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Archaean volcanic-hosted massive sulphides

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EXPLORATION MODEL

Examples
Scuddles, Gossan Hill, Teutonic Bore, Sulphur Springs, Mons Cupri, Salt Creek (Western Australia)

Target
- Typical size: 0.5–20 Mt.
- Typical grade: >10% Zn, 1% Pb, >1% Cu.
- Major metals: Zn & Cu.
- May contain Au & Ag credits.

Mining and treatment
- Lensoid shape; flanks difficult to mine.
- Uniform grades allow cost-effective assessment and mining.
- High SiO_2 content increases difficulty of ore extraction.
- Fine grain size and high concentrations of pyrite and chlorite decrease milling efficiency.

Regional geological criteria
- Sub-greenschist to amphibolite facies metamorphism.
- Archaean greenstone belts.
- Submarine tholeiitic or calc-alkaline basalt to rhyolite.
- Volcaniclastic sediments, sulphidic shales and BIF.
- Close to syn-volcanic faults.

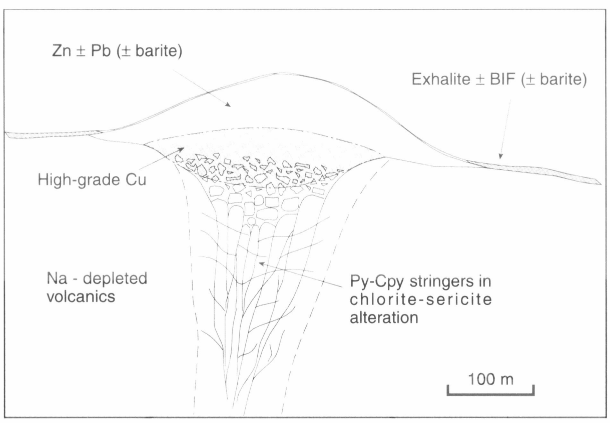

Figure 1. Factual cross-section of a typical VMS orebody.

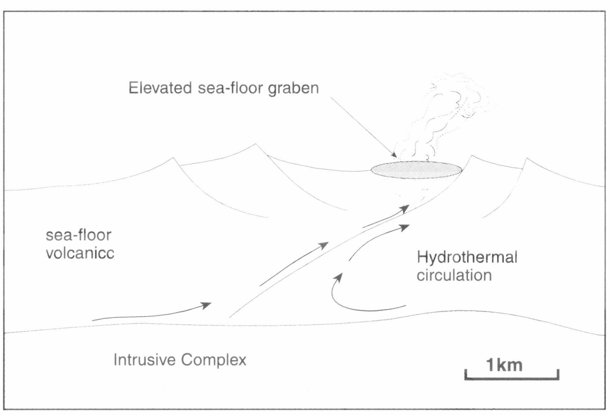

Figure 2. Schematic of ore deposit model.

Local geological criteria
- Exhalative sediments may provide target horizons.
- Local structure: seafloor graben.
- Age of host: 3.45–2.69 Ga.
- Direct link with submarine volcanic–intrusive suites in deep marine basins.

Mineralisation features
- Stratiform sulphide lenses with stringer zones.
- Ore minerals: sphalerite, chalcopyrite, galena.
- Gangue minerals: pyrite, pyrrhotite, magnetite, arsenopyrite, barite (at Sulphur Springs).
- Ore zoned with Cu below Zn–Pb ± sulphates.
- Stringer zones developed beneath some deposits.
- Magnetic pyrrhotite and magnetite present in some deposits.

Alteration
- Stratiform or cross-cutting Fe chlorite ± sericite ± carbonate footwall alteration.
- Above zone of feldspar destruction.
- With deep and distal epidotisation and spilitisation.

Deposit geochemical criteria
- Associated exhalite may be anomalous in Zn and chalcophile elements.
- Zn ratio (100Zn/(Zn+Pb)) = 70–100.
- Trace elements include As, Sb, Bi, Mo, Sn, Se, Ag, Au.
- Zones of Na depletion, Fe ± Mg enrichment in footwall alteration zones.
- Host volcanics may have distinctive REE patterns.
- S isotopes indicate dominantly juvenile source for S.
- Pb isotopes give model ages close to age of host rocks.

