Skellefte and Bergslagen Districts

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List of twelve key references
2. Skellefte and Bergslagen Districts
Global comparison of massive sulfides
GEODE

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2.1 Age and tectonic/structural setting

2.1.1 What is the age of your VMS district?

Skellefte District: 1.89-1.87 Ga
Bergslagen: 1.90-1.88 Ga

• Extent, type and precision of geochronology? (belt scale and deposit scale)

Skellefte District: About 5 high quality conventional U-Pb zircon dates on volcanic rocks and a similar amount on intrusive rocks. Lack of good data for the western part of the district. Indications of older pre 1.90 Ga intrusive rocks in the west and east. Precision for the zircon ages is typically ±10 Ma or less. The volcanic rocks seem to be notoriously hard to date.

Bergslagen: Similar amount of data, but lower volcanic sequences seem to be slightly older than Skellefte District at c. 1.90 Ga. While major suites of "synvolcanic intrusive rocks are coeval or slightly older (max. 10-15 Ma) in the Skellefte district, they seems to be slightly younger (less than 10 Ma) in the Bergslagen district.

Palaeontological control -

2.1.2 What is the current interpretation of the tectonic setting of your VMS district? (include a time-sequence diagram if available)

Skellefte District: Continental margin arc under extension, or accreted mature island arc
Bergslagen: Extensional back arc active continental margin magmatic region, (intracontinental rift?)

2.1.3 What is the tectonic interpretation based upon:

• structural mapping and interpretation? (quality of mapping?)

Skellefte district: Structural mapping done, but no conclusive evidence as to tectonic setting of the district. The district as a whole lacks high quality structural data.
Bergslagen: As above

• gravity and/or magnetic data (has it been used?)

Skellefte district: Gravity and magnetic data of high quality exist (airborne 200 line spacing at 40 m altitude, ground data mainly in house data at Boliden, some at the survey, but no conclusive evidence as to tectonic setting of the district.
Bergslagen: As above.

• any seismic sections?

Skellefte District. Reflexion seismics done offshore in the Bothnian bay by the BABEL group, which indicated a remnant subducted slab (subduction towards north) south of the Skellefte district, at present interpretations of a on shore reflexion seismic profile north of the Skellefte district are made to deliniate the Archaean-Proterozoic boundary.
Bergslagen: No seismic profiles done within Bergslagen proper.

- chemistry of volcanic rocks? What geochemical-tectonic classification was used?

Skellefte District: Then chemistry of volcanic (and intrusive) rocks has, together with isotope data, been the strongest evidence for palaeotectonic setting. Major contributions have focused on “immobile element” chemistry, mainly elements such as Zr, Ti, Y, REE’s. Tectonic classifications are standard diagrams based on these elements.
Bergslagen: As above.

2.1.4 Is there a comprehensive and high quality database of volcanic geochemistry to assist with tectonic interpretation?

- how many whole-rock/trace analyses on least-altered rocks?

Skellefte District: Over 1000 analyses exist, but since they have been collected and published by different research groups over the last 20 years the quality of data is hard to evaluate. Certainly at least 100 good well defined analyses of whole rock and traces (incl. REE’s) exist
Bergslagen: As above

- type and quality of trace element data?

See above. As data has been collected over the last 20 years, analytical methods are different, but the majority of data come from ICP-MS, ICP-AAS, and XRF, with variable quality and also made by 4 to 5 different labs.

- what isotope data are available?

Skellefte District: High quality Pb-isotope data on sulphides exist, other data: Stable isotopes: O- and H-isotopes exist from both silicates and carbonates to some extent (no thorough regional sampling has been carried out, but individual deposits or areas have been studied), S-isotopes from sulphides (and old analyses of sulphates) from some deposits exist. Radiogenic isotopes: Besides age determinations such as U-Pb on zircon, titanite, and monazite, provenance studies Rb-Sr on feldspars (and old isochrons which give to low ages), _Nd and Sm-Nd analyses are relatively numerous.
Bergslagen: As above

2.1.5 Have the district-scale and deposit-scale ore-fluid plumbing structures been identified?

Size of structures? How were they defined (mapping?, alteration?, aeromagnetics? geochemistry? Isotopes?)

Skellefte district:This kind of studies has not been published, although identification of alteration envelopes has been made in deposits scale studies. Speculations on heat sources and sub volcanic intrusions are common in most deposits studies but no direct genetic correlations have been established so far.
Bergslagen: As above. In Bergslagen speculations on regional alteration systems (district wide hydrothermal alteration) are based on geochemistry and alkali content of volcanic rocks.

2.1.6 Have detailed structural studies of the deposits been undertaken? Which deposits?

Skellefte District: Only few modern (since 1970ies) structural studies of deposits exist. The Boliden, Renström (unpubl.), and Kristineberg deposits have been studied in some detail.
Bergslagen: Only in house, non-published studies exist of Zinkgruvan and to some extent Garpenberg. No other deposits have been studied with modern structural techniques.

