Mineral Deposits and Earth Evolution

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Mineral Deposits and Earth Evolution

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Contents

Preface

Mineral deposits are the source of all the metals, industrial and bulk minerals that feed the global economy. In addition to being key primary sources of wealth generation, mineral deposits are also valuable windows through which to view the evolution and interrelationships of the Earth system. Unlike hydrocarbon deposits that are largely restricted to more recent phases of geological time, mineral deposits have formed throughout the last 3.8 billion years of the Earth's history. As such they preserve key evidence for early magmatic and tectonic processes, the state of the atmosphere and hydrosphere, and the evolution of life. Furthermore, the very activities of exploration, evaluation and mining of mineral deposits, generate more comprehensive 3D geological information than is generally obtainable in unmineralized rocks, and increasing amounts of this formerly proprietary data are being released into the public domain.

The greatly enhanced concentrations of metals and minerals found in mineral deposits, over normal rocks, are a result of transport, concentration and deposition at these keys sites by common Earth processes. Either these processes operated at greater rates (or greater efficiencies) than normal, or there were fortuitous combinations of processes acting in the right place and at the right time to bring about the formation of the deposit. This revolution from documenting mainly the descriptive aspects of mineral deposits (in order to recognize the next one better) to trying to understand processes and derive genetic models for how the mineralization formed has gathered pace dramatically over the last 30 years. This revolution has been picked up and driven by the most perceptive Earth scientists who have recognized the potential for using evidence preserved in mineral deposits to probe more fundamental questions about Earth history and the evolution of the Earth system with time.

This volume contains papers presented at the Geological Society's Fermor Flagship Meeting, entitled *World Class Mineral Deposits and Earth Evolution*, held at Cardiff University and the National Museum and Gallery of Wales from 18–21 August 2003. The aim of the 2003 Fermor Meeting was to bring together geologists from academia and industry to highlight the importance of mineral deposits in their own right and in understanding the many and varied links between mineral deposits and Earth system science.

The first two chapters deal with perhaps the longest-running and most fundamental process on the Earth, namely the accretion of extraterrestrial material to form our planet that has continued from the Hadaean to the present day. What is less well known is that many of the 150 or so impact craters that have been recognized thus far contain valuable mineral or hydrocarbon resources. The opening paper by **Grieve** reviews the key aspects of the impact process and crater formation, and how the formation of impact breccias and impact melts can lead to the development of mineral deposits and trap sites for migrating hydrocarbons. The value of the resources that are extracted is truly astonishing; US$18 billion annually, from North American impact structures alone! This is followed by a study of gold mineralization in the Witwatersrand Basin of South Africa by **Hayward *et al.*** Debate has raged recently over whether the enormous amounts of gold in the basin are of placer or hydrothermal origin. The giant Vredefort impact crater formed in the centre of the Witwatersrand Basin and heat generated by the impact almost certainly affected the gold-bearing rocks. **Hayward *et al.*** present mineralogical evidence to suggest that the gold, although modified, was primarily of placer origin. The impact event only produced a short-lived phase of brittle deformation and small-scale remobilization of gold.

The next group of papers covers the role of mineral deposits in constraining models of tectonic evolution on different scales. **De Wit & Thiart** present a statistical analysis of the metal distributions in the Archaean cratons and post-Archaean rocks of the former continent of Gondwanaland. Their analysis reveals that not only are Archaean cratons more richly endowed in metals than younger rocks (i.e. mineral diversity has apparently decreased with time), but that each Archaean craton also carries its own distinctive metal signature. These metal signatures appear to have been inherited close to the time that the craton separated from the mantle and reflect mantle heterogeneity as well as the tectonic and magmatic processes involved in craton formation. The reasons why the distributions of mineral deposits vary with time are examined in greater depth by **Groves *et al.*** They conclude that the temporal distribution of each mineral-deposit type is a function of formation and preservational processes. The most fundamental geodynamic control is exerted by the change from the formation of positively buoyant lithospheric mantle in the Archaean and Proterozoic to negatively buoyant lithospheric mantle in the Phanerozoic. Redox-sensitive sedimentary mineral deposits are most strongly affected by long-term oxidation by the atmosphere–hydrosphere–biosphere system.

