A Structural and Ore Geological study of the Palaeoproterozoic Stratabound Sala Zn-Pb-Ag deposit, Bergslagen, Sweden

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ABSTRACT

The following report provides an account on bedding features, the distribution and style of shear zones and the gross style of the mined Sala Zn-Pb-Ag-(Hg)-(Sb) deposit in Bergslagen, Sweden. It is a presentation of mesoscopic field relationships complemented with a review of earlier studies, maps and minor thin-section work. The results are presented in two geological maps, one profile as well as in this report. Based on the field observations made during the project, ideas of tectonic evolution, ore genesis and remobilization are discussed.

The stratabound Sala Zn-Pb-Ag-(Hg)-(Sb) deposit is believed to have formed epigenetically by sub-sea floor infiltration of metalliferous fluids into a buried stromatolite reef sparsely interbedded with volcanics. Prior to ore formation, the host rock accumulated in a shallow marine environment. The sedimentation was carbonate dominated and mainly occurred through growth of stromatolite reefs. Supply of siliceous material occurred periodically in the sedimentary basin, mainly from surrounding active volcanoes. This established interbedding between siliceous interbeds and carbonate in Sala. The siliceous interbeds have been Mg-altered and the carbonate has been dolomitized. At around 1890 Ga BP the supracrustals where intruded by a series of early Svecofennian granitoids.

The whole area underwent tectonic inversion and shortening during the Svecokarelian orogeny (peak ~ 1.85 Ga BP). The carbonate rocks were metamorphosed under lower greenschist-upper amphibolite conditions to dolomitic marble, yet stromatolitic textures are locally well-preserved. The siliceous interbeds were metamorphosed to skarn-rich lithologies. A phase of retrograde alteration also appears to have affected the lithologies. The host rock experienced several forms of deformation involving thrusting, ductile extension, two phases of folding, oblique reverse brittle-ductile shearing, as well as late brittle strike-slip movement. The mine is mainly confined to two large tectonic structures; The NW-trending Storgruvan Shear Zone whose strike is similar to the strike of the mine and the F1 Sala Syncline whose fold hinge is similar to the rake of the mineralization. The Sala Syncline is moreover refolded leading to local reversals in the plunge of the ore mineralization.

Kinematic indicators in the Storgruvan Shear Zone show that the most prominent movement was reverse dip-slip, leading to an upwards shift of SW segments. Horizontal slickensides on shear zone boundaries indicate that the shear zone has been reactivated during a later phase of brittle strike-slip faulting along cm-thin faults. A prominent branching zone of the Storgruvan Shear Zone coincides with a part of Sala Mine where anomalous Ag-Hg-Sb phases have been reported in the past. The old mine is confined between two the major branches of the shear zone.

Sphalerite ores occur in vein networks in direct proximity to well-preserved stromatolitic textures. These indicate that ore formation was not entirely texturally destructive. Stromatolitic way-up indicators indicate that galena ore appears stratigraphically higher than the sphalerite ores in the mine. The relationships between the shapes of the workings where ore was mined and measured bedding attitudes suggest that there was a stratigraphic control on ore formation. The ores were initially emplaced as stratabound ore bodies but are now concentrated in the hinges of folds and near the boundary to the Storgruvan Shear Zone.

Cover image: A drawing by Bo Svärd, showing a ‘markscheider’ (18th century mine surveyor) and his assistant mapping the 155 m level of Sala Mine.
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1. INTRODUCTION

Sala Mine is situated in the Bergslagen mining district in central south Sweden. It is one of Sweden’s foremost classical mines in both a historical and a geological context. The mine was in operation already during the end of the 15th century and mining continued on a continuous basis until 1908. In the early days, mining was focused exclusively on silver but towards the end of the mine’s lifetime, lead and zinc became more and more important for the mine’s economy. In the middle of the 20th century, short-term mining for zinc was undertaken but then, the focus had shifted to the newly discovered, yet now abandoned Bronäs Mine nearby. Today, the Sala Mine is a tourist mine run by Sala Silvergruva AB and the tourism venues have greatly increased its accessibility during the last decades.

In total, ~450 tons of silver, 35 000 tons of lead and an unknown amount of zinc were extracted from an estimated 5 million tons of mined material when the mine was in operation. There is currently no mining for metals in Sala but dolomite is mined in the nearby Tistbrottet mine by Björka Mineral AB and Tumi Resources Ltd. is investigating the area’s ore potential.

The anomalous richness in silver associated with Sala Mine has granted it epithets such as ‘the kingdom’s foremost jewel’ and ‘treasury of Sweden’ throughout history. This thesis in geology aims at studying the framework of this ‘treasury’ with special emphasis on structural geology, stratigraphy and the gross style of the mineralization.

The article was written as a project in Earth Science for Uppsala University, under the supervision of Prof. Hemin Koyi. The choice of subject was done partly on behalf of the personal interest of the author, partly after a suggestion from Tumi Resources Ltd. All ore analyses and thin-section preparation where funded by Tumi Resources Ltd. The project would never have been possible to achieve without the helpfullness of Sala Silvergruva AB who runs the current tourism operations.
2. AIM & APPROACH

The following presentation is mainly the result of a survey of two levels of Sala Mine with special emphasis on the mesoscopic style of ore bodies, stratigraphy and structural geology. The chosen study areas were the 55-60 and 155 meter levels, which are currently open for tourists and thus easy to access. Complementary observations were done in Tistbrottet, Herr Sten’s Level, Juthyllsgruvan, the Torg Shaft Section and the 85 m level of the mine. The results will be presented in two maps of the mine, one profile as well as pictures and stereograms within the report.

To the knowledge of the author, there are no older mine plans published which formally separate basic geological features such as bedding, faults and shear zones in Sala Mine. Instead, these have in the past been lumped together in a single old mining term named ‘sköl’ (singular). Different ‘skölar’ (plural) have been looked upon as representing a similar geological phenomenon despite their contrasting nature (e.g. in Sjögren, 1910).

As the major aim of this project is to study the structural geology of the mine, the ‘sköl’ terminology of old clearly has to be abandoned. It is a major source of confusion when reviewing the literature on Sala Mine and therefore, the ‘sköl’ terminology will be formally discussed in the light of the findings of this project. This will allow a more constrained picture on the relationship between the ore mineralization, bedding and structures.