2.1.7 What further research is needed to improve the tectonic interpretation

Skellefte District/Bergslagen: Improved geochronology. Good age determinations on host rock emplacement ages, dating of hydrothermal events. Reflection seismic data in profiles across the districts. Further geochemical studies based on current stratigraphic knowledge. Regional maps of both districts will be published in digital form by the Swedish survey within the next year. These data sets will improve our
models substantially.

2.1.8 List key references


Lagerblad, B., 1985: Hydrothermal alteration as a control of regional geochemistry and ore formation in the central Baltic Shield. - Geol. Rundsch., 74/1, 33-49.


2.2 Volcanic architecture

2.2.1 What are the scales of geological maps available for the district and the deposits? Has a comprehensive systematic stratigraphy been established for the district?

Skellefte District: Entire district mapped in 1:50 000 during the last 10 years. Regional maps available in 1:250 000. All in digital form. Deposit scale maps in house data of Boliden. Some published in Ph.D thesis form and a few in other publications. Some systematic stratigraphy has been established

Bergslagen: About 50% of the area is covered by 1:50 000 scale maps (digitalization in progress). Regional scale maps available at 1:250 000 scale. Deposit maps as for Skellefte district.

2.2.2 How do the VMS deposits relate to volcanic facies? Provide some sketch diagrams if available. Do the VMS deposits occur at a single stratigraphic position? Do the VMS deposits occur in proximal or distal volcanic facies? Percentage of volcaniclastic rocks versus coherent flows or intrusions?

See attached figures:
Bergslagen:

Ores
- Limestone skarn Zn-Pb-Ag-Cu
- Ash-siltstone Zn-Pb-Ag
- Banded iron formation, skarn Fe
- Apaite Fe

Facies associations
- Proximal massive to stratified pumice breccia intrusions
- Medial stratified pyroclastic debris
- Distal ash-siltstone, limestone
- Sandstone/mudstone basement derived sediments

Volcanic centre complexes
- (eg. Godegård)
- (eg. Garpenberg)
- (eg. Hållefors-Grythyttan)
- (eg. Ställdal-Lon and Grängesberg)

Stratabound Limestone-Skarn-associated Zn-Pb-Ag-Cu
- Silicified cap
- Marble
- Mg alteration
- K-Si-Mg alteration

Stratiform ash-siltstone-hosted Zn-Pb-Ag

(F) ZINKGRUVAN
(G) GARPNBERG

COMPOSITION SYMBOLS
- weakly to moderately porphyritic basalt
dolerite, gabbro
- weakly to moderately porphyritic dacite
- strongly porphyritic dacite
- weakly to moderately porphyritic rhyolite
- strongly porphyritic rhyolite
- extremely porphyritic rhyolite
- rhyolitic subvolcanic intrusion
- granite
- migmatite, gneiss
- microcline-rich rock (alteration)
mica skarn

TEXTURE SYMBOLS
- pumice-rich
- angular non-pumiceous clasts
- rounded clasts
- sandy, granular
- welded pumice
- accretionary lapilli
- crystal - vitric fall
- in situ breccia
- stratification
- vitric ash-siltstone with sandstone bed
- grey to black argillite
- strong disseminated sulphide
- siliceous chemical sediment

From Allen et al. 1996
2.2.3 What is the composition (rhyolite?, basalt?) of the VMS host package? Is there a change in volcanic composition at, or close to, the ore position?

See attached figures:
Skellefte District:

From Allen et al. 1996
Bergslagen:

From Allen et al. 1996
2.2.3 What is the interpreted range of water depth during deposition of the volcanic succession, and immediate host rocks? What criteria were used to estimate water depth (eg. volcanic facies, sedimentary structures, fossils, fluid inclusions)?

See attached figures: Criteria used are volcanic facies, sedimentary structures, and fluid inclusions. Sometimes volcanic facies and fluid inclusion estimates are contradictory.

Bergslagen is generally considered as a shallow marine to subaerial environment. See cartoon model above.

2.2.4 What further research is needed to define the relationship between ore formation and volcanic architecture?

Further detailed volcanological and sedimentological work in more areas within each district.

