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Broken Hill, Australia and Bergslagen, Sweden – Why God and Mammon bless the Antipodes!

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Abstract

The sulphide deposits of the Broken Hill and Bergslagen areas occur in Lower-Middle Proterozoic sequences of variably deformed low to high metamorphic grade rocks. The number of events of coeval deformation and metamorphism, intensity of deformation and grade of metamorphism at Broken Hill are higher than in the Bergslagen area. A long history of retrograde metamorphism has been recognised at Broken Hill. Furthermore, granitic rocks in Bergslagen are coeval with volcanicity associated with ore deposition or are post-tectonic whereas at Broken Hill all plutonic rocks can be related to events of metamorphism, especially retrogression. Bergslagen is characterised by abundant metavolcanics (especially explosive acid volcanics) and moderately shallow water sequences probably deposited in a rift whereas metasediments deposited in a deep rift predominate at Broken Hill. Mineralization at Broken Hill is at least two orders of magnitude larger than at Bergslagen, is intimately associated with three events of paired volcanism and is associated with a great volume of extremely diverse exhalite deposited in a moderately reducing environment.

The Bergslagen mineralization was probably deposited from numerous small seawater-dominated convective geothermal systems leaching metals from porous, permeable hot acid volcanic rocks. These geothermal systems produced regional alteration and localised intense footwall Mg-metasomatism associated with egress and ore deposition. In contrast, mineralization at Broken Hill formed in a deep rift every time there was a massive invasion of basaltic magma into faulted wet sediments. This increase in the geothermal gradient resulted in lower crustal melting, paired volcanism, initiation of geothermal systems, fault-bounded fluid ascent at the graben margin and with the resultant hydrothermal precipitation above the fault and the lack of widespread hydrothermal alteration.

It is suggested that the principal reason for the striking differences between Broken Hill and Bergslagen is that the proposed deep rift in thin crust at Broken Hill allowed tapping of anomalous metalliferous mantle fluid and the leaching of crustal rocks whereas at Bergslagen, there were possibly numerous small graben in an extenion zone hence heated seawater did not have access to a large volume of hot porous permeable crust for leaching, egress of the ore fluid was not focussed and there is no evidence for a mantle contribution to the ore fluid.

Introduction

The Broken Hill, Australia and Bergslagen, Sweden areas are similar in lithology, stratigraphy, depositional environment, mineral deposits, exhalites and tectonic history. After some 20 years of research on the Broken Hill area of Australia, two visits to the Bergslagen area, numerous visits to similar areas (e.g. Eastern Succession at Mt. Isa, Bushmanland of South Africa) and pre-ossification geological maturity of the author, it is suggested that although Broken Hill and Bergslagen have some similarities, the differences are outstanding and it is these dissimilarities that are highlighted herein in terms of a genetical model.

The data base at Broken Hill results from a hundred years of mining and exploration of over 5000 known occurrences of base metals, silver, cobalt, iron, manganese, gold, tungsten, tin, tantalum, titanium, niobium, lithium, beryllium, cesium, uranium, thorium, nickel, platinoids and nonmetallics; numerous mineral booms with the resultant intensification of exploration, mining and research; good exposures; no vegetation; a different exploration, financial and taxation philosophy; kangaroos; a repository at Broken Hill of over 1200 exploration and mining reports, scientific publications and theses; preservation of core at Broken Hill of thousands of diamond drill holes which are regularly relogged; the compilation of all known data from Broken Hill, the remapping of the 10 000 km^2 Willyama Supergroup and subsequent publication of 1:25 000 scale maps by the geological Survey of N.S.W.; co-operation between the numerous mining companies at Broken Hill; mining company support, co-operation and healthy competition between research Institutes interested in Broken Hill problems; and the testing of every new scientific, geophysical and geochemical technique at Broken Hill. It is no surprise that such a climate induces creativity (e.g. invention of flotation of sulphides) and has trained and stimulated generations of geoscientists.

Although the data base for Broken Hill is orders of magnitude larger than that for the Berslagen area (despite over a millenium of mining), it is a cruel irony that no substantial new ore reserves have been discovered outside the immediate area of the Broken Hill orebody since discovery on 5th September, 1883.

The aim of this paper is to attempt to explain why a sequence of eight stacked sulphide masses comprising at least 280 Mt of 20% (Pb + Zn) occur at Broken Hill in the Early-Middle Proterozoic Willyama Supergroup whereas massive sulphide deposits at least an order of magnitude smaller occur in the Middle Proterozoic South Svecofennian Volcanic Belt of Sweden.

Tectonic history

The Willyama Supergroup (~1820 Ma, Willis et al. 1983) and the volcano-sedimentary complex of the South Svecofennian Volcanic Belt in the Bergslagen area (1800–1900 Ma, Welin et al. 1980) have undergone multiphase deformation and metamorphism. At Broken Hill, the first generation of coeval granulite facies metamorphism (M1, $T = 760$–$800°$ C, $P = 5.2 - 6$ kb, $aH_2O = 0.3 - 0.6$, Phillips 1980) and nappe-like folding (D1) occurred at 1660 Ma followed immediately by coeval granulite facies metamorphism (M2) and isoclinal folding (D2) (Stevens 1986). Detailed studies on refolded isograds by Phillips (1980) showed that metamorphic grade in the Broken Hill area increases down stratigraphy and from the NW (amphibolite facies, $T = 500$–$580°$ C, $P = 3$ kb, $aH_2O = 1.0$) to the SE (Broken Hill area, granulite facies, $T = 760$–$800°$ C, $P = 5.2 - 6$ kb, $aH_2O = 0.3$–0.6).

In the Bergslagen area, a minor set of ENE-WSW and ESE-WNW trending open folds has superimposed tight folds trending NNW-SSE which are parallel to the axis of a proposed depositional basin (Saxå Basin, Oen et al. 1982). However, the author has noted a persistent prominent steeply-plunging lineation suggesting that the structural interpretation in the Bergslagen area is more complex than those published. Mineral assemblages of felsic, mafic and pelitic metasedimentary rocks described in Welin et al. (1980), Gaal (1982), Lagerblad & Gorbatschev (1985) and Kresten (1986) indicate an increase in metamorphic grade from lower greenschist facies in the west (Grythyttan area) to amphibolite facies in the east (eastern Bergslagen area).