Surficial geochemical criteria
- Pb typically less depleted than Cu and Zn in gossans.
- Pathfinder elements, As, Sb, Bi, Mo, Sn, Se, Ag and Au, relatively immobile during weathering and elevated in gossans and pisolitic laterite.
- In the Yilgarn, RAB drilling to base of weathering is most effective.
- In areas of less extreme weathering (Pilbara), deposits may have haloes defined by O isotopes and Na depletion (alteration indices useful).

Geophysical criteria
- Regional geophysics used to define stratigraphy and locate exhalite horizons.
- Electromagnetics and magnetics generally effective.
- Some sphalerite-rich ores with low pyrite and pyrrhotite contents are poor conductors.

Fluid chemistry and source
- Moderate salinity <5 wt% NaCl.
- Moderate temperatures, 200–350°C.
- Reduced, $H_2S > SO_4$.
- Source: sea water reacting with footwall volcanic succession ± magmatic fluids.

Comments on genesis

- Sulphides deposited from volcanic–hydrothermal systems at or immediately beneath the sea floor.
- Sea water reacts with volcanic–intrusive complex, leaching metals.
- May be a magmatic input of metals.
- Drop in temperature ± mixing with ambient sea water causes metal sulphide precipitation.

Introduction

The granite–greenstone terranes of the Pilbara and Yilgarn Cratons in Western Australia contain a number of volcanic-hosted, base-metal sulphide deposits. This type of deposit is an important exploration target in Archaean terranes worldwide for Cu–Zn–Pb–Au and Ag. The following brief descriptions of the more important Australian examples of this type of deposit are presented as aids for exploration.

The Pilbara Craton

Greenstone belts in the Pilbara Craton contain volcanic and sedimentary successions that range in age from ~3.52 to 2.9 Ga. Within the ~3.45 Ga Warrawoona Megasequence, in the east Pilbara, massive sulphide mineralisation is associated with intermediate to silicic calc-alkaline volcanic rocks at Big Stubby and Lennons Find.

Mineralisation at Big Stubby consists of subvertical lenses containing sphalerite, galena, pyrite and barite, within chert horizons (Reynolds et al. 1975, Sangster & Brook 1977), interlayered with tuffaceous turbidites and overlying a sequence of tuff breccias with minor intercalated volcaniclastic conglomerate and tuff. The oldest known volcanic-hosted massive sulphide deposit, Big Stubby has more in common with Kuroko Zn–Pb–Cu deposits, in terms of its mineralogy and metal contents, than it does with most other Archaean volcanic-hosted massive sulphide deposits (cf. Franklin et al. 1981, Barley 1992). Davies & Blockley (1990) quoted reserves of 0.1–0.2 Mt of 13.8% Zn, 4.5% Pb, 0.2% Cu, and 305 ppm Ag, with Zn-rich mineralisation, which typically contains several per cent barite, stratigraphically above Cu-rich mineralisation (Reynolds et al. 1975). Lenses of conformable Zn–Pb–Cu mineralisation also occur at Lennons Find (also called Yandicoogina) in intermediate to silicic volcanics that have experienced amphibolite facies metamorphism. Galenas from Big Stubby and Lennons Find give model ages of 3400–3500 Ma (Sangster & Brook 1977, Richards 1983).

Significant discoveries of massive Zn–Pb–Cu sulphide mineralisation have recently been made at Sulphur Springs in the Strelley Belt, approximately 50 km west of Marble Bar. Mineralisation at Sulphur Springs has a Pb–Pb galena age of 3257±8 Ma (Vearncombe et al. 1995), is barite-rich, and occurs at the top of a sequence of deep-water silicic volcanic and intrusive rocks and associated sedimentary rocks. It comprises massive Zn sulphide-rich lenses with typical upwards zonation of Cu to Zn–Pb and locally developed underlying stringer mineralisation (Morant 1995, Vearncombe et al. 1995). Published identified mineral resources at Sulphur Springs are 3.3 Mt 11% Zn, and 2.9 Mt 4% Cu.

