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Multi-stage enrichment processes for large gold-bearing ore deposits

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ABSTRACT

A review of previous studies of the world's large hydrothermal gold deposits indicates that the largest deposits tend to show complicated parageneses where multiple gold enrichment events and processes have been involved in the deposit generation. These observations suggest that multistage processes may even be a requirement for the formation of large deposits. In some deposits (e.g. Witwatersrand, Boddington Cadia, Sukhoi Log or Carlin) the different enrichment processes occur millions of years apart. In others, such as many large porphyry deposits, the different stages are much closer in time. In many deposits, particularly sedimentary-hosted deposits, early diffuse enrichment occurs within a particular province that is then upgraded by more focused processes (e.g., Sukhoi Log; Kalgoorlie). The presence of this early diffuse enrichment could explain the tendency for gold deposits to cluster into camps.

This model has important implications, as the presence or absence of multiple gold events could be used to discriminate, at the exploration and feasibility stages, between small deposits with single stage ore genesis and more complicated deposits with multistage enrichment and the potential for larger gold endowment.

1. Introduction

Large gold deposits (>10 million ounces Au) are rare geological feature and are formed by either:

1. A single unusual event.
2. An exceptional set of combined circumstances.

Previous studies reviewing the spectrum of large metallic deposits (Emsbo et al., 2006; Richards, 2013; Laznicka, 2014) suggest that the giant metallic ore deposits are not exceptional in their processes but circumstances have combined to form a much larger deposit than would otherwise exist. Part of the evidence cited for this is that very large deposits are not far outliers but rather conform to the overall characteristics of deposits in their class worldwide. The largest deposits are within the overall log-normal distribution of deposits in terms of grade (Fig. 1a) and continue the power law distribution in terms of size (Fig. 1b). In this study we review existing data from some of the world's largest gold deposits to elucidate whether the circumstances which led to gold enrichment were different from similar processes in smaller deposits. The impetus for this paper originates from various studies of gold deposits by the authors, where empirical observations suggested that the largest gold deposits tended to have very complicated multistage ore parageneses compared with smaller deposits. The exploration strategies that can be used to find new gold ores will necessarily differ depending on whether a single event or multiple events are involved. For example, in single-stage systems, searches should concentrate on the area near a discrete source region using a simple source-pathway-trap model. In the multi-stage systems a much more probabilistic strategy should be employed, involving the identification of multiple ore systems that overlap in space.

The origin of gold deposits has been the subject of considerable debate and remains controversial to this day. Most published ore deposit models in the literature to date involve gold being sourced from the mantle, the lower crust or the upper crust (Groves, 1993; Phillips and Powell, 2010; Thomas et al., 2011; Hronsky et al., 2012; Tomkins, 2013) transferred to hydrothermal fluids which carry the gold into a zone with a strong chemical (pH or Eh) or physical (temperature or pressure) contrast, leading to the deposition of gold in veins or within other minerals (particularly pyrite). Gold deposits are generally subdivided into a number of different styles based on the mineralogy and geometry of mineralisation and the rocks in which they occur. Within each type there are considerable variations and gradations.

Some studies of gold mineralization have proposed more complex models, requiring the formation of multiple vein arrays, mixing of isotopic sources and overprinting of alteration zones (e.g. Nichols and Hagemann, 2014), (e.g. Nichols and Hagemann, 2014). Complex relationships are particularly well-documented in forensic-type studies which use micro-analytical techniques such as electron, laser, X-ray, proton and ion beam techniques to study minerals and alteration

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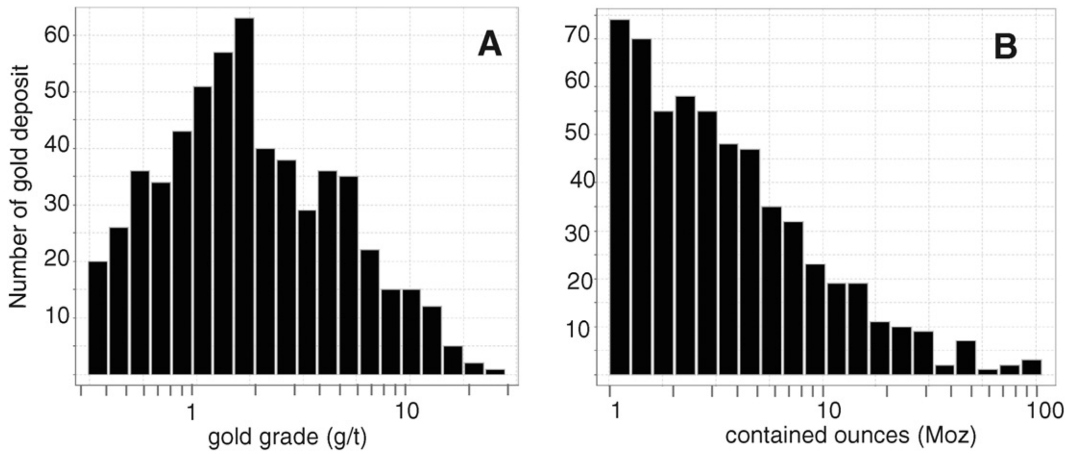

