Mineral Systems and Processes in New South Wales: a project to enhance understanding and assist exploration

ABSTRACT
This paper outlines a scheme to identify the mineral systems of New South Wales and the processes that produce mineral deposits. Mineral deposit and mineral system studies have been carried out by the Geological Survey of New South Wales since its inception in 1875. These studies continue to be a major focus of its ongoing work program. The current study is called the Mineral Systems and Processes project. Its aim is to identify the state’s mineral resources and improve exploration success. In addition, it provides both a platform for discussion with explorers and a mechanism to review and to improve the interpretation of the available data.

By 2010 DPI Minerals is committed to identify, outline and advise the Department of Lands of areas within New South Wales with significant mineral potential. The areas identified will be used in a project to review land zoning in all local government areas in the state. While carrying out this work the geoscientists involved will need to review information relating to individual mineral occurrences and ‘mineral districts’. The aim is to identify occurrences that formed as part of the same mineralising event and/or as part of the same mineral system.

The Minerals project team has created a preliminary mineral system classification scheme for use in New South Wales, which is presented and described here to assist exploration. The mineral classes used to describe deposit types are well known and have been described in numerous papers. As an ongoing evaluation, data gaps will be identified and that information will be used to target areas for future data acquisition, research (e.g. isotopic and age dating studies) and to further enhance the New South Wales classification system.

This project will add a new dimension to the existing MetIndEx (metallic, industrial and exploration) mineral occurrence database by providing additional details on the age, style and extent of individual mineral systems. This will give explorers and those making land-use decisions a better picture of major mineralising events and those mineral deposit types that may occur within individual terranes.

KEYWORDS: Mineral systems, classification, mineral deposits, New South Wales

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Editorial Note
The aim of this paper is to outline a new approach to the classification of mineral deposits and processes applicable in New South Wales. It has been developed by the DPI Mineral System (MinSys) project team to help identify mineralising events and the processes involved in these events. The aim of the project is to use the MetIndEx database and other databases to improve our understanding of metallogenesis of New South Wales.

In developing this classification scheme, the project team studied numerous earlier classification schemes and selectively incorporated concepts and ideas into the current proposal.

The project team is aware that a new classification scheme is likely to create vigorous discussion. For this reason, informed comment on the classification scheme is invited. This can be forwarded to peter.downes@dpi.nsw.gov.au
INTRODUCTION

Exploration involves an element of risk. The odds of exploration success are improved when explorers have an understanding of the mineral systems present in a region. In turn this improves the process of deposit modelling and targeting. A mineral systems study is being undertaken by the Geological Survey of New South Wales to provide a framework that extends the current collection of data on individual mineral occurrences to encompass the concept of mineral systems. It is an attempt to identify mineralising events and to identify the processes involved in such events. Studies into mineral systems and processes have been increasing in importance over the past few years (e.g. Wyborn et al. 1994; Cooke et al. 2000; Cooke & Simmons 2000). The elements of a mineral system and those parts used to classify systems are described in this paper. Solomon and Groves (1994) noted that any attempt at a classification for mineral deposits is inevitably controversial. Hence informed comment on the present proposal and the Mineral System classification scheme (Figure 1 — pages 8 and 9) is invited.

All Australian states maintain a list of mineral occurrences and record information on the main features present, plus resources and mining history. At present no state agency has a systematic record of possible mineralising events. There are, however, many map-, region- or time-based metallogenic studies that have identified and record information on mineralising events (e.g. Stevens 1972, 1975; Markham & Basden 1975; Matson 1975a, b; Bowman 1977a, b; and Fitzpatrick 1979a, b; and Solomon & Groves 1994). We note that Geoscience Australia is conducting a study into Australian Proterozoic mineralising events.

It has long been recognised that a single mineralising event can create a number of mineral styles or classes. Identification of this event is the first priority of this study. A chart of mineral system styles has been compiled (Figure 1). It provides a basis for delineating mineralisation classes, ore-forming processes and interpreted sources. The scheme is an attempt to link local terminology to broader, more international mineral deposit type descriptions and to integrative concepts, such as the source of the metals and fluids as well as mineralising processes. The chart is not meant to cover all eventualities but will handle most mineralising events and deposits presently identified in New South Wales. The rationale behind the chart is presented below.

