CHAPTER NINE

9 INDIRECT LINKS: HYDROTHERMAL MINERAL DEPOSITS

9.1 Introduction

In Chapters 2, 3 and 4 we have examined how doming of the crust, its rupturing and formation of a rift basin are processes that can be linked to mantle plumes. The East African Rift System, and its Red Sea and Gulf of Aden extensions are a modern example of this phenomenon; the Mid-Continent Rift System in North America is an ancient example. Another ancient example is the Damara-Ribeira rift systems, which subsequently evolved to ocean floor spreading, resulting in the separation of South America from southwestern Africa (Damara hotspot junction, discussed in Chapter 4).

"Deposits formed in continental hot spots, rifts and aulacogens" are discussed by Mitchell and Garson (1981), who included mineral deposits associated with intracontinental hotspots, such as Sn, Nb and U in peraluminous and peralkaline granites, REE in carbonatite; deposits associated with intracontinental rifts and aulacogens, such as REE, U and P in carbonatite and alkaline complexes, diamonds in kimberlite and porphyry Mo in biotite granite; stratabound Cu (e.g. Kupferschiefer in Europe, Copperbelt in central Africa), stratabound Pb-Zn-Ag (e.g. Sullivan in Canada, Mt. Isa and McArthur River in Australia), lacustrine brines and evaporites (East African lakes), polymetallic hydrothermal veins in granite (e.g. Mid-continent Rift System in North America). The Great Dyke and Bushveld Igneous Complex, discussed in Chapter 8 of this book, are also included in the rifts and aulacogen settings of Mitchell and Garson (1981).

Sawkins (1990) devoted a chapter to "Intracontinental hotspots, anorogenic magmatism and associated metal deposits", in which he included Sn in anorogenic granites, Fe-Ti in anorthosite, Ni-Cu-PGE in layered intrusions (e.g. Bushveld, Stillwater), Cu-Au-U-REE of the Olympic Dam type and deposits of carbonatite complexes. Sawkins (1990) considered rift-related magmatic and hydrothermal mineralisation in terms of early and advanced stages of rifting. The early rifting stages of Sawkins (1990) encompass hydrothermal Cu (e.g. Messina in South Africa), porphyry Mo (e.g. Oslo rift in Norway), magmatic Cu-Ni-PGE (e.g. Noril'sk in Russia),

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and the Archaean Witwatersrand Au-U conglomerates in South Africa. In the advanced rifting stages, he included the metalliferous deposits of the Red Sea, sediment-hosted massive sulphides (SEDEX), stratabound Pb-Zn-Ag of Mt. Isa, McArthur River, Hilton in Australia and Sullivan in Canada, Mississippi Valley-type (MVT) Pb-Zn, and the major Fe ores of Superior-type banded iron-formations. Pirajno (1992) discussed the major stratiform and stratabound base metal deposits and banded iron-formation (including Mn deposits) under the heading of "Continental rift environments".

Sawkins' division of early and advanced stages of rifting is a neat and convenient way of classifying rift-related ore deposits, although it is more realistic to see these ore systems as a time-continuum of closely-related phenomena, rather than separate events. What we observe and study are snapshots. Commonly, and again for the sake of convenience, we tend to focus on end-members of this continuum. In this book, we consider two groups of end-members: one group (1 and 2 below) includes ores that are formed from anorogenic magmas in intracontinental rift settings, the other group of end-members (3, 4 and 5 below) are, perhaps the better known sedimentary-hosted sulphide deposits of rift basins. Thus, the end-member ore systems considered are:

1. those that are formed from high-temperature fluids that emanate from anorogenic igneous complexes in intracontinental settings;
2. mesothermal and epithermal systems linked to hydrothermal convective cells activated by high T/P metamorphism induced by deep-seated heat sources;
3. surface deposits formed as precipitates from the discharge of thermal springs in lacustrine environments, during incipient stages of rifting;
4. high-temperature fluids that ascend along growth faults, to exhale at higher levels in a rift-related sedimentary pile (e.g. SEDEX deposits).
5. low-temperature metalliferous brines that move laterally across basins during compaction and lateral tectonic push (e.g. Mississippi Valley-type and stratabound Cu-Co-Ag deposits).

Mixing of two or more of the various types of fluids (magmatic, metamorphic and/or meteoric) is common and result in highly complex ore systems. Ultimately, the thermal energy is provided directly by igneous intrusions or indirectly by mantle plumes in a crust-attenuated environment. These categories of hydrothermal mineralisation can be considered singly or as part of regional-scale metallogenic processes that are associated with rifting.

In this chapter we examine some of the tectonic environments and associated ore deposits that are included in the first two categories listed

above, whereas some aspects of the last three categories are examined in Chapter 10. Thus, first we consider ore systems associated with the modern East African Rift System. Then, we look at mesothermal and epithermal mineralisation associated with intraplate anorogenic volcano-plutonic complexes.

We also examine the regional metallogeny of rift systems for which there is good evidence of mantle plume involvement, the Meso-Neoproterozoic Damara and Irumide orogens in southwestern Africa and the Mid-continent Rift System in North America. We conclude the chapter with a brief review of the controversial Archaean orogenic Au-bearing lode systems and their possible relationship to mantle plumes.

9.2 Ore deposits associated with intracontinental anorogenic magmatism

In this section we consider some of the ore deposits that are generated as a result of magmatic activity in intracontinental rifting environments. The hydrothermal systems that are linked to rift-related magmas are complex and also involve, in addition to magmatic hydrothermal fluids, meteoric and groundwater components. The resulting mineralisation can be classified in terms of distance from the causative intrusive complex, and depositional temperatures. In this book we use the terminology of epithermal (approximately <350°C) and mesothermal (approximately >350°C), without necessarily implying specific distance from cooling magmas.

We consider mineralisation that forms in, or is associated with: 1) ring complexes and carbonatites; 2) anorogenic alkaline magmas in extensional continental environments, such as the Proterozoic Cu-Au-U-REE-Fe deposits; and 3) mesothermal lodes, such as those of the Sabie-Pilgrim's Rest goldfield and; 4) the epithermal carbonate-hosted Carlin-type Au deposits. The precise origin of the last category is controversial, but, evidence is mounting that mantle plume-related magmatism in an extensional setting could have been the principal cause.

9.2.1 Ring complexes and carbonatites

Intracontinental magmatic processes include alkali ring complexes and carbonatites, discussed in Chapter 3. Africa is a continent particularly well-endowed with these magmatic complexes, ranging in age from Archaean to present-day. Indeed, the growth of the African continentral crust owes much to intraplate magmatic processes, as exemplified by the Bushveld Igneous Complex (Chapter 8). This important geological feature

of Africa has been emphasized by Burke (1996) and may be related to the stationary position of the continent over mantle plumes (see also Chapter 2 and Fig. 4.10), with which the anorogenic magmatism is probably linked. A special issue of the Journal of African Earth Sciences is devoted to intraplate magmatism in southern Africa (Dirks et al., 1999).

In Namibia and southern Angola, numerous anorogenic alkali ring complexes and carbonatites were emplaced during phases of Gondwana breakup and the opening of the South Atlantic ocean in the Mesozoic and Tertiary (138-132 and 37 Ma). Tin, W, Cu and even Au hydrothermal mineralisation is associated with these complexes (Pirajno, 1994; Pirajno et al., in press). Carbonatites are generally enriched in REE, Zr, P, F and Fe, which in some cases may reach economic grades.

In Namibia three provinces are associated with the opening of the South Atlantic and the Tristan da Cunha mantle plume (Pirajno, 1994; Pirajno et al., in press): 1) the Damaraland alkaline province of Jurassic-Cretaceous age; 2) the Auas province of Tertiary age; and 3) the Early Cretaceous Luderitz alkaline province (see Chapter 3 and Fig. 3.30). A fourth province, Kuboos-Bremem, is Cambrian in age and contains Mo porphyry style mineralisation (Bernasconi, 1986). Economically important is the Damaraland alkaline province, which extends for approximately 350 km from the Atlantic coast, and includes granitic, carbonatitic, volcanic and peralkaline complexes. The Brandberg granitic complex has considerable resources of REE, Zr, Nb and Y. The Erongo volcanic complex contains W, Sn and U mineralisation associated with a late B-rich granitic ring dyke. The Okorusu carbonatite complex is characterised by intense brecciation and fenitisation of the wall rocks, which host veins and replacement bodies of fluorite, apatite and limonitic Fe ore. Ore reserves are estimated at 6 Mt averaging 56% CaF_2 and 0.5% P_2O_5 (Premoli, 1993). Other carbonatite complexes (e.g. Kalkfeld) have disseminations and veins containing apatite, barite, monazite, strontianite, pyrochlore and pyrite (Pirajno, 1994).

Carbonatites and associated alkaline complexes in the Indian subcontinent have abundant resources of P (apatite), Fe (hematite and magnetite), Nb-U (pyrochlore), F (fluorite), REE, Th, U and Ba (Krishnamurthy et al., 2000). Some of the Indian carbonatite-alkaline complexes are present within northeast-trending rift structures in the charnockite mobile belts in the south and east of the subcontinent, others are part of the Deccan continental flood basalt province (see Chapter 3). Here, the Amba Dongar carbonatite complex contains reserves of about 12 x 10^6 tonnes of ore, with an average of 30% CaF_2, making it one of the largest fluorite deposits in the world (Krishnamurthy et al., 2000).

9.2.2 Proterozoic Cu-Au-U-REE-Fe deposits

Here we discuss the general features of a class of ore deposits referred to as Proterozoic Fe oxide (Cu-U-Au-REE), which includes the giant Olympic Dam (South Australia), the Kiruna Fe ore (Sweden), Fe-Cu mineralisation at Boss-Bixby and Pea Ridge (USA) and perhaps the giant Bayan Obo REE deposit of Inner Mongolia (Hitzman *et al.* 1992; Oreskes and Hitzman, 1993). Some of the economically more important Proterozoic Fe oxide-Cu-Au-REE-U deposits in the world are listed in Table 9.1.

Other deposits have been recognised that share some important features in tectonic setting (e.g. intracontinental anorogenic magmatism) and characteristics of ore deposition. These include the Vergenoeg magnetite-fluorite and Messina copper deposits in South Africa.

Table 9.1. Fe oxide-Cu-Au-REE-U of Proterozoic age (after Hitzman et al., 1992 and references therein).

Deposit	*Tonnages and grades*
Olympic Dam district (South Australia)	2 x 10^9 tonnes, 35% Fe, 1.6% Cu, 0.06% U_3O_8, 0.6 g/t Au
Redbank district (Northern Territory, Australia)	2 x 10^6 tonnes, 5-10% Fe, 2% Cu
Wernecke and Richardson Mountains (Canada)	1 x 10^6 tonnes, 29% Fe, 0.5 x 10^6 1% Cu
Bayan Obo district (Inner Mongolia, China)	45 x 10^9 tonnes, 33-35% Fe, 1-6.2% REO
Kiruna district (Sweden)	2.6 x 10^9 tonnes, 40% Fe
Boss Bixby, Pea Ridge and St. Francois Mountains (Missouri, USA)	~ 0.47 x 10^9 tonnes, 20-50% Fe

All of these deposits are linked to extensional and continental-margin settings with episodes of alkaline magmatism of Mid-Proterozoic age. The unifying factors are the common enrichment in iron, phosphorous, fluorine and widespread alkali metasomatism in the host rocks (Hitzman et al., 1992; Oreskes and Hitzman, 1993). To understand these deposit styles it is necessary to unravel the spatial and genetic relationship between the various mineralised manifestations, their depths of formation, and their erosion level (Fig. 9.1).