A long history of retrogression occurred at Broken Hill after high prograde metamorphism as transgressive conjugate arcuate sets of retrograde shears zones (M3, $T = 350$–$600°$ C, $P = 3$–5.5 kb, $aH_2O = 1.0$) coeval with open folding (D3) followed by lower metamorphic grade incipient pseudomorphous retrogression (300–500° C). A period of retrogression occurred between 1660 and 1490 Ma with major retrograde events at 1605 and 520–458 Ma (Stevens, 1986). Retrograde shear zones within prograde granulite areas have higher

P-T assemblages (T = 550–600° C, P = 5–5.5 kb) than those transgressing low metamorphic prograde areas (T = 350–530° C, P = 2–4 kb, Corbett & Phillips 1981). It appears that what are now retrograde shear zones were active before, during and after deposition of the Willyama Supergroup and overlying sequences at Broken Hill (Plimer 1975, 1984, Stevens 1986). Although there is widespread isotopic resetting and minor retrogression of sulphides in some ore deposits (Hellingwerf 1986), no prominent retrogression has been recorded for the Bergslagen area although any retrograde shear zones present would be covered by lakes or thick glacial drift.

The Broken Hill area, in contrast to the Bergslagen area, is of higher metamorphic grade, has a greater area of high metamorphic grade rocks, is more intensely deformed, has more prominent penetrative deformation, has an extensive history of retrogression, is transgressed by a multiplicity of retrograde shear zones and displays ubiquitous incipient pseudomorphous retrogression.

Lithology

Both the Bergslagen and Broken Hill areas are characterized by rocks of silicic and mafic metavolcanic and metasedimentary parentage. The estimated thicknesses of the sequences are 12 km (Bergslagen, Oen et al. 1982) and >6.8 km (Willis et al. 1983) however, the proportion of rock types varies significantly. The Bergslagen area is characterized by the predominance of metavolcanics whereas in the Broken Hill area, the sequence is dominated by metasediments and metavolcanics only occupy a small proportion of the sequence. Furthermore, in the Bergslagen area, metavolcanics of felsic and silicic composition are more abundant than mafic metavolcanics whereas the inverse is the case at Broken Hill.

Although Broken Hill has enjoyed more intense metamorphism and deformation than Bergslagen, the Willyama Supergroup contains ubiquitous preserved sedimentary structures within the metasediments (especially in the upper part of the sequence). Therefore, it can be expected that sedimentary and volcanic structures in both areas will be preserved (especially in the hinges of folds) and thereby can serve as a useful guide for ascertaining the depositional environment.

Metavolcanics

The metamorphosed deformed acid volcanics of the Bergslagen area (leptites) comprise recognisable felsic ash tuffs, agglomerates, amygdule-rich units, porphyritic lavas, crystal tuffs and lapilli tuffs (Vivallo & Rickard 1985, Hellingwerf 1986) suggestive of explosive acid volcanism. At Broken Hill, felsic gneiss which is chemically the composition of rhyolite (Himalaya Formation of the Thackaringa Group, Fig. 1) occurs as an extensive essentially structureless stratigraphic horizon suggestive of an air fall tuff origin whereas garnet-plagioclase gneiss of rhyodacitic composition (within the Cues Formation, Parnell Formation and Hores Gneiss, Fig. 1) probably occurred as rare but spatially and temporally widespread submarine ash flows. Quartz-albite rocks of the Thackaringa Group may represent altered rhyolitic airfall tuff. The structures in the rocks of acid volcanic origin indicate that the sequence in the Bergslagen area was proximal to explosive acid volcanism whereas at Broken Hill, acid volcanism was distal.

Bimodality of mafic and felsic volcanism is a feature of both areas. In the Bergslagen area metabasic sills, dykes and flows have been recognised. Spilitized pillow lavas are present, ophitic-textured sills and dykes are common and mafic lavas display porphyritic, glomeroporphyritic, vesicular and pilotaxic textures (Hellingwerf 1986). No relic structures or textures are recognised in the mafic granulites of the Broken Hill area. They probably represent metamorphosed mafic dykes, sills and airfall tuffs which, in places, have undergone pre-metamorphic hydrothermal alteration.

Bimodal volcanics of tholeiitic and rhyolitic composition occur in the lowermost 3600 m of the Willyama Supergroup (i.e. beneath the Sundown Group, Fig. 1). At Broken Hill, the association of mineralization with metavolcanics is more obtuse and prominent mineralization is hosted by metasediments and is only present where there is a significant increase in the volume of the tholeiitic

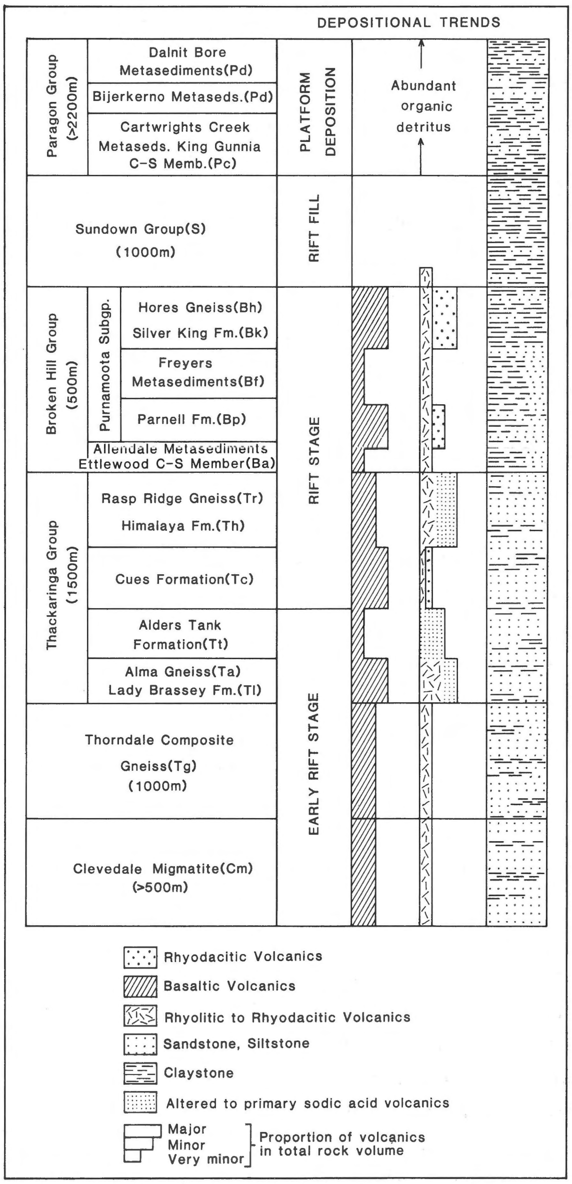

Fig. 1. Stratigraphy of the Lower Proterozoic Willyama Supergroup, Broken Hill district.