As for the importance in reviewing the ‘sköl’-terminology, the ‘skölar’ of Sala were largely un-mineralized but they showed such a strong relationship to the distribution of ore that they received names, such as ‘Storgruveskölen’ and ‘Sandrymningskölen’. Thus, it is not surprising that every detailed discussion on the genesis of the Sala deposit so far has involved the ‘skölar’ and their structural relationship to the ore in some way (e.g. Forselles, 1818; Sjögren, 1910; Grip, 1983). In the light of separation of ‘skölar’ into bedding and structures done in this project, the earlier theories of ore genesis in Sala will be reviewed.

In order to firmly consolidate a distinction between bedding features and structures in Sala Mine, stromatolitic textures were studied in detail. Well-preserved sections were logged in stratigraphic columns to exemplify the observed sedimentary sequences and the major way-up indicators used during the project. Likewise, shear zones and their surroundings were examined for traces of offset bedding planes, fabric and kinematic indicators. Sedimentary beds were measured, drawn on maps and plotted on stereonets to reveal the large-scale pattern of folding in the mine. Parasitic folds were likewise measured and made special subject for inquiry when identifying superposed folding. Observed folding patterns were compared with measurements of foliations
and lineations. With the structural geological frame-work clearer, the relationship between the ore-mineralization and the major structures was investigated.

Geological mapping underground was hampered by a veneer of secondary deposits, soot derived from the fire-setting mining method and shotcrete used to secure the workings. This was mainly a problem at the 55-60 m level and the northern part of the 155 m level where the degree of exposure is low. As the mine is a heritage site, there was a limit to the impact that could be done to its historical workings, e.g. cleaning soot-covered walls. Therefore a minimal impact approach had to be chosen. The fact that the mine is submerged under water below 155 m depth led to that many localities of geological interest were not accessible. Some of the workings in the mine are also very dangerous to enter and even above the groundwater table, many old workings were inaccessible. There are few accessible sections in the NW part of the mine and it was therefore not possible to produce a complete geological map of the mine.

To cope with the limited degree of exposure, mapping was anchored at sites where key geological features such as primary sedimentary bedding and structures were easy to identify. Mapping at these anchor-points was conducted in detail to resolve the relationship between the different structures. As these relationships became clearer, attempts to trace and extrapolate units and structures were undertaken to produce geological maps. Older mine maps from levels above and underneath the mapped levels proved useful for this matter and were studied in detail. A 3D-model of the mine was also studied to obtain an overview of the mineralization.

All measurements were made with a Silva Ranger Type 15-CL compass with clinometer. To avoid significant errors in the readings due to geomagnetic anomalies in the mine, readings were plotted on maps straight away and compared with reality. This showed that geomagnetic anomalies in the mine were few and local and that in general, the readings did not suffer from significant errors. The results of the project will be presented in the following chapters along with an overview of the geology of Sala Mine based on a literature review.

As a final note; nearly every gallery, shaft and working in Sala Mine has received a name which can be seen on maps of the mine. As a convention in the article, reference to a certain locality the mine will be followed by the level where the observation was made in brackets, e.g. ‘Bergenstierna (155 m)’. All the photographs were taken by the author except were else is noted.
3. REGIONAL GEOLOGY

The Stratabound Sala Mine Zn-Pb-Ag-(Hg)-(Sb) deposit belongs to the Bergslagen Ore Province of the Southern Svecofennian Domain (Allen et al., 1996). The Svecofennian Domain in turn belongs to a much more extensive unit named the Baltic Shield or Fennoscandia (Lindström et al., 2000). Fennoscandia constitutes the major part of the Swedish bedrock and extends far into the basement of east Europe. Here it is bordered by Sarmatia and Volgo-Uralia, all three together referred to as segments of the East European Craton (Gorbatchev & Bogdanova, 1993).

Fennoscandia is the result of a long period of crustal growth starting in the current NE of the shield during the late Archaean and ending in the current SW at the end of the Mesoproterozoic. The Paleoproterozoic segment of the shield is one of the largest metalliferous provinces on the planet. Most ore deposits are believed to have formed in the vicinity of island arcs or magmatic arcs or during accretion of crustal material to an Archaean (Karelian) Craton in the current north. This accretion is attributed to the Svecokarelian orogeny, which took place around 1.9 – 1.8 Ga BP and it is deemed to have been evolving at a very fast rate, involving voluminous magma production (Weihed et al., 2005).

The Bergslagen area, to which Sala belongs, has been interpreted as a microcraton which docked to the Northern craton ~ 1.88-1.87 Ga BP (Weihed et al., 2005). It hosts a diverse array of ore mineralizations, such as banded iron formations, magnetite skarns, manganiferous skarns and marble-hosted iron ores, apatite-magnetite iron ores, W skarns as well as stratiform and stratabound Zn-Pb-Ag-(Cu-Au) sulphide ores (Allen et al., 1996; Weihed et al., 2005). Besides Bergslagen, there are two other major ore provinces in Svecofennian Sweden, namely the Skellefte District and the Northern Norrbotten Area. All ore deposits of these three provinces are believed to have formed between 2.06 and 1.78 Ga BP (Weihed et al., 2005).
Age-wise, the supracrustals of Bergslagen cluster together with coeval calc-alkaline granitoids at 1.90-1.87 Ga BP. The succession is dominated by calc-alkaline rhyolites but minor amounts of calc-alkaline dacite and andesite occur as well as geochemically unrelated tholeiitic basalts. The volcanic succession is estimated to be 1.5 km thick overlying a thick succession of turbiditic metasediments in the east. In the west, the volcanic succession is estimated to be over 7 km with no known basement.

The environment where Bergslagen’s Svecofennian supracrustals accumulated has been interpreted as an intra-continental (alt. continental margin back-arc) extensional setting on continental crust. The general stratigraphic pattern can be attributed to an evolution from intense magmatism, thermal doming and crustal extension towards waning volcanism, waning extension and thermal subsidence and a change from extensional to compressional tectonics. The environment of deposition was mainly subaquatic, but fluctuated between shallow and moderately deep. However, it became significantly deeper during the deposition of the upper part of the succession (Allen et al., 1996).
The formation of Bergslagen’s numerous VMS\(^1\) deposits occurred between 1.91 and 1.88 Ga BP before the area underwent Svecokarelian tectonic inversion and accretion (Weihed et al., 2005).

Bergslagen is bordered by the Transscandinavian Igneous Belt to the west and south and by the Bothnian Basin to the north (S-type granitoids associated with migmatites, at 1.86-1.82 Ga BP) (Allen et al., 1996).