Typically, Fe oxide-Cu-Au-REE-U hydrothermal systems form in shallow crustal environments (4-6 km) and are the expression of volatile-

rich, alkaline magmas (Hitzman et al., 1992). Their global occurrence covers the time span of approximately 1.8 to 1.1 Ga and they appear to be linked to planetary-scale rifting events and the assembly and breakup of supercontinents, such as Rodinia (Unrug, 1997 and Chapter 2).

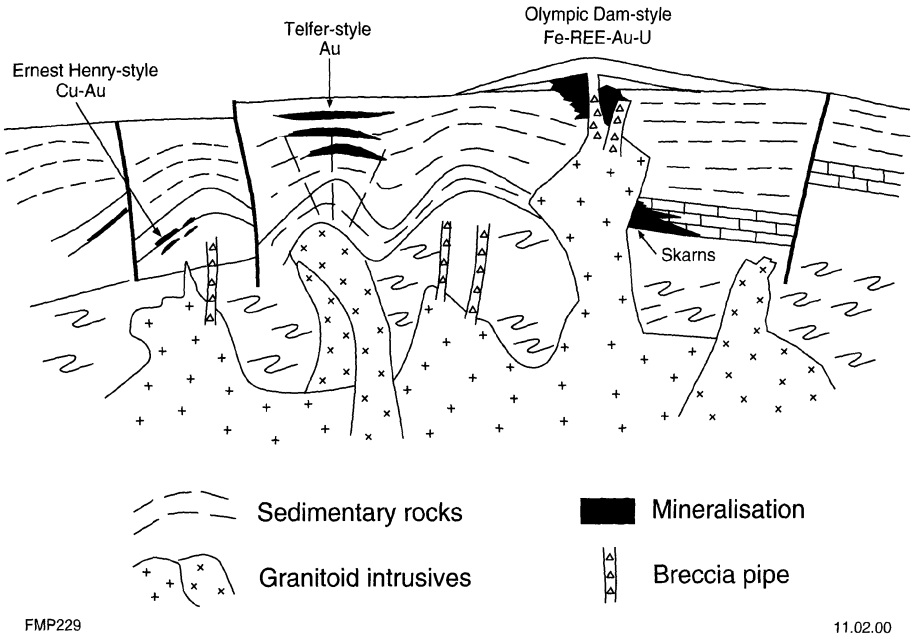


Figure 9.1. Conceptual model of ore systems linked to Proterozoic anorogenic magmatism. After McMaster (1998).

The assembly of the Proterozoic supercontinent Rodinia, may have acted as a large insulation blanket on sublithospheric mantle flow, resulting in accumulation of heat, rise of mantle diapirs, melting, rifting of the continental crust, and finally the inception of regional-scale hydrothermal systems at shallow levels in the crust (Fig. 9.1).

An alternative view is that of Barton and Johnson (1996) who suggested that Fe oxide-Cu-Au-REE-U mineralisation is common in both Proterozoic and Phanerozoic extensional environments. Although these authors did not dispute the link with continental hotspots, they proposed that the saline fluids reponsible for these deposits are sourced from evaporites. They cited examples of Holocene hydrothermal Fe oxides formed from evaporitic sources and the correlation of the Fe oxide-Cu-Au-REE-U of Mesozoic age with zones of low-latitude as revealed by continental reconstructions. The evaporitic source model of Barton and Johnson (1996) suggests that circulation of hydrothermal fluids is caused by magmatic

heat, and that the source of the metals is provided by igneous rocks, but that the metal transport is effected by chlorides supplied by evaporitic deposits. In addition, the widespread sodic alteration associated with the deposits is also related to the evaporites, which supplied the large amounts of Na to the hydrothermal fluids. Examples of Fe oxide-Cu-Au-REE-U deposits that may be linked to an evaporitic source include the Mid-Tertiary Cerro de Mercado (Mexico), the Jurassic Humboldt Complex, in the Basin-and-Range (USA), the Permo-Triassic Korshunovsk and Tagar in the Siberian platform (Russia) and the Bafq mining district in central Iran (Barton and Johnson, 1996).

In Australia, the Cloncurry district in the Mount Isa region, in northwest Queensland, is a major metallogenic province, which includes the Ernest Henry Cu-Au deposit with about 167 x 10^6 tonnes at 1.1% Cu and 0.5 g/t Au (Williams, 1998). The hosting rocks are part of the 1790-1740 Ma Mary Kathleen Group which is a package of metamorphosed evaporite-carbonate-clastic rocks. The alteration patterns are characterised by regional-scale Na and K metasomatism, phyllosilicate alteration, silicification and epithermal-style quartz-chalcedony (Williams and Blake, 1993). Regional alkali-feldspar (microcline, adularia and albite) metasomatism is associated with major fault zones along which the base metal deposits of the McArthur River-Mt Isa-Cloncurry base metal province (northern Australia), are situated. Some interpretations ascribe this regional alkali alteration to the action of meteoric waters that leached alkali metals from evaporite and carbonate beds (e.g. Davidson, 1998 and 1999).

In summary, an overall and idealised hydrothermal alteration zoning, as viewed by Hitzman et al. (1992), is as follows: a zone of sodic alteration (albite-magnetite-actinolite) is surrounded by a halo of dominantly potassic alteration (K-feldspar-sericite-magnetite). This deeper and higher-temperature sodic-potassic system is followed towards the surface by a zone of sericitic alteration (sericite-hematite-carbonate-chlorite-quartz, with lenses of massive Fe oxides (hematite or magnetite). Dykes or pipes of hematite-quartz breccia cut through the system.

In the next two sections we examine two examples: Olympic Dam, the key representative of the Proterozoic Cu-U-Au-REE ore deposits and the less-famous, but nevertheless interesting, Vergenoeg Fe-F deposit in the Bushveld region (South Africa). The reason for including the latter in our dicsussion is because it may represent the surface-expression equivalent of Olympic Dam.

9.2.2.1 Olympic Dam, South Australia

The world-class Olympic Dam deposit (approximately 2000 Mt with 1.6%Cu and 0.6 g/t Au, plus credits of Ag, U and REE; Table 9.1) is located approximately 520 km north-northwest of Adelaide, along the eastern margin of the Gawler Craton, in South Australia. The deposit was discovered after many years of detailed investigations and study by Western Mining Corporation geologists (Woodall, 1993). The initial concept was to locate a stratabound sedimentary rock-hosted copper deposit in a Proterozoic basin, in which the presence of thick basaltic successions would be the source of metals. This first study was integrated with geophysical data, and focused on gravity and magnetic anomalies on the Stuart Shelf, interpreted as possible buried basalts (Gawler Range volcanics). At the same time, analyses of tectonic lineaments by O'Driscoll (1985) revealed the presence of well-defined structural corridors along the areas of coincident gravity and magnetic anomalies. A synthesis of the data, integrated with field observations led to the siting of the first diamond drillhole in 1975, on the coincident gravity, magnetic and tectonic target. The initial model was incorrect, but the Western Mining Corporation's exploration team was quick to realise that something new and exciting had been discovered.

Since its discovery much has been published about the deposit. Information for the short review given below, is derived from Roberts and Hudson (1983), Reeve et al. (1990), Oreskes and Einaudi (1990; 1992), Cross et al. (1993) and Haynes et al. (1995).

The Olympic Dam deposit is a hydrothermal breccia complex that is hosted by a 1.59 Ga coarse-grained, A-type, syenogranite (Roxby Downs granite). The Olympic Dam mineralisation is characterised by hematite-quartz dyke-like breccia bodies that are up to 100 m wide and host the mineralisation (Olympic Dam Breccia Complex). The hematite-quartz breccia complex forms a zone elongated in a northwest direction, about 5 km long and 1.5 km wide in the central parts. The breccia complex is buried beneath 300 m of Neoproterozoic and Cambrian sedimentary rocks of the Stuart Shelf. There two main types of breccias: heterolithic and microbreccia. These are arranged into a pattern, which begins with brecciated granite at the periphery of the deposit, passing into the heterolithic breccia and hematite-quartz microbreccia in the central portions. The heterolithic breccia consists of fragments, less than 10 cm across, of hematite, crushed and altered granite in a matrix of quartz-hematite-sericite-siderite-chlorite. The clasts include fluorite, siderite, barite and pyrite as well as sedimentary material, such as bedded hematite, laminated barite and volcaniclastics. The heterolithic breccia grades into the hematite

microbreccia and fine-grained massive hematite-quartz. The hematite is largely a replacement mineral. The principal U mineral species include coffinite, pitchblende and brannerite. Rare earth-element minerals are monazite, xenotime, bastnaesite and florencite. Gold and Ag occur as native metals. The REE abundance is correlated with the increasing hematite content of the breccias. The formation of the breccias implies large-scale movements of high-pressure fluids, which locally resulted in fluidisation. The presence of sedimentary barite and hematite in the upper parts of the deposit suggests a phase of surface or near-surface exhlative activity.

Textural relationships and the distribution of sulphides indicate that they were deposited during the late stages of the mineralising event. The sulphides are zonally arranged around a central hematite core. From this core outward, a bornite + chalcopyrite assemblage changes to chalcopyrite + pyrite.

Alteration patterns at Olympic Dam begin with a fractured granite showing weakly sericitic and hematitic alteration. This becomes more intense towards the breccia bodies, where sericite, chlorite, epidote and hematite tend to become dominant, until hematite becomes more abundant and overprints all other phases. Late silicification appears to be associated with higher Au grades.

The extensive Fe metasomatism of the Olympic Dam granite and the large-scale hematite replacement and deposition was accompanied by fluorite, barite and REE-bearing mineral phases. The hydrothermal fluids were channelled upward along faults, while tectonic activity was ongoing and caused erosion of the breccia bodies and the altered granite. Collapse of the upper parts of the breccia system was accompanied by a waning phase of hydrothermal activity with deposition of sulphides. Supergene enrichment, with precipitation of chalcocite, took place as result of surface weathering during the Proterozoic. Finally, about 700 Ma ago the Olympic Dam deposit was buried by sediments, allowing its preservation.

Oreskes and Einaudi (1992), on the basis of fluid inclusions and stable isotope systematics, recognised two sources of fluids. An early fluid, of magmatic origin, produced most of the magnetite. This fluid is characterised by high $\delta^{18}O$ (about 10 permil) and high temperature (about 400°C). Later fluids deposited hematite and are associated with the Fe-rich breccias. Stable isotope studies show that these late fluids have $\delta^{18}O$ of less than 9 permil and temperatures between 200 and 400°C. Fluid inclusions indicate salinities ranging from about 7 wt% to 42 wt% NaCl equivalent.

Two models that attempt to explain the origin of the Olympic Dam

deposit were proposed by Oreske and Einaudi (1990) and Haynes et al. (1995). In the model suggested by Oreskes and Einaudi (1990), a rift basin formed on a basement of the 1.6 Ga Roxby Downs Granite, and was filled with clastic and volcanic sediments. Intense and widespread hydrothermal activity caused brecciation of the Roxby Downs Granite and pervasive metasomatism along graben faults. Fluids were exhaled at and near the surface with further infiltration of Fe-rich fluids into the sedimentary pile, and as faulting and hydrothermal activity continued, there was collapse of the central parts. The deposits were then eroded to the unconformity level (now about 300 m below the surface), where deposition of new sediments protected the mineralised rocks from erosion. In the model, proposed by Haynes et al. (1995), Olympic Dam began its history as a maar volcano, within which the Olympic Dam Breccia Complex developed; several pulses of oxidised and cooler meteoric water mixed with hotter deeply-sourced fluids with a main magmatic component, to form the ore zones.

