Deposits related to submarine volcanism - Volcanic Hosted Massive Sulphide (VHMS) Deposits - Examples

- GLY 361 - Lecture 11
Zonation

Most deposits show metal zonation→ changing physical and chemical conditions of circulating hydrothermal fluids within the wall rock.

- Temperature zonation results in the zoning of sulphide minerals within both the discordant stockwork zone and the conformable sulphide mound.

- Most deposits show a vertical zonation of Au, with the cooler upper portions generally more enriched in Au and Ag.
Zonation

• Core of massive pyrite, chalcopyrite around the throat of the vent system.

• Chalcopyrite-sphalerite-pyrite.

• Distal sphalerite-galena and galena-manganese.

• Chert-manganese-hematite.
Alteration

- Not associated with ore forming processes!

- Alteration haloes are typically:
  - Conical in shape
  - Occur mostly stratigraphically below the original fluid flow location (not necessarily the ore itself)
  - Zoned.
Alteration

- Most intense alteration (containing the stringer sulphide zone).
- generally located directly underneath the greatest concentration of massive sulphides, within the footwall volcanic sequence.
Alteration

- alteration zones are metasomatic effects:
  - Addition of:
    - K
    - Mg
    - Silica
  - Depletion of:
    - Na
Alteration

Footwall Alteration Zone:

- Alteration assemblages from core outwards (metasomatism):
  - Silica alteration zone
    - found in the most intensely altered examples, resulting in complete silica replacement of the host rocks, and associated with chalcopyrite-pyrite stringer zones.
Alteration

Footwall Alteration Zone:

• Alteration assemblages from core outwards (metasomatism):
  
  – Chlorite zone
    • found in nearly all examples, consisting of chlorite +/- sericite +/- silica. Often the host rock is entirely replaced by chlorite, which may appear as a chlorite schist in deformed examples.
Alteration

Footwall Alteration Zone:

- Alteration assemblages from core outwards (metasomatism):
  - Sericite zone
    - found in nearly all examples, consisting of sericite +/- chlorite +/- silica
Alteration

Footwall Alteration Zone:

- Alteration assemblages from core outwards (metasomatism):
  - Silicification zone
    - often gradational with background silica-albite metasomatism.
Alteration

Hanging Wall Alteration:

• Subtle alteration (no sulphide).
• x/cutting alteration pipes to semi-conformable regionally extensive zones.
• Complications: Metamorphism and deformation.
• e.g.: plume shaped zone of light green fuchsite-calcite alteration in pillow basalt (Heller Australia), quartz - sericite - chlorite ± carbonate.
Classification schemes

- Genetic environment
- Tectonic setting
- Composition
- Dominant host rock
Classification based on footwall lithology and geotectonic setting

- **Cyprus-type**: associated with mafic volcanics (tholeiitic basalts in ophiolite sequences) (divergent plate margins), Cu (Zn, Au), Phanerozoic. *e.g.* Troodos Massif (Cyprus).

- **Besshi-type**: associated with mafic volcanics and continental turbidites, Cu/Zn (Au, Ag). *e.g.* Sanbagwa (Japan).

- **Primitive-type**: associated with differentiated magmas of tholeiitic and calc-alkaline affinities uncertain origin, Cu/Zn and Au, Archaean. *e.g.* Canadian Archaean rocks.

- **Kuroko-type**: associated with felsic volcanics particularly rhyolite domes (convergent plate margins in island arcs or continental margins), Cu/Zn/Pb with Au and Ag, Phanerozoic. *e.g.* Kuroko deposits (Japan).
## Classification of VHMS deposits by Hutchinson (1980)

**Table 16.2 Volcanic-associated massive sulphide deposit types.**

<table>
<thead>
<tr>
<th>Type</th>
<th>Associated volcanic rocks</th>
<th>Clastic sedimentary rocks</th>
<th>Depositional environment</th>
<th>Plate tectonic setting</th>
<th>Known age range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Besshi</td>
<td>Within plate (intraplate) basalts</td>
<td>Continent-derived greywackes and other turbidites</td>
<td>Deep marine sedimentation with basaltic volcanism</td>
<td>Epicontinental or back-arc rifting and forearc</td>
<td>Early Proterozoic, Palaeozoic</td>
</tr>
<tr>
<td>Cu–Zn ± Au ± Ag</td>
<td></td>
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<tr>
<td>Cyprus</td>
<td>Ophiolitic suites, tholeiitic basalts</td>
<td>Minor or absent</td>
<td>Deep marine with tholeiitic volcanism</td>
<td>Oceanic rifting at accreting margin</td>
<td>Phanerozoic</td>
</tr>
<tr>
<td>Cu (± Zn) ± Au</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Kuroko</td>
<td>Bimodal suites, tholeiitic basalts, calc-alkaline lavas and pyroclastics</td>
<td>Shallow to medium-depth clastics, few carbonates</td>
<td>Explosive volcanism, shallow marine to continental sedimentation</td>
<td>Back-arc rifting, caldera formation</td>
<td>Early Proterozoic, Phanerozoic</td>
</tr>
<tr>
<td>Cu–Zn–Pb ± Au ± Ag</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Primitive</td>
<td>Fully differentiated suites, basaltic to rhyolitic lavas and pyroclastics</td>
<td>Immature greywackes, shales, mudstones</td>
<td>Marine, &lt;1 km depth. Mainly developed in greenstone belts</td>
<td>Much debated, major subsidence, fault-bounded troughs, back-arc basins?</td>
<td>Archaean–early Proterozoic</td>
</tr>
<tr>
<td>Cu–Zn ± Au ± Ag</td>
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</tr>
</tbody>
</table>
Cupreous pyrite type
Cu : Au