The New South Wales study does not involve computational modelling but, where available, those results will be incorporated into the dataset. To characterise mineral events and systems the study will compile and acquire such data as isotopic determinations, age dates, whole-rock and fluid/gas chemistry.
This mineral system and process study was initiated in response to a requirement to identify metallic mineral resources that are of state or regional significance and to plot the spatial extent of the mineralising system. In addition to its value in land-use assessments, the study provides a useful means of communicating ideas about mineralising events. The results of this project will thus benefit explorers and resource planners.

**PREVIOUS STUDIES**

Historically ore deposits have been described and classified using physical attributes such as mineralogy, commodity, ore textures, host rocks, and the geochemical signature. Such descriptive classification schemes have a long history and include those by Agricola (1556) and Cox and Singer (1986). A transition from observation-based schemes to those based on more evolved geological models occurred in the twentieth century (e.g. Lindgren 1933; Stanton 1972).

The Geological Survey of New South Wales has developed various classification schemes as part of the extensive metallogenic mapping of the state (e.g. Barnes 1988 for Broken Hill; Barnes et al. 1999 for New England). The MetIndEx database has several fields to describe mineral deposits, including local classifications and a version of Cox and Singer (1986). The information collected is valuable evidence of those deposits but has generally omitted data relating to the complete mineral system.

Park and MacDiarmid (1970) summarised the principal classification systems in use during the first half of the twentieth century. These include the Niggli (1929) classification which grouped epigenetic deposits into volcanic or near-surface and plutonic; the Schneiderhöhn (1941) classification where deposits were classified on the basis of ore fluid, mineral association and deep-seated vs near-surface; and the classic Lindgren (1933) classification. The Lindgren (1933) classification subdivided ore-forming processes into those related to mechanical processes and those related to chemical processes, with chemical processes being subdivided on the basis of the nature of the ore-forming mechanism as well as the temperature and depth of ore deposition. Park and MacDiarmid (1970) observed that while the Lindgren (1933) classification was the standard classification in the United States of America, at that time, the majority of deposits were classified by their metal content and form.

Probably the most widely accepted descriptive classification scheme used today is that by Cox and Singer (1986). The Cox and Singer (1986) review included 85 models grouped into 13 rock associations. However, many of the models were descriptive only and some models failed to separate different ore-forming processes. For example, they included orogenic gold and intrusion-related gold as low-sulfide gold systems. Furthermore, it can be noted that in some instances Cox and Singer (1986) separated ore deposit models that were formed by essentially the same process.

More recently, process-type models have been used to classify ore deposits. By identifying the ore-forming process it is possible to erect models that are both predictive and testable. These models often combine features in descriptive models with ideas and constraints from: tectonic setting; temperature of formation; chemistry and metal budget; fluid composition constraints; fluid history; and scale. Examples of process-driven models include the classic study by Lindgren (1933), as well as more recent examples, such as Stanton (1972), Solomon and Groves (1994), Groves et al. (1998) and Goldfarb et al. (2005) for orogenic Au and deformation; Cooke and Simmons (2000) on epithermal Au; and Cooke et al. (2000) describing northern Australian Proterozoic SEDEX deposits and oxidised fluids.

There can be a problem with many process-type ore deposit models in that they describe individual ore deposit types. With the notable exceptions of the comprehensive reviews by Solomon and Groves (1994) and Robb (2005), many previous reviews (e.g. Canadian ore-deposit types by Roberts & Sheahan 1988; Australian exploration models in the AGSO Journal 17(4) — Hodgson 1998) focussed on individual ore-deposit models and conditions of ore formation and fail to acknowledge that variations in the sources of magmas and/or fluids, precipitation mechanisms and/or environmental conditions will result in fundamentally different styles of mineralisation.

Solomon and Groves (1994), in their review of major Australian ore deposits, directly related fluids and geological processes to a range of ore deposit types. An example of this would be fluids derived from magma with a high oxidation potential that may result in porphyry Cu–Au mineralisation, Au in breccia pipes and/or Au, Zn and magnetite-rich skarns. This approach provides a mechanism for identifying large mineral systems.

**Photograph 1.** Ore from Northparkes porphyry Cu–Au deposit.
Just as petrologists group rocks into those formed by sedimentary, igneous and metamorphic processes, Robb (2005) suggests that ore deposits can be classified into those deposits related to igneous, sedimentary and hydrothermal processes. While this approach is not new (e.g. Stanton 1972) it provides a comprehensive framework for the development of a classification scheme that will allow for the identification of mineral systems.

