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THE BROKEN HILL PB-ZN-AG DEPOSIT, AUSTRALIA

by

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The Broken Hill Pb-Zn-Ag deposit, N.S.W., Australia occurs in the Lower Proterozoic Willyama Supergroup metasediments, metavolcanics and metaplutonics which have undergone numerous events of coeval deformation and high grade metamorphism. Maximum weathering and erosion of the Willyama Supergroup took place during the Late Proterozoic and Permian glaciations and some 100 Mt of massive sulphides have been removed during and after the Permian glaciation. The lowermost parts of the Willyama Supergroup comprise metamorphosed deformed felsic volcanics and immature clastic sediments interpreted as continental crust. The overlying sequence comprises felsic gneiss, amphibolite, albite rocks, metasediments and exhalites. These are interpreted as the products of intracontinental rifting or a hot spot resulted in crustal thinning, an elevated geothermal gradient and the deposition of bimodal volcanics, immature clastic sediments, hot spring precipitates and evaporites. This sequence is overlain by the Broken Hill Group comprising metasediments, amphibolite, felsic gneiss and sulphide rocks and associated quartz-sulphide, quartz-gahnite, quartz-garnet, quartz-magnetite with quartz-tourmaline exhalites. The change from evaporitic, lacustrine and shallow water conditions to the deep water high energy conditions of sedimentation of the Broken Hill Group is interpreted as sudden deepening coincidental with rifting, a great increase in the geothermal gradient, flooding of the sequence with basalt, lower crustal melting to produce volcanics and high level plutons and the cooling of these new crustal rocks with resultant submarine hot spring precipitates. The Broken Hill Group is overlain by metaturbidites (interpreted as rift fill) and carbonaceous metapelites, metapsammites and calc-silicates (interpreted as platform cover).

The Broken Hill Pb-Zn-Ag sulphide deposit has enjoyed a number of events of coeval high grade metamorphism and deformation. Deformation has produced attenuation of the sulphide masses, mass movement of sulphides into fold hinges, sulphide rock

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brecciation, chaotic folding and foliation, flow structures and injection of sulphides into silicate wall rocks. Sulphide rocks have a coarse grained granoblastic high metamorphic grade mineral assemblage comprising sulphides, pyroxenes, pyroxenoids, garnets, spinels and feldspar. Sulphide and silicate porphyroblasts are developed and transgressive sulphide-rich pegmatites are common.

At the waning stage of high grade metamorphism sulphide breccias were formed, sulphide minerals were injected into transgressive fractures and redistribution took place by secondary hydrothermal processes. The sulphide rocks moved relative to the enclosing psammitic and psammopelitic rocks and the sulphide-silicate interface is defined by silicate and sulphide mylonites. Exsolution and replacement of earlier prograde silicate and sulphide minerals formed a galaxy of new minerals. Secondary hydrothermal processes formed pegmatoid masses, transgressive sulphide-silicate veins and cavities.

The earliest dated retrogression was at 1570 Ma however field data suggest that retrogression took place before this time. It appears that retrogression continued for a considerable time. Retrogression of the sulphide rocks occurred in shear zones which transgressed and displaced prograde sulphide rocks resulting in brecciation, plastic flow, sulphide injection and retexturing. Ag, As, Sb, Cu and Pb moved from prograde sulphide rocks into shear zones and fold hinges and prograde minerals underwent retrogression to other sulphides, exsolution and replacement. Secondary hydrothermal processes formed transgressive Ag-rich quartz, sulphide and carbonate veins.

The sulphide rocks are transgressed and displaced by minor fault zones. Sulphide rocks were fractured and retextured and new phases formed by decomposition, exsolution and replacement. Sequential precipitation of carbonates and other phases on fault planes and in crystal-lined cavities is characteristic. The age of faulting is unknown.