The mineral assemblage includes pyrite, sphalerite, chalcopyrite, galena, tennantite, arsenopyrite, barite, pyrrhotite and quartz. Barite and galena are associated mainly in the upper and outer parts of the deposits. Pyrite is abundant and generally encloses the economic sulphides. Cryptocrystalline quartz and barite are the gangue minerals. The massive sulphides display a range of macro- and micro-scale textures which are similar to those found in black smoker chimneys and hydrothermal sulphide mounds on the modern ocean floor (Vearncombe et al. 1995). The stringer mineralisation comprises veins of quartz, pyrite and chalcopyrite, minor sphalerite and carbonate. Alteration zones, comprising carbonate, sericite and chlorite, are confined to the footwall volcanic rock. The texture and geochemistry of the Sulphur Springs gossan are described by Pickard (1993).

Surface gossans at Sulphur Springs, though leached and depleted in target and pathfinder elements relative to the sulphide body, are distinctively enriched in Ag, Sn, Sb, Bi, As, Au, Mo, Tl, Th, U and Se. The elements As, Ag, Bi and Ba proved to be potentially useful in gossan identification for the area.

In the west Pilbara, ~2.99 Ga intermediate to silicic volcanics and terrigenous sediments host Zn–Pb–Cu mineralisation at Mons Cupri and Salt Creek in the Whim Creek Belt. At Mons Cupri, mineralisation consists of a subvertical zone of iron-rich chlorite and carbonate alteration containing disseminated and stockwork chalcopyrite mineralisation overlain by a shallowly dipping massive sphalerite, galena, chalcopyrite lens in volcaniclastic and cherty sediments. The stockwork zone is approximately 1 km long and up to 250 m wide at the surface, narrowing to less than 25 m at depth. It extends to at least 200 m below the present surface, and Miller & Gair (1975) estimated that it contains approximately 10 Mt of 1% Cu.

Iron-rich chlorite and carbonate (dominantly siderite) alteration in the stockwork zone grades laterally into heterogeneously altered (with chlorite, carbonate and sericite) volcaniclastic rocks. This alteration is similar to alteration described for Archaean Mattabi-type Cu–Zn deposits in Canada (Morton & Franklin 1987).

The sequence hosting the massive mineralisation is up to 15 m thick and contains ore grade sulphides, (1 Mt of 3.6% Zn, 2.5% Pb, and 1.0% Cu) over an area of approximately 250 m by 400 m (Miller & Gair 1975). Mineralisation comprises coarse-grained pyrite, chalcopyrite, galena, sphalerite, tetrahedrite and trace amounts of bournonite and linnaeite, and lacks mineralogical banding (Tanner 1990).

At Salt Creek, stratabound Zn–Pb–Cu mineralisation occurs in a sequence of pyritic sandstones and shales, immediately above volcanic and volcaniclastic sedimentary rocks which are more intensely deformed stratigraphic equivalents of those at Mons Cupri and Whim Creek. Indicated reserves are 0.47 Mt averaging 8.4% Zn, 3.3% Pb, and 1.25% Cu. A model age of 2950±10 Ma has been obtained from galena from this deposit (Richards & Blockley 1984).

The Yilgarn Craton

The Yilgarn Craton is dominantly composed of 3.0–2.6 Ga granite–greenstone terranes. At Teutonic Bore in the Norseman–Wiluna Belt, massive sulphide mineralisation occurs in a ~2.69 Ga sequence of submarine mafic and silicic volcanic and epiclastic sedimentary rocks (Hallberg & Thompson 1985). This deposit was discovered in 1976, with reserves of 1.4 Mt, grading 16.4% Zn, 1.22% Pb, 4.16% Cu, and 52 ppm Ag (Greig 1984); mining commenced in 1980 and ceased in October 1984. Mineralisation occurs within a unit of pyritic black shale, chert and tuffaceous sedimentary rocks, which thickens from <3 m to ~20 m in the vicinity of mineralisation, and immediately overlies a 100 m thick sequence of pillowed basalts (Greig 1984). The basalt unit also contains minor interlayered cherts, pyritic black shales and epiclastic sediments, and overlies a thick sequence of mildly peralkaline rhyolite lavas and fragmental rocks.

