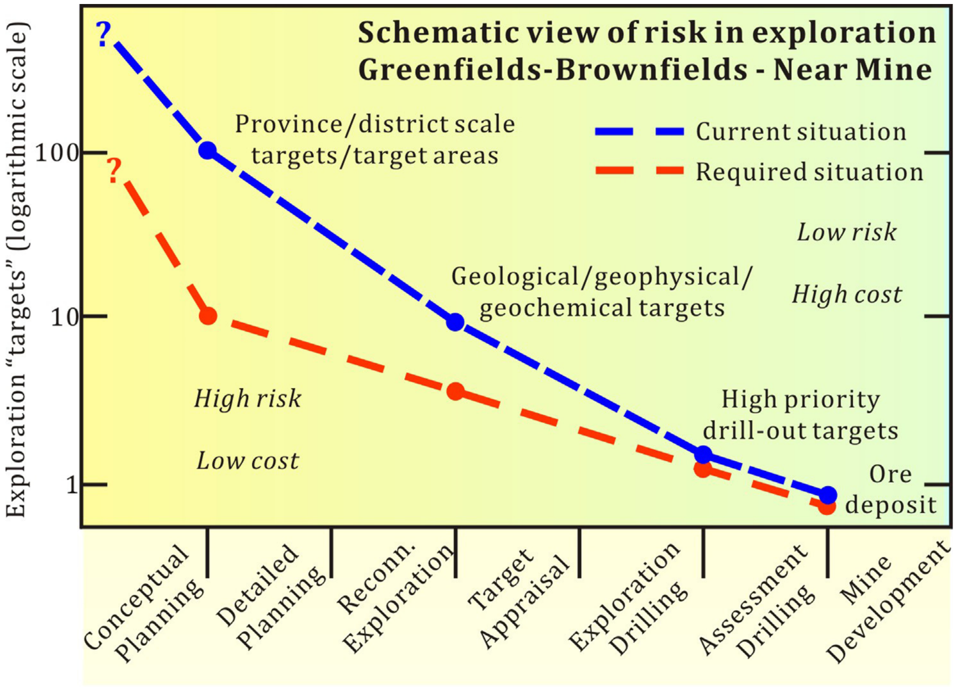


Figure 12. Schematic diagram showing current exploration targets at the province scale vs. required situation to lower risk at low cost in defining economic gold deposits from drilling of fewer targets that are highlighted as possessing a superior regional perspective.

