Economic Geology

BULLETIN OF THE SOCIETY OF ECONOMIC GEOLOGISTS

VOL. 105 | May | NO. 3

# Secular Variation in Economic Geology

RICHARD J. GOLDFARB,[1,†] DWIGHT BRADLEY,[2] AND DAVID L. LEACH[1]

[1]*U.S. Geological Survey, Box 25046, Mail Stop 973, Denver Federal Center, Denver, Colorado 80225-0046*

[2]*U.S. Geological Survey, 4200 University Drive, Anchorage, Alaska 99508-4667*

## Temporal Patterns of Ores

The temporal pattern of ore deposits on a constantly evolving Earth reflects the complex interplay between the evolving global tectonic regime, episodic mantle plume events, overall changes in global heat flow, atmospheric and oceanic redox states, and even singular impact and glaciation events. Within this framework, a particular ore deposit type will tend to have a time-bound nature. In other words, there are times in Earth history when particular deposit types are absent, times when these deposits are present but scarce, times when they are abundant, and still other times for which we lack sufficient data. Understanding of such secular variation provides a critical first-order tool for exploration targeting, because rocks that have formed or were deformed during a certain time slice may be very permissive for a given deposit type, whereas identification of rocks of less favorable ages would help eliminate large areas during exploration programs. Secular analysis, therefore, is potentially a powerful tool for mineral resource assessment in poorly known terranes, providing a quick filter for favorability of a given deposit type using age of host rocks.

Factors bearing on the known age distribution of a particular type of deposit include the following: (1) uneven preservation, (2) data gaps, (3) contingencies of plate motions, and (4) long-term secular changes in the Earth System. The present special issue of *Economic Geology* is focused on the latter factor, although all of these are interrelated. The selective preservation of certain mineral deposit types and the greater susceptibility for shallowly formed ores in tectonically active environments to be lost to erosion define a pattern that is superimposed on the secular formational trends (e.g., Groves et al., 2005a, b; Kerrich et al., 2005). With improved geochronological methods and the availability of information on important mineral deposits from most parts of the world, data gaps for defining broad temporal distributions of ore types are becoming smaller. It has been increasingly recognized that ore deposit formation is also correlated with plate tectonic setting. Nevertheless, a complex Earth history of supercontinent assembly and breakup has led to the fragmentation of many Paleozoic and Precambrian mineral provinces. The use of plate reconstructions in economic geology, although extremely controversial and conjectural before the late Paleozoic, is critical for defining these provinces prior to the added complications resulting from post-ore plate motions.

It is now well established that the temporal patterns of many types of mineral deposits (Fig. 1) reflect the formation or break-up of supercontinents and the preservation potential of deposits formed during these periods (Barley and Groves, 1992; Titley, 1993; Kerrich et al., 2005; Goldfarb et al., 2009). Approximate time periods for such formation and break-up, respectively, include 2800–2500 and 2450–2100 Ma for Kenorland, 2100–1800 and 1600–1300 Ma for Nuna/Columbia, 1300–1100 and 850–600 Ma for Rodinia, and 600–300 Ma and 200–60 Ma for Gondwanaland-Pangea. A new supercontinent, Amasia, has begun to form during the past 250 m.y., thus overlapping Pangea break-up. Many of the formation-preservation patterns are themselves controlled by progressive cooling of Earth, the change from a mantle-plume buoyancy style to subduction-dominated tectonics, a decreasing buoyancy of the subcontinental lithospheric mantle, and depth of ore formation. In general, orogenic Au, volcanogenic massive sulfide (VMS), epithermal Au-Ag, and porphyry Cu±Au and Mo porphyry deposits form in active margins during periods of supercontinent assembly. Numerous other ore deposit types show an association with supercontinent formation, but develop inland of the active margin. These include many of the MVT Pb-Zn deposits and unconformity-type U deposits. The Tertiary Carlin-type deposits within the deformed shelf sequences along the North American craton margin also appear to have formed during the ongoing growth of Amasia. Those ores associated with periods of supercontinent breakup or attempted breakup are more difficult to define. They probably include diamond, Bushveld-type Ni-Cu-PGE, IOCG, and clastic-dominated Pb-Zn (or SEDEX) deposits in intracontinental areas of failed rifting, and other clastic-dominated Pb-Zn deposits in areas of actual breakup. In all cases, however, these temporal/spatial distributions are ultimately controlled by the secular character of Earth history.

## Historical Understanding of Metallogeny and Earth Evolution

One hundred years ago, Lindgren (1909) first discussed the occurrence of "metallogenetic epochs" on Earth. Separately