Mining has greatly decreased in Bergslagen during the last century, yet there are still four sulphide mines in operation, namely Garpenberg, Garpenberg Norra, Lovisa and Zinkgruvan. Moreover, the Dannemora Iron Mine is currently being restarted (Peter Svensson of Dannemora Mineral, 2007 – personal communication).

\(^1\) VMS = Volcanic-associated Massive Sulphide deposits
4. LOCAL GEOLOGY

Figure 3 - Geological map of the Sala area modified after Ripa et al. (2002), Holmgren (2001), and Zensén in Tegengren (1924). Numbers denote other mines, prospects and quarries in the neighbourhood of Sala Mine (for an index see table 1). Regional F1 axial traces according to Ripa et al. (2002) have been marked in red. On the map, the F1 axial trace near Sala on the map by Ripa et al. (2002) has been removed since this hasn’t been confirmed in the mine. Instead a dashed red line has been added to show the F1 axial trace near Sala Mine.
<table>
<thead>
<tr>
<th>#</th>
<th>Name</th>
<th>Type</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bronäsvägen Mine</td>
<td>Mine</td>
<td>Argentiferous sphalerite and galena. Accessory barite, geocronite, boulangenite, pyrrargyrite etc. (Grip et al., 1983, Sala Mine’s mineral collection)</td>
</tr>
<tr>
<td>2</td>
<td>Nygruvan Mine</td>
<td>Mine</td>
<td>Unspecified silver ore (Tegengren, 1924)</td>
</tr>
<tr>
<td>3</td>
<td>Trundhemsgruvan Mine</td>
<td>Mine</td>
<td>Argentiferous galena (Author’s own observation)</td>
</tr>
<tr>
<td>4</td>
<td>Biskopsgruvan Mine</td>
<td>Mine</td>
<td>Unspecified silver ore (Tegengren, 1924)</td>
</tr>
<tr>
<td>5</td>
<td>Tistbrottet Mine (former quarry)</td>
<td>Dolomite</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Fintorpsbrottet Quarry</td>
<td>Quarry</td>
<td>Dolomite</td>
</tr>
<tr>
<td>7</td>
<td>Samuels Gruva Mine</td>
<td>Mine</td>
<td>Unspecified silver ore (Tegengren, 1924)</td>
</tr>
<tr>
<td>8</td>
<td>Prinsgruvan Mine</td>
<td>Mine</td>
<td>Unspecified silver ore (Tegengren, 1924)</td>
</tr>
<tr>
<td>9</td>
<td>Glasgruvan Mine</td>
<td>Mine</td>
<td>Sphalerite (Vogt, 1905), unspecified silver ore (Forselles, 1818)</td>
</tr>
<tr>
<td>10</td>
<td>Trefoten Mine</td>
<td>Mine</td>
<td>Talc, soapstone, potstone (SJögren, 1910), sphalerite (Vogt, 1905), unspecified silver ore (Forselles, 1818)</td>
</tr>
<tr>
<td>11</td>
<td>Malmgruvan Mine</td>
<td>Mine</td>
<td>Unspecified silver ore (Tegengren, 1924)</td>
</tr>
<tr>
<td>12</td>
<td>Finngruvan Mine</td>
<td>Mine</td>
<td>Unspecified silver ore (Tegengren, 1924)</td>
</tr>
<tr>
<td>13</td>
<td>Björkscärpningen Prospect</td>
<td>Prospect</td>
<td>Unspecified silver ore (Tegengren, 1924)</td>
</tr>
<tr>
<td>14</td>
<td>Förhoppningsgruvan Mine</td>
<td>Mine</td>
<td>Argentiferous galena with 'salite' (diopside) (Forselles, 1818)</td>
</tr>
<tr>
<td>15</td>
<td>Pers Koppargruva (Pehr’s Copper Mine)</td>
<td>Mine</td>
<td>Chalcopyrite, bornite. Accessory arsenopyrite, tetrahedrite, molybdenite, scheelite, bismuth, silver etc. (Per Nysten, 2007 – personal communication)</td>
</tr>
<tr>
<td>16</td>
<td>Bykgruvan Mine</td>
<td>Mine</td>
<td>Unspecified silver ore (Tegengren, 1924)</td>
</tr>
<tr>
<td>17</td>
<td>Knopersgruvan Mine</td>
<td>Mine</td>
<td>Unspecified silver ore (Tegengren, 1924)</td>
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<tr>
<td>18</td>
<td>Vattengruvan Mine</td>
<td>Mine</td>
<td>Unspecified silver ore (Tegengren, 1924)</td>
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<tr>
<td>19</td>
<td>Gravgruvan Mine</td>
<td>Mine</td>
<td>Unspecified silver ore (Tegengren, 1924)</td>
</tr>
<tr>
<td>20</td>
<td>Käringgruvan Mine</td>
<td>Mine</td>
<td>Unspecified silver ore (Forselles, 1818)</td>
</tr>
<tr>
<td>21</td>
<td>Anders Bergs gruva Mine</td>
<td>Mine</td>
<td>Unspecified silver ore (Tegengren, 1924)</td>
</tr>
<tr>
<td>22</td>
<td>Kisgruvan Mine</td>
<td>Mine</td>
<td>Pyrite, pyrrhotite (Grip et al., 1983)</td>
</tr>
<tr>
<td>23</td>
<td>Kokmans gruvor Mine</td>
<td>Mine</td>
<td>Sphalerite, galena, pyrite, chalcopyrite (Forselles, 1818)</td>
</tr>
<tr>
<td>24</td>
<td>Båtgruvan Prospect</td>
<td>Prospect</td>
<td>Galena occurrence (Meurman, 2000)</td>
</tr>
</tbody>
</table>
The Svecofennian supracrustal lithologies are the oldest known rocks in the Sala area. These were deposited, deformed and metamorphosed during the Paleoproterozoic era and today consist of marbles, metavolcanics and metasedimentary rocks (Ripa et al., 2002). The supracrustal suite is the foundation of Sala Mine and its surrounding quarries and mines as it hosts the resources that have been mined throughout history. Most of the description given below is based on the work of Ripa et al. (2002) and Allen et al. (2003b).

Sala Mine is hosted by the Finntorp formation which consists of dolomitic marble sparsely interbedded with felsic metavolcanics. Some of the felsic interbeds have well preserved primary features such as accretionary lapilli or cross-bedding (Ripa et al., 2002). Others have been hydrothermally altered to Mg-rich varieties, leading to an obliteration of primary features (Allen et al., 2003b).