Fig. 1. Histograms showing the log normal distribution of gold deposit grades and power law distribution of gold deposit size (resource for deposits >1 Moz). Data from NRH Research — 2013 Ranking Gold Mines & Deposits (http://www.visualcapitalist.com/wp-content/uploads/2013/11/global-gold-mine-and-deposit-rankings-2013.pdf).

zones within ore deposits (Oberthür et al., 1997; Large et al., 2009; Sung et al., 2009). These tend to show that the gold enrichment processes are protracted and in many cases more than one enrichment event has been documented. In some, there is evidence for early low-grade enrichment followed by a late high-grade overprint. In others, the scientific literature is divided as to whether the early or late events were responsible for the enrichment (e.g. the long running Witwatersrand debate; Large et al., 2013).

This paper briefly summarizes the some of the existing geological information for most of the world's large gold deposits with a view to comparing and contrasting gold enrichment processes in a number of different deposit styles to determine whether gold is introduced by a single discrete event or by a particular combination of events and circumstances. This paper is in no way comprehensive but outlines some of the temporal evidence for multistage gold concentration processes in some large deposits within a range of deposit styles. The paper focuses in particular on deposits on which the authors have worked over the last decade. Although this introduces a particular bias, we would argue that these sites are at least partially representative of large gold deposits worldwide (Fig. 2).

2. Witwatersrand

The Witwatersrand basin contains numerous strata-bound high grade gold deposits which are characterized by complex parageneses. Despite the very low metamorphic grade and the relatively undeformed nature of the 2.9–2.7 Ga host sedimentary rocks, no consensus has been reached on the source of the gold or the enrichment mechanisms. Some studies emphasize the presence of early detrital gold and early gold in pyrite in discrete conglomeratic horizons (e.g. Minter, 1999) while others focus on the hydrothermal alteration and the late introduction of the majority of the gold (Law and Phillips, 2006; Phillips and Powell, 2015). Some recent studies present models showing both early gold enrichment followed by the late re-introduction of gold (Mathur et al., 2013) with the earlier event cross-cut (Agangi et al., 2015) and overprinted by late stage overgrowth (Large et al., 2013) (Fig. 3). However, there is no consensus as to how much of the gold was introduced in the early stage and the amount added during the late hydrothermal overprint. It is difficult to see how these estimates of relative importance could be obtained using existing techniques. One problem with providing this type of estimate for the Witwatersrand deposits is that, as in

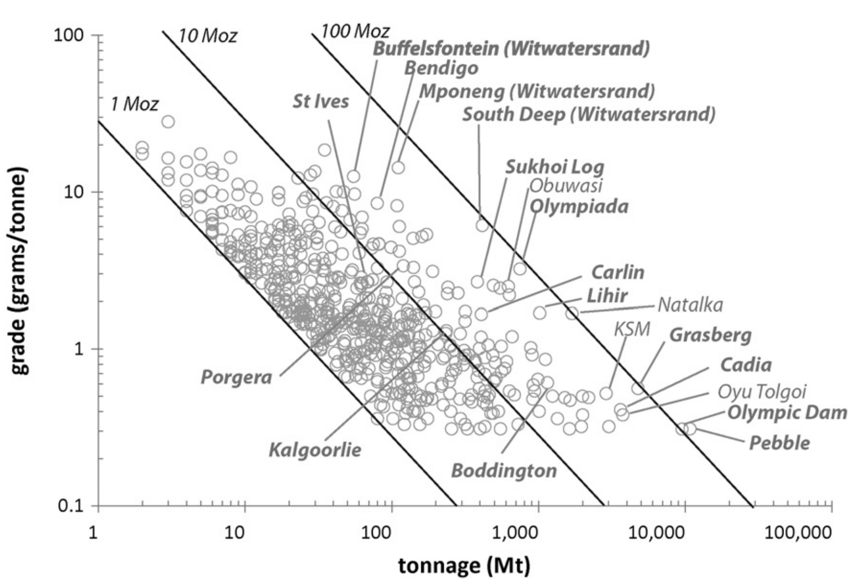

Fig. 2. Deposit size and grade, showing the deposits discussed in the text. Data as for Fig. 1 except for Olympic Dam (9833 Mt at 0.31 g/t; Kathy Ehrig, BHP pers. Com. 2014) and Bendigo (historical resource: 22 Moz at 8 g/t estimated from documents at http://www.unitymining.com.au/bendigo-goldfield-history/). Mines labeled in bold text are those discussed in the text.