**MINERAL SYSTEMS**

Wyborn et al. (1994, page 109) proposed that a mineral system could be defined as:

*all geological factors that control the generation and preservation of mineral deposits, and stress the processes that are involved in mobilising ore components from a source, transporting and accumulating them in more concentrated form and then preserving them throughout subsequent geological history.*

In the mineral system concept proposed by Wyborn et al. (1994), important geological factors for determining the characteristics of any hydrothermal system include both the sources of the mineralising fluids and ore-transporting ligands; sources of metals and other ore-forming components; the fluid migration pathway (including both recharge and discharge zones); thermal gradient; the energy source required to mobilise sufficient fluid to transport economic amounts of metal; a mechanism for focussing fluid flow at the depositional site and the physical and/or chemical depositional site properties sufficient to cause enhanced mineral precipitation at that site. Some of these features are shown in Figure 2.

In common with the ideas above, mineral occurrences as part of a mineral system are included and it is suggested that individual elements of a mineral system should be related in both time and space, have common metal and fluid sources as well as common ore transport and ore deposition mechanisms. This will result in similarities in the mineralogy, alteration style and commodities at individual deposits.

Variations in the rock chemistry and structural competency at the sites where mineral precipitation has been focussed and variations in the geological setting will result in differences between individual deposits and occurrences. The extreme complexity of many mineral systems is also recognised.

**Available datasets**

Fundamental datasets to be used in identifying individual mineral systems and mineralising events include the New South Wales mineral occurrence MetIndEx (metallic, industrial and exploration) database; existing geological maps; and geological, geophysical, geochemical, age dating and isotopic datasets.

The MetIndEx database holds significant information relating to the ore, gangue and alteration mineralogy present at many individual sites. Some of these data have the potential to provide constraints on the nature of the ore-forming fluids and potential metal-transporting mechanism. These constraints will provide insights as to the possible redox state (reduced, intermediate or oxidised) as shown by the presence or absence of minerals such as pyrrhotite, arsenopyrite, bornite, hematite and barite, and pH (acidic, near-neutral and alkaline) as shown by the presence or absence of minerals such as kaolinite, muscovite, K-feldspar, pyrite, magnetite etc., of the ore-forming fluid. For many deposits additional data is also available from a range of published and unpublished studies, including university research theses. These studies often contain information on the paragenesis of ore and gangue minerals plus alteration zonation. Fluid inclusion studies may provide data on the temperature and salinity of the ore-forming fluids, while alteration mineral geobarometry can point to the temperature of mineral formation.

The timing of mineralisation for many deposits in New South Wales is poorly constrained. This is a major challenge. Approximately 30 deposits have been directly dated. However, the timing of mineralisation for many deposits can be constrained by the age of the host unit and other geological relationships such as the degree of deformation, cross-cutting structural relationships and the relationship between the host unit and overlying units. Existing geological maps and unit descriptions can provide constraints as to the possible timing of mineralisation for some deposits, as will the degree of deformation and cross-cutting structural relationships.

Further, detailed descriptions of geological units and Geological Survey of New South Wales databases (such as the whole rock geochemical database and the petrological database) will help to identify rock packages associated with mineral systems. Additional interpretation of the available data, from diverse sources, may assist in identifying and understanding the distribution of mineral deposits. Some of the parameters include:

- the potential of the rock package as a source of metal(s) or sulfur
- the potential for there to have been a heat source to drive hydrothermal fluid circulation
- the varying potential along hydrothermal pathways to buffer metal-transporting fluids
- the possible trigger (or triggers) for mineral precipitation caused by differing reaction pathways in and near the site of deposition.
Figure 2. The mineral system concept of hydrothermal orebody formation (after Hagemann & Cassidy 2000).
For example, among others, Wyborn et al. (1994) noted that K–Na–Al silicate minerals, such as alunite, feldspars, muscovite and kaolinite, and carbonate-rich units are important pH buffers. Carbonate-rich units can react with acidic fluids (with resultant destabilisation of the metal-transport fluid) and can host skarn-type mineralisation. In addition, redox fronts such as those between black shales and hematitic sedimentary rocks can cause metal deposition (e.g. red bed copper). Identification of evaporate minerals in rock packages is important as they can generate high-salinity fluids with the capacity to carry a high base metal load (e.g. Mississippi Valley-type deposits).