The Finntorp formation is estimated to have a stratigraphic thickness of at least 300 m. It is underlain by the Sandtorp formation which consists of interbedded siltstone and marble. In addition to this interbedding, coarse volcanic lithologies seem to merge laterally into carbonate rocks. The Sandtorp formation passes downwards into the metavolcanic rocks of the Sommarhag formation. These are dominated by felsic (mainly rhyolitic but also dacitic) breccias to sand- and siltstones as well as mafic rocks and metavolcanic conglomerates (Ripa et al. 2002).

As for the stratigraphic overlier of the Finntorp formation, it is currently only poorly known but beds of volcanic siltstone with well-preserved accretionary lapilli have been observed in the upper part of the formation in the area of the Finntorpsbrottet quarry (Ripa et al., 2002; Allen et al., 2003b). Beds with accretionary lapilli have however not been observed in Sala Mine.

Ripa et al. (2002) concluded that the Sommarhag formation was most likely formed during the time referred to as the ‘intense volcanism and extension stage’ by Allen et al. (1996). Likewise did Ripa et al. (2002) conclude that the Sandtorp and Finntorp formation formed during the later ‘waning volcanism stage’ suggested by Allen et al. (1996).

The metavolcanites have been dated 1906-1891 Ma BP and are believed to be underlain by the Larsbo formation (Ripa et al., 2002) which is a key locality for correlation of the Bergslagen stratigraphy.

As can be seen on Figure 3, the Finntorp formation is delimited towards the east by an older intrusive of mainly granitic composition. This intrusive has been dated to 1891 Ma BP by Ripa et al. (1997). The contact between the intrusive and the supracrustal rocks is poorly known but it is at least partly structurally controlled according to Ripa et al. (2002). However, old mining maps of the Bronäs Zn-Pb-Ag Mine (Locality 1 on Figure 3) close to the border between supracrustals and granite indicate that the plutons interfinger with the supracrustals. Thus, the date gives an upper limit to the deposition of the Finntorp formation.
Grip et al. (1983) reported that the Sala granite dips underneath the supracrustal rocks and that the intrusive is chilled at the contact. Moreover, Högberg (1953) reported that rich talc-occurrences have been encountered at the contact between the supracrustals and the granite. These have even been mined, for example in Trefot Mine south of Sala (Locality 10 on Figure 3).

Besides the large intrusives, the Sala supracrustals are also intruded by intrusive metavolcanics which appear to be older than the Sala granite or coeval with it. These are referred to as the Eklöv formation and are according to Ripa et al. (2002) mainly of two types. The first one is similar to clast-carrying metavolcanites of the Sommarhag formation but has characteristic peperitic contacts towards the silty surroundings. The other type is a quartz-feldspar porphyry which sometimes is so rich in phenocrysts that it may be confounded with granite. Radiometric dating of the porphyry by Ripa et al. (2002) has yielded an age of 1892 ± 5/-4 Ma BP.

The preservation of sedimentary textures in Finntorp formation is exceptional for Bergslagen. Therefore, it is not surprising that Sala is one of Sweden’s most famous localities for Paleoproterozoic stromatolites. These were studied by Allen et al. (2003b) in the quarries Finntorpsbrottet and Tistbrottet2 near Sala Mine (Localities 5 & 6 on Figure 3). They found that even though original stromatolitic textures may have been obliterated by diagenesis, hydrothermal alteration, deformation and metamorphism, stromatolites may still be recognised where they are draped by another material. The draping material may preserve the stromatolitic micro-topography when burying it.

In the Finntorp formation, the draping units are most often the interbeds of metavolcanics. These beds most likely formed from sedimentation of terrestrial material and tephra fall but they sometimes show signs of reworking by waves (Allen et al., 2003b).

From observed sedimentary textures and measurements of C and O isotopes in samples of microbial mats, Allen et al. (2003b) interpreted the depositional environment of the carbonate as being a shallow marine volcanioclastic dominated basin accumulating during a time of reduced volcanioclastic sedimentation. They interpreted the interbedding as being due to repeated cycles of stromatolite reefs growing up to wave-base, becoming smothered by the dumping of felsic volcanic tephra fall from volcanic eruptions or wave-action, followed by basin subsidence to deeper water, which was followed by re-colonization of the microbial community and growth towards sea-level. Moreover, they observed that the dolomitic marble was primarily calcitic but was later dolomitized.

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2 To avoid confusion, Tistbrott started as a quarry but nowadays, dolomite is only mined underground and therefore Tistbrottet is nowadays a mine. Thus, Tistbrottet consists of an abandoned quarry section and an active mine section.
The tectonic history of the Sala area is not yet fully understood, yet there has been an increase in understanding due to the work of Ripa et al. (2002), Allen et al. (2003b) and Grip et al. (1983). Grip et al. (1983) suggested that the whole area west of Sala could be looked upon as a bowl formed by folding along NNE and NNW trending fold axes. Furthermore, they also added that aside from folding, the tectonic outline is also largely determined by ‘skölar’, a term which will discussed later in this report.

The metamorphic grade of the Sala area was estimated to be upper greenschist-lower amphibolite facies by Allen et al. (2003b). This was partly founded on the presence of the well to relatively well preserved metavolcanic and metasedimentary rocks in the Sala area. Metamorphism has however given rise to abundant formation of Mg-silicates where carbonates and siliceous rocks occur together. An increase in thermal metamorphic grade to upper amphibolite facies was noted southwards away from Sala by Ripa et al. (2002).

The ore mineralizations of the Sala area are mainly found within the marble. There are however some notable exceptions as for example the small Freberg Silver Mine, which is found ~1 km inside the Sala granite (Grip et al., 1983). The Freberg Silver Mine is not available for inspection any more but according to Tegengren et al. (1924), the ore is hosted by a ‘crush-zone’ inside the granite. As seen on Figure 3, there are also several mineralizations within the metavolcanics and at the border between metavolcanics and carbonate. The relationship between the numerous sulphide deposits on Figure 3 and Sala Mine is not entirely known but they may very well be related.
5. OUTLINE OF SALA MINE

5.1 General outline and development

Sala Mine (Swedish; Sala Silvergruva or Sala Gruva) is approximately 700 m long from the Torg Shaft in the SE to the Carl XI Shaft in the NW. The shafts are aligned S-SE / N-NW and the width of the mine area is approximately 80 m (not including the smeltery area to the east or the mine dumps to the west). The mine becomes progressively deeper from SE towards NW where a maximum depth of 318 m is attained.