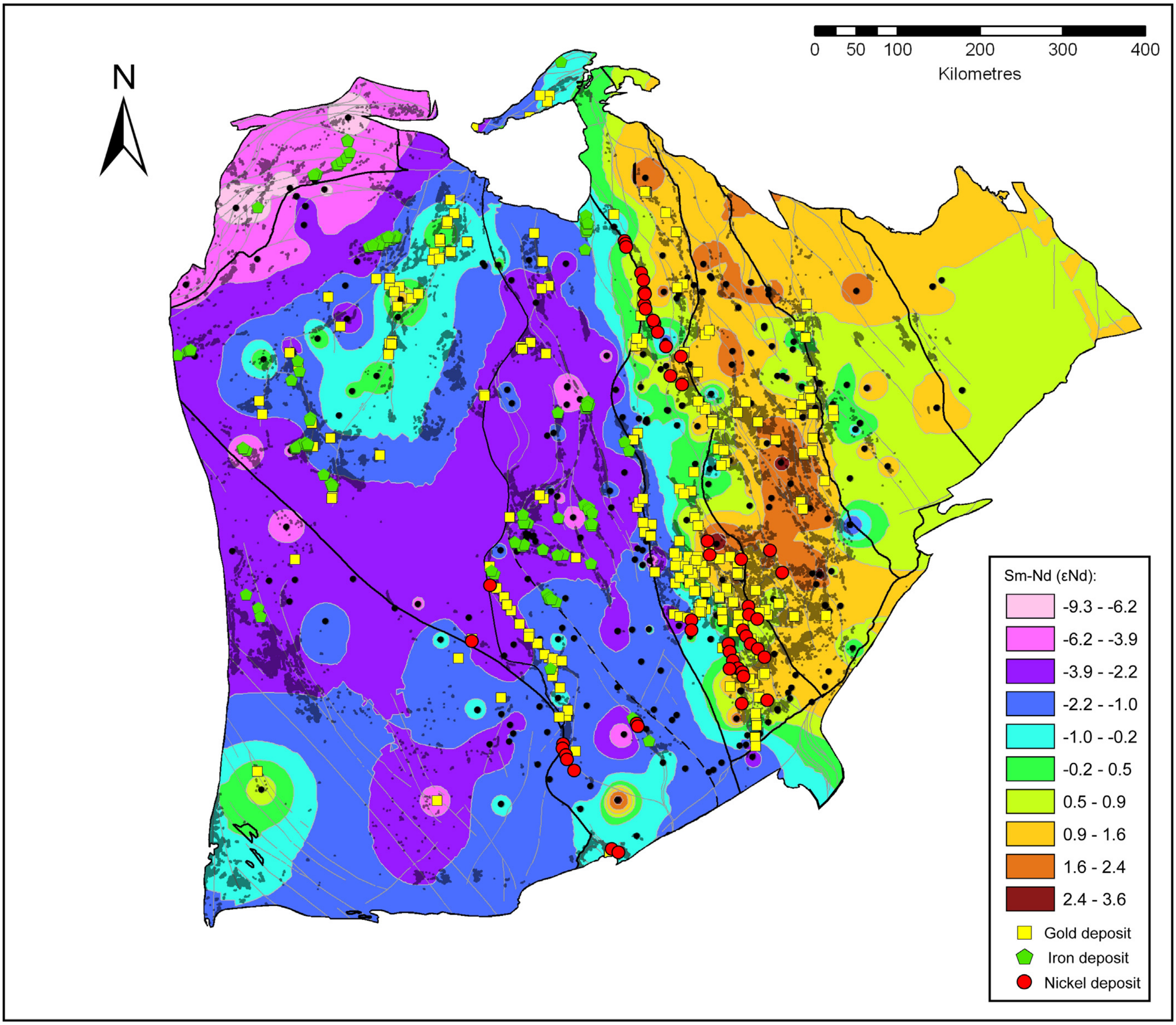


Figure 13. Epsilon neodymium isotopic map of the Yilgarn craton at 2.7–2.6 Ga, showing overlap in distribution or world-class ca. 2.7 Ga komatiite-associated Ni-Cu deposits and world-class ca. 2.65–2.64 Ga orogenic gold deposits. The strong NNW-trending gradient in the centre of the figure is interpreted to be the margin of the proto-craton at 2.7 Ga (after McCuaig and Hronsky, 2014).

however, not universal with many orogenic gold provinces spatially controlled by suture zones that are not lithospheric boundaries, particularly in the Phanerozoic.

5. Improved assessment of target potential

It follows from the discussion above that, in terms of Fig. 2, each district to deposit-scale target, instead of being viewed in isolation, should be tracked back up scale to determine its relative value in terms of its timing within the context of the supercontinent cycle for its specific deposit type and its tectonic setting as a generic factor. Specifically, craton margins, other lithosphere boundaries, and suture zones where potential crust-mantle interaction and reactivation have been identified from integrated geological, geochemical and geophysical studies, such as in the case of the North China Craton (e.g, Guo et al., 2013), should be buffered to determine the probability that any specific target has the potential to lie within a world-class gold province. Using this screening process, the number of preliminary targets selected for more extensive and expensive exploration drilling on the basis of local anomalism should significantly decline. This would hopefully produce the scenario shown in Fig. 12, where, if successful, the industry could emerge from its low base-rate situation.