† Corresponding author: e-mail, goldfarb@usgs.gov


0361-0128/10/3883/459-7



*Submitted: March 10, 2010*
*Accepted: May 3, 2010*

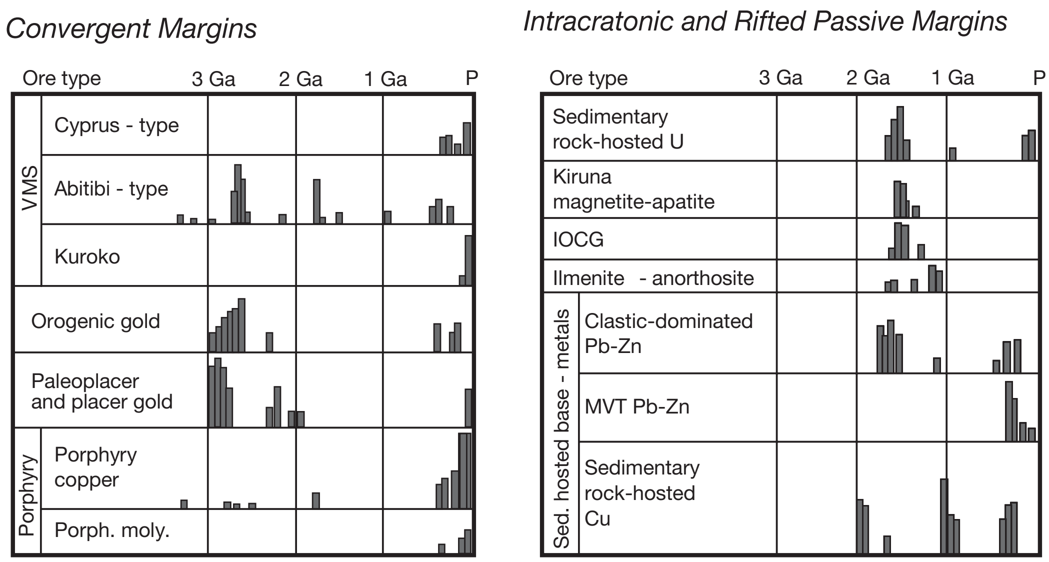


FIG. 1. Generalized temporal distribution of some important mineral deposits and association with convergent margins or intracratonic and passive continental margin rifting settings. After Meyer (1988), Barley and Groves (1992), and Groves et al. (2005a).

examining eastern and western North America, he noted the association of various ore districts with igneous and sedimentary rocks of specific time periods. Half a century later, prior to a modern-day understanding of plate tectonics and widespread application of isotopic dating, the distributions of ore deposits were broadly grouped according to tectonic setting. Metallogenic provinces were related to their host Precambrian shields and Phanerozoic stable regions and mountain belts, with the argument that this was a better approach than relating deposits to a specific epoch because some provinces may contain ores formed at different geologic times (e.g., Turneaure, 1955). Ore deposition was related to various igneous, metamorphic, and sedimentary processes, but there was no recognition of the importance of secular variation in Earth events. Workers such as Pereira and Dixon (1965), Rundkvist (1968), and Laznicka (1973), first noted in a broad way that Cr and Ni deposits, with an upper mantle connection, were relatively concentrated during early Earth processes and had the oldest ages; followed by Ag, Au, Cu, Pb, and Zn with many younger deposits; and then observed Hg, Sb, Sn, and W ores tended to be associated with still younger tectonic events. As pointed out by Laznicka (1973), these patterns reflect different crustal depths of the different deposit types and thus variations in preservation potential as discussed above.

With the establishment of modern plate-tectonic theory in the 1970s, there soon was a significant volume of literature summarizing the relationship between mineral deposits and their global tectonic setting (e.g., Rona, 1980; Mitchell and Garson, 1981; Sawkins, 1984). The nature of tectonic processes through time must be defined if the temporal evolution of mineral deposits is to be understood. However, as pointed out by Kerrich et al. (2005), these initial compilations were hindered by a strong bias in the early 1980s toward syngenetic models for genesis of many ore deposit types, the still limited amount of absolute dates for many deposits, and little research on Precambrian tectonics and the supercontinent cycle.

Nevertheless, at about the same time, economic geologists began to make important connections between mineral deposits and Earth evolution. Secular changes in sedimentary environments, lithospheric mantle, and the atmosphere and biosphere were beginning to be recognized as influential on the temporal distribution of ores (e.g., Watson, 1978), relationships that continued to be understood in more detail over the next few decades (e.g., Hutchinson, 1992, 1993). Anhaeusser (1981) and Lambert and Groves (1981) examined Precambrian granite-greenstone environments in the context of crustal evolution of early Earth, with both studies comparing Archean and younger tectonic regimes. The age distribution of mineral deposits, such as volcanogenic massive sulfide ores (e.g., Hutchinson, 1980), was shown to help understand secular patterns of global tectonics. Classic papers by Meyer (1981, 1988) provided links between the growing body of absolute age data for ore deposits and the tectonic and chemical evolution of Earth. He pointed out the existence of what we now call the "Boring Billion," which defines a large gap of more than a billion years from the late Paleoproterozoic to the late Neoproterozoic when many major mineral deposit types are absent from the geologic record. Veizer et al. (1989) grouped global ore deposits into five stages of metal recycling associated with variations in Earth evolution; these included the Archean greenstone, Late Archean to Paleoproterozoic cratonization, the ca. 1.8 ± 0.3 Ga rifting, 1.7 to 0.9 or 0.6 Ga stable craton, and Phanerozoic continental dispersal stages. The concept of continual recycling of Archean metal enrichments within younger crust associated with the same ancient blocks is now well recognized (e.g., de Wit and Thiart, 2005). In recent years, an improved overall understanding of Earth geodynamics has allowed for a more thorough recognition of global metallogenic province patterns (e.g., Blundell, 2002; Kerrich et al., 2005, 2008).

## Secular Variation of Mineral Deposits

This special issue of *Economic Geology* addresses the temporal distributions of many significant mineral deposit types, distributions that have been highly influenced by physical and chemical changes on the evolving Earth. Discussion of some common and economically important deposit types have not been included in this issue. The present-day distribution of economic porphyry (Cooke et al., 2005; Wilkinson and Kesler, 2009) and epithermal gold (Kesler and Wilkinson, 2009) deposits are highly skewed toward the late Cenozoic (Fig. 2). Most of these deposits that formed in the upper few kilometers of crust, before ca. 20 to 30 Ma, have been uplifted and eroded and thus lost from the geologic record (Groves et al., 2005a), although there are a few significant exceptions dating back through the Mesozoic (e.g., Ling et al., 2009), Paleozoic (e.g., Khashgerel et al., 2009), and even to the Late (Piercey et al., 2008a) and Early Archean (Harris et al., 2009). The secular distribution of orogenic gold, which correlates with periods of supercontinent growth (Fig. 3), was described in detail by Goldfarb et al. (2001). The distribution indicates that formation of these deposits strongly correlates with episodic crustal growth in the Late Archean and Paleoproterozoic and preservation of ores due to cratonization in association with a less dense, buoyant subcontinental mantle lithosphere (SCML). More continuous crustal growth on the cooler Earth during the most recent 1.75 Ga led to probable orogenic gold formation throughout the establishment of Cordilleran-style orogenic belts, with the earlier half to the period more deeply eroded and thus exposing mainly high-grade metamorphic rocks below gold-favorable zones (e.g., Tomkins and Grundy, 2009) of the Rodinian supercontinent (i.e., the "Boring Billion"). Carlin-type deposits are only widely recognized to-date in Nevada, USA, and along the southwestern edge of the Yangtze craton (e.g., Su et al., 2009), so our knowledge about these remains too limited to relate these gold ores to patterns in Earth history.