The rake\(^3\) of Sala Mine is approximately 325° 35°. The southernmost workings are thus the shallowest, for example the now collapsed Herr Sten’s Level (Swedish; Herr Stens Botten). Ore occurring directly at the surface near Herr Sten’s Level is believed to have lead to the initiation of Sala Mine before the beginning of the 16\(^{th}\) century (Norberg, 1978; Meurman, 2000).

As mining continued northwards, a steady increase in depth of the mineralization was encountered. In the 16\(^{th}\) century, this lead to the establishment of the Sandrymningen and Kungsrýmningen Levels just north of Herr Sten’s Level. The massive collapse structure seen on the profile is the result of reckless mining and several collapses during the 16\(^{th}\) century (Meurman,

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\(^{3}\) 'Rake’ is here taken as the longest line through the mined deposit, equivalent to the Swedish mining term ‘fältstupning’. For Sala, such a line would plunge from the surface at the Torg Shaft to the deepest part of the Carl XI Shaft.
The collapsed mine mainly consists of Herr Sten’s Level along with the Sandrymningen and Kungsrymningen Levels.

In the beginning of the 17th century, it was apparent that reckless mining posed a serious threat to the prosperity of the mine. A more rational mining technique was therefore desired and shaft mining was introduced in Sala. The map expression of this is that the collapse structure northwards gives way to a more symmetric array of shafts and galleries transecting large ore bodies. Not much is known about the original geometry of the collapsed mine and the ore bodies in the southern part look highly exaggerated on the map.

In 1604, the sinking of the Knekt Shaft (Swedish; *Knekt schaktet*) was started for purposes of exploration and instalment of a suction lift pump. The shaft reached a maximum depth of 190 m though today, the lower 30 meters are filled with mine waste. In 1622, the Makalös Shaft (Swedish; *Makalös schaktet*) was sunk for instalment of an ore hoisting device and to search for new ore-bodies. Both the Knekt Shaft and the Makalös Shaft were successful but the collapse of the old mine continued propagating northwards. For a while, the Makalös Shaft was the only functional shaft for ore hoisting and a collapse would be devastating. In the second half of the 17th century propagation of the collapse in Sandrymningen and Kungsrymningen rendered the Makalös Shaft unusable (Engelbertsson, 1987). The shaft is nowadays almost completely filled with mine waste.

The central shaft of the mine is the Queen Christina Shaft (Swedish; *Drottning Christinas schakt*), which is approximately 257 m deep. Sinking of the shaft started in 1650 and after 10 years of mining, a very rich ore zone was found at approximately 190 m depth (Engelbertsson 1987). This ore zone became known as the First Level (Swedish; *Första Botten*) and it was the first of the four Ore Levels. The sinking of the Queen Christina Shaft can be seen as a strategic move to intercept ore bodies encountered in the Makalös Shaft at a deeper level and at a safe distance from the collapse, before the Makalös Shaft became unusable. It shows that already in 1650, the rake of the Sala deposit had become apparent and was taken into consideration during the rational planning of the mine.

Shaft mining continued after the successful sinking of the Queen Christina Shaft. In 1670, work was started on sinking the Carl XI Shaft, which is the mine’s northernmost shaft. The sinking of the shaft was however extremely problematic and work had to be paused several times, e.g. due to problems with drainage (Norberg, 1978; Tegengren, 1924). The greatest depth of Sala Mine was reached in the northern part of the mine in the 1830’s. This is the depth of Carl XIV Johan’s Shaft, a small appendix to the Carl XI Shaft, ending 318 meters below the surface (Engelbertsson, 1987). No large ore zones were found during the sinking of this shaft as can be seen on the profile.
A return to the collapsed southern part of the mine was undertaken around the turn of the 18th century due to a decline in production from the Ore Levels at depth (Sjögren, 1910). This resulted in the sinking of the Latort Shaft (Swedish; Latorts schaktet) in 1695 and the Torg Shaft (Swedish; Torgschaktet) in 1725. Some new ore bodies could be exploited in the southern part of the mine, but the most important discovery during the 18th century was the finding of the Halfway Ores (Swedish; Halvvägsmalmerna) in the second half of the century. These ores occur in the central to northern part of the mine between 40 and 130 meters depth, halfway between the surface and the First Level. Their discovery greatly increased the otherwise meagre production of the mine during the 18th century (Engelbertsson, 1987).

In 1775, the youngest shaft of the mine was sunk; the Gustav III Shaft (Swedish; Gustav III schakt). The sinking of the Gustav III Shaft was initially done to improve the ventilation in the northern part of the mine. During the 1830’s it reached its maximum depth of 267 m and in 1847, it replaced the Knekt Shaft as Sala Mine’s pumping shaft (Engelbertsson, 1987).

The total tonnage of mined material is unknown as no production record was kept in the early days of mining. According to Grip et al. (1983), approximately 5 million tons of rock has been mined. From this approximately 450 tons of silver were extracted during the mine’s lifetime (Granström, 1940).

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4 The upper part of the Halfway Ores is originally referred to as ‘Fjerdedelsmalmerna’, yet they are here included with the Halfway Ores for simplicity and since they are continuous with the Halfway Ores.
5.2 Lithologies

5.2.1 Dolomitic marble

Sala Mine is volumetrically dominated by the dolomitic marble of the Finntorp formation and where interbeds of more siliceous material occur, these are commonly less than 0.5 m in width and widely spaced. Thicker siliceous interbeds occur west of the mine and can be seen in Tistbrottet and Finntorpsbrottet as noted earlier. The marble has a grain-size of less than 2 mm and it is relatively impure, leading to that it commonly has a green tone in hand-specimen. Minerals like chlorite, diopside, muscovite, talc, tremolite, serpentine and phlogopite are common silicate constituents in the marble of Sala Mine and its surroundings. Purely white marble is only locally observed in the mine.

In hand-specimen, the most common texture observed is white marble spotted with cm-size green lenses and spots of serpentine (e.g. Victoriaorten – 60 m) or skarn-rich marble (central Wallbergs Fältort – 155 m). The marble often also appear homogenously greenish due to fine-grained Mg-silicates being finely dispersed within the rock or rarely vaguely laminated or banded in hand-sample.