metavolcanics and where these tholeiitic metavolcanics are paired with rhyodacitic metavolcanics.

Although minor iron formations occur associated with mafic and felsic volcanism in the Thorndale Composite Gneiss (Fig. 2), the first main event of Pb-Zn-Ag ore formation in the Willyama Supergroup (Cues Formation e.g. Pinnacles Mine, Fig. 2) is hosted by psammitic and psammopelitic

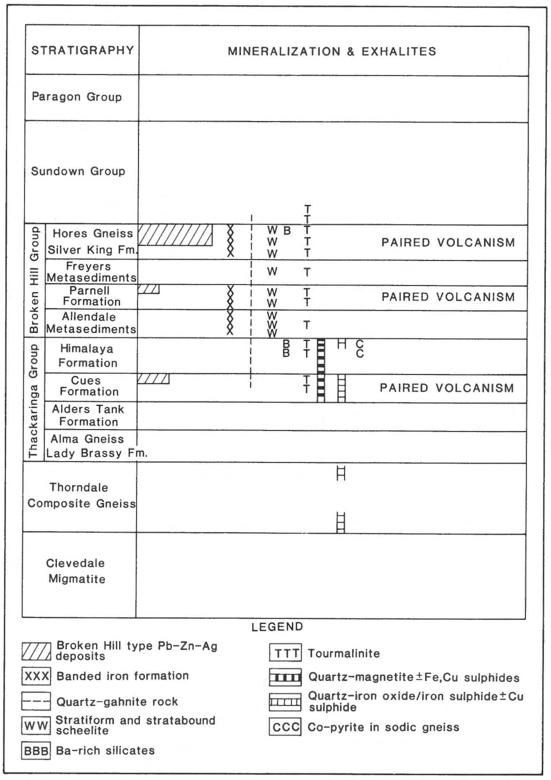

Fig. 2. Mineralization and exhalites at Broken Hill.

metasediments intimately associated with a sudden increase in the volume of mafic tholeiitic metavolcanics (amphibolite) and the first appearance in the stratigraphy of rhyodacitic volcanics (garnet-plagioclase gneiss). The overlying quartzofeldspathic rocks of the Himalaya Formation (interpreted as air fall tuffs) are characterized by extensive horizons of quartz-magnetite rocks (rarely with minor Fe and Cu sulphides associated with footwall Mg-rich alteration) whereas the quartz-albite rocks of the Himalaya Formation contain minor cobaltian pyrite.

In the Broken Hill Group, the Ettlewood Limestone within the Allendale Metasediments contains minor stratiform Zn-Pb and W mineralization (Plimer 1987) whereas Zn-Pb-Ag deposits of the Parnell Formation are hosted by psammopelites and psammites (Fig. 2). The Parnell Formation contains an increase in the volume of mafic tholeiitic metavolcanics (amphibolite) which occur stratigraphically within 50 m of mineralization and the stratigraphically uppermost portion of amphibolite spatially related to Zn-Pb-Ag mineralization rarely comprises a garnet-quartz-scheelite assemblage. Garnet-plagioclase gneiss (rhyodacite ash flow) occurs in close spatial association with Zn-Pb-Ag mineralization (Figs. 1 & 2). The Broken Hill Pb-Zn-Ag ore deposit occurs in metapsammites and metapsammopelites of the Hores Gneiss wherein there is a great increase in the volume of amphibolite and the intimate association of garnet-plagioclase gneiss with mineralization (Fig. 1). There is an inverse relationship between the thickness of the garnet-plagioclase gneiss and the thickness of the sulphide horizon suggesting that the rhyodacitic ash flow precursor may have formed palaeotopographic highs.

Metasediments

Some 70% of the Willyama Supergroup comprises metasediments which vary from well-bedded metasediments containing no quartzofeldspathic segregations to migmatites comprising primarily granitic and pegmatitic material with discontinuous layers, lenses and wisps of metasedimentary rock (Willis et al. 1983). The metasediments are largely confined to the middle and upper sections of the Willyama Supergroup.

Metasediments of the Broken Hill and Sundown Groups are psammopelitic and pelitic in composition with minor psammitic units. These rocks commonly display bedding and graded bedding. Willis et al. (1983) suggest that the metasediments of the Broken Hill and Sundown Groups were derived from within the local volcano-sedimentary environment with deposition by traction currents and turbidite fans. Metasediments of the Paragon Group are dominated by carbonaceous lithologies comprising graphitic psammites, phyllitic psammopelites and pelites, fine grained leucocratic psammites and calc-silicate horizons. Metasediments of the Paragon Group vary from massive to finely bedded with cross bedding, graded bedding and flame structures being common. Willis et al. (1983) suggest derivation of Paragon Group detritus from a distant landmass or older cratonic area with sedimentation from suspension deposits, contourites or sub-littoral sheet sands and fine grained turbidites.

Metasediments from the Lower Leptite Group of Oen et al. (1982) are rare, minor in volume and comprise volcanoclastic lithologies whereas in the Middle Leptite Group both limestone and volcanoclastic metasediments are present. The overlying Upper Leptite-Hälleflinta-Slate sequences of Oen et al. (1982) comprise volcanoclastics, carbonate rocks, tuffite, shale, siltstone and greywacke unconformably overlain by conglomerate. The transition from a lower dominantly metavolcanic sequence to an upper dominantly metasedimentary sequence is present in both the Bergslagen and Broken Hill areas although the total proportion of metasediments to metavolcanics in the preserved sequences is markedly different.