*Redox-related ore systems*

Stratiform iron deposits recovered from cherty, carbonate-rich, ferruginous sediments define most of the world's iron-ore resources. These include the ca. 2.6 to 2.4 and 2.1 to 1.8 Ga Superior-type iron formations, formed in passive margins and the source for the giant iron ore systems, and the smaller, mainly >2.5 Ga Algoma-type iron formations associated with oceanic volcanic rocks and some VMS deposits. Bekker et al. (2010) indicate, in agreement with Barley et al. (1997, 1998), that episodic mantle plume events, and not just shifts in the Earth System redox state, were critical for deposition of the iron ores. The abundance of this mafic magmatism at the Archean-Proterozoic boundary may have itself helped trigger

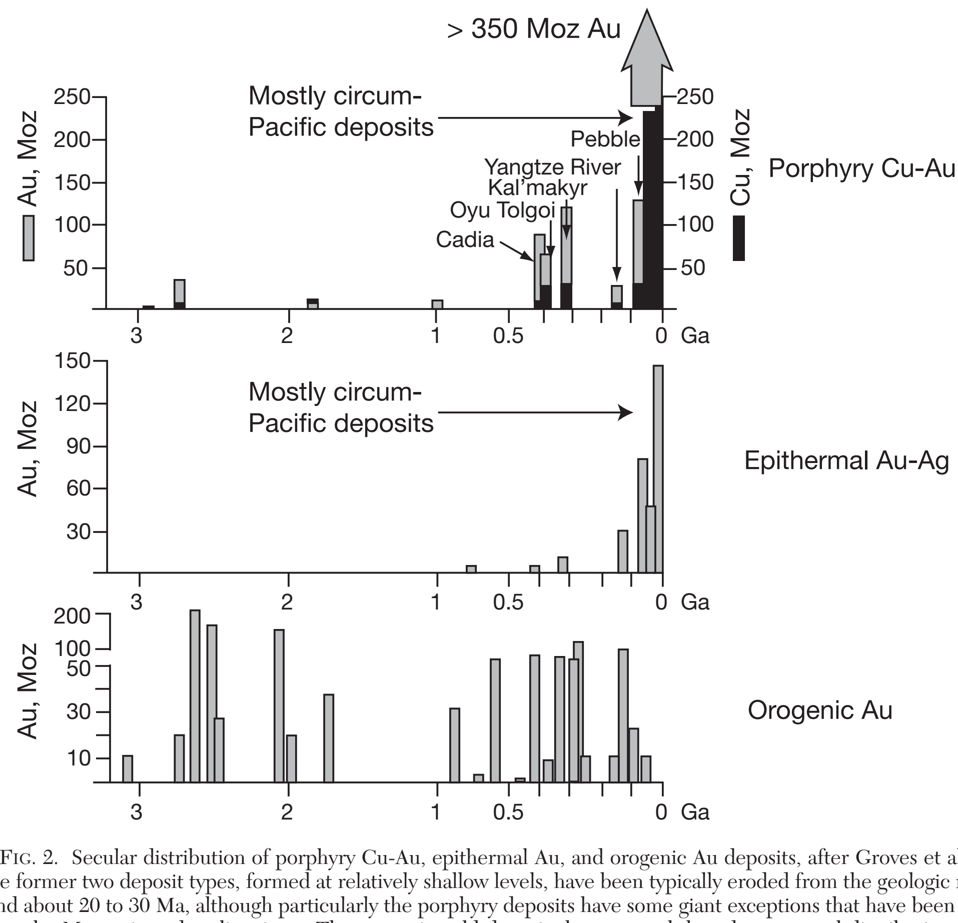


FIG. 2. Secular distribution of porphyry Cu-Au, epithermal Au, and orogenic Au deposits, after Groves et al. (2005b). The former two deposit types, formed at relatively shallow levels, have been typically eroded from the geologic record beyond about 20 to 30 Ma, although particularly the porphyry deposits have some giant exceptions that have been preserved since the Mesozoic and earlier times. The orogenic gold deposits have a much broader temporal distribution, reflecting their deeper levels of formation and thus greater likelihood to be preserved in older orogenic belts.