Stromatolitic textures are especially easy to recognise in the southern part of the mine. They are conspicuous where they are draped by interbeds such as chloritic drapes or thicker siliceous interbeds. Locally they occur with relatively well-preserved laminae but for the most, it seems as primary textures have been destroyed by pervasive recrystallisation during diagenesis, hydrothermal alteration, deformation and metamorphosis. The stromatolites generally occur as mm- to cm-sized flat-laminated stromatolites (*Figs. 8 & 9*), small (< 10 cm) digitate stromatolites, domal stromatolites as well as thin columns (*Figure 6*).

Many of the stromatolites contain green spots of serpentine or chlorite, possibly derived from infilled stromatolitic fenestrae and column interspace. This relationship may present an explanation for the spotted appearance of much of the marble in the mine. Moreover, the interspace material can sometimes be observed to define a faint fabric normal to bedding in the form of trains of calc-silicate minerals (S0’). This has also been observed in the neighbouring quarries by Allen *et al.* (2003b) and it is yet another possible explanation for the spotted appearance of the marble in Sala Mine. It is of course also possible that some of the serpentine spots are retrogressed metamorphic silicate porphyroblasts.

From comparison with the work of Allen *et al.* (2003b), the styles of the stromatolites in Sala Mine generally indicate formation in a shallow water environment. Yet, at some localities, the draped carbonate show a more jagged, vuggy and sharp surface than would be expected from
simple stromatolites accumulating below the wave-base. This could possibly be a result of dissolution during temporal sub-aerial exposure (Victor Melezhik, 2007 – personal communication). This would indicate that the environment of deposition may have ranged from sub-wave base to intertidal.

Figure 6 – Columnar and domal stromatolites draped by dark chloritic material (S0) on the wall of south Wallbergs Fältort (155 m). The interhead material (S0’) stands out and shows a convex downward outline. The lower carbonate layer has a more jagged topography, which may represent a dissolution surface. Pen for scale.

Figure 7 – highlighted column/dome interspace, showing the generally flat tops and concave downwards morphology of chloritic lenses. This is interpreted as reflecting sedimentation of fine-grained material into column or dome interspace. The flat tops faces upwards and provides the stratigraphic younging direction.
Carbonate breccias also occur in the mine, (e.g. Gruvdrängsorten – 155 m). The carbonate clasts may be of meter size and they occur in a matrix of Mg-silicates such as chlorite or serpentine. While some of the breccias are obviously the result of shearing or faulting, others are parallel to bedding, less strained and more local, suggesting that they are intraformational breccias. The intraformational breccias commonly show a very high clast/matrix ratio.

Figure 8 – Flat-laminated microbial mats observed perpendicular to bedding in the ceiling of central Wallbergs Fältort (155 m). The microbial mats are seen from below. Pen for scale.

Figure 9 – Flat-laminated stromatolitic (same as in Figure 8) observed parallel to bedding. Pen for scale.
**Figure 10** – Graphic log over the Kanalen Gallery (158 m – not visible on 155 m map), displaying the typical sedimentary features recognised in the southern part of the mine. Note the normal grading in metavolcanic bed and the constant direction of lobate stromatolites heads.
5.2.2 Metavolcanics and skarn

The metavolcanic rocks of the Sala area were geochemically analysed by Ripa et al. (2002). The analysed samples mainly defined a sub-alkaline trend with compositions ranging from rhyolitic to basaltic. Rhyolite is volumetrically dominant together with dacite, which is more common in the Sala area than in Western Bergslagen. The rhyolite was shown to have a composition similar to granites formed in island-arc environments in proximity to a subduction zone.

In Sala Mine, metavolcanic rocks occur as siliceous interbeds\(^5\) in the marble. There are no known geochemical analyses of metavolcanics from Sala Mine, but according to Allen et al. (2003b), the metavolcanics near the mine are commonly enriched in Mg. Due to the much altered state of the metavolcanics, no attempt will be made without geochemical analysis and thin-section work to identify their original compositions during this project. If they are similar to those described from the surrounding quarries by Allen et al. (2003b) and the Finntorp Formation in general by Ripa et al. (2002), it would be expected that rhyolitic original compositions predominate.

The metavolcanic beds are typically less than 0.5 m thick. They are altered to variable extent, but were originally most likely of volcaniclastic type with grain-sizes ranging from ash to sand. Some of the siliceous interbeds have a homogeneous, cherty groundmass, which may be white, green or more rarely pinkish. For these very cherty units, a volcanic origin has not always been possibly to establish and they could just as well be chemical precipitates which have sedimented on the carbonate.

The beds sometimes have a preserved lamination with 2-3 mm laminae of alternating light quartz-rich and darker chlorite-rich layers reminiscent of thinly laminated rhyolitic ash-siltstones (Swedish ‘hälleflinta’). In some beds however, a reminiscent laminated texture is seen, but with a higher proportion of talc and clayey substances replacing the quartz-rich bands. Some beds display normal grading from more massive sandy bottoms to laminated finer-grained tops though this relationship is locally obscured by the formation of large crystal aggregates of tremolite and diopside skarn during metamorphosis.

\(^5\) In the discussion, all non-dolomitic interbeds will be generally referred to as ‘siliceous interbeds’, meaning mainly skarn- and phyllosilicate-rich strata of probable metavolcanic origin. This is since it is not yet established that all of these, non-dolomitic beds are of volcanic origin though most appear to be.
At some locations, the siliceous interbeds contain massive carbonate sometimes holding galena, which is very unlikely for juvenile metavolcaniclastic rocks (e.g. Rapps ort - 55 m, Bergenstierna – 155 m). This lithology has been observed in the vicinity of the galena ore bodies of Johan & Liljenberg (55 m) and it transected the ore body before it was mined out.

Thin dark-green drapes of mainly chloritic composition are locally abundant in the marble and generally accentuate stromatolitic textures. The drapes are mainly < 1 cm thick, but thicker drapes also occur. The thinnest drapes have an undulating appearance, which resembles fold trains but where stromatolitic textures are preserved it is seen that this is rather an effect of the stromatolitic micro-topography unto which the precursors of the chlorite settled. Where thicker beds occur, it is seen that only the bottom of the chloritic beds has an undulating appearance while the top is relatively flat (Figure 6).