Although no firm criteria for the establishment of water depth exist, the enormous thickness of immature metasediments deposited as turbidites, the rarity of carbonate precursors and the lack of explosive volcanic acid igneous rocks at Broken Hill all suggest that deposition took place in a far deeper marine environment than in the Bergslagen area. The thickest and highest energy sequence of metasediments at Broken Hill occur associated with the main Broken Hill orebody suggesting that ore deposition was in the deepest part (i.e. graben) of the proposed rift. Wright et al. (1987) have suggested that the Broken Hill deposit formed in porous permeable shallow water sequences by replacement from formation waters however this novel suggestion is incommensurate with all geological, geophysical and geochemical data (Plimer & Lottermoser 1988).

Intrusions

The Bergslagen area contains a large volume of numerous generations of foliated Early (1890–1970 Ma) I-type and unfoliated Late (1820–1790 Ma) Svecofennian S-type felsic plutonic rocks of syenitic, granodioritic and granitic composition (Oen & Wiklander 1982, Åberg et al. 1983, Baker 1985, Baker & Drucker 1985, Kresten 1986, Patchett et al. 1987). Furthermore, the geochemistry and the initial extrusive ages of the metavolcanic rocks of the Bergslagen area (1900–1870 Ma) and the early orogenic Early Svecofennian granites (1890–

1870 Ma) strongly suggests a genetic relationship between the two groups of rocks (Baker 1985).

Geological maps of the Bergslagen area show that plutonic rocks of all generations occupy more than 50% of the land surface with the older metavolcanic and metasedimentary sequences occurring as disconnected inliers. In contrast, plutonic rocks of the Broken Hill area (zoned pegmatite dated at 1570 Ma related to the 1605 Ma period of retrogression; adamellite, 1490 Ma; ultramafic rocks, pyroxenite, 561 Ma; zoned pegmatites dated at 500 Ma related to the 520–458 Ma period of retrogression) and narrow dolerite dykes (? 1076 Ma) occupy less than 1% of the area.

At Broken Hill, there is no relationship between volcanism and plutonism, no spatial relationship between granitic rocks and mineralization and there is a close relationship between metamorphism and the generation of plutonic rocks. Numerous quartzofeldspathic rocks originally close to minimum melt composition at Broken Hill have undergone *in situ* partial melting during both M1 and M2 with crystallization at 1660–1605 Ma. These units commonly contain preserved ghost-like bedding coplanar with bedding in the enclosing rocks and are constrained as essentially strata-bound pegmatoid bodies by the more refractory enclosing pelitic metasediments. Post tectonic bosses and dykes of S-type adamellite are present in the lower metamorphic grade areas (Mundi Mundi Granite dated at 1490 Ma, Stevens 1986). This adamellite of S-type affinity contains primary muscovite, has no thermal aureole, only occurs in the lower metamorphic grade areas where, although both P and T of metamorphism were lower, $P_{\text{water}} \sim P_{\text{total}}$ hence quartzofeldspathic rocks could more efficiently partially melt. These granites are considered to be M2 anatectic melts which intruded hot rocks at depths of greater than 13 km which is commensurate with equivalent depths during D1 and D2 of 10–14 km and 16–18 km during D3. Immediately after the two principal periods of retrogression wherein $P_{\text{water}} \sim P_{\text{total}}$, rare metal-bearing zoned pegmatites were emplaced.

Environment of deposition of metavolcanics and metasediments

In the Bergslagen area, the tectonic setting has been described as a subduction environment on the geochemistry of altered volcanic rocks (Löfgren 1979, Loberg 1980). Alternatively, a rift environment has been suggested on the basis of lithology, presence of bimodal volcanism, the geochemistry of the least altered metavolcanics, the palaeogeographic orientation of the sedimentary basins and the geochemistry of anorogenic complexes in the older suite of granitoids (Oen et al. 1982, Baker & De Groot 1983, Baker 1985, Hellingwerf 1986). However, Cas & Wright (1982) stress that bimodality is a feature of volcanism in all environments. An ensialic spreading subsidence environment has been suggested by Vivallo & Rickard (1984).

The reconstructed stratigraphy of the Filipstad-Grythyttan-Hjulsjö region by Oen et al. (1982) incorporates an early volcanic stage (acid volcanics), an initial rift stage (acid volcanics, limestones and banded iron formations), a rift stage (altered acid volcanics, granites, mafic volcanics overlain by greywacke, siltstones and shales) and a post-rift stage (Hyttsjö suite of gabbros and granites). This reconstruction is remarkably similar to that of Willis et al. (1983) for the Broken Hill area which displays an upward trend from acid volcanics, minor mafic volcanics, intermixed immature terrigenous and acid volcanic detritus deposited in a shallow shelf-type environment (early rift stage) to a deeper water environment of intermixed terrigenous and volcanoclastic detritus, acid volcanics, mafic volcanics and paired basaltic and rhyodacitic volcanism intimately associated with ore deposition (rift stage). These sequences are overlain by rift fill material (turbidites, contourites) and shallow water shelf-type sediments.

At Broken Hill, the sediment immaturity, the irregular bedding geometry and the estimate of a moderate distance from source are all consistent with a shallow to moderately deep environment and hence a shelf, shallow basin or moderately deep rift environment would all be possible environments of sediment deposition. However, the preponderence of high Fe, tholeiitic and subalkaline metabasalts suggests that a deep rift is the most likely environment of deposition. The presence of numerous basaltic flows and sills throughout the history of the rift stage at Broken Hill suggests multiple intrusion into wet sediments thereby creating long-lived geothermal systems in wet sediments with older extensive acid volcanics acting as traps or aquifer caps thereby focussing geothermal fluids into active faults. As traction current and turbidite/contourite deposition is characteristic of the metasediments hosting the mineralization, clastic sediment deposition at the time of ore deposition by mass flow with some bottom current reworking is most probable. This implies that deposition of the eight principal ore lenses of the Broken Hill orebody was extremely rapid and occurred in between events of mass flowage probably resulting from the sudden deepening of the rift.