2.2.5 List key references


### 2.3 Styles of ore deposits

**2.3.1 Provide a table of tonnes and grade for major deposits (>1 million tonnes) (include economic and sub-economic or barren massive sulfides). How many additional deposits of less than 1 million tonnes are known in the district?**

Skellefte District: In total c. 85 deposits are known

<table>
<thead>
<tr>
<th>NAME</th>
<th>COMMODITY</th>
<th>STATUS</th>
<th>TONNAGE</th>
<th>Au (ppm)</th>
<th>Ag (ppm)</th>
<th>Cu (%)</th>
<th>Zn (%)</th>
<th>Pb (%)</th>
<th>As (%)</th>
<th>S (%)</th>
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<tbody>
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<td>LÄNGDAL</td>
<td>Zn-Cu-Pb</td>
<td>Mine</td>
<td>4330</td>
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<td>1.7</td>
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<td>1000</td>
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<td>1.17</td>
<td>0.07</td>
<td>19.6</td>
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<td>KRISTINEBERG</td>
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<td>23049</td>
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<td>1</td>
<td>3.7</td>
<td>0.5</td>
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<td>SVANSELE</td>
<td>Fe-sulphides</td>
<td>Prospect</td>
<td>2900</td>
<td>0.2</td>
<td>4</td>
<td>0.28</td>
<td>0.32</td>
<td>0.06</td>
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<tr>
<td>KEDTRÅSK</td>
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<td>24</td>
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<td>2.9</td>
<td>0.2</td>
<td>0.3</td>
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<td>UDDEN</td>
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<td>Prospect</td>
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<td>Closed mine</td>
<td>5012</td>
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<td>3</td>
<td>0.3</td>
<td>1.4</td>
<td>28</td>
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<tr>
<td>NÄSLIDEN NORRA</td>
<td>Zn-Cu-Pb</td>
<td>Closed mine</td>
<td>900</td>
<td>0.9</td>
<td>28</td>
<td>0.6</td>
<td>1.8</td>
<td>0.2</td>
<td>0.5</td>
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<tr>
<td>HOLMTJÄRN</td>
<td>Zn-Cu-Pb-Au</td>
<td>Closed mine</td>
<td>500</td>
<td>7.4</td>
<td>92</td>
<td>0.4</td>
<td>4</td>
<td>0.4</td>
<td>0.9</td>
<td>22</td>
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<tr>
<td>RÄKEJAUR</td>
<td>Zn-Cu-Pb</td>
<td>Closed mine</td>
<td>10400</td>
<td>1</td>
<td>50</td>
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<td>0.2</td>
<td>1.6</td>
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<td>LÄNGSELE</td>
<td>Zn-Cu-Pb</td>
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<td>12000</td>
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<td>3.9</td>
<td>0.3</td>
<td>0.4</td>
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<td>BOLIDEN</td>
<td>Zn-Cu-Au</td>
<td>Closed mine</td>
<td>8280</td>
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<td>50</td>
<td>1.43</td>
<td>0.92</td>
<td>0.27</td>
<td>6.83</td>
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<tr>
<td>RENSTRÖM VÄSTRA</td>
<td>Zn-Cu-Pb</td>
<td>Mine</td>
<td>9261</td>
<td>2.8</td>
<td>155</td>
<td>0.8</td>
<td>6.5</td>
<td>1.5</td>
<td>0.2</td>
<td>15</td>
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<td>KANKBERG</td>
<td>Zn-Cu</td>
<td>Mine</td>
<td>1800</td>
<td>2.6</td>
<td>52</td>
<td>1.4</td>
<td>1.8</td>
<td>0.3</td>
<td>1.2</td>
<td>35</td>
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<tr>
<td>ÄKULLA VÄSTRA</td>
<td>Cu</td>
<td>Closed mine</td>
<td>980</td>
<td>0.7</td>
<td>12</td>
<td>1</td>
<td></td>
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<td>34</td>
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<tr>
<td>PETKNÄS NORRA</td>
<td>Zn-Cu-Pb-Au</td>
<td>Mine</td>
<td>1300</td>
<td>5.6</td>
<td>103</td>
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<td>5.6</td>
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<tr>
<td>PETKNÄS SÖDRA</td>
<td>Zn-Cu-Pb</td>
<td>Mine</td>
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<td>0.4</td>
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<tr>
<td>RUJTDJEŠACKEN</td>
<td>Zn-Cu-Pb</td>
<td>Closed mine</td>
<td>4743</td>
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<td>10</td>
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<tr>
<td>STORLIDEN</td>
<td>Cu-Zn</td>
<td>Prospect</td>
<td>1800</td>
<td>0.3</td>
<td>30</td>
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<td>10</td>
<td></td>
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<tr>
<td>ADAK</td>
<td>Cu</td>
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<td>900</td>
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<td>8</td>
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<tr>
<td>BRÄNNMYRAN</td>
<td>Cu</td>
<td>Closed mine</td>
<td>978</td>
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<td>LINSDKÖLD</td>
<td>Cu</td>
<td>Closed mine</td>
<td>1700</td>
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<td>16</td>
<td>1.7</td>
<td></td>
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</tbody>
</table>
Bergslagen: A few deposits are listed below. Apart from these several hundred small occurrences of various type of base metal deposits exist. All is available from the Geological Survey of Sweden database on mineral deposits.