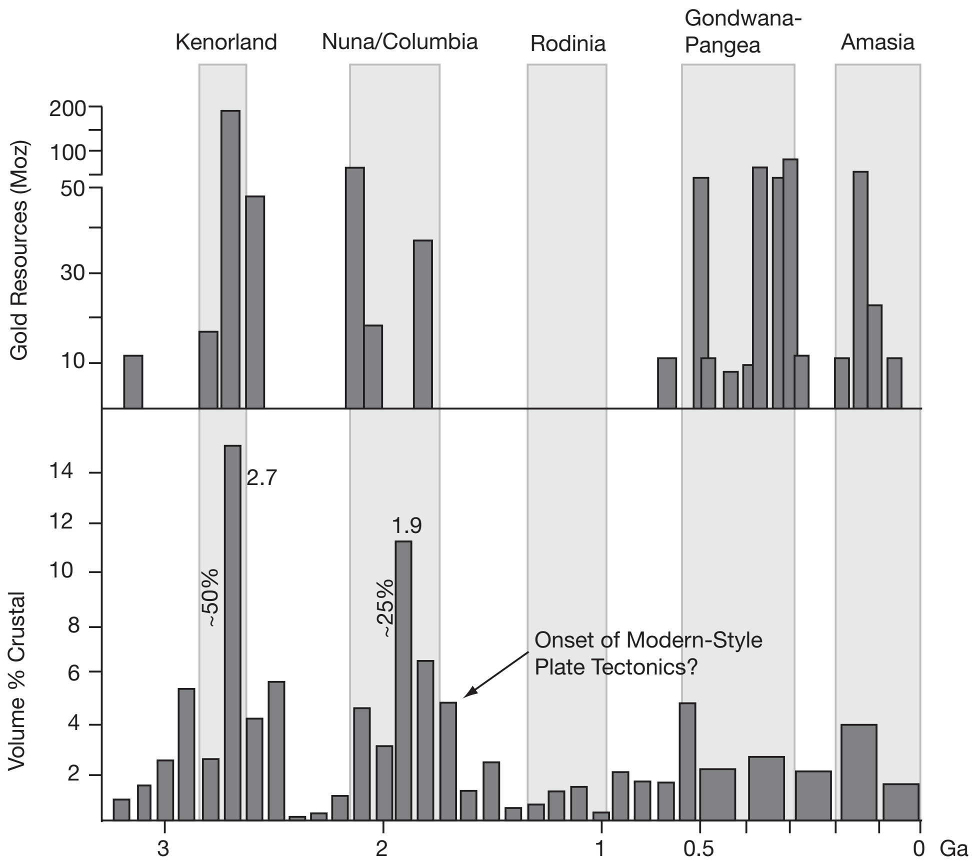


FIG. 3. Gold resources in orogenic gold deposits versus geologic time (after Goldfarb et al., 2001; Groves et al., 2005a) and crustal growth volumes versus time (after Condie, 2005). Orogenic gold deposits show a clear association with crustal growth and the growth of supercontinents over Earth history. In the Precambrian, plume-influenced tectonics were responsible for formation of much of the Earth's crust at ca. 2.7 and 1.9 Ga, also times when many early Earth gold deposits were formed and then preserved in stable cratonic blocks. Cordilleran-style tectonics began to dominate Earth by 1.7 Ga and new gold deposits formed in the associated accretionary orogens. However, most of the Rodinian belts have been eroded down to high-grade metamorphic basement rocks, which are below gold-favorable areas, and thus there is a "Boring Billion" gap, despite supercontinent growth within the Mesoproterozoic to Neoproterozoic time span.

the ca. 2.4 Ga Great Oxidation Event (GOE), leading to formation of some of the younger Superior-type iron formations. A distinct gap in iron deposition from ca. 1.85 to 0.75 Ga, sometimes even related to a temporary slowdown or cessation of plate tectonics during the Boring Billion is stressed by Bekker et al. (2010) to reflect an anomaly still requiring a much greater understanding. Slack and Cannon (2009) have related this time with a stratified and suboxic global ocean, with little Fe mobilization, to the Sudbury impact event.

The evolution of Earth's sulfur cycle is critical to defining the metallogenic history of many base metal-rich deposit types. Farquhar et al. (2010) describe Archean and earliest Paleoproterozoic marine conditions characterized by relatively low sulfate and limited sulfur cycling. With the onset of the Great Oxidation Event, ocean waters from 2.4 to 1.8 Ga became more sulfate rich and this eventually led to the formation of some of the oldest sedimentary rock-hosted Cu, Pb, and/or Zn deposits. During the Boring Billion, complex and heterogeneous marine conditions are suggested, which include coexisting sulfidic and anoxic, nonsulfidic ocean pools. With the colonization of oceans by animal life at the end of the Neoproterozoic, Farquhar et al. (2010) describe a second GOE that can be correlated with extensive MVT mineralization and possibly clastic-dominated Pb-Zn formation in passive margins.

The largest manganese ore deposits, all ultimately associated with sea-floor volcanism, are concentrated at 2.3–1.8 Ga, 800–600 Ma, and 28 Ma. Maynard (2010) examines the long-term relationships between these manganese ores and evolving seawater chemistry. Each episode of manganese ore formation on the margins of euxinic ocean basins was focused in a geographically restricted region. Thus, in contrast to the iron deposits that tend to be controlled by global events, local basin tectonics controlled formation of much of the world's manganese resources. Maynard (2010) also points out the greater chemical complexity of manganese ores over time, with younger deposits having greater trace element enrichments. He relates this to an increased diversity of sedimentary environments over Earth history.

Uranium deposit types and their temporal distribution can be divided into four main groups over Earth history (Cuney, 2010). Prior to the Late Archean, reducing conditions and the restriction of uranium concentrations to refractory minerals in the earliest felsic magmatic rocks (tonalite-trondhjemite-granodiorite) hindered formation of any uranium ores on early Earth. Between 3.1 and 2.2 Ga, the development of potassic and peraluminous magmas led to high-temperature uraninite crystallization and subsequent paleoplacer formation. Similar to Fe, S, and Mn, the GOE during the Paleoproterozoic also provided an important control on uranium distribution. Oxidation of uraninite to form soluble uranyl ions led to the concentration of many large deposits associated with redox boundaries in epicontinental sedimentary basins, with saline and oxidized ore fluids sourced from either the basement rocks or, preferably, the basin itself (e.g., Alexandre et al., 2009; Cloutier et al., 2009). Finally, Cuney (2010) stresses that widespread evolution of land plants in the Silurian provided reduced traps in continental strata for the numerous roll front-type uranium deposits formed at relatively recent times.