Mineralisation comprises a conformable massive sulphide lens 320 m long, up to 30 m thick, and with a down-dip extension of 280 m, underlain by irregular stringer mineralisation. Pyrite, sphalerite, chalcopyrite and galena are the major sulphide minerals, with traces of pyrrhotite, famatinite, cosalite, aikinite, bismuthinite and stannite, with quartz and siderite gangue (Greig 1984). Massive sulphides are generally banded from <1 mm up to 1 m, locally with pyrite nodules, colloform textures and sulphide breccia, as well as minor contortions and folds. The massive lens had a Zn-rich core with Cu most abundant near its base and top. The major stringer sulphides are pyrite, chalcopyrite and sphalerite, which occur as disseminations in veins with quartz, siderite (or ankerite) and chlorite. The stringer zone contained a further 0.75 Mt of 2.38% Cu, 1.92% Zn, and 52 ppm Ag (Greig 1984).

Proximal alteration beneath the ore body is heterogeneous and dominated by chlorite, siderite, ankerite and sericite, with chloritoid, andalusite and kyanite probably resulting from metamorphism of alteration assemblages. Alteration involved enrichment in Fe, Mg, K, residual enrichment in Al, and depletion in Ca, Na and Sr (Greig 1984).

The style of mineralisation and alteration at this deposit is also similar to that of Mattabi-type deposits in Canada. Nickel

(1984) described the mineralogy and geochemistry of the weathering profile developed on the Teutonic Bore mineralisation, which was weathered to a depth of ~75 m. In an upward profile, the primary ore has initially weathered to a transition zone of supergene sulphides (containing abundant secondary ore minerals) then to an oxide assemblage, then to leached oxides, and finally to gossan. Gossan samples are depleted in Cu and Zn relative to sulphide mineralisation, but contain significant Pb, Sb, Sn and As where these elements are preserved as stable secondary ore minerals.

In the Murchison Terrane, Cu–Zn massive sulphide mineralisation is associated with ~2.95 Ga. volcanic and sedimentary rocks in the Golden Grove Belt at Gossan Hill, Scuddles, and numerous other prospects. The facies association in this belt (Clifford 1987, 1992) includes (1) proximal effusive volcanic rocks (low aspect ratio lavas and associated autoclastic breccias), (2) distal volcanic products (mass flow resedimented pyroclastic debris), (3) background sedimentation (reworked volcanogenic and terrigenous mass flow sediments, turbidites), and (4) chemical sediments (cherts, sulphides, oxides). The epiclastic facies (2 and 3) comprise a range of mass flow deposits. Primary pyroclastic deposits are restricted to distal, water-lain, air-fall tuffs. Proximal effusive volcanic rocks include lava flows (andesites, dacites and rhyolites) and associated autoclastic breccias, with abundant syn-volcanic dykes.

Mineralisation occurs over a restricted stratigraphic interval towards the top of a thick sequence of resedimented pyroclastic deposits, and immediately preceding the major period of effusive volcanism. Geochemical data (Ashley et al. 1988, Whitford & Ashley 1992) indicate that mineralisation occurred during a change from distal to proximal volcanism, also characterised by a change from Zr-rich to Zr-poor magmas. Zones of maximum syn-depositional subsidence (reflected by gross stratigraphic thickening) and syn-depositional extensional faults (indicated by abrupt thickening of mass flow facies) appear to be most prospective (Clifford 1987). The environment of deposition was a deepwater (>1 km) extensional basin.

Copper–zinc gossans were first discovered at Gossan Hill in 1971 (Frater 1983). Mineralisation at Gossan Hill is stratabound with a broad concentric ore-mineral zonation defined by a central massive magnetite–pyrite–chalcopyrite–pyrrhotite association, passing upward and outward into pyrite–magnetite–chalcopyrite–sphalerite–pyrrhotite, and ultimately into a bedded pyrite–sphalerite–galena association (Frater 1983). Published reserves are 15 Mt of Cu mineralisation @ 3.3% Cu, 0.1% Zn, 14 ppm Ag, and 0.1 ppm Au, and 1.7 Mt of Zn mineralisation @ 14% Zn, 1.6% Pb, and 0.4% Cu (Frater 1983).