### Base Metal Sulfide Ore Deposits in Bergslagen

TABLE 1. Tonnage, Grade, Host Rocks, and Ore Type of Some Iron Oxide, Iron-Manganese Oxide, and Base Metal Sulfide Ore Deposits in Bergslagen

<table>
<thead>
<tr>
<th>Deposit</th>
<th>Ore Type</th>
<th>Host Rocks</th>
<th>Tonnage (mt)</th>
<th>Grades</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blotberget</td>
<td>Apatite iron ore</td>
<td>Intrusive dacite porphyry</td>
<td>43.7</td>
<td>60% Fe, 0.7% P</td>
</tr>
<tr>
<td>Grangesberg</td>
<td>Apatite iron ore</td>
<td>Intrusive dacite porphyry</td>
<td>197.9</td>
<td>58-64% Fe, 0.3-1.3% P</td>
</tr>
<tr>
<td>Stripa</td>
<td>Banded iron formation</td>
<td>Ash-siltstone</td>
<td>16.7</td>
<td>50% Fe</td>
</tr>
<tr>
<td>Norberg</td>
<td>Banded iron formation</td>
<td>Ash-siltstone?</td>
<td>25.5</td>
<td>34-46% Fe</td>
</tr>
<tr>
<td>Timansberg</td>
<td>Skarn- and dolomite-hosted iron ore</td>
<td>Limestone-dolomite, skarn</td>
<td>0.4</td>
<td>25-67% Fe</td>
</tr>
<tr>
<td>Smaltarmossen</td>
<td>Skarn iron ore</td>
<td>Limestone-dolomite skarn</td>
<td>5.7</td>
<td>35-46% Fe, 1-3% S</td>
</tr>
<tr>
<td>(Garpenberg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stallberg</td>
<td>Manganese ferous skarn and carbonate-hosted iron ore</td>
<td>Limestone-dolomite skarn</td>
<td>6.1</td>
<td>50% Fe, 5% Mn</td>
</tr>
<tr>
<td>Dannemora</td>
<td>Manganiferous skarn iron ore and carbonate-hosted iron ore</td>
<td>Dolomite, skarn</td>
<td>54.3</td>
<td>52% Fe, 2-3% Mn</td>
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<tr>
<td>Langban</td>
<td>Combined iron and manganese oxide-silicate ores</td>
<td>Dolomite, skarn</td>
<td>1.3</td>
<td>32-65% Fe, 0.7-14% Mn</td>
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<tr>
<td>Falun</td>
<td>Pyritic SVALS</td>
<td>Felsic volcanics, limestone-dolomite skarn</td>
<td>28.1</td>
<td>2-4% Cu, 4% Zn, 1.55 Pb</td>
</tr>
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<td></td>
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<td></td>
<td></td>
<td>13-24 g/t Ag, 2-4 g/t Au</td>
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<tr>
<td>Garpenberg</td>
<td>SVALS and pyritic SVALS</td>
<td>Limestone-dolomite skarn, felsic volcanics</td>
<td>21.5</td>
<td>Garpenberg: 5.3% Zn, 3.3% Pb</td>
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<tr>
<td></td>
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<td></td>
<td>0.3% Cu, 98 g/t Ag, 0.65 g/t Au</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td>Garpenberg N: 3.0% Zn, 1.4% Pb,</td>
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<tr>
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<td>157 g/t Ag, 0.1 g/t Au</td>
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<td></td>
<td>150-&gt;3,000 g/t Ag, 12% Zn, 1-2% Pb</td>
</tr>
<tr>
<td>Sala</td>
<td>SVALS</td>
<td>Limestone-dolomite skarn</td>
<td>5.0</td>
<td>7.1% Zn, 2.2% Pb, 0.9% Cu, 0.4g/t Au, 42 g/t Ag</td>
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<td>Saxberget</td>
<td>SVALS</td>
<td>Limestone-dolomite skarn</td>
<td>6.8</td>
<td>3 Mt at 20-40% Fe, 1 Mt high-grade Zn ore or unknown grade</td>
</tr>
<tr>
<td>Ryllshyttan</td>
<td>Combined skarn iron ore and SVALS</td>
<td>Limestone-dolomite skarn</td>
<td>4.0</td>
<td>Lens K (M.Ripa, unpub. data): 1-4% Zn, 0.3-1% Pb, 10 g/t Ag, 20-35% Fe, 7% Mn, Lens M (M.Ripa, unpub. data): 3.2% Zn, 15.6% Pb, 320 g/t Ag, Lens L (M.Ripa, unpub. data): 30% Fe, 12% Mn</td>
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<tr>
<td>(Garpenberg)</td>
<td>Combined manganiferous skarn iron ore and SVALS</td>
<td>Limestone-dolomite skarn</td>
<td>6.4</td>
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<tr>
<td>Stollberg</td>
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</tr>
<tr>
<td>Oster Silvberg</td>
<td>Pyritic SAS</td>
<td>Ash-siltstone</td>
<td>0.2</td>
<td>5.6-22.5% Zn, 1.2-2.9% Pb, 45-70 g/t Ag, 4.5-7 g/t Au, &gt;0.9% Cu</td>
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<tr>
<td>Zinkgruvan</td>
<td>SAS</td>
<td>Ash-siltstone, quartz-rich chemical sediment</td>
<td>+43.0</td>
<td>Nygruvan: 10% Zn, 1.5% Pb, 45 g/t Ag Knalla: 6% Zn, 5.5% Pb, 100g/t Ag</td>
</tr>
<tr>
<td>Uto</td>
<td>Combined SAS and SVALS</td>
<td>Ash-siltstone, limestone-dolomite skarn</td>
<td>0.2</td>
<td>4% Zn, 1% Pl, 40 g/t Au</td>
</tr>
</tbody>
</table>