*Base metal-rich deposits with redox associations*

Patterns of VMS deposits over time resemble those for the orogenic gold deposits mentioned above. Huston et al. (2010) describe four metallogenic periods, from 2740–2680, 1910–1840, 510–460, and 390–355 Ma. These time periods represent a combined 200 m.y., or <5 percent of Earth history, and almost the entire metal endowment of the VMS ores are concentrated within them. These four periods represent times of supercontinent growth. As with orogenic gold, Rodinia's orogenic belts, however, lack significant VMS deposit formation. Huston et al. (2010) relate this to the lack of slab rollback and thus restricted formation of back-arc extensional basins within the overthrust plate during Rodinian growth. They also note the younger VMS provinces to be associated with (1) a greater S contribution from more oxygenated seawater relative to the more common leaching of S from the volcanic pile in Precambrian systems; (2) more abundant barite in a more oxygenated environment, although there is an association of younger VMS ores with global ocean anoxia (Piercey et al., 2008b); and (3) higher Pb concentrations with a more evolved crust. The more saline nature of early Earth oceans can explain the common higher ore grades and larger tonnages of many of the older VMS deposits.

The sedimentary rock-hosted Pb-Zn deposits have a complex secular distribution, although one clearly dominated by the oxygenation of Earth (Leach et al., 2010). Both the clastic-dominated Pb-Zn ores formed within passive margins, back-arc regions, and continental rifts, and the MVT deposits formed in carbonate platform sequences, first become significant in the geologic record at ca. 2.0 to 1.6 Ga. Their emergence correlates with significant near-surface Earth changes subsequent to the GOE, which include increased sulfate availability, enhanced Pb and Zn mobility in the surface environment, formation of sulfate-bearing evaporates and red beds, abundance of sulfate-reducing bacteria, and development of important redox gradients. The economically more significant MVT deposits did not develop until the Phanerozoic, after the late Neoproterozoic 2nd GOE; this corresponds to a time when oxidized brines and evaporates at low latitudes became abundant, and coarse-grained, permeable carbonate platforms became important in the geologic record. The MVT deposits reached their maximum abundance during the final assembly of Pangea, from Devonian into the Carboniferous, and in Cretaceous-Tertiary during the onset of the assembly of Amasia (Leach et al., 2001). Mixing of multiple brines may have played a key role in MVT ore deposition (Anderson, 2008; Murphy et al., 2008; Shelton et al., 2009); topographically driven fluid flow was likely common (Pannalal et al., 2008). Leach et al. (2010) note how the extensive global recycling of sedimentary rock systems has led to a very censored distribution of Proterozoic and Phanerozoic Pb-Zn ores, with passive margins defining regions with the only significantly preserved parts of original base metal endowments. Whereas most of the preserved Pb-Zn ores are found in low metamorphic grade rocks, the poorly understood Broken Hill-type ores probably represent clastic-dominated deposits that are relatively anomalous due to high-grade of metamorphism (e.g., Groves et al., 2008).

Development of redox boundaries after the GOE event also imposes a major control on the development of stratiform sedimentary Cu deposits. Hitzman et al. (2010) note that the giants among these copper systems, such as the Neoproterozoic deposits of south-central Africa and the Permian deposits of northern Europe, developed in association with failed rifts and intracratonic basins during episodes of supercontinent breakup. Oxidized basin brines led to formation of areal extensive copper belts over periods of many tens of millions to hundreds of millions of years at redox boundaries within the evolving basins. The copper in the ores has been suggested, in some cases, to reflect progressive diagenetic alteration of the footwall aquifers by the brines (Brown, 2009). Hitzman et al. (2010) suggest that increased magnesium and sulfate concentrations in the world oceans during periods of widespread glaciation may have led to more abundant S-rich brines and thus enhanced periods of copper deposition.

*Deposits with magmatic controls*

Naldrett (2010) favors formation of magmatic Ni-Cu and PGE deposits at any time during Earth history when mafic or ultramafic magmas typically interact with sulfide-rich crust (or, in rare cases, the S may be mantle-derived; e.g., Seat et al., 2009). The contaminated magmas become saturated in sulfide and immiscible sulfide liquid segregates from the melts. However, the type of deposit and ore metals vary over time. The Ni-Cu sulfide deposits associated with komatiites range in age from ca. 2.7 to 1.9 Ga. A concentration of important examples at 2.7 Ga in the Yilgarn craton and at 1.9 Ga in the Superior province suggests plume associations, although it remains controversial as to whether many of the ore-hosting komatiites are extrusive or intrusive (e.g., Houlé et al., 2008). These mantle magmas are associated with the hotter early Earth and, although some older examples of this magmatism exist between 3.5 and 3.0 Ga, a lack of interaction with felsic crust may have hindered Ni-Cu ore deposit formation. Other Ni-Cu sulfide deposits are associated with younger ca. 1.1 to 0.25 subvolcanic mafic intrusions related to flood basalt events and rifting. Interaction of PGE-enriched magmas with evaporite-bearing country rocks at shallow levels has been suggested to explain the Ni-Cu-PGE association on some subvolcanic bodies (Li et al., 2009). The reason for restriction of anorthosite-related ores to the Proterozoic is uncertain, although Kerrich et al. (2005) suggest plume impingement on Rodinia, and the Sudbury ores (Ames et al., 2008) represent a unique impact event in Earth history. The important PGE-rich deposits (i.e., Bushveld, Great Dyke, Stillwater) are Late Archean to Paleoproterozoic in age, with the important and unusual PGE-bearing early komatiitic magmas in these systems also perhaps are products of a hotter mantle on early Earth (Naldrett, 2010).

An understanding of the secular history of the iron oxide Cu-Au (IOCG) group of deposits depends on classification of what appears to be a poorly defined deposit type in the literature. As explained by Groves et al. (2010), many Fe- and Cu-dominant skarns, carbonatite-hosted ores, and iron oxide deposits are consistently misclassified as IOCG deposits. They define IOCGs more restrictively as very large Precambrian Cu, Au, LREE, Fe, and sometimes U enriched, structurally controlled deposits, with giant breccia systems, silica destructive and broad sodic or sodic-calcic alteration haloes, and temporal associations with alkaline to subalkaline basic to ultrabasic mantle magmas. Such deposits are localized in intracratonic settings, typically 100 to 200 km inland from the craton margins, where Kerrich et al. (2005) describe anomalous extension and anorogenic magmatism between areas of Archean and Proterozoic subcontinental lithospheric mantle. The partial melting of metasomatized subcontinental lithospheric mantle margins to the cratons, either by mantle underplating or plume episodes, is argued by Groves et al. (2010) to produce the volatile-rich mantle derived magmas that mix with more felsic crustal melts, and subsequently are responsible for a lengthy and complex fluid exsolution history. Because these deposits develop in buoyant and refractory Paleoproterozoic and older cratonic regions, even shallowly formed IOCG deposits, such as Olympic Dam, have been preserved since the Precambrian.