Kieslager type
Cu - Zn : Au

Primitive type
Zn - Cu : Ag - Au

Polymetallic type
Zn - Pb - Cu : Ag - Au

Oceanic rift ridge
Tension

Trench Volcanic arc
Compression

Back-arc basin
Tension

Massive sulphide bodies

Cupreous pyrite type

Continental crust

Ophiolite

Volcanic arc

Back-arc or post-arc volcanism

Cyprus

Besshi

Primitive

Kuroko
MAFIC
- Ophiolite
- Potter

BIMODAL-MAFIC
- Noranda
- Kidd Creek

MAFIC-SILICLASTIC
- Windy Craggy
- Besshi

BIMODAL-FELSIC
- Mt. Read
- Kuroko

BIMODAL-SILICLASTIC
- Bathhurst
- Iberian Pyrite

Barrie and Hannington, 1999
Geological map of Cyprus, simplified and modified after Greensmith (1994), Cyprus Geological Survey and others. This map shows the relationship of the Kourion and Akrotiri pebble depositional area to the Troodos igneous source. Transport is by the Khouris River and tributaries and is seasonal. Ian West & Joanna Bentley (c) 2007.
Ophiolite succession

Ocean Floor

Magma Chamber

Convection

Pillow Basalts
Sheeted Dikes
Layered Gabbro
Layered Peridotite

Crust

Mantle
Ophiolite succession

Spreading above subduction zone

Sole formation above old crust

Final emplacement onto continent
VMS Fluid Circulation

Fig. 6.7 Diagram showing how sea water circulation through oceanic crust might give rise to the formation of an exhalative volcanic-associated massive sulphide deposit.
The Troodos Massif

• Description:
  – Elliptical body of mafic and ultramafic rocks that was formed in the Cretaceous (85 Ma).

• Deposits generally very small:
  – Apiliki (1.65 Mt), Limni (3.6 Mt), Marouvouni (15 Mt, grading 3.5 to 4.5 % Cu and 0.5 % Zn), Skouriotissa (6 Mt), Kalavassos (1.9 Mt), Mathiatis, Mousolos (1.6 Mt), Kokkinoyia, Agrokipia and Kooinopezoula deposits.
The ore bodies lie within the top of the pillow lava sequence.
Many of them are immediately adjacent to steep normal faults.
Most of the deposits occur in local basins that probably formed as fault controlled sea-floor depressions.
The footwall rocks are brecciated and extensively altered.
• **Features of ore bodies:**
  - Few cm up to 5 m capping of ochre horizon layered sediment (goethite, quartz, illite and jarosite).
  - The ore consists of porous banded blocks of py and marcasite with cpy and lesser sp, in a sandy friable sulphide matrix.
  - Basal siliceous ore zone of py and cpy in a quartz matrix (some ore bodies have significant sp content).
  - Footwall stock-work zone formed by sulphide quartz veins containing py, cpy and sp. Disseminated py also occurs in the altered lava.
FIG. 30. Typical stratigraphic columns of the Cyprus ore deposits, after Constantinou (1976). Note that zone B is a siliceous sulfide zone.
GREEN TUFF BELT, JAPAN
Kuroko Type (Pb-Zn-Cu)
The Kuroko deposits are located within the 1500km long Miocene Green Tuff belt in NW Japan with most important deposits within the Hokuroku Basin.

Cretaceous to the Early Miocene: Japan volcanic arc part of a continental margin arc along the eastern margin of the Eurasian continent. Late Oligocene/Middle Miocene: Japan separated from the Eurasian continent during back-arc extension.

The Green Tuff belt represents the marine volcanic and sedimentary succession that formed along the eastern, arc-side of the back-arc basin in response to rifting.

Represent type examples of polymetallic conformable lenses of massive sulphide ore forming in a (back-arc) rifting-type tectonic environment and exhibiting close stratigraphic relationships to submarine felsic volcanism.
Green Tuff Belt

- Deposits occur in a narrow time-stratigraphic interval within deep marine, bimodal (rhyolite-basalt) volcanic intervals.