From Allen et al. 1996
2.3.2 What is the degree of metamorphism, deformation and recrystallization in the ores. Does it vary from deposit to deposit in the district?

The metamorphism is generally in middle greenschist to middle amphibolite grade, in both Bergslagen and the Skellefte district. The larger part of the Skellefte District is in greenschist facies. Deformation is often intense and multiphase, recrystallization and local remobilization is common, although relict colloform sulphides have been described from some VMS ores in the Skellefte district and well preserved stromatolites and gypsum pseudomorphs are described from Bergslagen.

2.3.3 Cu-type, Cu-Zn-type, Cu-type, Au-only, barite-only, pyrite-only)? Give a cartoon model of each type present, showing simple geology, morphology of the deposit and metal zones. Do not use genetic classifications such as kuroko type or Cyprus type, but use metal content and ratios – Cu/(Cu+Zn) and Zn/(Zn+Pb). (e.g. Large, 1992: ECON. GEOL. V87, p 473)

Skellefte District

Metal ratios for Skellefte District VMS-deposits

- Rhyolite cryptodome-tuff volcanoes VMS >1.1 Mt
- Rhyolite cryptodome-tuff volcanoes VMS <1.1 Mt
- Other VMS >1.1 Mt
- Other VMS <1.1 Mt
2.3.4 Are stringer zones present or economic? What is their mineralogy? Are there any deposits that comprise only stringer sulfides?

What has been interpreted as stringer zones is present in several of the Skellefte District ores. Normally these zones are pyrite dominated. Laver may constitute a deposit with only stringer type ore. In Bergslagen vein type sulphides occur at several places but are normally not unambiguously interpreted as stringer ore. In Zinkgruvan Cu-rich dissemination and vein type ore in the footwall to the Zn-Pb ore has yet not been proven to be related to the stratiform Zn-Pb ore.
2.3.5 *What are the major textures in the massive sulfides – massive featureless, banded, brecciated? Are these textures interpreted to be primary or deformation-related. Key evidence?*

As stated above most sulphide textures are metamorphic, but massive, banded and breccia style textures all occur. The genetic interpretations differs and while some are attributed to postdepositional deformation and metamorphism, primary colloform textures have been detected at least in the Skellefte District. In some deposits sulphide mylonites resembles primary banded ore.

From Svensson 1983

2.3.6 *Did most deposits form on the seafloor or by replacement below the seafloor or a combination of both? Key evidence? If sub-seafloor, how far below the seafloor? Evidence?*

From volcanic facies studies it is now clear that many of the Skellefte District ores are sub seafloor
replacement ores. Commonly these ores replaces volcanic sediments but for instance in the West Mauliden deposit massive sulphide ore has replaced a coherent subvolcanic intrusion. As some ores also seem to be exhalative in part the interpretation is that the depth of replacement beneath the seafloor may be less than 50m. In Bergslagen Zinkgruvan style deposits are generally interpreted as exhalative (see above cartoon), while the more complex and highly deformed deposits like Garpenberg have been suggested to be replacement ores.

2.3.7 Did the seafloor deposits form in brine pools, or as mounds, or are both types represented, or did they form by some other mechanism? Key evidence? Is there general agreement on the mechanism of formation?

In our view not enough studies have tried to answer this question. Probably both in Bergslagen, while in Skellefte district mound style may be the dominating or only style of seafloor deposits.

2.3.8 List key references for each deposit


Further references for individual deposits in these two references.

2.4 Exhalites

2.4.1 Are “exhalites” (Fe, Si or Mn, units) present at the same stratigraphic level as the ores? Are other styles of ore-equivalent horizons developed, eg; sulfide-bearing epiclastics, pyritic black shales, limestones? Are the exhalites true seafloor precipitates or simply alteration (silicification?) of tuffaceous sediments? Key criteria?

Exhalites have been described from both Skellefte district and Bergslagen, but not really proved. Stratigraphic key horizons like pyrrhotitic black shales seem to immediately overlie most VMS deposits in the Skellefte district. Chert horizons have been described from some areas in the Skellefte district, and chemical sediments/precipitates have been mapped in some areas. The Zinkgruvan ore extends for several km’s along strike and may have an “exhalite” style continuation outside the mineralized area.