A benefit of the approach is that exploration is then focussed along lithosphere boundaries where other deposit types (e.g., intrusion-hosted and komatiite-associated Ni-Cu deposits (Begg et al., 2010; Maier and Groves, 2011) also occur, potentially leading to incidental discovery of deposit types other than those initially sought. The spatial coincidence of world-class orogenic gold districts and komatiite-associated Ni-Cu deposits along lithospheric boundaries defined by radiogenic isotope ratios in the Archean Yilgarn Block (Fig. 13) is a specific example. On the southern margin of the Yilgarn Block, the recent world-class Nova Ni-Cu discovery (Bennett, 2013), in a similar tectonic position to the world-class Tropicana gold deposit (Blenkinsop and Doyle, 2014), is an excellent example of coincident deposit types along a specific lithosphere boundary.

6. Concluding statement

Mineral exploration is currently a low base-rate industry with an unhealthy conjunction of declining greenfield discoveries and increasing costs of discoveries. There are several reasons for this. Geologically, one major reason is that exploration targets commonly are not viewed in terms of the geochronological suitability of host rocks and potential ore type in terms of the supercontinent cycle and regional geodynamics. Thus, specific mineral deposit types develop at specific periods in Earth history. Another problem is that exploration prospects are commonly not adequately assessed in terms of the suitability of their terrane or province scale tectonic setting. At this scale, the locations of most gold deposit styles are strongly controlled by first-order structures such as craton margins, other lithospheric boundaries, or suture zones. It is only by more selective district-scale exploration based on proximity to these first-order structures that the currently declining exploration success rate can be reversed. This is vital to the mineral exploration industry as only new greenfield discoveries can replenish declining metal resource inventories in the medium to long term.

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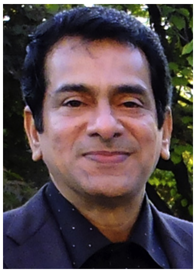
Prof. David I. Groves is Emeritus Professor in the Centre for Exploration Targeting at the University of Western Australia (UWA) and Visiting Professor at the China University of Geosciences Beijing. Educated at Varndean Grammar School in Brighton, UK, and Hobart High School, Tasmania. BSc Honours (First Class) and PhD from the University of Tasmania, Honorary DSc from UWA. Former Director of Key Centre for Strategic Mineral Deposits and Centre for Global Metallogeny at UWA. Supervised over 250 BSc Honours, MSc and PhD students. Published approximately 500 papers and book chapters. Former President of Geological Society of Australia, SEG and SGA. Awarded 11 Research Medals including Gold Medals of SEG and SGA (only economic geologist to hold both) and the Geological Association of Canada Medal, plus other medals from Australia, South Africa and UK. Currently Consultant to the mineral exploration industry and brokers and investors in Canada with exploration properties in Africa, South America and Greenland. Most recently a novelist The Exodus Equation and The Digital Apocalypse.



Prof. M. Santosh is Foreign Expert and Professor at the China University of Geosciences Beijing (China), Specially Appointed Foreign Expert of China, and Emeritus Professor at the Faculty of Science, Kochi University, Japan. B.Sc. (1978) from Kerala University, M.Sc. (1981) from University of Roorkee, Ph.D. (1986) from Cochin University of Science and Technology, D.Sc. (1990) from Osaka City University and D.Sc. (2012) from University of Pretoria. Founding Editor of Gondwana Research as well as the founding Secretary General of the International Association for Gondwana Research. Research fields include petrology, fluid inclusions, geochemistry, geochronology and supercontinent tectonics. Published over 350 research papers, edited several memoir volumes and journal special issues, and co-author of the book ‘Continents and Supercontinents’ (Oxford University Press, 2004). Recipient of National Mineral Award, Outstanding Geologist Award, Thomson Reuters 2012 Research Front Award, Global Talent Award, Island Arc Award and Island Arc Award and Thomson Reuters Thomson Reuter Highly Cited Top Frontier Researcher in the World award.