The Broken Hill orebody comprises 8 sulphide horizons in the southern end of the field, two of which are continuous for the 7.5 km strike length of the orebodies. The morphology suggests deposition in a half graben. The lack of a prominent footwall alteration zone suggests fault-focussed hydrothermal fluid flow or stratal flow. The presence of discrete sulphide rocks with very low Si and Al contents hosted by high energy psammitic sediments suggests that ore precipitation was very rapid. Above, at the edge and underneath the sulphide masses are garnet-quartz and quartz-magnetite-garnet-F apatite rocks suggesting that the geothermal system associated with ore deposition evolved in both space and time from more oxidising (? lower T), to more reducing (? higher T) and to more oxidising (? lower T) conditions. REE studies of exhalites associated with the Broken Hill orebody demonstrate that ore fluids at the depositional site are similar to modern hydrothermal fluids at mid ocean ridges or the Red Sea metalliferous sediments whereas those exhalites beneath, peripheral to and above the sulphide rocks have REE patterns similar to hydrothermal precipitates which have been exposed to seawater for some time. These data suggest that sulphide deposition was in rapid in anoxic second order basins and that hydrothermal precipitates in second order basins, first order basins and on horsts can be differentiated. The orebody geochemistry suggests a mantle component (CO_2, F, LIL) and an evaporitic component (Br, I). Radiogenic and stable isotope studies suggest that the sulphide rocks have a mantle (S, Sr), a lower crustal (Pb) and a continental evaporitic component (B). REE data is equivocal however a modified seawater dominated system is not excluded.

A perennial problem at Broken Hill has been the energy and the volume of fluid required to deposit 300 million tonne of high grade sulphide rocks. Recent work has shown the presence of plutons coeval with mineralisation and the abundance of evaporitic rocks stratigraphically beneath the sulphide rocks. Intrusion of high level plutons, basalts and felsic volcanics into wet deep water sediments, evaporites and volcanics associated with an event of rifting could produce a massive geothermal system. This pluton-driven hydrothermal system in thin crust in wet sediment beneath the sea floor could contain mantle, lower crustal, modified seawater and evaporitic components, could be a short-lived high energy system focussed in the deepest half graben or second order basin and could produce supersaline fluids with a high metal-carrying capacity. Sudden P-T-X changes to this fluid upon entry into a deep water anoxic basin could result in the rapid deposition of large quantities of submarine hydrothermal precipitate with extensive spillover into first order basins and on to horsts.

Similar environments exist in the Bohemian Massif and the Svecokarelian of Sweden. It is argued that the repeated and more mature rifting at Broken Hill and pluton-driven hydrothermal systems in evaporites resulted in sulphide rock masses at least two orders of magnitude larger than at Bodenmais (Germany) or in the Bergslagen area of Sweden.

The intrusion of a high pressure granite (1570 Ma) and deposition of fluvioglacials at 1100 Ma show that in the Middle Proterozoic, there was at least 12 km of uplift of Willyama Supergroup rocks. Weathering and erosion of the Willyama Supergroup at Broken Hill commenced in the Middle Proterozoic and continued through the Late Proterozoic glaciation. Because the Broken Hill orebodies have been partially retrogressively metamorphosed, deformed, sheared, partially remobilised and intruded by minor pegmatites during the Delamerian Orogeny dated at 520 Ma, it is highly unlikely that the orebodies underwent the Late Proterozoic weathering and erosion. However, substantial weathering and erosion of the orebody took place during the Permocarboniferous glaciation and a large volume (possibly as much as 100 Mt) of massive sulphide was removed at this time. This huge mass of Pb, Zn and Ag may have been removed to and concentrated in the Palaeozoic-Mesozoic-Tertiary basin to the east of Broken Hill however it is more likely that the products of weathering were infinitely diluted in Permian seawater.

Fluctuating temperate, tropical and arid climatic regimes in the Tertiary and minor block uplift resulted in a spectacular metastable assemblage of secondary oxides, halides, tungstates, molybdates, phosphates, carbonates, sulphates and sulphides for which Broken Hill is famous. The secondary zone has a crude zonation from an uppermost gossan, an oxide zone, a complex zone and a carbonate zone. Carbonates directly overlie fresh sulphides, no supergene zone is developed, weathering is to a maximum depth of 1200 m and the secondary zone shows evidence of multiple collapse, rejuvenation and mineral reprecipitation. These features are interpreted as the orebody's response to changing groundwater compositions during the changing of climates during the Tertiary and Holocene.