THE LATE ARCHAEAN METALLOGENIC BONANZA

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Summary

The late-Archaean metallogenic bonanza, of giant to world-class orogenic gold, VMS, komatiite Ni and rare-metal pegmatites, plus BIF, illustrates the global heterogeneity of ore deposits. The formational driving force appears to be the interaction of mantle plumes with convergent plate-tectonic settings, which produced a combination of: i) anomalous volcanism and sedimentation, ii) accelerated organic and hydrothermal activity in a suboxic hydrosphere, and iii) accelerated closure of margin basins and accretion of terranes. The resultant decompression melting at the base of the lithosphere produced buoyant continental lithosphere which preserved the voluminous ore deposits. A similar, although lesser, event occurred in the Palaeoproterozoic. Cooling of the Earth and a progression to modern-style plate tectonics resulted in the generation of linear, rapidly uplifting orogens from which most of the ore deposits were lost to erosion. Only in the late-Palaeozoic and Mesozoic has the balanced conjunction of formational and preservational processes seen a return to the preservation of metallogenic bonanzas of orogenic-style ore deposits around the margins of the external oceans of those periods.

Introduction

Late-Archaean terranes are some of the most richly mineralised on Earth (Fig. 1), not only in terms of the mineral deposit styles which formed during the Archaean, but also in terms of the deposit styles which developed on or adjacent to Archaean cratons after their stabilisation (e.g. diamonds in kimberlites, Cu-REE in carbonatites, some Cu-Au-Fe-oxide ores, bauxites, beach sands). As such, their metallogeny has been extensively reviewed in the literature (e.g. Hutchinson et al. 1971, Anhaeusser 1981, Franklin and Thorpe 1982, Thurston and Chivers 1990, Groves and Barley 1994).

The most widespread mineralisation style is orogenic lode-gold deposits (Groves et al. 1998), which occur on almost all cratons which contain Late-Archaean granitoid-greenstone terranes, with numerous world-class deposits of this type in the Superior Province, in particular the Abitibi sub province of Canada, the Slave Province of Canada, the Yilgarn Block, particularly the Norseman-Wiluna Belt, of Western Australia, the Kolar Belt of India, the Quadrilatero Ferrifero in Brasil, and the Zimbabwe Craton, particularly Midlands Belt, of southern Africa. Giant deposits occur at Timmins, Canada, Kalgoorlie, Western Australia, and Kolar, India. Some authors believe that the super-giant Witwatersrand gold deposits of South Africa are of hydrothermal origin (e.g. Phillips et al., 1987; Barnicoat et al., 1997), whereas others believe that they are palaeoplacers (e.g. Minter et al., 1993). Irrespective of which model is correct, widespread Late-Archaean hydrothermal gold mineralization is implicated, either in the Basin or in the source.

Volcanogenic massive sulphide (VMS) deposits are extremely widespread in the Superior Province, particularly Abitibi Belt, where the giant Kidd Creek and Horne mines are sited (e.g. Fyon et al. 1992), but are relatively rare elsewhere, although significant deposits do occur in the Yilgarn Block of Western Australia (e.g. Barley, 1992). Similarly, komatiite-hosted Ni-Cu deposits (e.g. Lesher 1992) are extremely widespread in the Yilgarn Block of Western Australia, where they include the giant Kambalda deposits, but are relatively rare in other terranes, although examples have been mined in the Abitibi Belt near Timmins (e.g. Fyon et al. 1992), in Zimbabwe (e.g. Williams 1979) and in Brazil (e.g. Brenner et al. 1990).

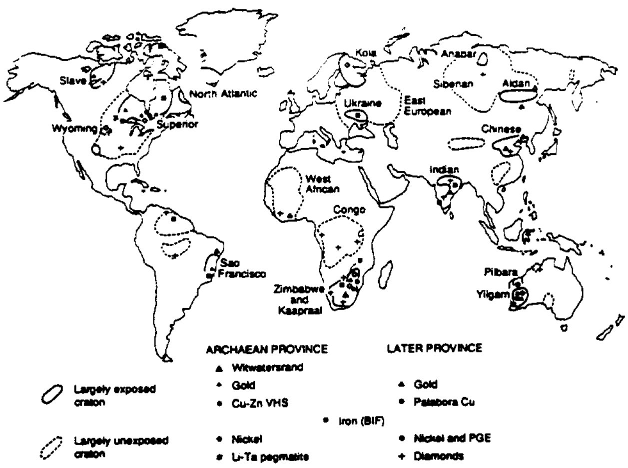

Figure 1. World map showing the distribution of some world-class mineral deposits in major Archaean cratons. From Groves and Barley (1994).