Ore deposition

Hydrothermal alteration

It has been long known that metavolcanics and metasediments of the upper segment of the stratigraphy of the Bergslagen area are enriched in K in contrast to metavolcanics of the lower section of the stratigraphy which are enriched in Na (Sundius 1923). The Bergslagen area is characterised by diverse types of regional alteration (Baker & De Groot 1983). Superimposed upon this regional alteration are distinct intense (Koark 1962, Berge 1978, Baker & De Groot 1983, Hellingwerf 1986) and subtle alteration patterns (Lagerblad & Gorbatschev 1985, Lagerblad & Ripa in prep.) which are spatially related to the occurrence of exhalative sulphide mineralization. Although Mg-rich footwall alteration assemblages wherein Mg, Fe, S, Si and K are enriched at the expense of Na and Ca (e.g. Falun) occur in the proposed fluid conduit for exhalative sulphide ore deposits, not all Mg-rich alteration assemblages are intimately associated with exhalative ores. Those associated with ore deposits are richer in Fe, Cu, Pb, Zn, Ba and Mn than those not associated with mineralization (Lagerblad & Ripa in prep.).

At Broken Hill, no regional pre-metamorphic hydrothermal alteration has been recognised despite intense exploration and research. However, very subtle chemical patterns are associated with the Broken Hill ore deposit (Plimer 1979) and minor Broken Hill-type deposits in the Cues Formation, Parnell Formation and Hores Gneiss. Slight depletion of Na_2O and enrichment of MnO, FeO and TiO_2 are present in the metasediments and metavolcanics enclosing the sulphide rocks and, within 500 m of the Broken Hill orebodies, there is an intensification of alteration characterized by depletion in Na_2O, CaO, MgO and Sr and an enrichment in SiO_2, K_2O, MnO, Rb, Pb, S and possibly FeO and TiO_2 (Plimer 1979). These more intense alteration patterns spatially associated with the footwall rocks to the Broken Hill deposit and are best exemplified by an increase in Rb/Sr from <1 (500 m from orebodies) to >100 (wall rocks enclosing orebodies) however no alteration zones or pipes *per se* have been delineated. It is surprising that no distinct alteration is associated with an ore deposit as large as Broken Hill however this lack of upward and outward fluid flow and water-rock reaction may suggest that the ore fluids at Broken Hill were very strongly localised along proposed faults and that hydrothermal processes were very rapid.

In the Bergslagen area, it has been proposed that the presence of regional alteration results from geothermal cells comprising seawater heated by cooling volcanics and associated granitic intrusions (Baker & De Groot 1983, Baker 1985, Lagerblad & Ripa in prep., Hellingwerf 1986). These geothermal fluids would have circulated through and altered the whole sequence with the numerous more intense zones of Mg-metasomatism associated with sulphide mineralization being fluid conduits at the sites of debouchment. At Broken Hill, the slight alteration present is spatially associated with mineralization and there is no evidence that the pile of sediments and volcanics were altered by circulating geothermal fluids and hence it is suggested that the ore fluids were very strongly focused, possibly controlled by the faults at the rift graben margin. Such a fluid conduit would allow no lateral movement of fluid which could produce regional alteration or distinct alteration zones associated with mineralization. In contrast, the Bergslagen area is characterized by explosive volcanism which would have created large volumes of porous permeable reactive rocks ideal for seawater penetration and the resultant establishment of numerous seawater-dominated convective geothermal cells.

Exhalites

In both the Bergslagen and Broken Hill areas, exhalites occur as stratiform bodies coplanar with bedding in the enclosing metasediments and metavolcanics. These horizons are commonly discontinuous because of rapid sedimentary and volcanic facies changes and attenuation and dismembering as a result of deformation.

Iron- and manganese-rich exhalites, cherts and manganoan carbonate rocks occur at various stratigraphic levels in the volcanic sequence at Bergslagen. At high stratigraphic levels, these exhalites are associated with sulphide ores, K-rich metavolcanics and occur at the top of a bimodal suite of volcanics immediately beneath metagreywackes. The iron-rich exhalites at higher stratigraphic levels are commonly rich in Mn whereas, lower in the stratigraphy (i.e. Na-rich metavolcanics), the iron-rich exhalites are Mn-poor and comprise skarn and quartz-banded ores.

The main facies of iron-rich exhalites (Frietsch, 1982) are quartz-hematite-magnetite rocks (quartz banded iron ores), 'skarns' (i.e. uneconomic rocks) comprising small non manganiferous (<1% MnO) and manganiferous (1–8% MnO) horizons of magnetite, carbonates and calc-silicate minerals, carbonate banded ore (carbonates, calc-silicate minerals) and apatite-bearing ores (magnetite-apatite-quartz-silicates). These rock types suggest that the oxide facies (quartz banded ores), oxide-silicate facies (non-manganiferous), silicate-carbonate facies (manganiferous), carbonate facies (carbonate banded ore) and phosphatic facies (apatite iron ores) of iron formations were all present. The diverse mineralogy, layering and interdigitation of these iron formation facies suggest that there were local variations in Eh and pH suggesting fluctuations in fluid composition or the environment of deposition.

No relationship between the diverse facies of exhalites and various types of sulphide mineralization in the Bergslagen area has yet been established although the ore-equivalent horizon is characterized by a higher Mn content (Lagerblad & Ripa in prep.).

At Broken Hill, there are over 500 km cumulative strike length of exhalites, a great diversity of exhalite types and a facies relationship of various exhalite facies to massive sulphide mineralization. Except for iron formations, exhalites in the Bergslagen area are relatively rare, minor in cumulative strike length and lack a great diversity. For example, the discovery of a gahnite-bearing rock or a tourmalinite is a great rarity and of interest in the Bergslagen area whereas it is *passé* at Broken Hill. At Broken Hill, there is a similarity in exhalite zoning with Bergslagen on the regional stratigraphic scale: iron-rich exhalites occur lower in the stratigraphy (Thackaringa Group) whereas manganese-rich exhalites occur higher in the stratigraphy (Broken Hill Group) associated with massive sulphide mineralization. At Broken Hill siliceous, manganiferous, ferruginous (sulphide, carbonate, silicate, phosphatic, oxide), zincian, plumbian, barian, calcareous and boron-rich exhalites have been recognised and facies relationships with exhalative sulphide mineralization have been established (Plimer 1986).

