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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