Other mineralization styles which are important, at least locally, include rare-metal pegmatites such as the giant deposits at Tanco, Canada, Bikita, Zimbabwe, and Greenbushes, Western Australia, with others mined from the Sao Francisco Craton of Brazil, and porphyry-style Cu-Au deposits, for example McIntyre, Timmins, and Boddington (?), Yilgarn Block. The late-Archaean was also the period of deposition of many of the extensive BIF successions which were the protores for the enriched iron ores formed in the Proterozoic.

This late-Archaean metallogenic bonanza, with its numerous examples of world-class to giant ore deposits in a variety of categories, is not unique. Rather, it is one example of the heterogeneous distribution of ore deposits in time and space which has been emphasised by numerous authors, most notably Meyer (1988). Figure 2 (from Meyer 1988) shows this heterogeneous distribution with geologic time, and well illustrates the late-Archaean metallogenic bonanza. The reasons for this heterogeneity are controversial. and have been hotly debated. They are discussed briefly below.

Heterogeneous Distribution of Mineral Deposits with Time

This subject has been discussed by Barley and Groves (1992) and Barley et al. (1998), and is only briefly summarised here. Basically, there are four main factors which, in combination, can explain the heterogeneous distribution of mineral deposits throughout time: 1) the evolution of the hydrosphere - atmosphere, 2) a secular decrease in global heat flow, 3) long-term tectonic trends affecting both the evolution of tectonic settings and their preservational potential, and 4) within this long-term tectonic trend, cyclicity due to the supercontinent cycle. There is likely to be feedback between the various tectonic, chemical and biological cycles (e.g. Titley 1993), particularly at the time scale of the supercontinent cycle.

Deposits that may be primarily influenced by the evolution of the Earth's hydrosphere-atmosphere are those in which the metals show multiple oxidation states and ore precipitation is related to redox reactions. Thus, BIF is best developed in the late-Archaean and Palaeoproterozoic, uranium deposits, excluding those in pegmatites, evolve from Archaean palaeoplacers through Proterozoic unconformity-related deposits to Phanerozoic sandstone-roll deposits and, finally, Tertiary-Recent calcrete-hosted deposits, and sedimentary manganese deposits evolve in the Phanerozoic. This can explain part of the recorded heterogeneity. Similarly, deposits which form in convergent-margin settings around external (Pacific-style) oceans show a different temporal pattern than those that formed on the margins of internal (Atlantic-style) oceans or in anorogenic settings (Fig. 2), presumably reflecting their different timing with respect to the several hundred million-year long supercontinent cycle (e.g. Barley et al. 1998). In addition, komatiite-hosted Ni-Cu deposits are essentially restricted to the Archaean and Palaeoproterozoic, presumably due to a hotter Earth at that time.

Finally, some deposit styles such as porphyry Cu-Au-Mo and high - and low- sulphidation epithermal Au-Ag deposits, which have formed in the Tertiary to Recent around the Pacific Rim (e.g. Sillitoe 1997), are located in areas of extremely rapid tectonic uplift. This, combined with their relatively shallow level of emplacement, means that they will be rapidly eroded, thus explaining their paucity in terranes older than the Mesozoic (Fig. 2).