Additional constraints on the sources of metals and the nature of the ore-forming fluids can be provided by isotopic data. Systematic studies into the lead isotope composition of individual deposits have been ongoing for the last 20 years through a collaborative project between the CSIRO Division of Exploration and Mining and the Geological Survey of New South Wales. This collaborative project resulted in the seminal paper by Carr et al. (1995). That paper outlined the lead isotope systematics for much of the Lachlan Orogen and provides insights into the sources of metals and possible timing of mineralisation for many deposits. Other stable isotope data, such as sulfur isotope data, will provide further information on the potential sources of sulfur and metals involved in individual deposits.

**Building the model**

Selection and integration of data to identify individual mineral systems will be the major challenge for this project. Building individual data models will involve the identification of possible sources of metals, ore transportation mechanisms, the assessment of potential modifiers to the metal transporting fluids (host rock package and resultant rock buffers) and the identification of temperature, chemical, physical and timing constraints to mineralisation. Some of the important elements to be considered in building the model are the:

- metal source
- transport mechanism
- source of sulfur
- nature of fluid/intrusion — oxidised vs reduced; acidic vs neutral vs alkali
- temperature gradient
- mode/mechanism of precipitation (including fluid mixing, boiling, cooling, sulfidation reactions, pH change)
- heat sources including both magmatic and/or deformation related
- tectonic setting e.g. compression vs extension
- possible timing of mineralisation
- preservation.

In our system the model for each mineral system is characterised by four items:

1) mineralisation source
2) a descriptive term for the dominant processes or ‘association’
3) fluid/magma/chemical or physical features
4) deposit type.

The first three items identify the source and possible transport parameters for a mineralising event. The final item encompasses the trap and its outflow features.

**PROPOSED FRAMEWORK**

The Mineral Systems and Processes classification scheme is summarised as Figure 1. An explanation of the columns is provided below. The column headings marked # in the discussion below relate to systems and processes and are universally applicable. The list of deposit types is not complete for Australia. However, care has been taken to ensure that it does include those present in New South Wales.

**Mineralisation source #**

The dominant source(s) of the medium transporting/concentrating ore. Relates to magmatic processes, fluid sources and other processes.

**Association #**

A generic term providing a description of the process and mineral classes related to that system.

**Fluid and/or magma type #**

Description of important features of the fluid, magma and/or process involved. The fluids are variants of a restricted number of ‘common’ types that are amended by factors such as fluid/wall rock interactions.

**Deposit type #**

A list of deposit types present in each association. Note that some deposit types may appear in more than one association.

**Examples #**

Examples of deposits from New South Wales have been assigned to a major type. Where there is no appropriate New South Wales example an interstate example has been chosen.
ORE DEPOSIT MODELS

Summary descriptions of the ore deposit models for the deposit types listed on the chart are being compiled. These summaries include the model definition, synonyms, fluid chemistry and source, mineralogy, a discussion on genesis and a reading list. As examples, the summary sheets for orogenic gold and VMS (volcanogenic massive sulfide) deposits are included as Appendices 1 and 2. The remaining deposit types will be written up progressively and made available via the NSW DPI website (www.dpi.nsw.gov.au/minerals/geological/about/deposit-mapping).

IMPLEMENTATION

The aim of the Minerals Systems and Processes project is to identify mineralising events and individual mineral systems. Evidence on age, element and isotope chemistry, mineral assemblage, trap features, alteration and tectonic setting will be used to assign deposits to an event and a system. The revised MetIndEx database will therefore include a deposit and its affiliation to an event and a system. The scale of some systems may create problems. They may extend over a large area, but appear at surface as separate ‘islands’. The compiler will need to consider if it is appropriate to subdivide the system.

In the initial stages the assignment of deposits to a system may need to be a ‘best guess’. The intention is for the process to be dynamic in character and to update the interpretation/assignment as new information appears. Where the lack of data prevents classification, the gap in information will be noted. This gap analysis will assist in the development of future work plans.

Where possible the deposit will be placed in a deposit type (e.g. orogenic gold, skarn or VMS). Note that this class may be mapped to a Cox and Singer class. The extent of an individual system may be traced as a polygon or a number of polygons and presented as a set of digital map layers.

MetIndEx will be expanded to incorporate fields on mineral systems, their characteristics and age. Over time, as the study of systems across New South Wales progresses, these areas will portray a picture of mineral events and related deposit styles.