Mineralisation comprises tabular pods and lenses of massive sulphides (pyrite with subordinate chalcopyrite, pyrrhotite and sphalerite) and magnetite, with magnetite and sulphides in approximately equal proportions. Disseminated and vein mineralisation is also common, but less abundant than massive mineralisation and lenses of massive mineralisation which are surrounded by chlorite schist. Alteration in the footwall includes iron-rich chlorite, carbonate (siderite, ankerite), talc and minor chloritoid, and involved addition of Fe, Mg and CO_2, subtraction of Na and Ca, and redistribution of Si and K (Frater 1983). In the hanging wall, tabular, conformable bodies of sphalerite, pyrite and galena mineralisation occur associated with magnetite-bearing chert.

At the Scuddles deposit, mineralisation occurs as massive sulphide lenses with an underlying zone of stockwork zinc mineralisation. Mill et al. (1990) reported a total mine recoverable reserve of 10.5 Mt of 11.7% Zn, 0.8% Pb, 1.2% Cu, 89 ppm Ag and 1.1 ppm Au. The deposit contains three massive sulphide ore types: massive sphalerite (>50% sphalerite), which forms the stratigraphic top of the deposit and interfingers with the massive pyrite zone(<50% sphalerite, <5% chalcopyrite), and Cu-rich massive pyrite (>5% chalcopyrite), which is generally located near the base of deposit. The magnetite-rich mineralisation typical of Gossan Hill is not common at Scuddles, although laminated magnetite-bearing cherts (or iron-formation) occur immediately above, and distal to, mineralisation. The massive ore is underlain by a 40–50 m wide stratabound zone of stockwork pyrite–chalcopyrite mineralisation, varying in intensity from >80% sulphide, directly beneath the massive sulphides, to <10% sulphide. Intensely altered rocks containing Fe-rich chlorite and carbonates are associated with stockwork development (Ashley et al. 1988, Mill et al. 1990).

Massive sulphide mineralisation comprises coarse-grained sphalerite and pyrite, with lesser chalcopyrite, galena and pyrrhotite, and traces of arsenopyrite, tetrahedrite, mackinawite and cassiterite. Gangue minerals include magnetite, quartz, sericite, talc and carbonate. Sulphides exhibit a range of primary and secondary textures, including colloform intergrowths of pyrite with sphalerite, chalcopyrite and galena. Ores are variably recrystallised and a strong tectonic fabric or banding has generally been superimposed on the massive sulphides.

Mineralisation at Scuddles and Gossan Hill overlies a 10 km long by 300 m thick zone of pervasive stratabound quartz–chlorite–sericite–carbonate–sulphide alteration. In this zone, Fe and Mg contents generally increase towards mineralisation with patchy depletion in Na, Sr and K. Smith et al. (1980) and Smith & Perdrix (1983) described geochemical characteristics of Golden Grove gossans and pisolitic laterite. The gossans and adjacent laterite are enriched in a suite of chalcophile and associated elements, such as As, Sb, Bi, Mo, Ag, Sn, and Se. Smith & Perdrix (1983) showed that pisolitic laterite is a potentially useful sampling medium during regional exploration for deposits of this type in areas of laterite cover.

References

Ashley, P.M., Dudley, R.J., Lesh, R.H., Marr, J.M. & Ryall, A.W., 1988. The Scuddles Cu–Zn prospect, an Archaean volcanogenic massive sulfide deposit, Golden Grove District, Western Australia. Economic Geology, 83, 918–951.

Barley, M.E., 1992. A review of Archaean volcanic-hosted massive sulfide and sulfate deposits in Western Australia. Economic Geology, 87, 855–872.

Blockley, J.G., 1971. The lead, zinc and silver deposits of Western Australia. Geological Survey of Western Australia, Mineral Resources Bulletin, 9, 234 pp.

Clifford, B.A., 1987. Volcanic-sedimentary facies associations hosting the volcanogenic massive sulphide mineralisation at Golden Grove, Western Australia. Proceedings Pacific Rim Congress, Gold Coast, Australia, 871–875.

Clifford, B.A., 1992. Facies and palaeoenvironment analysis of the Archaean volcanic-sedimentary succession hosting the Golden Grove Cu–Zn massive sulphide deposits, Western Australia. PhD thesis, Monash University, Melbourne (unpublished).