- Formed on and below the seafloor, mainly in the upper, proximal part of these volcanoes.

- Due to the young age and extensive research of the Green Tuff Belt, there is a more detailed and reliable record of this belts evolution than for most other VHMS districts.
Green Tuff Belt

- 3 basic ore types:
  - low grade stockwork (Keiko) ore - quartz veinlets with py and cpy
  - yellow (Oko) ore – massive py + cpy
  - black (Kuroko) ore – massive gn, sp, barite ±cpy ±py
Zonation

Cu-rich near center, Zn-rich, to Pb-rich at outer edges of deposit.
Clastic Ore, Motoyama Deposit, Hokuroku
Graded bedding in ore from the Furutobe mine, Akita Prefecture, Japan.

The flame-shaped structure at the top of the graded unit is the product of soft sediment deformation.

Most of the clasts are individual crystals of pyrite, barite, and quartz or are altered footwall fragments, but a few are crystal aggregates containing sp or cpy.

Specimen = 6 cm high.
Pyritic stringers in silicified tuff
KIDD CREEK, CANADA
Primitive Type (Zn-Cu)
Reserves

- 2005 reserves: 19Mt
  - Grade: 1.8% Cu, 5.5% Zn, 0.18% Pb and 53g/t Ag.

- Resources: 14.5Mt
  - Grade: 2.4% Cu, 6.0% Zn, 0.3% Pb and 75g/t Ag.

- Production: ± 138.5 Mt @ 2.4 %Cu, 6.5%Zn, 0.2%Pb and 89g/t Ag.
Underground Mining

- The mine started production in 1966 from an open pit.

- The orebody is now mined at depth through three shafts as the No.1, No.2 and No.3 Mines.

- Blasthole stoping with cemented backfill is used to extract the ore underground, Kidd Creek being the world’s second-largest user of cemented backfill (after Mt Isa in Australia).
• Kidd Creek is based on a rich, steeply dipping VHMS deposit located in the Archaean Abitibi greenstone belt.

• 2 major orebodies (North and South Orebodies), with associated smaller lenses.

• Ore is hosted in felsic rocks of the Kidd Volcanic Complex and is cut by mafic sills and dykes.

• The deposit lies near the top of an overturned, steeply dipping rhyolitic volcaniclastic pile.

• Structural deformation resulting from several phases of folding (at least 3) and faulting affects the distribution of sulphide lenses.
Fig. 1. The Abitibi greenstone belt, after Goodwin and Ridler (1970) and Naldrett (1973).
• 3 ore types predominate:
  – massive, banded and bedded (MBB) ores (py, sp, cpy, gn and po)
  – breccia ores containing fragments of the MBB ores
  – stringer ores consisting of irregular cpy stringers cutting a siliceous volcaniclastic host.
Field of Canadian Archean Cu-Zn Deposits

- Kidd Creek
- Geco-Manitouwadge
- Val d'Or-Joutel
- Sturgeon Lk.
- Slave Province
- All Other Archean Cu-Zn Deposits
Alteration Model proposed for the Kidd Creek deposit

- **Hanging Wall**: +K₂O, +MgO, +Zn, Mn, CO₂, LREE, F, B, Sn

- **Marginal Zones**: +MgO, +K₂O, +Zn, CO₂, Mn, +F, B, Sn, ±SiO₂

- **Conformable Cu Stringers & Massive Black Chlorite**

- **Envelope of Cu-Stringer Mineralization**: - Na₂O, K₂O, CaO, Rb, Sr, Ba, LREE
VHMS Exploration Guide
Mineral exploration companies are exploring for seafloor massive sulfide deposits; however, most exploration is concentrated in the search for land-based equivalents of these deposits.

GEOCHEMICAL SIGNATURE:

- Cu, Zn; common depletion of Ca and Na of footwall rocks; less common, local minor Na enrichment; possible local K enrichment.

- Prominent Fe and Mn enrichment in footwall stringer zone.

- Zn, Hg and Mg halos.
GEOPHYSICAL SIGNATURE:

- Sulphide lenses usually show either an electromagnetic or induced polarization signature depending on the style of mineralization and presence of conductive sulphides.

- In recent years borehole electromagnetic methods have proven successful.

- Due to the high density of the deposits, some have marked gravity anomalies which is of use in exploration.
OTHER EXPLORATION GUIDES:

• Mafic ophiolitic volcanic rocks; transition to argillite; clustering or alignment of deposits indicative of fault control; ochre and exhalite (chert) horizons; regional pyritic horizons.

• Explosive felsic volcanics, volcanic centres, extensional faults, exhalite (chert) horizons, pyritic horizons.