Factors Favouring Formation of Mineral Deposits in the Late Archaean

Barley et al. (1998) explain the abundance of orogenic mineral-deposit styles in the Late Archaean in terms of the metallogenic and environmental consequences of intrabasinal plumes and a global plume breakout during the first half of a global tectonic (supercontinent) cycle. Coincident and globally distributed komatiite volcanism at about 2.7 Ga provides the evidence for the global plume event. Overlapping calc-alkaline felsic volcanism in several terranes (e.g. Abitibi Belt, Canada; Eastern Goldfields, Western Australia) indicates that these plumes impinged on volcanic arc environments in convergent margin settings. The consequences of these plume impingements were very similar to those of the Cretaceous plume breakout in the Pacific Ocean (e.g. Vaughn 1995). Peak submarine magmatism was accompanied by marine transgression and therefore flooding of previously exposed continental crust. Elevated hydrothermal activity and widespread suboxic conditions in submarine basins are reflected by sulphidic carbonaceous shales, containing the organic remains of bacterial communities ($\delta^{13}C$ more negative than -40 per mil : Hayes et al., 1983), and banded iron formations (BIF).

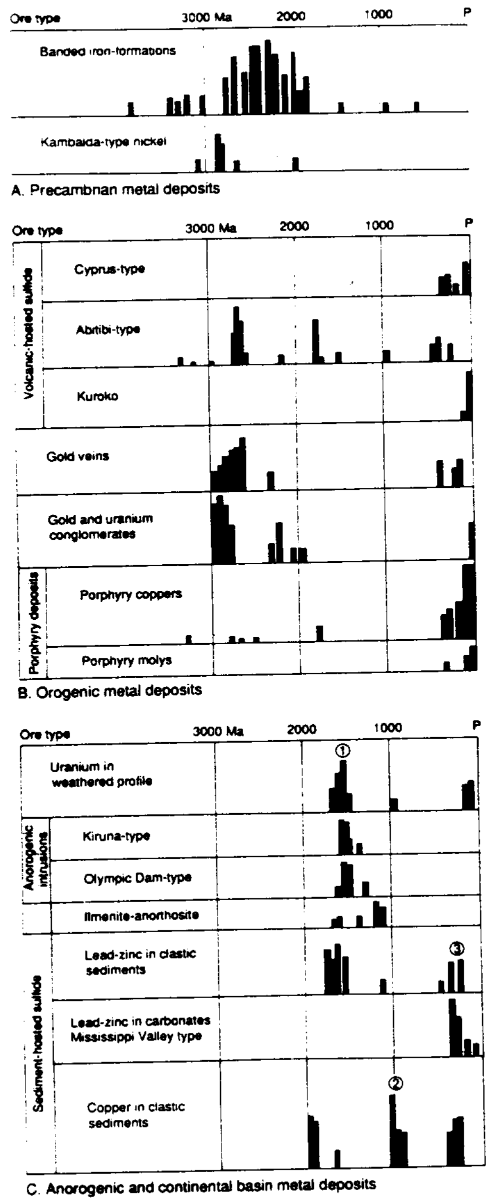

Figure 2. Distribution through time of some major styles of mineral deposits that formed in orogenic and anorogenic/continental basin settings. Adapted by Barley and Groves (1992) from Meyer (1988). More precise data for orogenic lode-gold deposits are given by Goldfarb et al. (in press).

The widespread submarine volcanism and hydrothermal activity in a suboxic ocean led to the formation of giant sulphate-free VMS deposits in contrast to the sulphate-bearing VMS that had formed prior to 3.0Ga (e.g. Barley 1992, Vearncombe et al. 1995). The sulphidic black shales provided the sulphur source (not generally available in earlier Archaean environments) for the giant komatiite-hosted Ni-Cu deposits, as submarine komatiite flows thermally eroded their substrate (e.g. Frost and Groves 1989; Lesher 1989). It is also likely that the intensely hydrothermally altered (H_2O-CO_2) basalts and carbonaceous, sulphidic metal-rich sediments provided fertile source materials for auriferous hydrothermal fluids as they were subducted below the continental crust and/or continental arcs that were to form the orogenic belts in which orogenic lode-gold deposits would later form (e.g. Groves et al. 1998). Enhanced subduction rates related to plume activity probably accelerated accretionary processes, enhancing the formation of the orogenic gold deposits. It is probable that porphyry-style and epithermal deposits would have formed in the volcanic arcs, but that they were rapidly eroded and generally not preserved: the occurrence of some deposits suggests that they did form and were preserved under special circumstances. Thus, there is an adequate model for the formation of the widespread orogenic mineral deposits that make the Late Archaean such a metallogenic bonanza.