Haynes et al. (1995) conducted numerical modelling of the Olympic Dam hydrothermal system and concluded that fluid mixing was the dominant process for the origin of the ores. This mixing involved fluids of magmatic origin, deep meteoric fluids and cooler, near-surface, oxidised meteoric water. The main Cu-Au-U orebody was formed within a reservoir of saline groundwater. This groundwater introduced the Cu, Au, U and S into the breccia complex and mixed with hotter water, which introduced Fe, F, Ba and CO_2. Their model suggests that the precipitation of the Fe oxides and sulphides was the result of sulphate reduction and ferrous iron oxidation ($Fe^{2+} \rightarrow Fe^{+3}$).

U-Pb zircon dating of the Olympic Dam fragmental rocks, tuffs and cross-cutting dykes (1584-1597 Ma) cannot be distinguished from the age of the host Roxby Downs granite. On the basis of these age constraints, Campbell et al. (1998) suggested that Roxby Downs-like granitoids are the product of large-scale crustal melting due to emplacement of mantle melts in a rift setting. The rifting episode affected the Gawler Craton (South Australia) and may have been related to a mantle plume (Campbell et al., 1998).

9.2.2.2 Vergenoeg Fe oxides-fluorite deposit, South Africa

The Vergenoeg deposit, containing Fe oxides (hematite, magnetite, and supergene goethite), fluorite and sulphides, is hosted by rhyolitic pyroclastic rocks of the Rooiberg Group (discussed in Chapter 8). The eruption of the Rooiberg rhyolitic rocks took place at about 2.06 Ga. The deposit was studied in detail by Crocker (1985), whilst more recent works can be found in Borrok et al. (1998) and Martini and Hammerback (1998). Other and

possibly genetically related deposits in the region, include a fluorite-magnetite-Cu-Au at Slipfontein hosted by Bushveld granite (Bobbejankop granite), the Buffalo Fluorspar deposit and the Zwartkloof fluorite-magnetite-fayalite veins, also hosted by Rooiberg rhyolitic rocks.

The Vergenoeg deposit consists of a pipe-like body, with a diameter of about 900 m at the surface, decreasing to about 400 m, at a depth of 600 m (Martini and Hammerback, 1998). The pipe is formed by magnetite, siderite, fayalite and fluorite, cutting through the Vergenoeg Pyroclastic Suite. In the upper parts of the pipe, a porous hematite-goethite gossan, containing up to 20% fluorite, minor cassiterite, apatite and REE minerals, constituted the main orebody from which fluorite was extracted. The gossan cap grades through a transition zone into unoxidised ore. Sulphides (pyrite, chalcopyrite, arsenopyrite, sphalerite) are present in the deeper levels of the pipe. Ore grades range from 20 to 40% CaF2 and 50 to 60% Fe_2O_3 (Martini and Hammerback, 1998).

The Vergenoeg pipe is a volcanic vent, from which the pyroclastic material was erupted. An apron of fluorite-hematite-rich fragmental rocks (agglomerates, breccias, epiclastic rocks) surrounds the pipe. These rocks are divided into a basal massive quartz-feldspar felsite unit (possibly an ignimbrite), overlain by a massive fluorite-hematite and a breccia-agglomerate unit. The massive fluorite-hematite unit is interpreted as a lava flow of immiscible Fe-rich magma (Borrok et al., 1998). The breccia and agglomerate rocks contain large fragments of rhyolite and hematite enclosed in a matrix of hematite and fluorite. Also present is a rock that consists of irregular masses of cryptocrystalline silica with inclusions of hematite and fluorite. This rock type can be interpreted as a possible sililceous sinter deposit. At the top of the pyroclastic suite is a fine-grained banded iron-formation-like rock, with mud cracks and ripple marks. A schematic section through the Vergenoeg pipe is shown in Fig. 9.2.

Borrok et al. (1998) recognised an assemblage of primary minerals in the lower part of the pipe. The primary assemblage consists of fluorite, fayalite, ilmenite, apatite, allanite and pyrrhotite. Early and late secondary assemblages developed by alteration of the primary assemblage. The early secondary assemblage contains ferroactinolite, grunerite, titanian magnetite, quartz and sulphides. The late secondary assemblage is formed by alteration of the primary and early assemblages and consists of magnetite, stilpnomelane, biotite, hematite, siderite, sphene, apatite and REE minerals.

The iron-rich nature of the Vergenoeg lithologies and other localities nearby appear to be the result of plutonic, volcanic exhalative and metasomatic activities, whose precise nature and relationships are poorly under-

stood. This large-scale and nearly pervasive Fe enrichment was considered by Crocker (1985) as a general trend of Fe-Ca-F-CO_2 enrichment due to immiscibility of Fe-oxide-rich magmatic fractions. Exsolution and degassing of HF may have been an important factor, responsible for the pervasive Fe-F alteration in the region. In Crocker's model, HF-rich fluids flowing through an Fe-rich protolith, such as the mafic rocks of the Bushveld Igneous Complex, leach Ca and Fe to form fluorite, chlorite, Fe-actinolite and Fe oxides. As the fluids move upward and lose pressure, magnetite, siderite and fluorite are precipitated. One of the reactions proposed by Crocker (1985) is:

$$4Ca_2Fe_5Si_8O_{22}(OH)\ (\text{Fe-actinolite}) + 16HF + 6O_2 \rightarrow 8\text{fluorite} + 10\text{hematite} + \text{Fe-actinolite} + 32\text{quartz} + 10H_2O$$

Other models, based on fluid inclusion studies, suggest that the Vergenoeg mineralisation is the result of Fe-rich, high-temperature (> 500°C) and high salinity magmatic hydrothermal solutions (Borrok et al., 1998).

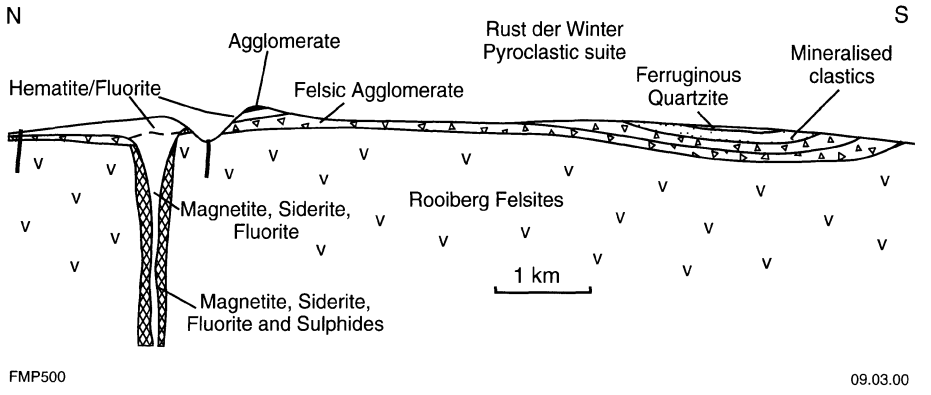


Figure 9.2. Schematic section showing stratigraphic relationships between the Vergenoeg volcanic pipe, its pyroclastic ejecta and epiclastic sediments.

9.2.3 Mesothermal ore deposits

Many metalliferous lodes and veins owe their origin to regional anorogenic metamorphism and dewatering of rock sequences, where the heat energy is provided by deep-seated large intrusions. An example of this situation is the Sabie-Pilgrim's Rest district (South Africa), where numerous gold with minor base metal lodes are related to hydrothermal circulation powered by heat induced by the emplacement of the Bushveld

Complex. These have been referred to as mesothermal ore deposits (Anderson et al., 1992; Boer et al., 1995), but are different from the orogenic mesothermal lode Au deposits as defined by Groves et al. (1998).

9.2.3.1 Sabie-Pilgrims Rest, South Africa

The Sabie-Pilgrim's Rest goldfield has produced about 186 000 kg of gold since its discovery in 1873. There are several works that discuss various aspects of the Sabie-Pilgrim's Rest mineralisation, including the early detailed work of Swiegers (1949), Tyler (1986), Ash and Tyler (1986), Anderson et al. (1992), Boer et al. (1993), Harley and Charlesworth (1994) and Boer et al. (1995).

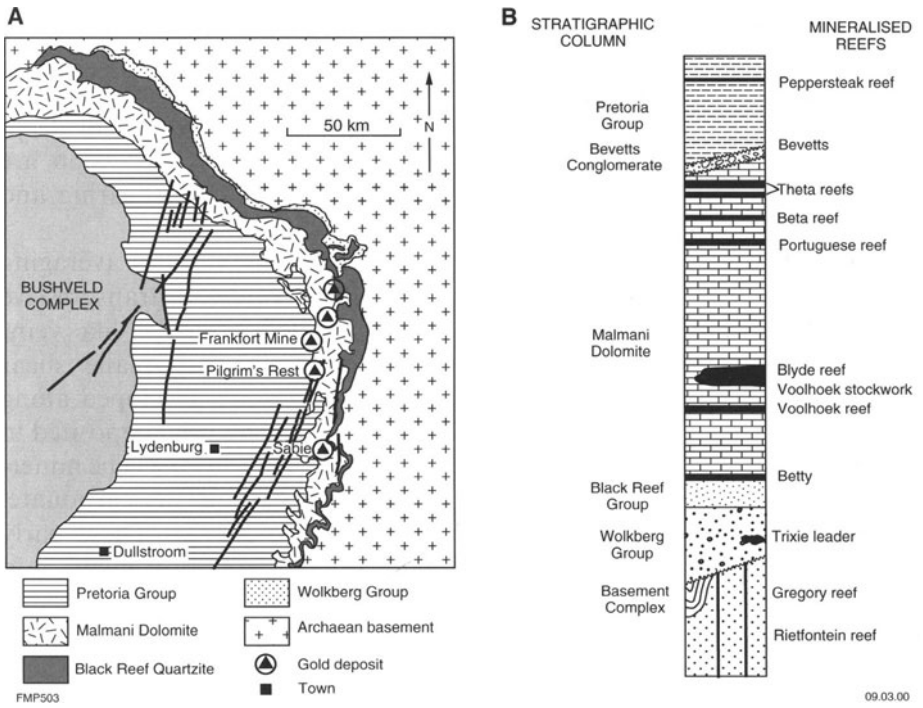


Figure 9.3. (A) Simplified geology of the eastern part of the Transvaal Basin, showing principal gold deposits of the Sabie-Pilgrim's Rest goldfield; (B) schematic stratigraphic column of the Lower Transvaal Supergroup, showing position of selected auriferous reefs. After Tyler (1986).

The Sabie-Pilgrim's Rest goldfield is located on the eastern margin of the Palaeoproterozoic Transvaal Basin (Fig. 9.3). The lodes are referred to as reefs, some of which are veins that cut through the basement, others are

parallel to bedding within the Transvaal Basin sedimentary rocks. The sedimentary succession in the region includes the Wolkberg Group that lies unconformably on Archaean basement, followed upward by the Black Reef Quartzite Formation and the carbonate units of the Malmani Dolomite.

The Wolkberg Group is interpreted as an early rift phase of the Transvaal Basin. This was followed by a phase of thermal relaxation, and the deposition of the quartz-arenite of the Black Reef Formation, which is 25-30 m thick. The overlying Malmani Dolomite Subgroup is a thick succession of shales and chemical sediments that varies in thickness from 700 m in the Pilgrim's Rest area, to 350-400 m in the Sabie area. The overlying sedimentary rocks of the Pretoria Group are about 7000 m thick in the region. The regional dip of the sedimentary rocks is only a few degrees to the west. Pre- to post-Bushveld sills considerably thicken the sedimentary package. In addition, north-northeast-trending dyke swarms of Bushveld Complex age are present. The dykes were probably emplaced in deep-seated crustal structures that in the basin's sedimentary succession are manifested as sets of joint and fractures. Bedding-parallel shearing and thrusting are common in the shale and dolomite rocks.