Harcouët *et al.* place constraints on the evolution of temperature during the Eburnean orogeny in the Ashanti Belt of Ghana using finite-element thermal modelling. In order to satisfy the observed thermobarometric regime, they conclude that an anomalously high mantle heat flow (at least three times the present value) must have been in operation. Such a thermal anomaly may explain the widespread development of gold mineralization in the Ashanti Belt. This theme is expanded by **Leahy *et al.*** who evaluate the distribution of giant gold deposits using a plate-tectonic framework. They propose a new six-fold geodynamic classification system for gold deposits that emphasizes subduction and crustal accretion zones. **Leahy *et al.*** conclude that the distribution of giant gold deposits is controlled by fluid access to regional gold sources and is ultimately a function of the amount of oceanic crust (the principal source for gold) that is consumed during successive orogenic episodes.

The idea that the deep-seated source rocks (often lower crustal rocks) determine the metal composition and sulphur-isotopic ratio of mineral deposits is explored further by **Lowry *et al.***, who consider the potential for terrane discrimination using mineral deposits. They describe significant differences in the sulphur isotope signatures and metal contents of mineral deposits from different terranes making up Northern Britain, and show that these differences are most probably related to the major basement blocks that were amalgamated during the Caledonian orogeny. The most exciting use of this approach comes when mineralization styles for the British terranes are compared with mineral deposits of similar age, and comparable terranes, in Eastern Canada, as similar patterns are evident. This compositional inheritance suggests that mineral deposit signatures can constrain models of terrane accretion, even where the orogenic zone has been rifted apart in more recent times.

The Uralide orogenic belt is one of the world's great metallogenic provinces and contains mineral deposits associated with pre-, syn-, and post-collisional events during formation of the orogen. **Herrington *et al.*** present an analysis of the Uralide tectonic framework, using different classes of mineral deposit, to constrain the formational settings of the different tectonic blocks. The recognition of major north–south trending strike–slip faults and thrusts suggests that instead of multiple collided magmatic arcs there may only be two arcs, separated by the continental sliver of the East Mugodzhar Precambrian massif, and accretionary wedges of the Transuralian zone. **Herrington *et al.*** suggest that newly recognized strike–slip faults can be traced from the Polar Urals to the Tien Shan for more than 4000 km, approximately along the collision zone between the two arc systems. These studies illustrate that apparently parochial studies of mineral deposits can stimulate fundamental questions about regional tectonic settings and can lead to conclusions of much wider significance.

Sediment-hosted mineral deposits occupy a special niche in studies of the Earth System because, if they are truly syndepositional, they may preserve direct evidence for the state of the atmosphere and hydrosphere at the time the deposit formed. One of the most exciting recent discoveries in the Archaean rock record is the presence of mass-independent sulphur-isotope fractionations in volcanogenic massive sulphide deposits and banded iron formations. **Farquhar & Wing** review the evidence for these isotope fractionations. They describe the extent of the effect in the Archaean rock record, compared to younger rocks, and conclude that the fractionation may have occurred via ultraviolet photolysis of sulphur dioxide in the atmosphere and transfer of elemental sulphur to the Earth's surface. If this is correct, the implications of this discovery for the Earth's early atmosphere are profound; the Earth's early atmosphere would have lacked a UV shield (like the modern ozone layer) and possessed very low concentrations of free oxygen.