In the Cues Formation, Pb-Zn and Zn-Pb sulphide orebodies show a lateral facies change over 700 m strike length to a Mn fayalite-MnCaFe garnet-sphalerite-galena assemblage (i.e. carbonate-sulphide facies), thence a Mn hedenbergite-Fe, Mn, Ca garnet-cummingtonite-sphalerite assemblage (i.e. silicate-sulphide facies) and finally a Mn hedenbergite-Fe, Mn, Ca garnet-magnetite assemblage (i.e. silicate-oxide facies). Five metres above the sulphide orebodies is a discontinuous Fe, Mn, Ca garnet-magnetite-quartz horizon (i.e. silicate facies). Garnets show a distinct chemical change along strike from mineralization from a calcic spessartine to a manganoan almandine. Such facies changes strongly suggest that sulphide deposition was in areas of lowest Eh and that Eh (and possibly pH) conditions changed rapidly both spatially and temporally. This is in accord with extremely rapid ore deposition (possibly in the order of thousands of years) in a deep active rift wherein high energy sediment was been continually added via turbidity currents.

In the immediately overlying Himalaya Formation, quartz-magnetite rocks (i.e. oxide facies of iron formation) are the characteristic exhalite. They are continuous horizons for many kilometres, are thickened at isoclinal D_2 fold hinges, contain no Mn minerals, no sulphides and no silicates and are not associated with any ore deposit type. Minor discontinuous barium silicate beds with no spatial relationship to iron formations or mineralization occur in the Himalaya Formation.

Calc-silicates (Ettlewood Calc-Silicate Member) in the overlying Allendale Metasediments are a Zn- and W- bearing exhalite comprising abundant grossular, diopside, plagioclase and quartz. They have a close spatial association with tourmalinites which occur less than 10 m stratigraphically above and below the calc-silicate horizon (Plimer 1987) whereas both silicate facies iron formation and minor quartz-gahnite beds occur in the strike-equivalent Allendale Metasediments.

The overlying Parnell Formation is the host for numerous small Broken Hill-type Pb-Zn deposits and minor stratiform scheelite deposits (Plimer 1987). Closely spatially associated with the sulphide rocks are large quantities of stratiform and stratabound siliceous rocks comprising quartz (commonly bluish) with minor but variable quantities of calcian spessartine, sulphides, gahnite and plumbian orthoclase. Associated with this proximal exhalite facies are minor quantities of calcian spessartine rocks (coticule rocks) which contain minor quartz and ferromagnesian silicates. More distal to mineralization in both space and time are green plumbian orthoclase-rich rocks (amazonite) with minor biotite and quartz, tourmalinite (quartz-tourmaline with variable admixtures of biotite, fluorapatite, spessartine, scheelite, gahnite, plumbian orthoclase, ilmenite, magnetite and aluminium silicates) and extensive horizons of quartz-gahnite rocks with variable but minor quantities of sphalerite, fluorapatite, tourmaline, ferroan spessartine, plumbian orthoclase, aluminium silicates, muscovite, biotite and ilmenite. Gahnite is considered a rare mineral in the Bergslagen area however some hundreds of kilometres of discontinuous narrow (<2 m) quartz-gahnite horizons (commonly containing over 10% Zn) are characteristic of the ore-equivalent stratigraphic position in the Parnell Formation. The only areas in the Parnell Formation which contain sulphides are those where there is a diversity of exhalite types present, numerous discontinuous stacked exhalites are present above and below mineralization, the stratigraphic package is thicker and amphibolite is very close (<30 m) to the mineralized horizon and displays evidence of pre-metamorphic hydrothermal alteration (i.e. elevated FeO, MnO, TiO_2 and K_2O and lower CaO and Na_2O reflected in higher almandine, ilmenite and biotite and lower feldspar contents).

The overlying Freyers Metasediments contain minor discontinuous quartz-gahnite and tourmalinite horizons and it is in the overlying Hores Gneiss that the Broken Hill ore deposit occurs. The basal segment of the Sundown Group also contains minor quartz-gahnite and tourmalinite horizons, both of which are considered exhalite facies which are distal in space and time to sulphide mineralization.

The rocks immediately enclosing the Broken Hill ore deposit are stratiform and stratabound siliceous rocks with minor and variable quantities of sulphides, calcic spesartine, plumbian orthoclase and silicates. The most outstanding siliceous proximal indicator to mineralization is an bluish opalescent massive quartz rock with minor interstitial galena and chalcopyrite which occurs as irregular bodies between ore lenses, as discordant masses and veins, as strike-equivalent beds (with minor calcic spessartine and gahnite). Other siliceous rocks have a variable calcic spessartine content and there is a complete spectrum of rocks from quartzite *sensu stricto* to garnet-bearing quartzite to garnetite ('garnet sandstone', a friable calcic spessartine rock with minor quartz, argentian galena, chalcopyrite, arsenopyrite and scheelite). Plumbian orthoclase (-quartz-gahnite-spessartine) rocks occur within this package of unusual rocks as stratabound pegmatites, pods and discordant ptygmatic veins.

Strike-equivalent horizons to these proximal exhalites are abundant discontinuous narrow horizons of quartz-gahnite rocks which contain variable but minor quantities of sulphides, FeMnCa garnet, plumbian orthoclase, biotite, aluminium silicates, ilmenite and fluorapatite. Minor tourmalinite and unusual exhalite assemblages containing variable amounts of spessartine, gahnite, tourmaline, quartz, zincian ilmenite, zincian biotite and plumbian orthoclase have recently been recognised as the ore equivalent 4 km along strike from the Broken Hill mines. These tourmaline-rich rocks are considered to be a boron-rich iron formation which occurs distal in space and time to sulphide mineralization. Up to fifteen very narrow (<1 m) horizons of magnetite-quartz-calcic spessartine-fluorapatite units occur beneath and commonly almost stratigraphically equivalent to the massive sulphide mineralization at Broken Hill. These rocks are the least abundant exhalite in the ore-equivalent stratigraphy, are given the unfortunate misnomer of 'banded iron formation' and increase in base metals along strike towards mineralization (Stanton 1972).