The reefs of the Sabie-Pilgrim's Rest goldfield have grades averaging from 3 to 8 g/t Au. Reefs range from stratiform (flat reefs), transgressive leaders, vertical lodes to irregular bodies. Flat reefs are sheet-like veins that follow near-horizontal bedding planes and bedding-plane shear zones. Many of the reefs in the Malmani Dolomite are developed along carbonaceous shaly horizons, which are thought to have been deposited in lagoonal settings. Locally, relic algal structures are discerneable. The mineralogy of the flat reefs includes an early assemblage of quartz, carbonate, pyrite and subordinate scheelite, arsenopyrite and galena. These early phases are commonly ruptured by later bedding-plane movements and introduction of gold, chalcopyrite, bismuthinite, tetrahedrite and galena. Leader reefs are transgressive veins that usually emanate as off-shoots from flat reefs. Vertical lodes occur mostly in the Archaean basement and the overlying Wolkberg Group rocks. They are quartz veins that have great lateral and vertical extent and are emplaced along faults, joints, dykes and shear zones, generally striking north-south. One vertical lode, Bokwa Stotz Reef, is 47 km long and cuts through 1000 m of stratigraphy (Harley and Charlseworth, 1994). Irregular bodies include stockworks, pockets and lenses.

Fluid inclusion studies, carried out by Ash and Tyler (1986) and Anderson et al. (1992), revealed that the fluids contained variable amounts of CO_2, CH_4, H_2O, NaCl, KCl and $CaCl_2$. Measured salinities range from

15 to 30 wt.% NaCl equivalent and homogenisation temperatures from about 100 to about 400°C. Interestingly, samples of fluid inclusions from stratigraphically deeper deposits homogenised at 300-400°C, whereas measurements from stratigraphically shallower deposits gave results in the range 100-200°C.

On the basis of their results, Anderson et al. (1992) proposed that the Sabie-Pilgrim's Rest mineralisation was formed by mixing of fluids at various stratigraphic levels. Low-temperature chloride-rich basinal brines of high to moderate salinity migrated and interacted with higher-temperature CO_2-rich and Au-bearing fluids. These CO_2-rich fluids may have originated from the devolitilisation of the carbonate rocks, due to high heat flow related to Bushveld magmatism. The source of the gold is as yet unknown, and leaching of the precious metal from the underlying basement lithologies is a possibility.

Boer et al. (1995) also invoked the Bushveld magmatism as the thermal event responsible for the hydrothermal convection that produced the Sabie-Pilgrim's Rest goldfield. Their evidence is based on several key features. One is age relationships, which show that vein systems cut pre-Bushveld mafic intrusions, but Bushveld pyroxenite dykes cut the mineralisation. Another is the heterogenous nature of the fluids, a component of which was probably from a deep-seated source. Boer et al. (1995) classified the Sabie-Pilgrim's Rest mineralisation as a type of mesothermal gold deposit, and acknowledged that the Sabie-Pilgrim's Rest goldfield has a clear spatial association and age relationship with the Bushveld Complex.

Finally, Harley and Charlesworth (1994) compared the Sabie-Pilgrim's Rest mineralisation to that of the Neoproterozoic Telfer (Western Australia) and the Meso-Neoproterozoic Passagem de Mariana (Minas Gerais, Brazil). In making this comparison, they pointed out the stratiform nature of the quartz reefs, the association with carbonaceous lithologies, ore mineralogy and metal association (Au-Cu-Bi-As) and magmatic fluid sources.

9.2.4 Carlin-type epithermal ore deposits

Since its discovery in the 1962 the Carlin deposit, of Tertiary age, in Nevada (western USA) has lent its name to a type of fine-grained disseminated Au-Ag hydrothermal mineralisation, hosted by carbonate rocks. The Carlin-type deposits in the western USA contain reserves that are in excess of 1500 t of gold (Sillitoe and Bonham, 1990). The discovery of similar deposits in the region and elsewhere, made it clear that Carlin was most probably an end-member of a group of deposits that displays considerable

variations in their geological, mineralogical and geochemical features. Carlin-type deposits are also present in Italy (Lattanzi, 1999), southern China (Cunningham et al., 1988; Zhai and Deng, 1996) and in Iran (Mehrabi et al., 1999).

Here, we focus on the classic area of Nevada and Utah, where the largest concentration of these deposits is present, and also examine Carlin-type mineralisation in Italy.

9.2.4.1 Carlin ore deposits in western USA

In Nevada, most deposits are situated along three major mineral belts: Carlin, Cortez and Getchell. This region is in the Basin-and-Range province, situated between the Colorado Plateau in the east and the Sierra Nevada in the west (Fig. 9.4). Much has been written on the Carlin-style deposits of the western USA; some of the key works are Radtke et al. (1980), Tooker (1985), Bagby and Berger (1985), Berger and Bagby (1991), Kuehn and Rose (1992, 1995). Bagby and Berger (1985), accepted the epithermal nature of the Carlin deposits, but preferred to refer to them as "sediment-hosted, disseminated precious-metal".

The Basin-and-Range province is a high plateau terrain (average of 1500 m above sea level), formed by extensional tectonics, which extends from the western USA to Mexico (Fig. 9.4). Parsons (1995) gave a comprehensive account of the geological and geophysical features of the province. His work is summarised below. Two extensional styles are recognised in the Basin-and-Range: metamorphic core complexes, in which mid-crustal rocks are exhumed by low-angle faulting, and higher-angle block faulting. Magmatic activity in the province began about 40 Ma ago, and, although highly variable in its products, it is typically bimodal.

In the Basin-and-Range, precious metal mineralisation is common and appears to be related to the extensional-thermal event that created the province. Hot springs and geothermal systems associated with the volcanism are still active today. Various lines of evidence, including gravity (see Chapter 4) and seismic data, suggest that the Basin-and-Range is underlain by upwelling asthenosphere, which accounts for the nature and composition of the volcanism, its elevated topography and the ongoing hydrothermal activity. Two stages of magmatism have been recognised: an older stage, from about 40 to 5 Ma, involving melting of mafic material in the mantle lithosphere, followed by (since about 5 Ma) melting of the asthenosphere (Leeman and Harry, 1993).

To explain the tectonic evolution of the Basin-and-Range, Parsons (1995) considered four possibilities: 1) back-arc extension; 2) orogenic thickening; 3) passive rifting; and 4) the Yellowstone mantle plume. The

Yellowstone hotspot is a likely control because of the broad topographic elevation (hotspot swell or uplift, Chapter 2) and the low-density mantle interpreted from geophysical data (Chapter 4). The North American plate moved southwestward, over the Yellowstone hotspots during the last 17 Ma, producing the Snake River Plain and Columbia flood basalts, discussed in Chapter 3. Parsons et al. (1994) suggested a four-step evolution for the Basin-and-Range, involving horizontal subduction, crustal thickening, back-arc extension and ponding of the Yellowstone plume, causing uplift, magmatism and extension (Fig. 9.4; see also Chapter 6).

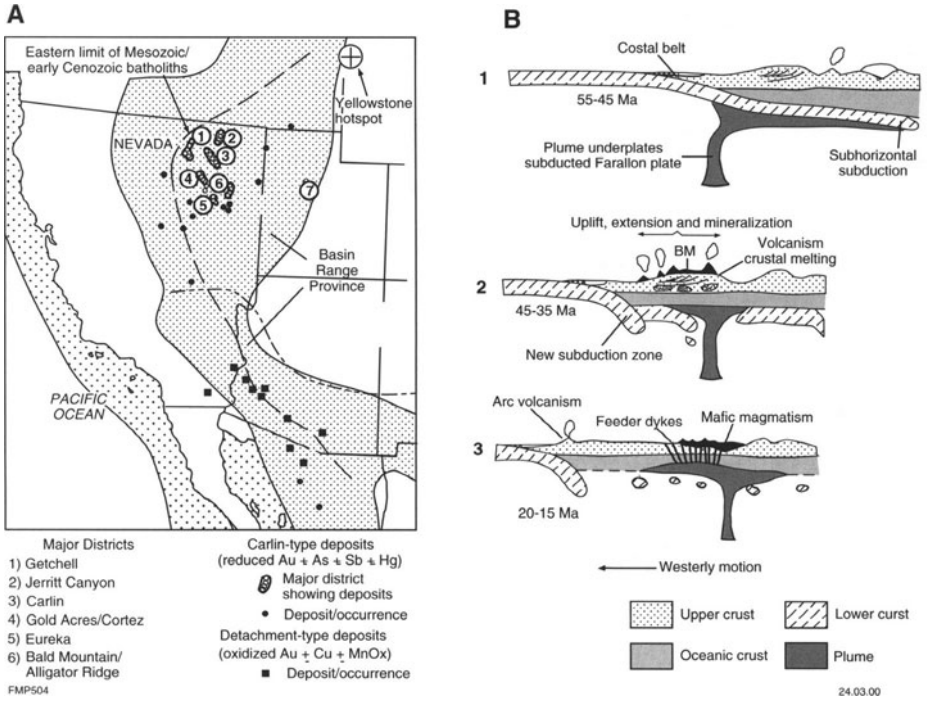


Figure 9.4. (A) Schematic map showing: 1) extent of the Basin-and-Range province in the western USA and Mexico; and 2) location of major districts containing Carlin-type deposits in Nevada; note position of the Yellowstone hotspot (after Ilchik and Barton, 1997). (B) Schematic evolutionary tectono-magmatic sequence of the western USA; between 55 and 45 Ma flat subduction extends about 1200 km into the continent and is above the Yellowstone hotspot (1); between 45 and 35 Ma the mantle plume incorporates material from the subducted slab, the plume generates uplift, extension and magmatism, it is at this time that important mineralising events take place, including Mo-Cu porphyry systems and the epithermal gold deposits; (2); between 20 and 15 Ma plume breakout causes bimodal magmatism with dyke emplacement and flood basalts (after Oppliger et al., 1997).

Bagby and Berger (1985) defined two subsets of the sediment-hosted Carlin-type deposits: 1) jasperoidal and 2) Carlin sensu-stricto. There is a complete gradation between the two, and both have a strong correlation with Hg, As, Tl and Sb. The jasperoidal subset includes deposits hosted in jasperoid, quartz veins and silicified wall rocks. The term jasperoid refers to an epigenetic body that consists of fine-grained ferruginous chert, which has replaced a pre-existing rock. Most jasperoid bodies are structurally controlled or located at contacts between carbonate rocks and shale. The dominant ore mineralogy consists of Fe oxides, pyrite and micron-sized gold. The Carlin subset is characterised by evenly disseminated gold and silver in rocks that are not obviously silicified. The ore zones are tabular or pod-like and extend several tens of metres from the controlling structures.

Radtke et al. (1980) classified the Carlin unoxidised ore into: normal, siliceous, pyritic, carbonaceous and arsenical. In normal ore, 25 to 50% of the original calcite was removed by the hydrothermal solutions, and small amounts of pyrite, fine silica and gold were introduced. Gold is associated with organic carbon. Carbonaceous ore contains up to 5 wt% organic carbon, is dark grey to black in colour and also contains small veinlets of hydrocarbons. In addition to pyrite, the carbonaceous ore also contains reagar, orpiment, stibnite, cinnabar, sphalerite, galena and a mineral called carlinite (Tl_2S). Gold is associated with the carbonaceous material and forms coatings on the pyrite. Arsenical ore, as the name implies, contains high abundances of As, due to the presence of realgar and orpiment. Here too gold is associated with carbon. Siliceous ore only accounts for about 5% of the unoxidised mineralisation, contains large amounts of introduced silica and grades into the jasperoidal subset. Gold is associated with pyrite, realgar and stibnite. Pyritic ore is characterised by the high pyrite content, some of which is framboidal.