CONCLUSION

The project to identify mineralisation events and systems is a logical extension of the ongoing study into mineral deposits and mineral districts. It does not replace the task of recording the details of mineral occurrences or identifying the style of mineralisation. The MetIndEx database, which holds information on around 30 000 mineral occurrences, is the primary data source for this project. The authors believe that the project to acquire these data and to identify mineral events and systems will radically improve the datasets and our understanding of mineralisation in New South Wales.

Figure 1, outlining the classification scheme, represents the current understanding of the range of processes and mineral deposit types present in New South Wales. It has been developed for use by the Mineral Systems project team when assigning a deposit type and process/association style to a particular event. This information will be useful to other geoscientists, especially mineral explorers. The authors fully acknowledge that ideas and concepts produced in earlier studies have been incorporated in this scheme.

The ultimate aim is to produce a spatial and temporal view of mineralising events in New South Wales. This is an ambitious target which will take time and effort, but the reward is better resource modelling and exploration targeting.

ACKNOWLEDGEMENTS

We wish to acknowledge the thoughtful comments and past work made by many Geological Survey of New South Wales geologists including Dave Forster, Lindsay Gilligan, Rob Barnes and Phil Blevin. The manuscript was reviewed by Paul Ashley and Richard Facer carefully edited the text and made many useful comments. Their contribution is acknowledged. Cheryl Hormann prepared the figures and Geneve Cox prepared the manuscript for this publication.
Mineral systems in New South Wales

Mineralisation source

Magmatic

Mafic (problematic)

Intermediate (incl. porphyry)

Granite

Cu–Au–Fe–REE IOCG deposits

Skarn

Epithermal

Hydrothermal: variable magmatic input

Association

Magmatic

Mafic (problematic)

Intermediate (incl. porphyry)

Granite

Cu–Au–Fe–REE IOCG deposits

Skarn

Epithermal

Hydrothermal: variable magmatic input

Fluid/magma type

Magmatic — little or no H₂O involved in ore formation.

Magmatic to Hydrothermal

Magmatic

Mafic (problematic)

Intermediate (incl. porphyry)

Granite

Cu–Au–Fe–REE IOCG deposits

Skarn

Epithermal

Hydrothermal: variable magmatic input

Deposit type

Post-orogenic magmatic fluids mixed with meteotonic or seawaters. Some are enriched in uranium.

Hydrothermal: metamorphic Au

End-member fluids include strongly acidic and oxidised fluids (high sulfidation) and weakly acidic to weakly alkaline reduced fluids (low sulfidation).

High sulfidation (Au–Cu)

Intermediate sulfidation (Ag–Au–base metal)

Low sulfidation (Ag–Au)

Low temperature (<400°C), moderately acidic reduced H₂O–CO₂-rich fluids. Fluids are mostly metamorphic in origin.

Reduced to relatively oxidised (pyrrhotite–pyrite-stable) saline fluids at temperatures 250–340°C.

Reduced to relatively oxidised (pyrrhotite–pyrite-stable) saline fluids at temperatures 250–340°C.

Broken Hill type

Broken Hill type

Mt Isa Cu

Tallawang (Fe)

Peak Hill (Au)

Gedigbuinb (Au)

Verranderen (Ag–Au–base metal)

Drake (Ag–Au–base metal)

Pambula (Au)

Valhav (Au)

Woodlaw (Pb–Zn–Cu minor Ag–Au)

Captains Flat (Pb–Zn–Cu minor Ag–Au)

Lewis Ponds (Pb–Zn–Cu minor Ag–Au)

Burapa (Cu–Zn–Pb)

Gulf Creek (Cu minor Zn)

Kempfield (Ag–barite)

Gurrundah (barite)

Moderate temperature (<400°C), metal-charged reduced and slightly acidic fluids. Initial ore-forming fluids are often seawater-dominant though a magmatic component can be present. Metals are leached from host sequence.