2.4.2 Are exhalites developed at other stratigraphic levels above or below the ore position? How far above or below?

See above.

2.4.3 Can the exhalites be mapped along strike from the deposit (how far?), and are they useful for exploration? How do you distinguish ore-associated exhalites from barren exhalites?

See the Zinkgruvan case above. Since little work has been done the last 10 years on exhalites at the present we are not sure how to distinguish or even if exhalites are important.

2.4.4 Is there a geochemical database for exhalites in your belt (how many samples, REE data, isotope data)?

No
2.4.5 List key references

Hedström, P., Simeonov, A. & Malmström, L., 1989: The Zinkgruvan ore deposit, south-central Sweden: A Proterozoic, proximal Zn-Pb-Ag deposit in distal volcanic facies. - Econ Geol., 84, 1235-1261
Lagerblad, B. & Gorbatschev, R. 1985: Hydrothermal alteration as a control of regional geochemistry and ore formation in the central Baltic Shield. - Geol. Rundsch., 74/1, 33-49.

2.5 Alteration facies

2.5.1 Have hydrothermal, regional diagenetic, and regional metamorphic mineral assemblages and textures been identified? Criteria used for discrimination?

This is a fundamental problem in especially the greenschist facies areas as the hydrothermal and metamorphic mineral assemblages (chlorite, sericite, biotite ± actinolite) are similar. Normally however the relationship between mineral paragenesis and deformation is discriminating in late stage metamorphic overgrowth. In many cases however it can not be excluded that even if deformation overprints the minerals may still be metamorphic. Mineral assemblages in amphibolite facies rocks are of course normally easier to attribute to metamorphism although in some cases people argue for hydrothermal garnet and tourmaline, in Bergslagen.

2.5.2 What (if any) is the immediate footwall alteration mineralogy and zonation? Is the footwall alteration more commonly in stratabound zones or as pipes? What is the depth extent and surface area relative to the deposit?

Footwall alteration is a normal feature in all (?) deposits in the Skellefte district. Normally a zoning from distal (or main) quartz-sericite-pyrite, extending from 100m to over 1 km along strike to 2 km into the footwall. An inner chlorite±cordierite±andalusite-pyrite-chalcopyrite±sphalerite zone occur in some deposits. Notably the Boliden deposit is an exception with a core of sericite-quartz-andalusite-corundum high alumina zone and an outer chloritic zone is present. In Bergslagen extensive potassic, silicic and Mg rich alteration occurs in the footwall to the Zinkgruvan deposit, while the Garpenberg style deposits have intense Mg-rich (phlogophite-biotite-talc-almandine-cordierite-amphibole-quartz) footwall alteration zones.

2.5.3 What (if any) is the extent and mineralogy of hangingwall alteration? Give morphology, dimensions and mineral zonation.

Few examples are known, but in the Holmtjärn deposit in the Skellefte district strong pyritic, quartz-sericite alteration extends 150m into the hanging wall, in some deposits disconitnous dolomite-calcite-chlorite-talc±tremolite rocks occur directly above or laterally adjacent to ore lenses which now are interpreted as sub seafloor alteration zones.

2.5.4 What particular alteration indices (vectors to ore) have been tested or proposed?

In house data.

2.5.5 Has a single database of alteration geochemistry been compiled for the district? (number of samples?). By whom? and is it available?

A database exist at the Geological Survey of Sweden which is available.

2.5.6 Is there a database of whole rock oxygen isotopes? (number of samples?) Is data available on H or C isotopes?

Very limited data exist on silicate minerals (more on carbonates), and to our knowledge data has not been compiled in a single database.
2.5.7 Have deep semi-conformable alteration zones been identified? What is their dimension, mineralogy, and chemical characteristics? Is there evidence for metal depletion?

In Bergslagen regional scale alkali exchange has been suggested. In this model Na and Mg were enriched while other elements including metals were leached from the lower volcanic rocks. Near seafloor K-Na exchange reactions formed K-rich rocks, hence the classical lower Na-leptites and upper K-leptites of Bergslagen.

2.5.8 Is alteration geochemistry used to assist exploration in the district?

Yes.

2.5.9 List key references


2.6 Hydrothermal geochemistry

2.6.1 Are there systematic published studies on the mineralogy, mineral paragenesis and mineral chemistry of the ores and altered host rocks. Which deposits?

Most deposit studies include mineralogical, and some mineral chemical data. See reference list below.

2.6.2 Are the temperature, salinity and chemistry of the ore fluid well constrained from deposit data? What is the quality of primary fluid inclusion data?

Fluid inclusion data exist from a number of deposits in both the Skellefte District and Bergslagen. The data is interpreted by fluid inclusion experts to include primary ore-related inclusions, and hence the temperature, salinity, and fluid chemistry are interpreted as well constrained for some deposits.