The association of the gold with organic carbon, and locally with hydrocarbons, is typical of most Carlin-type deposits. This organic carbon consists of veinlets, seams and particles of amorphous carbon. The precise relationship between gold and carbon is unknown, although the reducing power of the carbon may have been the catalyst for the precipitation of the gold. Organic carbon was probably introduced with the main-stage hydrothermal fluids, but in terms of ore genesis it appears that the role of the carbonate rocks is of greater importance. The removal of calcite and its replacement by silica-rich gold-bearing ore fluids was a key factor in the formation of the orebodies. Thus, the main stage of hydrothermal activity consisted of decalcification, argillisation, silicification and pyritisation (Radtke et al., 1980). In the Alligator Ridge district (Nevada)

Carlin-type ores are associated with liquid hydrocarbons, where it is found as fluid inclusions in calcite and realgar and in vugs (Hulen and Collister, 1999). Homogenisation temperatures of the oil-bearing inclusions are lower than 150°C. Hulen and Collister (1999) suggested that the Alligator Ridge (Yankee Basin) fossil hydrothermal system is similar to active, but Au-poor, geothermal system that are associated with oil reservoirs. Hulen and Collister's work has important implications because it may provide a link between Carlin-type gold deposits with Mississipi Valley Type (MVT) base metal deposits, which are also associated with a rift-basin setting and oil reservoirs, as detailed in Chapter 10.

Genetic models that have been proposed for the origin of Carlin-type deposits, include magmatic and non-magmatic models. In one magmatic model, the mineralisation is the result of distal deposition from magmatic hydrothermal fluids that originate in porphyry stocks (e.g. Sillitoe and Bonham, 1990). Berger and Bagby (1991) also invoked a magmatic model. They considered that the Carlin deposits were formed as a result of granodioritic or alkaline intrusions, which produced stockworks and skarn deposits just above their roof zones. Deeply circulating meteoric waters mixed with the magmatic-hydrothermal solutions, to rise along faults and to form jaspers first. At a later stage replacement ore zones affected the finely laminated sedimentary rocks, whose carbonate and organic-rich composition was particularly favourable for the precipitation of gold and associated sulphides. In a non-magmatic model, Ilchik and Barton (1997) proposed that meteoric fluids were heated by high thermal gradients during crustal extension and the gold was scavenged by interaction of the fluids with the sedimentary rocks at depth.

Oppliger et al. (1997) linked the Carlin-type deposits with the Yellowstone hotspot (Fig. 9.4). They argued that the impingement of the Yellowstone plume beneath north-central Nevada in the Eocene, resulted in metasomatism, thermal weakening of the lithosphere and magmatism. This, in turn, caused metamorphic devolitilasation of the lower crust (see Chapter 6) and widespread hydrothermal convective circulation in the upper crust. They also argued, quoting Rock and Groves (1988), that the source of gold and associated elements, may have been the core-mantle boundary, where the plume originated.

9.2.4.2 Carlin-type mineralisation in Tuscany, Italy

In peninsular Italy, recent discoveries have been made in central-southern Tuscany, where pyrite, base metals, Sb and Hg have been mined for more than 2500 years. The Tuscan province, on the inner side of the northern Apennines, comprises an area where magmatic activity, consisting

of granitic and felsic volcanic products developed during the Tertiary and Quaternary. The province is characterised by high heat flow, which is largely responsible for the widespread hydrothermal flux in the region. An overview of the Italian epithermal precious metal deposits is given by Lattanzi (1999).

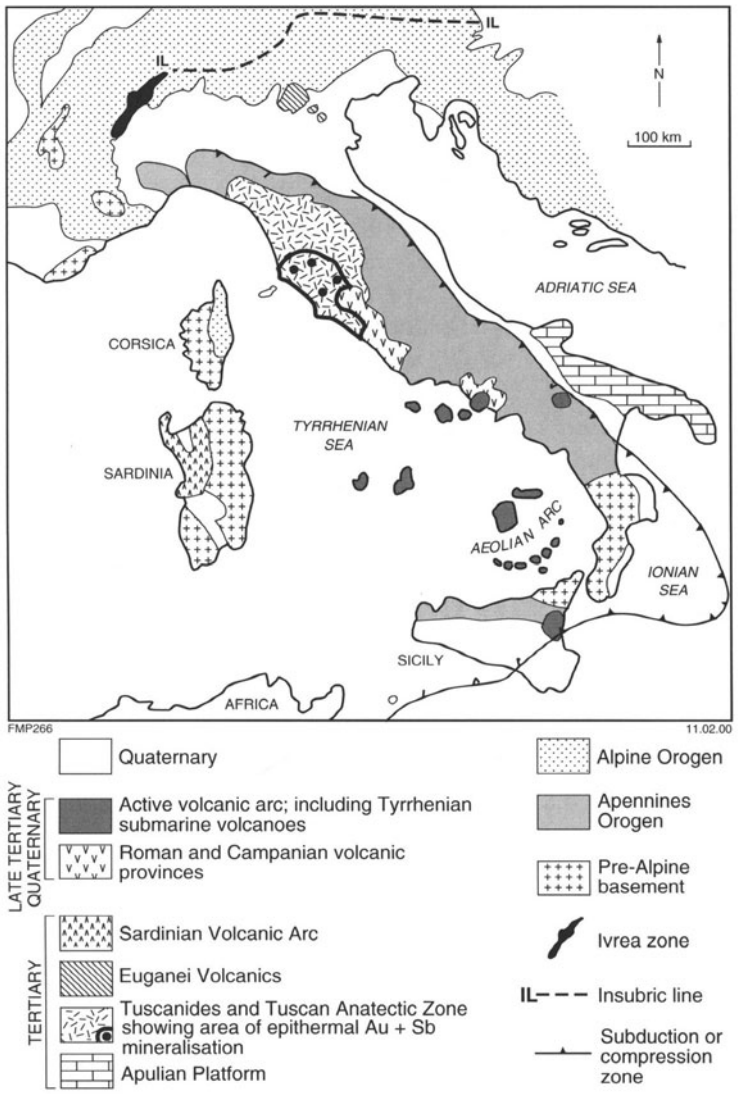


Figure 9.5. Schematic geotectonic map of Italy, showing distribution of Carlin-type epithermal mineral deposits in the Tuscan Province. Modified after Zuffardi (1985).

The epithermal Au mineralisation of central-southern Tuscany (Fig. 9.5) is hosted in Mesozoic carbonate units, known as "calcare cavernoso", which as the name implies is a highly permeable rock type. These units belong to the Tertiary Apennine orogen, which in Tuscany from bottom to top include: a Palaeozoic-Triassic metamorphic basement (Tuscan metamorphic complex), Triassic-Oligocene clastic, "calcare cavernoso" units, chert and shale (Tuscan Nappes or Series), flysch units of Cretaceous to Eocene age, and the "Neoautoctono" consisting of post-orogenic sedimentary rocks (Tanelli et al., 1991). The Tuscan Series is the main reservoir for the subsurface hydrothermal circulation.

Surface and near-surface Sb-Hg mineralisation is common. Cinnabar is present in porous rocks, in fractures and replacing carbonate rocks . Stibnite is associated with pyrite, marcasite, realgar, cinnabar, barite, gypsum, fluorite and quartz, and also replaces limestone. Very fine Au mineralisation (10 to 15 μ), present in late-orogenic northwest-trending structures, is associated with extensive silicification (jasperoid) of the carbonate rocks, below or at the contact with overlying impermeable flysch units (Tanelli et al., 1991), although hydrothermal alteration is by no means confined to carbonate rocks. In the jasperoidal rocks, base metal, Hg, Sb and Au mineralisation and accompanying alteration phases show a depth-controlled zonation. Chalcedony, quartz, epidote, calcite and sericite, with varying amounts of pyrite, stibnite, galena, tetrahedrite, cinnabar, arsenopyrite and gold are followed upward by alunite, kaolinite, smectite, gypsum, calcite, pyrite, haematite, barite, Sb-Hg-As sulphates, fluorite and gold (Tanelli et al., 1991). Supergene alteration, mainly as Sb-Fe-Mn oxides and hydroxides also contain gold. Fluid inclusion studies indicate homogenisation temperatures of 115 to 230 °C and NaCl-equivalent salinities ranging from 1 to 4 wt% (Tanelli et al., 1991). In some prospects, grades of between 5 and 25 g/t Au have been recorded in drill-holes (M. de Angelis, pers. comm. 1997).

The frequency and extent of the mineralisation, areas of alteration, presence of numerous hot springs and geothermal fields (Larderello and Mt. Amiata), are indicative of a large scale hydrothermal system. A genetic model of the carbonate-hosted epithermal Au mineralisation in Tuscany is presented in Fig. 9.6. Tanelli et al. (1991) suggested that the Tuscan hydrothermal system is the result of high heat flow related to Pliocene-Quaternary crustal thinning and mantle upwelling. Crustal partial melting resulted in extensive granitic magmatism, which vented at the surface to produce the acid and alkaline Roman Volcanic Province.

From a more global perspective, the Tuscan anatectic and Roman volcanic provinces, associated block faulting and crustal thinning, may be

related to a sheet-like region of mantle upwelling. This is the hypothesis put forward by Hoernle et al. (1995), who on the basis of seismic tomography, integrated with Pb, Sr and Nd isotopic data, suggested that extension, rifting and volcanism (tholeiitic to alkaline) propagated from the eastern Atlantic (Canary Islands) to the central European and western Mediterranean volcanic provinces. The authors further suggested that the varied and complex tectonic and magmatic expressions of this vast region may all be surface manifestations of this upwelling hot mantle sheet.

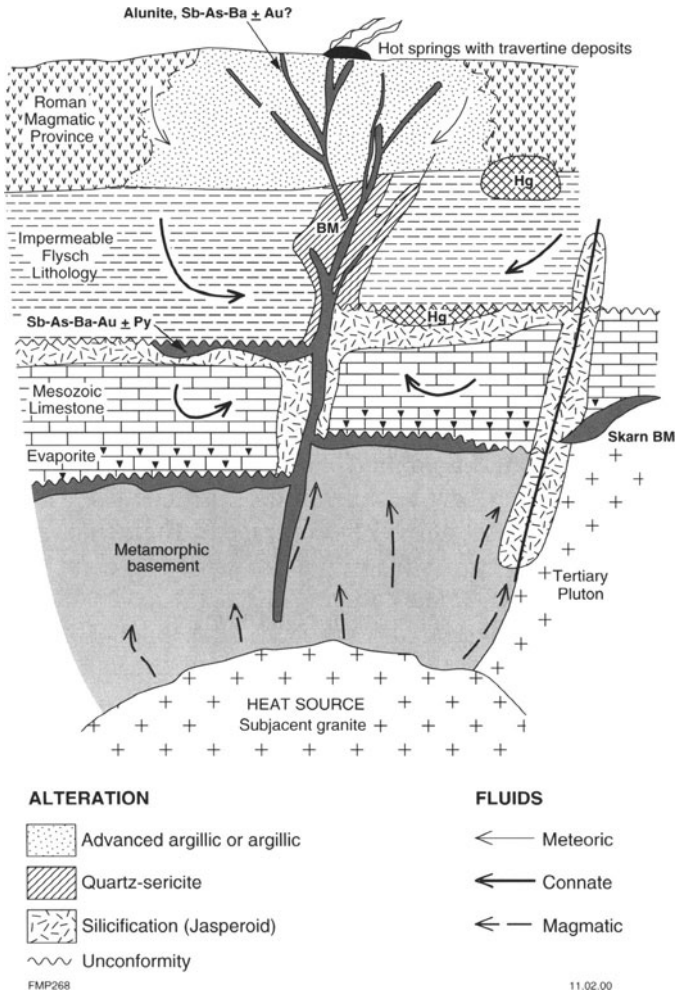


Figure 9.6. Conceptual ore genesis model for the Tuscan epithermal mineralisation in central Italy. After Moroni and Pirajno (1989) and Lattanzi (1999). BM is base metals.