Factors Favouring Preservation of Mineral Deposits in the Late Archaean

There are clearly coincident tectonic, magmatic and environmental factors operating in the Late Archaean to explain the enhanced metal inventory of the greenstone terranes of this age. There is also evidence to suggest that similar factors may have operated in the Palaeoproterozoic (ca 2.1 - 1.9 Ga) when similar associations of giant orogenic gold depoists (e.g. Ashanti), world-class VMS deposits (e.g. Flin Flon) and komatiite-associated Ni-Cu deposits (e.g. Raglan) are associated with greestone belts containing komatiites and high-MgO basalts (Goldfarb et al. in press). However, given that the concept of the supercontinent cycle is correct, there has to be an additional factor to explain the preservation of the deposits in the late-Archaean and Palaeoproterozoic terranes and their abundance in the Phanerozoic, but their virtual absence in the Meso- and Neoproterozoic (Fig. 2).

Goldfarb et al. (in press) point out that the Late Archaean and Palaeoproterozoic metallogenic bonanzas correlate well with the major sudden and rapid episodes of growth of juvenile continental crust (e.g. Stein and Hoffman 1994, Condie 1995). These two episodes of Precambrian continental growth and related metallogeny are currently best explained by major mantle overturning, perhaps from a layered mantle to one with a transient whole-mantle convection (e.g. Davies 1995), in the hotter early Earth. Resulting mantle plumes during the convective phase presumably generated the vast amounts of new crust due to decompression melting at the base of the lithosphere, with both mantle melting producing voluminous volcanic rocks and impinging plumes causing massive crustal melting and associated voluminous granitoid plutonism. As suggested by Barley et al. (1998), this would have led to the generation of refractory, but buoyant, continental lithosphere that is responsible for the preservation of the highly mineralised late Archaean (and Palaeoproterozoic) cratons. For example, Abbott (1996) shows that mantle plume interaction with subduction zones may have been a crucial factor in the long-term buoyancy of sub-arc mantle and preservation of Archaean juvenile arcs. Goldfarb et al. (in press) further argue that this combination of plume- and plate- tectonics was responsible for preservation of large, relatively equidimensional continental masses that were geometrically most suitable for the long-term preservation of highly-mineralised mid-crustal orogens. They suggest that the paucity of orogenic mineral deposits in the Meso- to Neo- Proterozoic reflects a transition to more modern-style plate-tectonics, with lesser plume activity, with the generation of more linear orogenic belts on less-buoyant lithosphere, such that even the orogenic mineral deposits were eroded in more rapidly uplifting orogens. Evidence from around the convergent margins of the Pacific Rim, particularly the giant placer gold fields, suggests that the orogenic lode-gold deposits in these linear orogenic belts may be lost to erosion within 100 to 150 m.y. of their formation, explaining the increasing abundance of preserved lode-gold deposits in the late-Palaeozoic and Mesozoic (Fig. 2).

Conclusions

The late-Archaean metallogenic bonanza of giant to world-class orogenic lode-gold, VMS, komatiite-hosted Ni-Cu and rare-metal pegmatites, plus the BIF precursors to the giant Proterozoic iron ores, represents one of the best examples of the extremely heterogeneous temporal distribution of ore deposits at the global scale. It appears to owe its origin to interaction of mantle plumes with convergent plate-tectonic settings in which a combination of anomalous volcanism, sedimentation, organic activity and hydrothermal activity in a suboxic hydrosphere, increased rates of subduction with associated accelerated closure of marginal basins and accretion of terranes, and enhanced preservation in buoyant lithosphere which resulted in the enhanced formation and preservation of the orogenic mineral deposits. An event of similar, although lesser, metallogenic significance in the Palaeoproterozoic probably reflects a similar conjunction of processes, with progressive evolution to modern-style plate-tectonic resulting in greater erosion of the orogenic deposit styles in Meso- to Neoproterozoic terranes, with extensive gold placer fields in the Phanerozoic terranes and increased preservation of primary deposits in the late Palaeozoic and Mesozoic to produce metallogenic bonanzas of similar magnitude. Goldfarb et al. (in press) provide a detailed discussion of this evolution with respect to orogenic lode-gold deposits.

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