2.6.3 Is there any evidence for fluid boiling, give details?

?

2.6.4 What hydrothermal thermodynamic modelling has been attempted? What modelling software was used (if any)?

No.

2.6.5 What additional information is required to develop robust geochemical models?

Further stable isotope and fluid inclusion (melt inclusion) studies from well constrained samples together with more whole rock and mineral chemical data is required. It is still in many ways possible to argue that the available results are influenced by later metamorphism and deformation.

2.6.6 List key references

Lindblom, S. & Burke, E., 1988: Raman spectrometry and microthermometry data on CO-Ch-bearing fluid inclusions in quartz from the Saxberget Zn-Pb-Cu-Ag deposit, Central Sweden - Geologie en Mijnbouw,
Broman, C., 1992: Unpublished PhD thesis Stockholm University. The most comprehensive work on fluid inclusions from VMS ores in the Skellefte District

2.7 Source of fluids, sulfur and metals

2.7.1 How extensive is the S isotope database on ores, sulfates and host rocks (numbers of analyses)? What is the range of del 34S? Do the massive sulfides and stringer zones have the same mean value and range? What is the interpreted source(s) of sulfur?

Some S-isotope data exist, but has not been compiled during the last 10 years.

2.7.2 How extensive is the Pb isotope database on ores and host rocks (number of analyses and range of 206/204Pb and 207/204Pb ratios on ores?). What is the interpreted source of metals?

Skellefte district
c. 100 sulphide analyses and slightly less whole rock.

2.7.3 Is there any other isotopic data (Os/Ir, Sm/Nd, Sr) that may assist in determining the source of metals?

Sm/Nd and Rb/Sr data exist for both the Skellefte District and Bergslagen, however the dataset has limited valued for determining the source of metals, but is rather used for petrogenetic studies.
2.7.4 Is there any evidence for magmatic fluid/metal input? If so what is the key evidence?

Stable isotope data (S, O, H) indicate a substantial magmatic input, furthermore coeval porphyry style mineralizations in the Skellefte district indicate magmatic origin for metals. This is less evident in Bergslagen, where many models invoke derivation of metals from the leached lower volcanic pile (see above).

2.7.5 What further research is required to determine the source of fluids, sulfur and metals?

Little has been done on stable isotope, and fluid inclusion geochemistry in a modern sense. Detailed sampling programmes from well-defined samples would substantially help in interpretations on source of fluids, sulphur and metals.

2.7.6 List key references

Gebeyehu, M. & Vivallo, W., 1991: Ore lead isotopical composition of Lower Proterozoic volcanogenic sulfide ores at Garpenberg, south central Sweden., - GFF, 113, 7-14

2.8 Subvolcanic intrusions

2.8.1 Have syn-volcanic intrusions been identified and are they associated with VMS deposits? What is their composition and are they composite?

Subvolcanic intrusions have been identified in especially the Skellefte district and is a key player in most VMS-deposits (see tuff-cone model above). The composition of these are normally rhyolitic or rhyodacitic, quartz-feldspar of feldspar porphyritic. Possibly also mafic subvolcanic intrusions (dykes) exist, but they have not been studied in any detail. Part of the major synvolcanic batholiths are also regarded as high level intrusions, and in the Skellefte district porphyry style Cu-Au mineralization is associated with these quartz-feldspar porphyries. In Bergslagen subvolcanic intrusions have been identified in several places, albeit not as closely associated with VMS deposits as in Skellefte district.

2.8.2 Classify them as shallow (<1000 m from the lowest VMS horizon), epizonal (1000-3000 m) or deep (>3000 m). Is there more than one level present? What is their geometry and dimensions.

This awaits interpretation in Skellefte district and Bergslagen. Most probably all types exist, and are associated with mineralization. In a regional scale more than one level is present since they are not exactly coeval (probably within 10 Ma) and intrude an active tectonic environment. Dimensions are extremely variable.
from thin dm wide dykes to larger batholiths perhaps in the order of 20 x 20 km? However, this has not been studied in any detail.

### 2.8.3 Are they hosted by comagmatic volcanics? Underlying basement?

The synvolcanic intrusions have generally been regarded as comagmatic with the volcanic rocks in both Skellefte district and Bergslagen. New data from the Skellefte District indicate that a straightforward genetic relationship between major calc-alkaline batholiths and the volcanic rocks (including coherent lavas and subvolcanic intrusions/domes) does not exist. However, it is still accepted that the subvolcanic intrusions and coherent lavas (which are sometimes indistinguishable) are comagmatic with the volcaniclastic rocks they intrude or are interlayered with.

### 2.8.4 Are they identified as comagmatic to VMS-hosting strata by: a) geology; b) igneous geochemistry, and/or c) geochronology?