Within the Hores Gneiss and the basal section of the overlying Sundown Group associated with the Broken Hill ore deposit, there are extremely rare ellipsoids of calc-silicates which commonly contain scheelite. The origin of these masses is not known.

The lack of great diversity of exhalites and the abundance of Fe- and Mn-rich exhalites in the Bergslagen area strongly suggests a more oxidising environment of deposition and slight submarine slopes. In contrast, at Broken Hill the most abundant exhalite is quartz-gahnite rock suggesting that the exhalative fluids at Broken Hill were very rich in metals. The diversity, relative rarity of oxidised facies, stacking and rapid facies changes of exhalites at Broken Hill suggests deeper water deposition wherein there were great changes in the palaeotopography. This is commensurate with a deep rift environment, the palaetopographic distribution of the garnet-plagioclase gneiss and numerous graben with reduced assemblages (sulphide and proximal exhalite deposition) and horsts with slightly more oxidised assemblages (distal exhalite deposition) somewhat similar to the Red Sea.

Mineralization

In both the Bergslagen and Broken Hill areas, the Pb-Zn sulphide ore deposits have undergone metamorphism and deformation and the resultant ores are texturally similar (e.g. Stöllberg and No. 3 lens, Broken Hill).

There are a number of significant differences. The Broken Hill deposit is significantly larger in tonnage and ore grade and the total contained metal at Broken Hill is two orders of magnitude greater than for the Bergslagen Pb-Zn deposits. At Broken Hill there have been over 350 mineral species recorded however there is a paucity of iron sulphides and Mg minerals and an abundance of manganese silicites, calcite, fluorite, fluorapatite. The Broken Hill ore deposits are characterized by primitive Pb and Sr isotopes ratios, $\delta^{34}S$ values of zero and a high large lithophile ion concentration (e.g. U, Th) (Plimer 1979, Both & Smith 1975, Gulson et al. 1983). In contrast, Johansson & Rickard (1985) suggest a crustal origin for the lead from Garpenberg, Damberg and Saxberget. The REE patterns of the exhalites and ore deposits at Broken Hill are similar to those derived from mid ocean ridge vent fluids (Lottermoser pers. comm.) in contrast to those from the Bergslagen area which suggest derivation from upper crustal sialic rocks (Vivallo 1987). At Broken Hill, there are no massive iron sulphide deposits with Cu, Zn, Pb, Ag and Au in metamorphosed, deformed, hydrothermally altered acid volcanics (e.g. Falun).

Furthermore, in contrast to the Bergslagen area, at Broken Hill there is a stacked sequence of eight ore horizons (C lode, B lode, lower A lode, upper A lode, upper 1 lens, lower 1 lens, 2 lens, 3 lens) representing four cycles of ore deposition wherein the ore fluids evolved in both space and time, probably as a result sequential precipitation, Eh, pH, temperature and fluid composition changes.

Discussion

Any discussion, comparison and contrasting of Broken Hill and Bergslagen is greatly constrained by the small size and uncertainty (e.g. penetrative deformation structures) of the data base for the Bergslagen area.

It is suggested that the ore deposits in the volcanic-dominated sequence in the Bergslagen area formed as a result of explosive acid volcanism which, in the final stages, was bimodal with mafic volcanism. Such volcanism and ore deposition could have occurred in an extensional segment of a subduction zone (cf. Kuroko deposits of Japan). However, the predominance of felsic over mafic volcanism, absence of ophiolite compolexes, the continental tholeeitic nature of the metabasalts, the virtual absence of andesites, the diapiric nature of tectonics (i.e. passive margin) and the metamorphic facies all argue against subduction-related models (Baker & De Groot 1983, Vivallo & Rickard 1985, Baker 1985, Hellingwerf & Oen 1986, Vivallo 1987). The rift setting was, on the basis of the abundance of explosive acid volcanism, sedimentary structures and sediment facies, moderately shallow (i.e. oxidising) water depth. Explosive volcanism would have physically prepared the sequence by creating numerous fluid conduits (e.g. faults) and increasing the porosity and permeability of a sequence of reactive felsic and glassy rocks. Cooling of this newly-formed crust by seawater ingress, heating of seawater, leaching of metals from this hot segment of upper crust, exchange of OH^- and the resultant pH decrease and the establishment of a recharging convective geothermal system would have resulted in the observed regional alteration of the volcanics, multiple egress of the hot fluids from faults (i.e. numerous small ore deposits associated with more intense hydrothermal alteration) and derivation of metals from a relatively small volume of newly-formed hot crust. Although submarine slopes would be expected to be steep associated with acid calderas, the exhalite facies indicate that the palaeoslopes associated with the more distal Pb-Zn mineralization were only slight with deposition of sulphides in depressions (Fig. 3).

In contrast, the Broken Hill ore deposits appear to have formed extremely quickly in a deep rift. This deep rift and the thinner sequence of rocks suggests that there was more direct access to the mantle beneath the Broken Hill than at Bergslagen. The sequence is dominated by sediments and a major ore-forming geothermal system was initiated thrice (Cues Formation, Parnell Formation, Hores Gneiss) by a voluminous invasion of primitive basaltic magma into a sequence of faulted wet sediments. This probably resulted in the melting of lower crustal material and the observed paired basaltic-rhyodacitic volcanism at the highest geothermal gradient coincident with deposition of sulphide ore deposits and a great diversity of exhalite facies types (Fig. 4). Later tectonism in a zone of very high geothermal gradient of a thin sequence of rift fill (in contrast to a thicker sequence at Bergslagen) would have resulted in a higher metamorphic grade more intensely deformed assemblage cut by plutonic rocks of metamorphic origin at Broken Hill.