Diamond deposits are similarly related to intracratonic extensional zones and alkaline magmatism in Archean cratonic areas. Gurney et al. (2010) indicate that metasomatism of the subcontinental lithospheric mantle below the Siberian, Slave, and Kaapvaal cratons as far back as the Early and Middle Archean was responsible for formation of macrodiamonds in preexisting harzburgite, lherzolite, websterite, and eclogite, and such terrestrial diamonds formed at depth throughout Earth history. Nevertheless, all known and important kimberlite and lamproitic dikes, which define the volatile-rich asthenospheric magmas that have stripped the diamonds from the base of the subcontinental lithospheric mantle and transported them to the surface, are Mesoproterozoic or younger, with most being Mesozoic-Cenozoic in age; Paleoproterozoic and older macrodiamonds are mainly present as paleoplacers. Older kimberlite dikes are suggested to be unrecognized because of either their small volume, burial by widespread cover rocks, and/or erosion of these volcanic pipes. Gurney et al. (2010) suggest that supercontinent break-up and also changes in far-field plate stresses are the ultimate controls on episodic kimberlite magmatism.

### *Paleoclimatic impact*

Intense tropical chemical weathering to form Fe ores as laterites, some also enriched with other trace metals such as Ni and Au, and Al ores as bauxites, is controlled by paleoclimate. Temporal patterns show widespread and intense events controlling most ore formation. Retallack's (2010) synthesis suggests eight very significant periods of bauxite and laterite formation during the past 100 m.y. of Earth history, with each episode lasting <100,000 years. Global warming and greenhouse gas outbursts that correlate with the laterization and bauxitization may result from meteorite impact or continental flood basalt events. Similar events older than the mid-Cretaceous are likely back through geologic time, but are much more difficult to assess.

## Acknowledgments

This special issue of *Economic Geology* would not have been possible without the timely and thorough manuscript reviews by Bill Cannon, Larry Cathles, Sarah Gleeson, Wayne Goodfellow, Jens Gutzmer, Mark Hannington, Murray Hitzman, Heinrich Holland, Charles Jefferson, Craig Johnson, Karen Kelley, Rob Kerrich, Duncan Large, Chusi Li, Peter Lightfoot, Barry Maynard, Tom McCandless, Tom Nash, Steve Piercey, Charlotte Schreiber, Thomas Statchel, and Tim White. The guest editors would also like to thank many of the authors for their extreme patience with the always difficult logistics of getting a series of interrelated papers published simultaneously in a single special volume.

## REFERENCES

Alexandre, P., Kyser, K., and Jiricka, D., 2009, Critical geochemical and mineralogical factors for the formation of unconformity-related uranium deposits: Comparison between barren and mineralized systems in the Athabasca basin, Canada: ECONOMIC GEOLOGY, v. 104, p. 413–435.

Ames, D.E., Davidson, A., and Wodicka, N., 2008, Geology of the giant Sudbury polymetallic mining camp, Ontario, Canada: ECONOMIC GEOLOGY, v. 103, p. 1057–1077.

Anderson, G.M., 2008, The mixing hypothesis and the origin of Mississippi Valley-type ore deposits: ECONOMIC GEOLOGY, v. 103, p. 1683–1690.

Anhaeusser, C.R., 1981, The relation of mineral deposits to early crustal evolution: ECONOMIC GEOLOGY 75TH ANNIVERSARY VOLUME, p. 42–62.

Barley, M.E., and Groves, D.I., 1992, Supercontinent cycles and the distribution of metal deposits through time: Geology, v. 20, p. 291–294.

Barley, M.E., Pickard, A.I., and Sylvester, P.J., 1997, Emplacement of a large igneous province as a possible cause of banded iron formation 2.45 billion years ago: Nature, v. 385, p. 55–58.

Barley, M.E., Groves, D.I., Krapez, B., and Kerrich, R., 1998, The Late Archean bonanza: Metallogenic and environmental consequences, the interaction of mantle plumes, lithospheric tectonics and global cyclicity: Precambrian Research, v. 91, p. 65–90.

Bekker, A., Slack, J.F., Planavsky, N., Krapež, B., Hofmann, A., Konhauser, K.O., and Rouxel, O.J., 2010, Iron formation: The sedimentary product of a complex interplay among mantle, tectonic, oceanic, and biospheric processes: ECONOMIC GEOLOGY, v. 105, p. 467–508.

Blundell, D.J., 2002, The timing and location of major ore deposits in an evolving orogen: the geodynamic context: Geological Society of London Special Publication 204, p. 1–12.

Brown, A.C., 2009, A process-based approach to estimating the copper derived from red beds in the sediment-hosted stratiform copper deposit model: ECONOMIC GEOLOGY, v. 104, p. 857–868.

Cloutier, J., Kyser, K., Olivo, G.R., Alexandre, P., and Halaburda, J., 2009, The Millennium uranium deposit, Athabasca basin, Saskatchewan, Canada: An atypical basement-hosted unconformity-related uranium deposit: ECONOMIC GEOLOGY, v. 104, p. 815–840.

Condie, K.C., 2005, Earth as an evolving planetary system: Amsterdam, Elsevier, 447 p.

Cooke, D.R., Hollings, P., and Walshe, J.L., 2005, Giant porphyry deposits: Characteristics, distribution, and tectonic controls: ECONOMIC GEOLOGY, v. 100, p. 801–818.