Orogenic base metal

Sandstone-hosted

Stratabound sediment-hosted Cu deposits

Continental rift

Low temperature (<150°C)

High salinity epigenetic low-temperature (<150°C)

Reduced SEDEX systems

Carbonate-hosted

Carbonate base-metal (excluding skarn)

Sandstone-hosted

Chemical

Mechanical

Residual

Surficial

Surface

Inferred

Examples

Figure 1. Mineral systems in New South Wales (modified from Downes et al., 2008).
REFERENCES


APPENDIX 1

Model — orogenic gold systems

Definition

Orogenic gold deposits have been defined by Groves et al. (1998) as low-sulfide mesothermal gold deposits that are associated with deformed regionally metamorphosed terranes of all ages. The deposits formed during compressional to transpressional deformation at convergent plate margins in both accretionary and collisional orogens. The majority of deposits are interpreted as having formed
post-peak metamorphism. Many Phanerozoic deposits are hosted by marine sedimentary rocks accumulated on pre-collision continental margins and/or prograding arc-trench complexes that have been subsequently deformed (Bierlein & Crowe 2000). Intrusion-related and epithermal deposits are excluded from this model.

**Synonyms**

Previously, many orogenic gold deposits were classified as lode gold deposits; low-sulfide gold–quartz deposits; structurally controlled gold deposits; slate belt-hosted, sediment-hosted or turbidite-hosted gold deposits; and/or as mesothermal gold vein systems.

**Fluid chemistry and source**

Gold is typically transported as a reduced bisulfide complex (Au(HS)₂⁻ for sub-greenschist/greenschist facies and as AuHS⁺ for amphibolite facies (McCuaig & Kerrich 1998) — by low- to moderate-salinity (generally 3 to 7 wt% NaCl equiv), near-neutral to slightly alkaline, mixed H₂O–CO₂ ± CH₄-rich fluids that are relatively reduced (Ridley & Diamond 2000). There is an overall uniformity in the values for the stable isotopes, (δ¹⁸O, δ¹³C and δ³⁴S) in the ore-forming fluids within individual gold deposits and goldfields but differences between separate goldfields (McCuaig & Kerrich 1998). In general, fluids are in equilibrium with the host-rock sequence although not with the immediate wall-rock sequence.

Gold solubility is dependent on pressure, temperature, pH and fO₂ with gold being precipitated by phase separation, sulfidation reactions, pH and fO₂ changes, fluid mixing and/or chemisorption reactions (McCuaig & Kerrich 1998). For orogenic gold deposits fluid–wall-rock interactions, resulting in sulfidation reactions, are interpreted to be the most common ore-precipitation mechanism. However, Goldfarb et al. (2005) noted that pressure fluctuations may also be important. The variation of pressure from superlithostatic to near-hydrostatic conditions could result in fluid unmixing which may result in the localisation of high-grade ore shoots containing coarse-grained gold (Groves & Foster 1991). Fluid mixing is unlikely to be a major cause of gold deposition in many deposits. However, it may be important in orogenic gold–base metal deposits and some near-surface systems.

The initial sources of gold and fluids remain controversial. Possible fluid sources include: mantle-derived; crustal-derived; magmatic; and/or metamorphic de-volatisation (Figure a). Gold concentrations in the upper mantle and crustal rocks are typically between 1 ppb and 10 ppb, with mafic rocks generally having higher gold concentrations than felsic rocks (Viljoen et al. 1970). Furthermore, Ridley and Diamond (2000) suggested that sequences containing significant volumes of mafic rocks and/or calc-silicate schists and/or greywacke can provide all possible reservoirs for the generation of gold-bearing fluids.

**Traps and settings**

The majority of large deposits are located in and around low displacement faults c.<100 m adjacent to high-displacement, crustal-scale shear zones. Fluid migration and focussing is controlled by a coupling between deformation processes, rock permeability and fault-system architecture (Cox 1999). By analogy to modern seismogenic systems, Robert et al. (1995) and Cox et al. (2001) proposed that the deposit-hosting structures are repeatedly re-activated by aftershock structures that formed around larger shear systems.

Most deposits formed in the brittle–ductile transition zone with typical temperature conditions between 250°C and 450°C, and depths of formation from 4 to 15 km (Kerrich & Cassidy 1994). Phanerozoic deposits are generally hosted by greenschist facies metamorphic grade rocks (Goldfarb et al. 2005) and generally formed at 275–350°C and depths of formation from 2 to 6 km (Bierlein & Crowe 2000). Deposit styles can be broadly grouped into: (a) ductile to brittle shear zones/faults with or without veins; (b) stockworks, breccias and fracture arrays; (c) fold hinges/saddle reefs and foliated zones (Hagemann & Cassidy 2000). Dilational structures caused by fault geometry, ductility contrast and/or folding localise many deposits. Furthermore, chemically favourable lithologies, including Fe-rich basalts, iron formation and carbonaceous pelitic units, are important in localising mineralisation as a large chemical contrast promotes destabilisation of the Au-bisulfide complex.