The mineralogical, chemical and isotopic characteristics of the Broken Hill deposit suggest that the ore fluid was dominantly of mantle origin and contained significant metals, CO_2, F and B. The volume, aerial extent and facies relationships of quartz-gahnite rocks suggests that the ore fluid contained a high metal content, every time there was a slight elevation in geothermal gradient fluids of this composition were released and that most of the quartz-gahnite rocks (probably precipitated as opaline silica-hydrothermal clay with adsorbed Zn-zincian carbonate) derive from overflow of the metal-bearing hydrothermal fluid from the deeper graben onto the deep but more oxidised horsts. Multiple dilation and throttling of the fluid conduit fault and multiple instantaneous covering of hydrothermal precipitates by turbidities would allow stacking of sulphide horizons and exhalites at the site of deposition in the graben. Intense fluid focussing could have occurred because of a trap or aquifer cap (e.g. Himalaya Formation) however it is more likely that fluid focussing was along faults bounding the graben. Fluid flow rates in such an environment are such that lateral movement to form regional hydrothermal alteration is most unlikely as are intense footwall alteration zones.

It is proposed that the extraordinary high grade of Broken Hill ore, the large volume (and resultant large quantity of contained metal) and the unusual mineralogy and geochemistry of the ore require a plumbing connection to the mantle to supply large

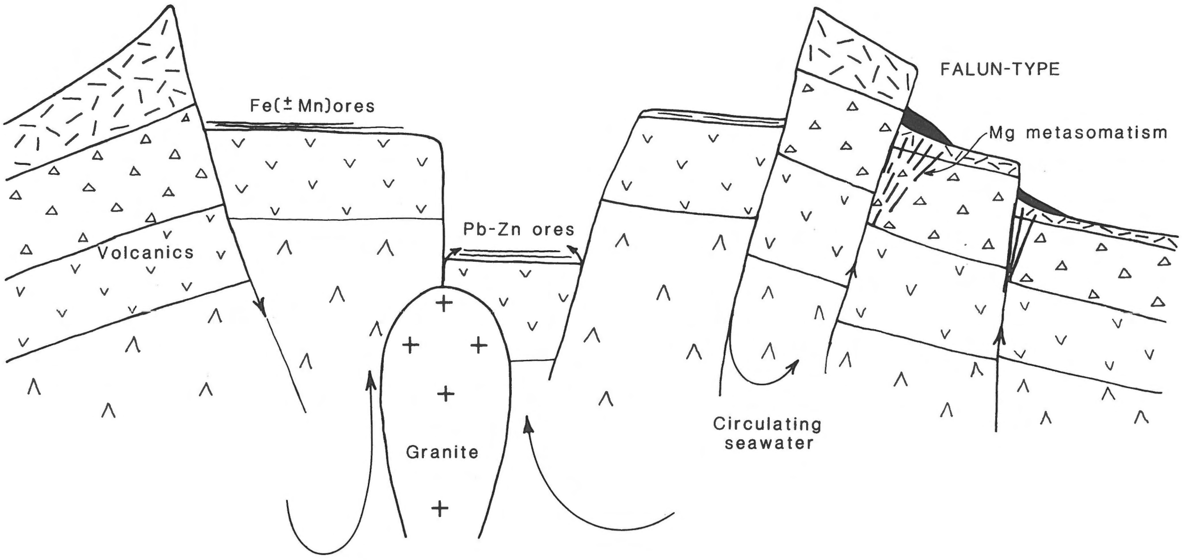

Fig. 3. Model for the formation of the Bergslagen deposits.

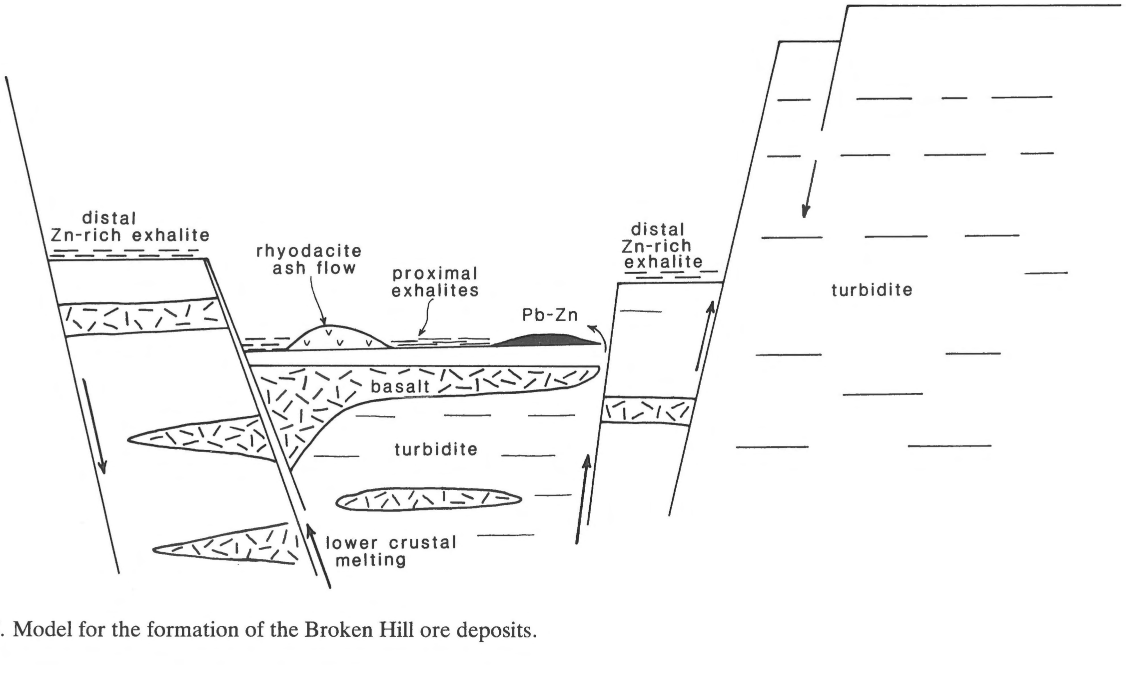

Fig. 4. Model for the formation of the Broken Hill ore deposits.

quantities of fluid of unusual composition. Such a proposition is compatible with the presence of metasediments which suggest a relatively thin sequence in a deep rift, the metavolcanics, the extremely localised hydrothermal alteration and the distribution of exhalites in space and time. There is no doubt that both God and Mammon bless the Antipodes because other Proterozoic deposits which formed in rift settings (e.g. Olympic Dam, Mount Isa) are also extremely high grade and very large tonnage.

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