Cuney, M., 2010, Evolution of uranium fractionation processes through time: Driving the secular variation of uranium deposit types: ECONOMIC GEOLOGY, v. 105, p. 553–569.

de Wit, M.J., and Thiart, C., 2005, Metallogenic fingerprints of Archean cratons: Geological Society London Special Publication 248, p. 59–70.

Farquhar, J., Wu, N-P., Canfield, D.E., and Oduro, H., 2010, Connections between sulfur cycle evolution, sulfur isotopes, sediments, and base metal sulfide deposits: ECONOMIC GEOLOGY, v. 105, p. 509–533.

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

Goldfarb, R.J., Groves, D.I., Kerrich, R., and Leach, D.L., 2009, Metallogenic evolution on an evolving Earth: Proceedings of the Tenth Bienniel SGA Meeting, Townsville, Australia: p. 11–13.

Groves, D.I., Condie, K.C., Goldfarb, R.J., Hronsky, J.M.A., and Vielreicher, R.M., 2005a, Secular changes in global tectonic processes and their influence on the temporal distribution of gold-bearing mineral deposits: ECONOMIC GEOLOGY, v. 100, p. 203–224.

Groves, D.I., Vielreicher, R.M., Goldfarb, R.J., and Condie, K.C., 2005b, Controls on the heterogeneous distribution of mineral deposits through time: Geological Society of London Special Publication 248, p. 71–101.

Groves, I.M., Groves, D.I., Bierlein, F.P., Broome, J., and Penhall , J., 2008, Recognition of the hydrothermal feeder to the structurally inverted, giant Broken Hill deposit, New South Wales, Australia: ECONOMIC GEOLOGY, v. 103, p. 1389–1394.

Groves, D.I., Bierlein, F.P., Meinert, L.D., and 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, v. 105, p. 641–654.

Gurney, J.J., Helmstaedt, H.H., Richardson, S.H., and Shirey, S.B., 2010, Diamonds through time: ECONOMIC GEOLOGY, v. 105, p. 689–712.

Harris, A.C. White, N.C., McPhie, J., Bull, S.W., Line, M.A., Skrzeczynski, R., Mernagh, T.P., and Tosdal, R.M., 2009, Early Archean hot springs above epithermal veins, North Pole, Western Australia: New insights from fluid inclusion microanalysis: ECONOMIC GEOLOGY, v. 104, p. 793–814.

Hitzman, M.W., Selley, D., and Bull, S., 2010, Formation of sedimentary rock-hosted stratiform copper deposits through Earth history: ECONOMIC GEOLOGY, v. 105, p. 627–639.

Houlé, M.G., Gibson, H.L., Lesher, C.M., Davis, P.C., Cas, R.A.F., Beresford, S.W., and Arndt, N.T., 2008, Komatiitic sills and multigenerational peperite at Dundonald Beach, Abitibi greenstone belt, Ontario: Volcanic architecture and nickel sulfide distribution: ECONOMIC GEOLOGY, v. 103, p. 1269–1284.

Huston, D.L., Pehrsson, S., Eglington, B.M., and Zaw, K., 2010, The geology and metallogeny of volcanic-hosted massive sulfide deposits: Variations through geologic time and with tectonic setting: ECONOMIC GEOLOGY, v. 105, p. 571–591.

Hutchinson, R.W., 1980, Massive base metal sulphide deposits as guides to tectonic evolution: Geological Association of Canada Special Paper 20, p. 659–684.

——1992, Mineral deposits and metallogeny: Indicators of Earth's evolution, *in* Schidlowski, M. et al., eds., Early organic evolution: Implications for mineral and energy resources: Berlin, Springer-Verlag, p. 521–545.

——1993, Some broad processes and affects of evolutionary metallogeny: Resource Geology, Special Issue 15, p. 45–54.

Kerrich, R., Goldfarb, R.J., and Richards, J., 2005, Metallogenic provinces in an evolving geodynamic framework: ECONOMIC GEOLOGY 100TH ANNIVERSARY VOLUME, p. 1097–1136.

Kerrich, R., Goldfarb, R., Cline, J., and Leach, D., 2008, Metallogenic provinces of North America in a superplume-supercontinent framework: Arizona Geological Society Digest 22, p. 55–72.

Kesler, S.E., and Wilkinson, B.H., 2009, Resources of gold in Phanerozoic epithermal deposits: ECONOMIC GEOLOGY, v. 104, p. 623–633.

Khashgerel, B-E., Rye, R.O., Kavalieris, I., and Hayashi, K-I. 2009, The sericitic to advanced argillic transition: Stable isotope and mineralogical characteristics from the Hugo Dummett porphyry Cu-Au deposit, Oyu Tolgoi district, Mongolia: ECONOMIC GEOLOGY, v. 104, p. 1087–1110.

Lambert, I.B., and Groves, D.I., 1981, Early earth evolution and metallogeny, *in* Wolf, K. H., ed., Handbook of stratabound and stratiform ore deposits: Amsterdam, Elsevier, v. 8, p. 339–447.

Laznicka, P., 1973, Development of nonferrous metal deposits in geological time: Canadian Journal of Earth Sciences, v. 10, p. 18–25.

Leach, D.L., Bradley, D., Lewchuk, M.T., Symons, D.T.A., de Marsily, G., and Brannon, J., 2001, Mississippi Valley-type lead-zinc deposits through geological time: Implications from recent age-dating research: Mineralium Deposita, v. 36, p. 711–740.

Leach, D.L., Bradley, D.C., Huston, D., Pisarevsky, S.A., Taylor, R.D., and Gardoll, S.J., 2010, Sediment-hosted lead-zinc deposits in Earth history: ECONOMIC GEOLOGY, v. 105, p. 593–625.

Li, C., Ripley, E.M., and Naldrett, A.J., 2009, A new genetic model for the giant Ni-Cu-PGE sulfide deposits associated with the Siberian flood basalts: ECONOMIC GEOLOGY, v. 104, p. 291–301.