This upwelling mantle sheet may be linked to the Central Atlantic Magmatic Province, which Oyarzun et al. (1997) ascribed to a mantle plume located at an ancient triple junction between North America, Africa and Western Europe (see Chapter 2 and Fig. 2.5). The plume material migrated westward, resulting in time-transgressive magmatism from the Cape Verde and Canary islands in the southwest in the Cretaceous to the Massif Central and the Rhine Graben, and reaching the Bohemian Massif and perhaps northern-central Italy in the late Cenozoic. The Tuscan anatectic province may be a distal expression of this Atlantic mantle plume.

9.3 Metallogeny of the Damara and Irumide orogens, southwestern Africa, and the Mid Continent Rift System, USA

This section presents a regional overview of the metallogeny of two important rifting systems that can be related to mantle plume activity, the Neoproterozoic Damara and Irumide orogens in Namibia, and the Mid Continent Rift System in North America.

9.3.1 Metallogeny of the Damara and Irumide orogens

In Chapter 4 we discussed the Mesoproterozoic Irumide and the Neoproterozoic Damara orogens, which connect with the Lufillian and Zambezi fold belts to the northeast and towards the interior of the southern African subcontinent (Fig. 9.7). We also examined the hypothesis that these orogens were formed during a series of rifting events, which resulted from the impact of a mantle plume, and illustrated in Fig. 4.12. The Damara and Irumide orogens are chosen for our discussion, because of their contrasting geological features, in spite of their common origin as rift systems that developed on continental crust. The subsequent geological history took these orogens on different evolutionary paths, and their metallogeny reflects this evolution.

9.3.1.1 Damara metallogeny

The Damara Orogen has been the focus of intensive studies (e.g. Miller, 1983; Martin and Eder, 1983) and is well-endowed with a range of diverse mineral deposit types (Pirajno, 1992; Mineral Resources of Namibia, 1992; Steven et al., 1994).

The metallic mineral deposits of the Damara belt cover a wide range of types, and were formed during: 1) extensional phases with the development

of metalliferous deposits in intracontinental rifts, continental shelf and oceanic crust environments, and 2) convergence and collision tectonics, with the development of metalliferous deposits associated with metamorphism and the generation of crustal partial melts. The distribution of metallic ore deposits of the Damara Orogen is shown in Fig. 9.7.

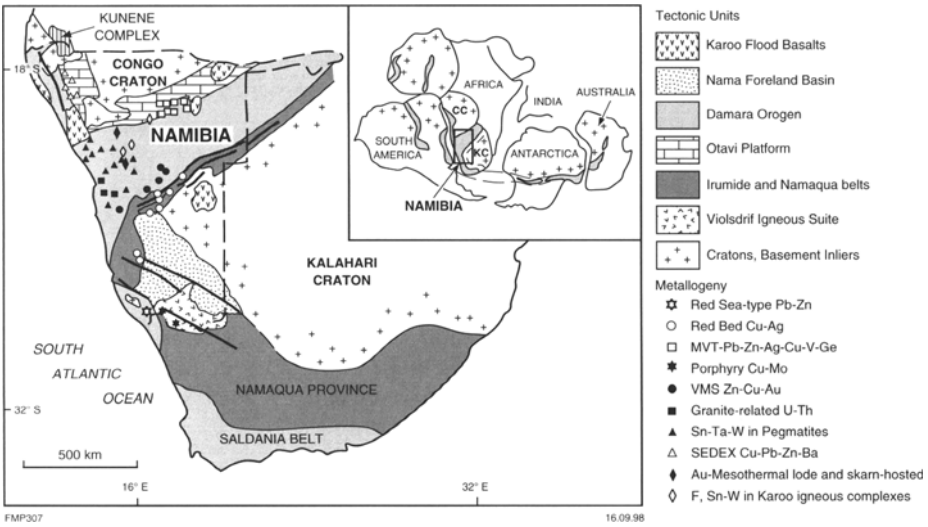


Figure 9.7. Simplified geology of southwestern Africa, showing the distribution of selected mineral deposits in Namibian part of the Damara Orogen. The adjacent Irumide Orogen, which contains stratabound base metal sulphide deposits, probably also originated through rifting processes induced by a mantle plume (compare this figure with Fig. 4.12). Inset shows the position of the Damara Orogen and its correlation with orogens of the same age in a Gondwana reconstruction (compare this inset with Fig. 3.25).

During extension, numerous lenses of volcanogenic massive sulphides (Cu-Zn-Ag-Au) were formed in oceanic crust, later to become part of the Matchless Amphibolite Belt. One of these, the Otjihase deposit, had reserves of about 16 Mt at 2% Cu, 0.3-0.6% Zn, 9-10 ppm Ag and 0.35-0.5 ppm Au. The surface expression of this mineralisation is characterised by distinctive gossanous magnetite quartzite outcrops associated with gossan lenses intercalated with schist. The Northern Platform carbonate rocks (Otavi Group) host about 600 Mississippi Valley-type (MVT) ore deposits and occurrences, the most famous and largest of which are the inoperative Tsumeb, Kombat, Berg Aukas and Abenab polymetallic deposits in the Otavi Mountain Land (Frimmel et al., 1996). The mineralisation is contained in a variety of loci including pipes, solution breccias, shear

zones and fractures. Two types of deposits are recognised (Pirajno and Joubert, 1993): Tsumeb type and Berg Aukas type. The former is characterised by complex ores containing sulphides of Cu, Pb, Zn, Ag, As, Ge, Cd, W, Ga, and Fe-Mn oxides and silicates. The latter is characterised by Pb, Zn and V, and is similar to the Pb-rich members of the classic MVT deposits in the USA. The MVT deposits of the Damara Belt have been correlated with similar ore deposits in the Lufillian arc (Katangan sequence), such as the Kabwe Pb-Zn deposit in Zambia (Kamona et al., 1999). We return to discuss the Otavi MVT deposits in Chapter 10. Scheelite mineralisation hosted by stratiform tourmalinite rocks is present in rocks of the Kuiseb Formation. Grades are up to 2.6% WO_3, with anomalous Sn and F (Steven and Moore, 1995). The origin of this mineralisation is not known, but a syngenetic mechanism in an extensional setting is considered possible.

Convergence and collision resulted in the emplacement of late- and post-tectonic granitoids, resulting in a range of types and styles of magmatic and epigenetic Au, U, Cu, W, Sn, Ta and REE mineralisation. An excellent and detailed review of the Damaran epigenetic mineralisation can be found in Steven (1993).

Gold ± Cu ± Bi ± W-skarn mineralisation is present in marble rocks of the Karibib Formation, near the towns of Karibib and Usakos. The currently operating Navachab mine, came into production in 1990 with an ore reserve of 11 Mt at 2.6 g/t Au. Similar occurrences in the region include Onguati, Brown Mountain, Habis and Otjimboyo.

At Ondundu, Au is associated with a package of stacked quartz veins hosted by lower-greenschist facies turbidites of the Kuiseb Formation. The veins vary in thickness from 2 cm to 1 m and are developed along a strike length of approximately 4 km. The style of the Ondundu mineralisation is very similar to the saddle reef deposits of the Slate Belt in Victoria (Australia; Ramsay and Vandenberg, 1990; Phillips and Hughes, 1995).

Pirajno and Jacob (1988, 1991) observed that many of the hydrothermal Au deposits in the Damara Orogen are located within isograds defining areas of medium- to high-grade regional high-temperature, low-pressure metamorphism, and that they are distributed around positive gravity anomalies (Fig. 9.8). The distribution of these Au deposits around a central zone of high-grade metamorphism and anatexis, suggests that they may be linked to thermal and metamorphic gradients in the plume-related triple junction, where the three arms of the Damara Orogen converge (see Chapter 4).

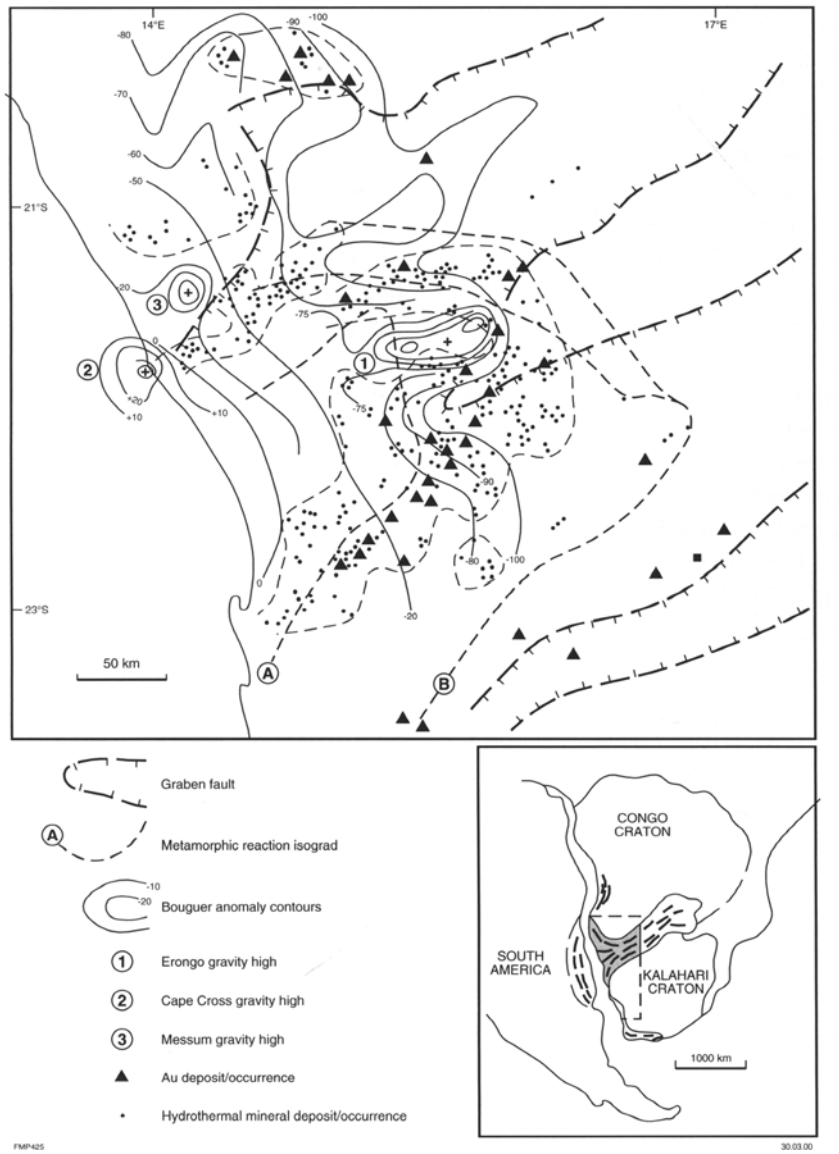


Figure 9.8. Simplified sketch of part of the intracontinental branch of the Damara orogen, showing tectono-stratigraphic zones, metamorphic isograds and distribution of hydrothermal occurrences and Au deposits. Note that the mineral occurrences and deposits are almost entirely located between the amphibolite (A) and greenschist (B) isograds. Inset shows the position of the orogen prior to the opening of the South Atlantic ocean, and the triple junction, where the rift arms converge. After Pirajno and Jacob (1988 and 1991; isograds after Porada, 1979). See also Fig. 4.12.