As has already been outlined, there appears to be a transition between skarn- and phyllosilicate-rich layers and more pristine metavolcanics in Sala Mine. Probably, they both share a similar origin (e.g. ejecta from volcanic eruptions or wave-reworked volcaniclastic material) but have afterwards been altered to different degrees by secondary processes. It was demonstrated by Allen et al. (2003b) that the thin chloritic drapes found in the surrounding quarries were hydrothermally altered rhyolites. Early syn-volcanic metasomatic Mg-alteration of volcanics have been described from ore-bearing areas in Western Bergslagen (e.g. Baker & de Groot, 1983; Lundström, 1987; Trädgårdh, 1991) and possibly, the Mg-alteration of the beds in Sala Mine can be correlated with this regional metasomatic alteration phase.
An enrichment of Mg in metavolcanics may be derived directly from early hydrothermal interactions between sea-water and sediments in a marine environment. Chlorite can form through hydrothermal breakdown of feldspars as reported from the Hjulsjö area in Western Bergslagen. Mg-alteration of volcanics may also result from hydrothermal reactions in an environment where dolomite exists together with feldspar at temperatures in excess of 350° (Baker & de Groot, 1983).

Another possibility for the skarn-abundance in many of the interbeds is sedimentary reworking by waves after the volcaniclastic material had settled. Such reworking was observed in the neighbouring quarries by Allen et al. (2003b). Sedimentary reworking could lead to that the siliceous material of the metavolcanics was mixed with carbonate material. During metamorphosis, the siliceous interbeds would develop variable amounts of skarn depending on the relative amounts of carbonate and siliceous material in each interbed.

The thicker metavolcanics commonly have a rim of tremolite needles or talc at both the top and the bottom of the bed. The marble directly adjacent to the siliceous interbeds appear bleached relative to the rest of the surrounding dolomitic marble. These relationships are most likely related to later metamorphism rather than primary deposition. Metamorphic reactions between dolomite and silica involving the expelling or adding of volatiles give rise to a variety of magnesium silicates such as talc, tremolite and diopside as well as carbonate (Yardley, 1989). To summarize, sedimentary reworking and hydrothermal alteration followed by metamorphosis to skarn during regional metamorphism may very well explain the current field appearance of the siliceous interbeds in Sala Mine. Another aspect which will be considered later is that a phase of retrograde metamorphosis may also have affected the siliceous interbeds.

Except for occurring concordantly within metavolcanic beds or at the interface between carbonate and siliceous interbeds, skarn also occur disseminated in the marble, as discordant veins and vein-systems as well as in pods. As has been reported by earlier observers (Forselles, 1818; Sjögren, 1910; Tegengren, 1924), skarn mineralizations generally accompany the ore mineralization in Sala and show a volumetric relationship to the tonnage of ore. In Wallbergs Fältort (155) and near the Bergenstierna ore body (155 m), it can be seen that there is a silicate mineral zonation in the skarn veins.

5.2.3 Dolerite

Dolerite only occurs rarely in the mine and it is post-tectonic relative to the Svecokarelian orogeny. The best known example is a dike that is present in the northern part of the mine (“Trappskölen”) according to Gumaelius (1873). Dolerite can furthermore be seen in Tistbrottet in the west and in the Trundhem Mine just north of Sala Mine (Locality 2 on Figure 3). The dolerite
is dark grey-green to black in colour fine-grained and often intersected by numerous fractures. The dolerite display columnar jointing and appears to lack a contact aureole.

The dolerite dike of Trappskölen in the northern part of the mine could not be visited during this project but it strikes $\sim 075^\circ \ 75^\circ$ according to Gumaelius (1873). No radiometric dating has been performed on the dike, but according to Ripa et al. (2002), the $\sim$ east-west trending dolerite dikes of the Sala area probably belong to a generation of dolerite dikes intruded around 1530 Ma BP.

Figure 12 - A $\sim$ E-W trending dolerite dike in Tistbrottet (Locality 5 on Figure 3). The dolerite dike dips towards the south and is seen in the western wall of the quarry. Note the en-echelon style of the dyke.
5.3 Structural geology

5.3.1 Sala Mine in 3D

*Figure 13* – 3D perspective view of Sala Mine seen towards the east, almost perpendicular to the rake. The picture is extracted from the computer in Sala Silvergruva AB’s tourist reception.

*Figure 14* – 3D perspective view of Sala Mine seen towards SSW, perpendicular to the rake.
The pictures above are extracted from a 3D-model of Sala Mine, which can be accessed on the visitor’s computer of Sala Silvergruva AB’s tourist reception. The model is incomplete and not flawless but it is based on very detailed mine maps produced by mine surveyors when the mine was in operation. Thus, the model provides a good overview of the mine in 3D.

As can be seen in the model, a characteristic trait of ore bodies is a degree of incoherence. Thus, the ore is concentrated in ore-zones surrounded by un-mineralized sections. This has since old added complications in following the mineralization. Grip et al. (1983) summarized the Sala mineralization as a system of several groups of ore-bodies trending N 35° W along a relatively narrow zone of 80-100 m width.

During this project, it has been observed that the main controls on the present morphology of the mine (excluding shafts and galleries) are sedimentary bedding, folds, faults and shear zones as well as the extent of the ore mineralization itself. For example, ore-bodies often strike sub-parallel to sedimentary strata (e.g. Johan & Liljenberg – 60 m, Rosenblad – 155 m, Rödstjärten – 155 m, Bergenstierna – 155 m) and are often bound laterally on one or both sides by steep shear zones (e.g. Bergenstierna - 155 m, Hjärnes – 155 m, Namnlösen - 155 m). Younger faults, which are often slickensided have also been important in determining the present shape and distribution of the ore deposits (e.g. Bergenstierna – 155 m). Moreover, Rödstjärten (155 m) is located in the hinge of a minor F1 fold. There also appear to be thickening of the ore zone in the central part of the mine between the Queen Christina Shaft and Gustav III Shaft.

All of these features will be outlined in more detail in the following chapter, but first the significance of the old ‘sköl’ terminology will be discussed in the light of these observations.
### 5.3.2 The ‘Sköl’-system

A review of the old literature on Sala Mine (Forselles, 1818; Gumaelius, 1873; Sjögren, 1910; Magnusson, 1973) reveals that large planar structures, which appeared to pose a control on the distribution of ore in the mine, were labelled with the old Swedish mining term ‘sköl’. This means that in many descriptions of the mine (e.g. Sjögren 1910), silicous interbeds and shear zones are often listed under the same banner.