All three (bearing in mind that geochronology has not the kind of resolution that is needed since all rocks are within errors the same age between 1.88 to 1.89 Ga in the Skellefte district, except that the major calc-alkaline batholiths seems to be slightly older in the Skellefte district (excluding cogenesis?) and slightly younger in Bergslagen.

### 2.8.5 Are they related to district-scale alteration zones? Key evidence?

No work done on this.

### 2.8.6 Do they contain extensive areas of alteration? Do they contain base-metal and/or gold occurrences?

Some VMS mineralization is replacing coherent lavas and subvolcanic intrusions in the Skellefte district. As mentioned above several of the major “synvolcanic” intrusions in the Skellefte district are calc-alkaline tonalites-granodiorites, which are extensively hydrothermally altered and contain porphyry-style Cu-Au mineralization.

### 2.8.7 List key references


### 2.9 Hydrogeological modelling

#### 2.9.1 Are there any published or unpublished hydrogeological models for the district or for individual deposits? What software package was used?

No.

#### 2.9.2 Are there any data on the original porosity and permeability of the volcanic and sedimentary facies in the succession?

No.
2.9.3 Have regional or local hydrothermal fluid pathways been defined? Using what data or criteria?

No.

9.4 Have any heat sources or fluid driving mechanisms been defined?

Only speculated on. Normally the synvolcanic subvolcanic intrusions have been regarded as heat engines for the hydrothermal systems.

2.9.5 What research is required to develop robust hydrogeological models? What computer codes are suitable and available? What computer code developments are needed to better constrain 3D heat and fluid flow modelling?

This must be an extremely hard thing to do in polydeformed and metamorphosed district with poor outcropping like the Skellefte district and Bergslagen, but any ideas on this subject are welcome.

2.9.6 List key references

2.10 Exploration criteria

2.10.1 How were the known deposits found? Provide a list with dates and the key methods. (e.g. outcropping gossan, gravity, magnetics, soil geochemistry etc.)

The vast majority of ores both in the Skellefte district and Bergslagen were found by boulder tracing, combined with especially EM-slingram which actually was first developed in the Skellefte district by Boliden. Discoveries during the last 20 years of blind deposits have used a combination of magnetics, EM, downhole EM, and geological modelling. Geochemical exploration has been used in understanding known alterations systems and deposits, and has primarily been used in regional exploration for gold-lode deposits. The Storliden deposit (discovered in 1998) in the Skellefte district which is a blind ore-body that was found by airborne EM (GEOTEMO), followed up by ground surveys such as horizontal loop electromagnetics (BL-EM) and total field magnetics, and later TEM, IP and Mise-a-la-Masse surveys.

2.10.2 Currently, what are the key methods used by companies to identify 1) prospect areas, and 2) drill targets?

See above, in drill target downhole logs with EM, magnetics and even radar and gravity are continuously being developed.


Data is available from the Geological Survey of Sweden. Airborne magnetics with a 200m line spacing and 40m altitude covers the entire Skellefte district and 90% of Bergslagen. Additional airborne VLF, and radiometric (U, Th, K) exist for large areas. The lithogeochemical database contains 5000-6000 analyses.
Elektromagnetisk
information

- VLF
- Sagnant
Magnetfeltsinformation

- Mått överfåden i digonal form.
- Fläkten 1000 m, övrigt 30-100 m över nivån.
- Över havet är procentvärden 1 000 m.
2.10.4 What percentage of the volcanic district is under shallow cover? Have any deposits been discovered in the covered areas?

In this respect 95% of the area is covered by glacial till.

2.10.5 What exploration methods need to be considered or further researched in your district?

The Skellefte District and Bergslagen are fairly well covered with modern exploration data, but detailed ground and downhole measurements would improve our understanding of the nonexposed bedrock.
2.10.6 List key references

Visit SGU homepages at www.sgu.se

2.11 Research strengths for your VMS district

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<td>9. Subvolcanic intrusions</td>
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</table>

1 = Adequate database and extensive interpretation of data
2 = Adequate database but little interpretation
3 = Extensive interpretation but inadequate database
4 = Moderate database and interpretations (needs improvement)
5 = Inadequate database and little interpretation

2.12 List of twelve key references

List the major references, even if the interpretations differ from those generally accepted. The key references should include those that have the major geological, geochemical etc data (maps and tables) and also those that contain important discussions and interpretations. Make sure the titles of key maps or map series are included. List key unpublished references (e.g., theses) especially if they contain critical data not available elsewhere.

Six references have been chosen for each of Bergslagen (first six) and Skellefte district (last six). Note that this is biased by my view.


4) Lagerblad, B. & Gorbatschev, R., 1985: Hydrothermal alteration as a control of regional geochemistry and ore formation in the central Baltic Shield. - Geol. Rundsch., 74/1, 33-49.

5) Lundström, I., 1987: Lateral Variations in Supracrustal Geology within the Swedish part of the Southern