![Photograph 3. Orogenic low-sulfide gold-bearing veins at Adelong.](image)
Possible fluid sources for the formation of gold deposits in metamorphic terranes include meteoric, metamorphic, magmatic and mantle reservoirs (modified from Goldfarb et al. 2005, in turn after Hagemann & Cassidy 2000). Goldfarb et al. (2005) noted that stable isotope data generally exclude a significant meteoric fluid component and a variety of geochemical data are not consistent with a direct fluid input from the mantle.
**Deposit mineralogy**

Orogenic gold deposits are typified by quartz-dominant vein/breccia systems with low (<5%) sulfide contents. They are spatially associated with zoned hydrothermal alteration haloes (centimetres to kilometres in extent) that show consistent mineralogical changes relative to the host-rock type and the metamorphic grade at which the deposits formed (e.g., Goldfarb et al. 2005). At low to moderate metamorphic grades, the alteration mineralogy commonly includes albite, carbonates (calcite, dolomite and ankerite), alkali minerals (sericite, muscovite, biotite and K-feldspar), chlorite and sulphides (pyrite, pyrrhotite and arsenopyrite). Diopsid and amphiboles are found in higher metamorphic grade deposits. Other minor minerals that may be present include galena, chalcopryite, sphalerite, tungsten minerals (generally as scheelite), bismuth- and tellurium-bearing mineral phases, stibnite and tourmaline.

**Discussion**

Much of the fluid inclusion and isotopic data for orogenic gold deposits is equivocal. Ridley and Diamond (2000) suggested that the errors involved in fluid inclusion studies on orogenic gold deposits are significantly larger than is generally assumed. Furthermore, the data from O- and H-isotope studies of vein and alteration assemblages are consistent with a metamorphic derivation although there is evidence for mantle- and/or magmatic-derived fluids (Golding & Wilson 1988) and for meteoric waters (Hagemann et al. 1994). C-isotope compositions of carbonates associated with gold mineralisation are not diagnostic of a single source. They do not differentiate between mantle and magmatic sources of carbon (e.g., Golding et al. 1987). S-isotope data suggest that the sulfur source was relatively uniform and that sulfur could not differentiate between mantle and magmatic sources of gold deposits. Evidence for mantle- and/or magmatic-derived fluids (Golding & Wilson 2000). Archaean orogenic gold deposits. In: Hagemann S.G. & Brown P.E. eds. Gold in 2000 pp. 63–103. London, Blackie.

**Further reading**


**APPENDIX 2**

**Model — volcanogenic massive sulfide deposits**

**Definition**
Volcanogenic massive sulfide (VMS) deposits are stratabound accumulations of sulfide minerals that precipitated at or near the seafloor in spatial, temporal and genetic association with contemporaneous volcanism (Franklin et al. 2005).

**Synonyms**
In North America and Europe these deposits are termed VMS (volcanogenic massive sulfide) deposits whereas in Australia they are more commonly termed VHMS (volcanic-hosted massive sulfide) deposits. Other terms include the Kuroko-type which is a Zn–Pb–Cu variant; Cyprus-type, which is an ophiolite-hosted Cu–Zn variant; and Besshi-type, which is a Cu-rich variant that occurs in oceanic back-arc settings. Modern analogues are formed on the seafloor from sulfide-bearing fluids emanating from ‘black smokers’.

**Fluid chemistry and source**
The mineralising fluids may be derived from recycled seawater and/or from magmatic fluids. The input from magmatic sources is difficult to determine and can vary from minor to dominant. Close to the site of sulfide deposition the ore-forming fluid is moderately acidic (pH of 2.7 to 3.8) and temperatures in the range 200°C to 350°C. Franklin et al. (2005) noted that, given the solubilities of copper and zinc, for precipitation to occur, a temperature no less than 260°C is required. Seawater is reduced as it moves from the recharge zone to the trap site. This delivers sulfur and metals to a depositional site (trap). The solubility of metals in the fluid depends on the concentration of complexing ligands (Cl, S, H, O). In rare cases, the fluid at the site of deposition can remain weakly oxidised. The system is driven by heat provided from magmatic (sub-volcanic) sources.