Granite-related and pegmatite-hosted Sn-W ± Ta mineralisation is present at several localities in the Damara Orogen (Pirajno and Jacob, 1987). These can be grouped into three zones or belts: 1) Brandberg West-Goantagab; 2) Strathmore-Uis and Neneis-Kohero belts; 3) Erongo-Karibib. Brandberg West, was mined between 1945 and 1980, during which some 14 000 t of concentrate was produced. The Brandberg West-Goantagab mineralisation consists of quartz veins associated with greisen-type alteration and Fe-Sn-rich replacement bodies. The deposits have a distinct spatial association with circular structures, possibly related to concealed granitic intrusions. The Strathmore-Uis stanniferous pegmatite field is one of the largest in Africa. The now abandoned Uis mine exploited a group of unzoned pegmatites which had reserves in excess of 100 Mt at grades of about 0.15% Sn, with Ta being recovered as a by-product. The host rocks are spotted pelitic schist of the Kuiseb Formation. Tourmalinisation of the schist is present up to 200 m away from the pegmatites. The Erongo-Karibib field is characterised by zoned pegmatites containing Sn, Li, Be, Cs and Nb-Ta minerals. The Rubicon mine exploited a complexly zone pegmatite containing petalite, amblygonite, lepidolite, beryl, pollucite and bismuth.

Uranium mineralisation is widespread in the high-grade western end of the Central Zone. Alaskite-hosted U is mined at Rossing, but similar mineralisation is also present at Goanikontes, Ida Dome and Valencia. The alaskites have ages ranging from 542 to 470 Ma, are located on on the margins of basement domes and are hosted in rocks at the Nosib-Swakop Groups boundary. Ore minerals include uraninite, betafite, uranophane, carnotite and some niobates. The origin of the mineralisation is related to partial melting of Nosib Group and U-enriched basement rocks, within the area of the inferred triple junction (see Fig. 4.12).

9.3.1.2 Irumide metallogeny

The northeast-trending, 1000-km long, Irumide belt contains volcano-sedimentary successions that accumulated in several rift basins, such as Koras, Sinclair, Klein Aub, Witvlei, Ghanzi and Lake Ngami, between Namibia and northern Botswana (Fig. 9.7). The volcano-sedimentary successions are characterised by bimodal volcanic rocks of rhyolitic and basaltic composition, conglomerates, sandstone, shale and carbonate rocks. The volcanic rocks of the Irumide belt (Koras-Sinclair-Ghanzi rift) have been correlated with the mafic volcanic rocks of the Umkondo Group, as part of a Proterozoic continental flood basalt province (Hanson et al. (1998; see Chapter 3). Stratabound Cu-Ag deposits are present in these rift basins, constituting the Kalahari copperbelt (Fig. 9.7).

Cu and Cu-Ag mineralisation in the Klein Aub, Dordabis, Witvlei and Lake N'gami rift basins is hosted by coarse clastic sediments, shale and mafic volcanics. The Klein Aub Cu-Ag deposit, about 180 km south of the Namibian capital city Windhoek, is contained within stacked bands of fine-grained laminated siltstone and argillites of the Klein Aub Formation (Sinclair Group). The mineralised horizons are from 0.5 to 1.5 m thick and are cut off by a reverse fault. Several ore shoots are present along 6 km of strike length; some of the shoots extend to 600 m below the surface and their plunge coincides with the direction of palaeocurrents, suggesting a sedimentological control. The mineralisation consists mainly of chalcocite with lesser amounts of pyrite, chalcopyrite, bornite, digenite and covellite. The siting of the silver metal is unclear, but it could be associated with hematite (Tregoning, 1987). The sulphides form either fine disseminations or are distributed along cleavage planes and bedding plane fractures (Borg and Maiden, 1987).

Lead isotope studies indicated that the mineralisation is sourced from basement rocks. Sulphur isotopic values range from – 20 to – 40 permil $\delta^{34}S$, suggesting bacterial-mediated fractionation.

Borg and Maiden (1987) proposed a multistage ore genesis for the Klein Aub mineralisation, involving leaching of metals from the underlying mafic volcanic rocks, which locally contain native copper in lava flow tops. These authors envisaged four main stages, which from oldest to youngest, are: 1) extrusion of basaltic lavas and red-bed deposition in an environment of block faulting; followed by 2) a marine transgression, accompanied by a change from oxidising continental conditions to a reducing shallow marine environment, where organic sulphur enabled the formation of syn-sedimentary sulphides; and then 3) fluid flow through compaction and basin dewatering leached metals from basement rocks, basalts and red beds. The fluids precipitated Cu on contact with sulphur-bearing sediments. A fourth stage involved metamorphism and deformation, which resulted in devolitilisation reactions (see Chapter 6) and the production of hot fluids. These latest fluids leached more metals from the basaltic lavas. The hydrothermal alteration of these basalts is used as evidence of fluid circulation. Faults provided the channelways for the upward movement of these fluids. This scenario is similar to that of the stratabound Cu mineralisation of the Mid-continent Rift System of North America, which is the topic of the next section.

9.3.2 Metallogeny of the Mid-continent Rift System, North America

On the eastern side of the North American continent the Neoproterozoic (about 1.1 Ga) Mid-continent Rift System hosts numerous mineral deposits. The general geology of the Mid-continent Rift System is discussed in Chapter 3. Here we examine the metallogeny associated with this major continental rift, which extends along a north-northeast trend for about 2000 km from Kansas, in the USA, across Lake Superior into Ontario, where it swings southeastward into Michigan (Fig. 3.26). Norman (1978) reviewed the mineral deposits of the Lake Superior region, and Nicholson et al. (1992) reviewed the regional metallogeny of the Mid-continent rift. Most of the information in this section is taken from these authors.

The Mid-continent rift contains magmatic and hydrothermal mineral deposits. Magmatic deposits include Ni-Cu and Ti-Fe ± V in the Duluth Complex (Minnesota), briefly discussed in Chapter 8 (Fig. 8.15). Cu-Ni ± PGE deposits, other than those of the Duluth Complex, are those of the Crystal Lake and Mineral Lake gabbroic intrusions in Ontario.

Other magmatic deposits include U-REE-Nb-Cu in the carbonatite-alkaline ring complexes of Coldwell, Killala Lake and Prairie Lake (Ontario), and the base metal-Au-Ag-bearing breccia pipes in the Tribag area (Ontario). These complexes consist mainly of gabbro, nepheline syenite and syenite, with gabbro at the rim and the syenetic units in the core. One the resources of these ring complexes is pyrochlore (Nb) in the syenite and disseminated Cu sulphides in the marginal gabbroic rocks. The Prairie Lake carbonatite-ijolite ring complex contains greater than 1% apatite, whereas a reserve of about 200 000 t of pyrochlore, with grades of 0.09% U_3O_8 and 0.25% Nb_2O_5 was delineated during exploration in the 1960s.

Breccia pipes on the eastern side of Lake Superior (Tribag area) contain disseminated Cu and Cu-Mo mineralisation. These pipes are emplaced within Archaean basement rocks, about 6 km from the contact with overlying Keeweenawan basaltic lavas. The breccia pipes have a diameter of approximately 100 m at the surface, and the breccia fragments consist of Archaean metavolcanic and granite rocks, and diabase cemented by quartz, carbonate and ore minerals. Hydrothermal alteration is dominated by sericite. Sulphide mineralisation consists of chalcopyrite, pyrite, sphalerite, galena, tetrahedrite and molybdenite. The pipes are similar to those at Messina, northern Transvaal (South Africa), in one of the rift arms of the Tuli-Sabi-Lebombo hotspot junction (Chapter 4; Pirajno, 1992). Always in the Tribag area, stockworks containing Cu and Mo

sulphides are present in a 1070 Ma porphyritic quartz-monzonite stock that intruded Archaean basement.

Hydrothermal ore deposits of the Mid-continent rift include syn-late rifting stratabound and/or stratiform Cu ± Ag mineralisation. These include the famous native copper deposits of the Keweenaw peninsula (Michigan), such as the sandstone-and shale-hosted White Pine deposits (Michigan) and various polymetallic veins and lodes. Keweenawan copper had been exploited by indigenous Americans prior to the advent of the Europeans.

Native copper and silver, associated with chalcocite, are present in brecciated and amygdaloidal basaltic lava flow tops and interflow clastic sedimentary units. The strataboound and lode native copper deposits extend for some 100 km in the Keweenaw peninsula of Lake Superior, from which about 5 x 10^6 tonnes of copper metal have been mined between 1845 and the 1960s.

In the White Pine area the mineralisation is within the Parting Shale Member of the Nonesuch Shale Formation, which overlies the basaltic lavas and minor rhyolites of the 5000 m-thick Portage Lake Formation. The Nonesuch Shale Formation is 180 m thick and consists of interbedded shale and siltstone. The main ore minerals are native copper, chalcocite, pyrite, bornite, chalcopyrite and native silver. There appears to be an association with the carbonaceous sedimentary rocks. A broad lateral and vertical zonation is characterised by a lower native copper zone, followed upwards by a chalcocite-native copper zone, then a chalcocite zone overlain by an extensive pyrite-dominated area (Brown, 1971). Although the mineralisation is stratabound, on a regional scale the zoning patterns are transgressive to bedding. The cupriferous zones reach a maximum thickness at the intersection of the White Pine fault with a sandstone palaeohigh. Copper grades decrease away from the fault suggesting that it acted as a channel for the hydrothermal fluids. Brown (1971) suggested that the origin of the Keweenawan native copper deposits is related to chloride-rich brines (basinal and/or magmatic?). These brines leached the metals from the basement and the mafic rocks, which have an average of about 120 ppm Cu. The metals were then deposited in the porous lava flow tops and in the reducing environment of the overlying sedimentary rocks.

9.4 Archaean lode Au deposits

Lode Au deposits in Archaean granite-greenstone terranes are well-known and constitute a major resource of this precious metal in Western Australia, South Africa, Zimbabwe, Canada, India, Russia and Brazil.

Archaean lode Au deposits form a coherent genetic group, which for many years have been considered as, and are still popularly labelled as mesothermal lodes in predominantly greenschist facies rocks of greenstone successions (Groves and Foster, 1993; Groves, 1993; Groves et al., 1995). The classic example is probably the giant Golden Mile deposit of Kalgoorlie in Western Australia.

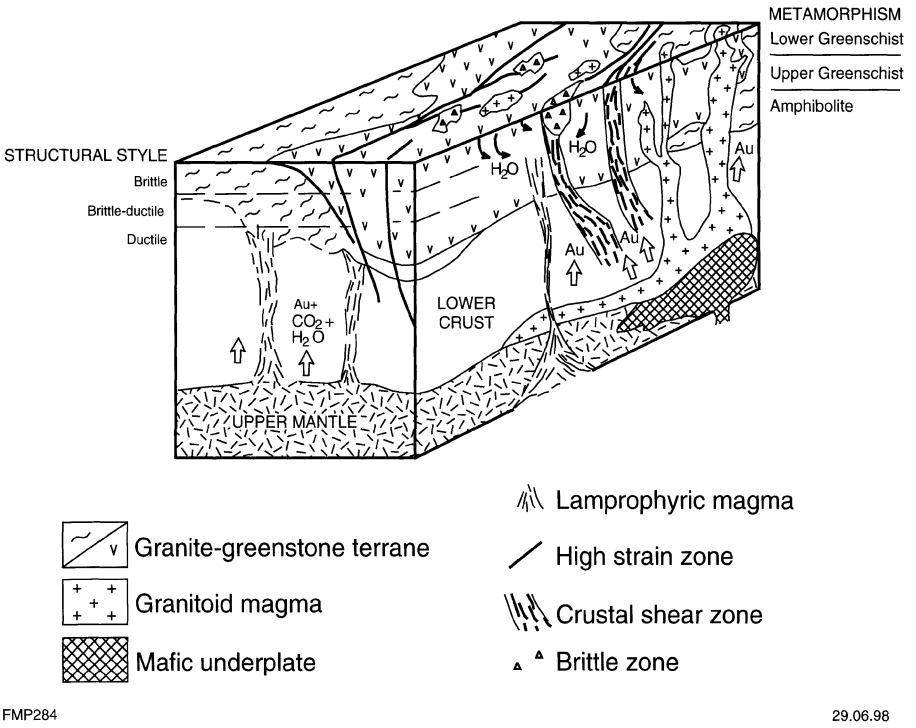


Figure 9.9. Schematic block diagram showing the crustal continuum model, in which mantle degassing (CO_2 + H_2O + Au), metamorphic devolatilisation reactions, granitic, mafic and lamprophyric melts combine to activate complex and large scale hydrothermal systems. Fluids are channelled along major crustal shear zones; cool meteoric waters may locally mixed with hotterCO_2-bearing deeply-sourced fluids. The mafic underplating, lamprophyric melts and granitoids may be linked with mantle plumes impinging at the base of the crust. This diagram is based on Groves and Foster (1991), Groves (1993) and Groves et al. (1995).