Iron deposits are particularly important indicators of redox conditions in seawater and sedimentary porewaters. Modern and ancient euxinic sediments are often enriched in iron that is highly reactive with dissolved sulphide, compared to continental margin and deep-sea sediments. **Raiswell & Anderson** outline a model where this iron enrichment arises from mobilization of dissolved iron from anoxic pore waters into overlying seawater, followed by transport into deep-basin environments and precipitation as iron sulphides in sediments. The addition of reactive iron to deep-basin sediments is determined by the magnitude of the diffusive iron flux, the export efficiency of recycled iron from the shelf, the ratio of source area to basin sink area and the extent to which reactive iron is trapped in the deep basin.

The discovery of life around modern deep-sea hydrothermal vents has led to the suggestion that ancient VMS and SEDEX deposits may also contain the fossils of organisms living on the vents when they were active, and that such environments may have been the warm oases where life on Earth first developed. Biological activity produces recognizable shifts in carbon and sulphur isotopes that may leave a fingerprint of ancient life in the early rock record. **Grassineau *et al.*** carried out a stable isotope study of cherts, iron formations and massive sulphides and unmineralized rocks in the 3.8 Ga Isua greenstone belt (Greenland) and the 2.7 Ga Belingwe greenstone belt (Zimbabwe). Their data suggest that recognizable isotope signatures of biological origin exist in both greenstone belts. They attempted to estimate the degree of change in biological activity over the billion years that separates the two settings. **Grassineau *et al.*** suggest that early life at Isua was most likely present in transitory, short-lived, settings whereas a billion years later at Belingwe, the biological carbon and sulphur cycles were in full operation, with the development of well-established algal mat communities.

The normal processes of erosion, transport, sorting and grading of sediment can also lead to some spectacular mineral deposits, none more so than the giant diamond (mega) placers of the SW African coast. The paper by **Bluck *et al.*** provides the first comprehensive synthesis of the tectonic and sedimentary factors that lead to the formation of the Orange River and Namaqualand mega-placers. Their study indicates that formation of a diamond mega-placer requires the interaction of several key factors that may extend back over large periods of geological time. These are: first, an adjacent craton hosting diamondiferous kimberlites and secondary alluvial deposits that may be remobilized; second, a drainage system that encompasses as much of the craton as possible and that focuses the supply of diamonds to a limited point; and third, a high energy regime at the terminal placer site that removes the fine grained sediment accompanying the diamonds. **Bluck *et al.*** describe how the tectonic and geomorphological evolution of southern Africa led to this fortunate combination of events and ultimately the formation of some of the most valuable diamond deposits ever discovered.

Over the last 40 years, many innovative analytical techniques have been developed by mineral deposits researchers. Increasingly sophisticated and micro-analytical techniques are being applied to hydrothermal mineral deposits to obtain direct information about the compositions and P/T conditions of the mineralizing fluids. The final paper by **Heinrich *et al.*** describes how the direct analysis of metals in individual fluid and melt inclusions from minerals in porphyry Cu–Au–Mo deposits is now achievable using laser ablation ICP mass spectrometry. Their study shows that a feature such as the economically important ratio of Au to Cu is inherited from the magmatic source and that bulk grade of different porphyry deposits is optimized when a large influx of magmatic fluids are cooled through 420–320 °C over a restricted flow volume.

As stated at the outset, the economic value of mineral deposits is self-evident. What this volume illustrates is that there is an accompanying body of research that is aimed at understanding long-term Earth processes and that mineral deposits are unique and vital probes into the functioning of the Earth system. Mineral deposit studies contribute to a much wider range of fundamental, and regional, research questions than may appear obvious at first. The range of contributions in this volume illustrates this link clearly. For most 'economic' geologists it has been self-evident that mineral deposits can contribute intellectual as well as monetary wealth to society. However, many within the wider geological community, and funding organizations, are less aware of this than they should be. Mineral deposits and the interlinking processes that formed them have always been at the centre of Earth system science and the more people with different backgrounds and ideas that work on them, the greater their contribution can be. We hope that this volume will inspire more novel research on these wonders of nature.

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