Davies, B.M. & Blockley, J.G., 1990. Copper, lead and zinc. Geological Survey of Western Australia, Memoir 3, 631–639.

Franklin, J.M., Lydon, J.W. & Sangster, D.F., 1981. Volcanic-associated massive sulphide deposits. In: B.J. Skinner (editor), Economic Geology 75th Anniversary Volume. Economic Geology Publishing Company, El Paso, 857–919.

Frater, K.M., 1983. Geology of the Golden Grove Prospect, Western Australia: a volcanogenic massive sulfide–magnetite deposit. Economic Geology, 78, 857–919.

Greig, D.D., 1984. Geology of the Teutonic Bore massive sulphide deposit, Western Australia. Australasian Institute of Mining and Metallurgy, Proceedings, 289, 147–156.

Hallberg, J.A. & Thompson, J.F.H., 1985. Geologic setting of the Teutonic Bore massive sulfide deposit, Archaean Yilgarn Block, Western Australia. Economic Geology, 80, 1953–1964.

Mill, J.H.A., Clifford, B.A., Dudley, R.J. & Ruxton, P.A., 1990. Scuddles zinc–copper deposit at Golden Grove. Australasian

Institute of Mining and Metallurgy, Monograph 14, 583–590.
Miller, L.J. & Gair, H.S., 1975. Mons Cupri copper–lead–zinc deposit. Australasian Institute of Mining and Metallurgy, Monograph 5, 195–202.
Morant, P., 1995. A case history of the Panorama Zn–Cu volcanogenic massive sulphide deposit. Australian Institute of Geoscientists Bulletin, 16, 75–84.
Morton, R.L. & Franklin, J.M., 1987. Two fold classification of Archaean volcanic-associated massive sulfide deposits. Economic Geology, 82, 1057–1063.
Nickel, E.H., 1984. The mineralogy and geochemistry of the weathering profile of the Teutonic Bore Cu–Pb–Zn–Ag sulphide deposit. Journal of Geochemical Exploration, 22, 239–264.
Pickard, A.L., 1993. The Sulphur Springs Archaean Volcanic Massive Sulphide Gossan. BSc Hons thesis, University of Western Australia, 102 pp (unpublished).
Reynolds, D.G., Brook, W.A., Marshall, A.E. & Allchurch, P.D., 1975. Volcanogenic copper–zinc deposits in the Pilbara and Yilgarn Archaean Blocks. Australasian Institute of Mining and Metallurgy, Monograph 5, 185–195.
Richards, J.R., 1983. Lead isotopes as indicators of old stable craton in Western Australia. Geochemical Journal, 17, 241–246.
Richards, J.R. & Blockley, J.G., 1984. The base of the Fortescue Group, Western Australia. further galena lead isotopic evidence of its age. Australian Journal of Earth Sciences, 31, 257–268.
Sangster, D.F. & Brook, W.A., 1977. Primitive lead in an Australian Zn–Pb–Ba deposit. Nature, 270, 423.
Smith, R.E. & Perdrix, J.L., 1983. Pisolitic laterite geochemistry in the Golden Grove massive sulphide district, Western Australia. Journal of Geochemical Exploration, 18, 131–164.
Smith, R.E., Frater, K.M. & Moeskops, P.G., 1980. Golden Grove deposit, Yilgarn Block. Journal of Geochemical Exploration, 12, 195–199.
Tanner, H., 1990. The stratigraphic setting and a depositional model for the Mons Cupri volcanogenic massive sulphide deposit, Pilbara Craton, Western Australia. BSc Hons thesis, University of Western Australia, Nedlands, 60 pp (unpublished).
Vearncombe, S.E., Barley, M.E., Groves, D.I., McNaughton, N.J., Mikucki, E.J. & Vearncombe, J.R., 1995. 3.26 Ga black smoker-type mineralisation in the Strelley Belt, Pilbara Craton, Western Australia. Journal of the Geological Society, 152, 587–590.
Whitford, D.J. & Ashley, P.M., 1992. The Scuddles volcanic-hosted massive sulfide deposit, Western Australia: geochemistry of host rocks and evaluation of lithogeochemistry for exploration. Economic Geology, 87, 873–888.

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