Precipitation of metals and ligands can be triggered by cooling, dilution, increase in pH and/or the addition of H₂S via mixing with seawater. Most authors argue that the Pb–Zn–Ag metals are derived from the volcanic–sedimentary pile. However, Pb-isotope data also suggest that some metals were sourced from basement rocks. The source of Cu–Au is less certain. Gold-rich deposits are interpreted to be submarine analogues of high-sulfidation epithermal Cu–Au deposits in which these metals (plus Co, Bi, Te, In and Sn) were derived from a magmatic source (Hannington et al. 2005).

Precipitation of chalcopyrite is temperature-dependent whereas sphalerite and galena are also affected by pH changes during cooling. This leads to the deposition of separate Pb–Zn and Cu ores.

**Traps and settings**
VMS deposits are submarine and occur in back-arc and inter-arc volcanic basins with a range of compositions and in mid-oceanic ridge settings. Current evidence suggests water depth of 800 m to 2000 m. There is growing evidence that the lithologies and their metal components, ‘leached’ by the circulating fluids, are reflected in the sulfide deposits (Tornos & Heinrich 2008). This is reflected in the metal variations between Cu–Zn Cyprus types derived from sequences dominated by mafic units and Pb–Zn–Ag deposits found in more felsic volcanic–sedimentary fore-arc and back-arc settings.

Franklin et al. (2005), using mainly Canadian Archean examples, argued that it is possible to classify the deposits by sedimentary lithofacies associations — with those authors suggesting that classes can be distinguished by metal ratios, volcanic–sediment sequence and dominant lithological compositions.

At present the proposal of Franklin et al. (2005) is a minority view. Most workers recognise two styles of seafloor sulfide deposition (mounds or brine pool), and sub-seafloor (replacement) deposits. Mound or ‘Hokuroko’ deposits form by accumulation of sulfides about ‘black smokers’ whereas brine pool deposits form as sheets or lenses within seafloor depressions. Sub-seafloor replacement deposits can be massive, lensoidal or disseminated in nature. Stringer or feeder zones are associated with all deposit types.

**Comments on genesis**
The seafloor deposits form by accumulation of sulfides from metal-charged fluids issuing from vents or pipes. It can be described as a hydrothermal exhalative process. The depositional setting usually involves extension, commonly rifting of a volcano-sedimentary sequence at inter-arc or back-arc locations.

The form of seafloor deposits is determined by the density of the ‘exhalative fluid’, or brine. Dense fluids settle in depressions (rifts, collapsed calderas etc.) to precipitate as sulfide sheets. The less-saline buoyant brines are more typical of black smokers and need more favourable conditions or a ‘capping’ to allow deposition of massive sulfides. The brines will otherwise be dispersed into the surrounding sea to form an extensive ‘halo’ of disseminated sulfide. A second control is the porosity of the host sequence; with sub-seafloor lenses forming in more porous units as a result of fluid mixing/cooling/pH etc. whereas seafloor deposits result from a more focussed fluid flow.
Deposit mineralogy
Most deposits exhibit lateral and vertical zonation of metals (e.g. Cu, Au–Pb, Zn, Ag, Au–Ba), isotopes (particularly S) and alteration. The copper-rich footwall (stringer zone) is normally cross-cutting veins, disseminated sulfide and lenses. The overlying massive sulfides may be banded, massive and/or brecciated.
Sulfide abundance ranges from major to minor and includes pyrite, sphalerite, galena, chalcopyrite with or without tetrahedrite–tennantite, arsenopyrite and pyrrhotite. Major gangue minerals include chlorite, sericite, barite and carbonates.

Discussion
VMS deposits generally occur in moderate to deep water intra-ocean or ocean–continent extensional environments. Deposits are generated in a variety of thermal and extensional structural settings where the hydrothermal system is active for a relatively short period (10,000 to 100,000 years). The position of the sub-volcanic intrusions, which generally occupy extensional faults and high heat flow regime are critical to the creation of convection and hydrothermal cells.

Three alteration zones are recognised as vectors to mineralisation, each with its own mineralogical characteristics. These include: source areas, which are the site for mineral/metal dissolution and are called semi-conformable (shallow and deep) alteration zones; footwall alteration zones; and hanging-wall alteration zones (Franklin et al. 2005).

Further reading


Photograph 4. Woodlawn open cut — a VHMS deposit.
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‘A revised Triassic stratigraphy of the Lorne Basin, New South Wales’ by W. Pratt

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