Lindgren, W., 1909, Metallogenetic epochs: ECONOMIC GEOLOGY, v. 4, p. 409–420.

Ling, M-X., Wang, F-Y., Ding, X., Hu, Y-H., Zhou, J-B., Zartman, R.E., Yang, X-Y., and Sun, W-D., 2009, Cretaceous ridge subduction along the lower Yangtze River belt, eastern China: ECONOMIC GEOLOGY, v. 104, p. 303–321.

Maynard, J.B., 2010, The chemistry of manganese ores through time: A signal of increasing diversity of Earth-surface environments: ECONOMIC GEOLOGY, v. 105, p. 535–552.

Meyer, C., 1981, Ore-forming processes in geologic history: ECONOMIC GEOLOGY 75TH ANNIVERSARY VOLUME, p. 6–41.

——1988, Ore deposits as guides to geological history of the Earth: Annual Review of Earth and Planetary Sciences, v. 16, p. 147–172.

Mitchell, A.H.G., and Garson, M.S., 1981, Mineral deposits and global tectonic settings: New York, Academic Press, 410 p.

Murphy, F.C., Ord, A., Hobbs, B.E., Willetts, G., and Barnicoat, A.C., 2008, Targeting stratiform Zn-Pb-Ag massive sulfide deposits in Ireland through numerical modeling of coupled deformation, thermal transport, and fluid flow: ECONOMIC GEOLOGY, v. 103, p. 1437–1458.

Naldrett, A.J., 2010, Secular variation of magmatic sulfide deposits and their source magmas: ECONOMIC GEOLOGY, v. 105, p. 669–688.

Pannalal, S.J., Symons, D.T.A., and Sangster, D.F., 2008, Paleomagnetic evidence for an Early Permian age of the Lisheen Zn-Pb deposit, Ireland: ECONOMIC GEOLOGY, v. 103, p. 1641–1655.

Pereira, J., and Dixon, C.J., 1965, Evolutionary trends in ore deposition: Institute of Mining Metallurgy Transactions, v. 74, p. 505–527.

Piercey, S.J., Chaloux, E.C., Péloquin, S.A., Hamilton, M.A., and Creaser, R.A., 2008a, Synvolcanic and younger plutonic rocks from the Blake River Group: Implications for regional metallogenesis: ECONOMIC GEOLOGY, v. 103, p. 1243–1268.

Piercey, S.J., Peter, J.M., Mortensen, J.K., Paradis, S., Murphy, D.C., and Tucker, T.L., 2008b, Petrology and U-Pb geochronology of footwall porphyritic rhyolites from the Wolverine volcanogenic massive sulfide deposit, Yukon, Canada: Implications for the genesis of massive sulfide deposits in continental margin environments: ECONOMIC GEOLOGY, v. 103, p. 5–33.

Retallack, G.J., 2010, Laterization and bauxitization events: ECONOMIC GEOLOGY, v. 105, p. 655–667.

Rona, P., 1980, Global plate motion and mineral resources, *in* Strangway, D.W., ed., The continental crust and its mineral deposits: The Geological Association of Canada, Special Paper 20, p. 607–622.

Rundqvist, D.V., 1968, Accumulation of metals and the evolution of the genetic types of deposits in the history of the earth: Proceedings of the 23rd International Geological Congress, Prague, v. 7, p. 85–97.

Sawkins, F.J., 1984, Metal Deposits in Relation to Plate Tectonics: Berlin, Springer-Verlag, Berlin, 325 p.

Seat, Z., Beresford, S.W., Grguric, B.A., Gee, M.A., and Grassineau, N.V., 2009, Reevaluation of the role of external sulfur addition in the genesis of Ni-Cu-PGE Deposits: Evidence from the Nebo-Babel Ni-Cu-PGE deposit, West Musgrave, Western Australia: ECONOMIC GEOLOGY, v. 104, p. 521–538.

Shelton, K.L., Gregg, J.M., and Johnson, A.W., 2009, Replacement dolomites and ore sulfides as recorders of multiple fluids and fluid sources in the southeast Missouri Mississippi Valley-type district: Halogen-$^{87}Sr/^{86}Sr$-$^{18}O$-$^{34}S$ systematics in the Bonneterre Dolomite: ECONOMIC GEOLOGY, v. 104, p. 733–748.

Slack, J.F., and Cannon, W.F., 2009, Extraterrestrial demise of banded iron formations 1.85 billion years ago: Geology, v. 37, p. 1011–1014.

Su, W-C., Heinrich, C.A., Pettke, T., Zhang, X-C., Hu, R-Z., and Xia, B., 2009, Sediment-hosted gold deposits in Guizhou, China: Products of wall-rock sulfidation by deep crustal fluids: ECONOMIC GEOLOGY, v. 104, p. 73–93.

Titley, S.R., 1993, Relationship of stratabound ores with tectonic cycles of the Phanerozoic and Proterozoic: Precambrian Research, v. 61, p. 295–322.

Tomkins, A.G., and Grundy, C., 2009, Upper temperature limits of orogenic gold deposit formation: Constraints from the granulite-hosted Griffin's Find deposit, Yilgarn craton: ECONOMIC GEOLOGY, v. 104, p. 669–685.

Turneaure, F.S., 1955, Metallogenic provinces and epochs: ECONOMIC GEOLOGY 50TH ANNIVERSARY VOLUME, p. 38–98.

Veizer, J., Laznicka, P., and Jansen, S.L., 1989, Mineralization through geologic time: recycling perspective: American Journal of Science, v. 289, p. 484–524.

Watson, J.V., 1978, Ore-deposition through geological time: Proceedings of the Royal Society London, v. 362, p. 305–328.

Wilkinson, B.H., and Kesler, S.E., 2009, Quantitative identification of metallogenic epochs and provinces: Application to Phanerozoic porphyry copper deposits: ECONOMIC GEOLOGY, v. 104, p. 607–622.