Archaean lode Au mineralisation is hosted in ductile shear zones, brittle-ductile, brittle fault zones, brittle quartz vein arrays and replacement style quartz reefs in banded iron-formation and other Fe-rich rocks. In addition to Au, other elements that are present, either as ore minerals or in various phases in alteration envelopes are Ag, As, W, Bi, Te, Pb, Sb, and B.

In the Yilgarn Craton (Western Australia), lode Au deposits form a broadly synchronous (2635 ± 10 Ma) group, over a range of epithermal to mesothermal styles, metamorphic environments from greenschist to granulite facies, and hosting lithologies (Groves, 1993; Groves et al., 1995). The mineralising fluids are typically deeply sourced, of low-salinity, containing H_2O, CO_2 and CH_4, with temperatures ranging widely from 180°C to more than 700°C, and pressures of 1 to 5 kb (Groves et al. 1995). Mixing with cooler meteoric waters is suggested in some cases, especially for those deposits that are hosted in brittle structures and low-grade metamorphic rocks. The timing of the Archaean Au mineralisation is syn- to post-peak metamorphism.

Data integrated from regional, structural, mineralogical, isotopic, fluid inclusion, geochemical, alteration and tectonic setting studies have led to the crustal continuum model advocated by Groves (1993), a version of which is illustrated in Fig. 9.9. The crustal-continuum conceptual model predicts that lode Au mineralisation is by no means confined to greenschist facies rocks, but can also be found in higher grade terranes. The results are clearly illustrated in Fig. 9.10, which shows the more significant Au discoveries in Western Australia, since 1986.

A direct genetic link, if any, between granitoid intrusions and the Archaean Au mineralisation remains elusive. The spatial and temporal relationship of the lode mineralisation to granitic rocks in Western Australia was investigated by Witt (1991), who noted the association of the lode mineralisation with K-metasomatism (muscovite, biotite, K-feldspar) in the thermal aureoles of late syntectonic granitoids emplaced in the final stages of the tectonic history of greenstone belts. This work led to the "synmetamorphic lateral fluid flow" genetic model of lode Au mineralisation in the Kalgoorlie and Norseman terranes in Western Australia (Witt et al., 1997). In this model, large-scale fluid flow systems are envisaged in two main stages. In the early stage, pervasive deeply-sourced fluid flow is channeled along shear zones; in a later stage, tectonic uplift and granitic intrusions promote lateral flow of fluids first towards areas of high heat flow and then along structural paths of decreasing temperature (Witt et al., 1997).

Smithies and Champion (1999) noted that crustal-scale hydrothermal activity appears to be associated with volumetrically minor felsic alkaline plutons, which were intruded along major crustal structures at 2650-2630 Ma, during peak metamorphism. Smithies and Champion (1999) suggested that this crustal-scale hydrothermal activity resulted from metamorphic dehydration of the crust, associated with an input of volatiles from the mantle. This mantle activity, according to these authors,

could have been related to processes of crustal delamination, similar to those described in Chapter 4.

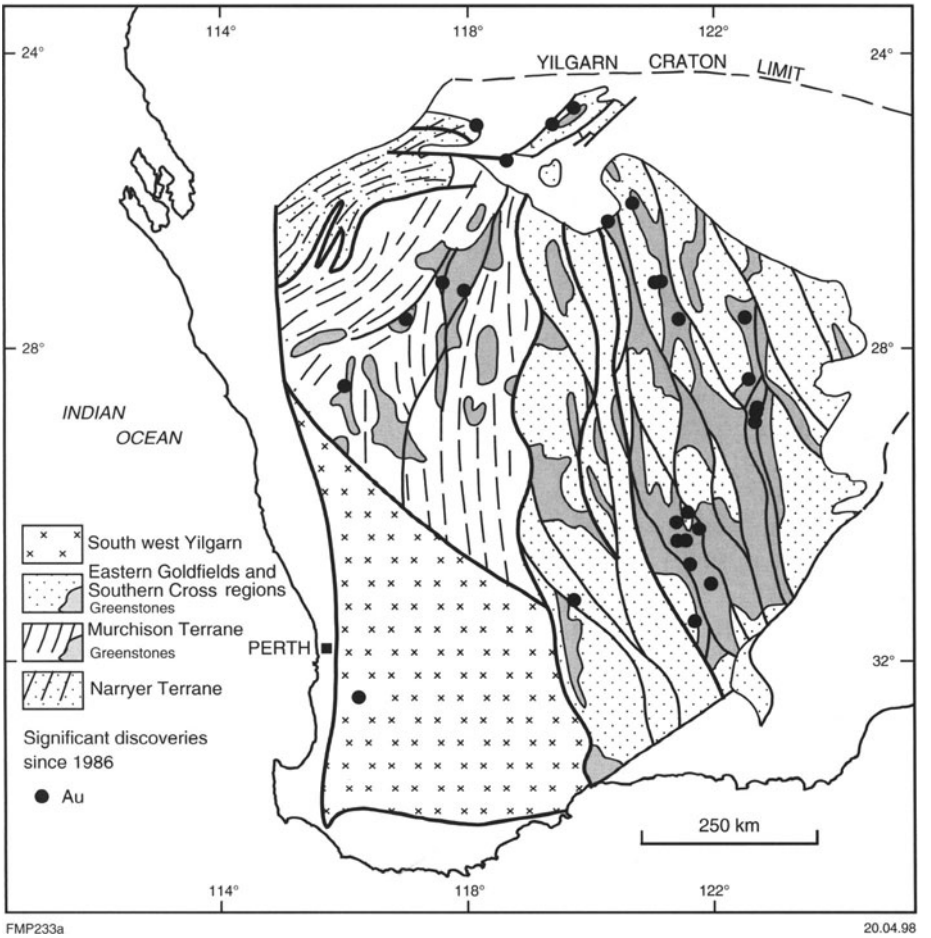


Figure 9.10. Simplified geological map of the Yilgarn Craton, showing distribution of principal Au deposits discovered since 1986. After Myers (1995).

Qiu and Groves (1999) proposed that unstable thickened crust, due to a continental collision event in the southwest Yilgarn Craton, was followed by lithospheric delamination and extensional collapse, which resulted in a major tectonomagmatic event between 2640 and 2630 Ma. This was a craton-scale thermal anomaly that would have been responsible for much of a giant hydrothermal system, resulting in the widespread Au minerali-

sation of the Yilgarn Craton. This collision event in the southwest Yilgarn Craton produced suites of granitic rocks, ranging from A-to I- and S-type, which are interpreted by Qiu and Groves (1999) as representing massive melting of the lower crust. These authors suggested that asthenospheric mantle upwelling due to lithsopheric delamination occurred towards the end of the collision event.

The ultimate origin of the Archaean fluids, however, remains contentious. Two end-member theories may be considered. One is that the large volumes of fluids were generated during the tectonic assembly of a cratonic province, of which the present-day Yilgarn is but a remnant. This is the view suggested by Myers (1995) and supported by Qiu and Groves (1999), who postulated that the Yilgarn craton was formed through the collision and amalgamation of accreted island-arc terranes. After the assembly of these terranes, the fluids passed through dextral transcurrent fault zones, which mark terrane boundaries. The other theory, perhaps implied in the crustal-continuum model is that fluids may be linked to interaction of mantle plumes with the lithosphere (Barley et al., 1998).

Interaction of a mantle plume with an island arc has been suggested for the Archaean Au mineralisation of the Abitibi greenstone belt in Canada (Wyman et al., 1999).

9.5 Concluding remarks

Ring complexes, many associated with carbonatite, are a common feature of intracontinental rift systems. Here we have examined those of the Damara province and briefly mentioned those of the Mid-continent Rift System. Various lines of evidence suggest that these complexes may result from distal effects of mantle plumes. Ring complexes and breccia pipes testify to localised episodes of melting, associated with the development of large volumes of volatiles, which in some cases break through towards the surface to form pipes with a great variety of shapes, sizes and mineral content.

Similarly, Olympic Dam-type polymetallic deposits appear to be related to a special type of anorogenic magmatism that was particularly well represented during the Proterozoic. In this book we have examined Olympic Dam and the less known Vergenoeg deposits, with the latter possibly being the volcanic expression of the former. The anorogenic magmatism that is responsible for the genesis of Olympic Dam-type deposits is linked to rifting and mantle plume events.

The emplacement of large, mafic-ultramafic layered igneous intrusions in the upper levels of the continental crust, causes major thermal anomalies.

We discussed this at some length in Chapter 6. This heat anomaly generates large-scale hydrothermal convective systems, which result in the emplacement of precious and base metal mesothermal ore deposits. Here, we have considered the example of the Sabie-Pilgrim's Rest goldfield in South Africa, which appears to be related to the thermal anomaly created by the Bushveld Complex.

In other instances, magmas of felsic composition are emplaced in regions of the crust that have been subjected to extension. This extension is explained as the mechanical result of the impingement of mantle plumes. This seems to be the case for the Basin-and-Range province in western USA, a region that lay above the Yellowstone hotspot and is endowed with a great variety of mineral deposits, of which the Carlin-type gold ores are perhaps the most famous. The Carlin-type epithermal gold mineralisation is much sought after in many parts of the world.

Gold mineralisation that resembles the Carlin-type is present in the carbonate rocks of Tuscany, very close to Rome. Ironically so, because in spite of the excellent mining skills acquired by the Romans elsewhere in Europe, they failed to recognise the presence of gold in their home country, although some justification must be allowed owing to the commonly "invisible" nature of epithermal Au. The Tuscan Carlin-type gold mineralisation is full of promises, in terms of possible future exploitation. Like the Basin-and-Range province, the Tuscan anatectic province too seems to have a link with the uprise of asthenospheric material, again with thermal anomalies, melting, plutonic and volcanic activity and surface manifestations ranging from active geothermal systems to hydrothermal mineralisation.

Continental rift systems are endowed with many different types of ore deposits, as exemplified by the Damara and Irumide orogens in Namibia, which were probably formed above a major hotspot junction. Some of the hydrothermal ore deposits of the Mid-continent Rift System in North America have similarities with those of younger rifts, such as the Tuli-Sabi-Lebombo in southern Africa. The widespread Fe and alkali alteration effects of these regions are reminiscent of the Olympic Dam-type deposits. This general feature could be exploited in the search of similar ore deposits in younger rift systems.

The origin of Archaean lode deposits have been and are still being debated, but evidence of mantle plume involvement is now being considered and tested.

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