In a way, it is understandable why this has come to be. The hydrothermally altered and metamorphosed metavolcanic rocks have already been described as being dominated by phyllosilicates, skarn and soft minerals such as talc. They are often weak from a rock mechanical perspective, especially where they have a rim of talc at the interface to the carbonate. Likewise, the shear zones are composed of highly strained and fracture-rich lithologies rich in chlorite, talc, serpentine as well as carbonate and are also relatively weak. Both often possessed a very deep dark-green colour, which stood out in relation to the more light-coloured dolomitic marble. Most importantly however; the ‘skölar’ generally occurred close to an ore body.

For the mine workers of Sala Mine, ‘sköl’ simply appears to have referred to layers of rocks (straight or curved, vertical or near horizontal) which were exotic relative to the surrounding dolomitic marble, occurred in association with an ore body and was of poor rock quality. Indeed, most of the major collapses that have occurred in the mine have been initiated along a ‘sköl’ (Engelbertsson, 1987). Thus, ‘skölar’ were interesting to the engineers of the mine both from an economical perspective and a safety perspective.

The most detailed accounts of ‘skölar’ occurring in Sala mine are those of Forselles (1818), Gumaelius (1873) and Sjögren (1910). From these descriptions it appears that several of the ‘skölar’ have received names due to the importance the mine management saw in keeping track of them. Both Sjögren (1910) and Forselles (1818) reported that some ‘skölar’ varied in thickness at length and very often, track was lost of the ore as the ‘skölar’ disappeared.

The most famous ‘sköl’ is the steep ‘Storgruveskölen’ or ‘Storgruvegången’, which follows the trend of the ore deposit from SE towards NW and thus served as an excellent marker for following the Sala ore (Forselles, 1818). On the sides of ‘Storgruveskölen’, there are several other ‘skölar’ that dip towards ‘Storgruveskölen’ and ‘converge’ with it at depth (Forselles, 1818; Sjögren, 1910). The cross-section of the mine by Forselles (1818) (Figure 16) exemplifies this relationship.

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6 Forselles was the managing director of the mine 1817-1855. He was also a modern geologist for his time and conducted a scientific investigation and a revision of the ‘skölar’ of Sala Mine in 1818. Thus, even though his report is almost 200 years old, it is included as the observations of Forselles (1818) are highly interesting.
From a structural geological view-point two possible interpretations immediately emerge for
the ‘skölar’ on Forselles profile:

1: The central ‘sköl’, ‘Storgruveskölen’ (n) is a fault or shear zone near the centre of a synform; the converging
‘skölar’ are folded layers cut by the shear zone or fault.

2: The large-scale structure is a flower structure with a central fault or shear zone branching out into several
complementary shear zones or faults.

A revisit to ‘skölar’ described by earlier observers such as Forselles (1818) and Sjögren (1910)
show that ‘Storgruveskölen’ is a steep brittle-ductile shear zone which anastomoses around shear
pods, while most of the moderately dipping ‘skölar’ that ‘converge’ with ‘Storgruveskölen’ at
depth are siliceous interbeds. The sedimentary nature of the latter is confirmed by the fact that they
parallel and drape stromatolitic bedding, whereas the tectonic nature of the former is confirmed by
the fact that it cuts and displaces bedding. The ‘convergence of skölar’ is thus not the result of
anastomosing and flowering shear zones or faults, but rather sedimentary strata being cut by shear
zones and faults. ‘Storgruveskölen’ is however by no means the only shear zone in the mine.
To summarize, the following conclusion on the term ’sköl’ can be drawn for Sala mine:

1: The word ‘sköl’ provides no genetic information whatsoever
2: ‘Sköl’ is a very loosely defined term, from the mine workers’ point of view a layer of exotic composition or structure relative to the surrounding dolomitic marble
3: The ‘skölar’ potentially impose stratigraphic or structural control on the distribution of ore in Sala Mine
4: The ‘skölar’ can be of much lower rock quality than the surrounding marble.
5: The ‘skölar’ are not always laterally continuous features

Because of this, the term ’sköl’ is abandoned and a new terminology is favoured in this article. The following table serve as a bridge between the terminologies of old articles such as Forselles (1818) and Sjögren (1910) with the one preferred here:

<table>
<thead>
<tr>
<th>Historical term</th>
<th>New term</th>
<th>Geological nature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trappskölen</td>
<td>Trappskölen Dolerite Dike</td>
<td>Dolerite dike</td>
</tr>
<tr>
<td>Storgruveskölen</td>
<td>Storgruvan Shear Zone</td>
<td>Shear zone</td>
</tr>
<tr>
<td>Sandrymningsskölen</td>
<td>Sandrymning Bed</td>
<td>Bed</td>
</tr>
<tr>
<td>Greve Bielkes sköl</td>
<td>Greve Bielke Bed</td>
<td>Bed</td>
</tr>
<tr>
<td>Skänkebornsskölen</td>
<td>Skänkeborn Bed</td>
<td>Bed</td>
</tr>
<tr>
<td>Torkels sköl</td>
<td>Torkel Bed</td>
<td>Bed</td>
</tr>
<tr>
<td>Kungsrymningsskölen</td>
<td>Kungsrymning Bed</td>
<td>Bed</td>
</tr>
<tr>
<td>Rinmans sköl</td>
<td>Rinman Bed</td>
<td>Bed</td>
</tr>
</tbody>
</table>

However, even though the Storgruvan Shear Zone and the hydrothermally altered metavolcanics are different phenomena of different geological age, bedding parallel shear has occurred along some beds, for example in the Sandrymning Bed near Bergenstierna (155 m).

The hydrothermally altered metavolcanics are commonly enriched in lubricative and platy minerals such as talc and chlorite and this opens for the possibility that beds may have functioned as slip surfaces when favourably oriented during deformation. Allen et al., 2003b reported such bedding parallel shear from Tistbrottet and it is a common phenomenon within the mine itself. On the whole it seems as the siliceous interbeds have been far from passive markers during the different deformation episodes affecting the Finntorp formation.
5.3.3 Tectonic outline

Obtaining observations of bedding in the mine posed one of the greatest challenges during the project. This is because the siliceous interbeds are few, much disrupted, seldom laterally continuous and the degree of exposure is often relatively poor in the mine, especially in the northern part. The marble is also relatively homogenous, recrystallised and locally skarn-veined. As has already been mentioned, stromatolites are locally found in the mine and they are especially well-preserved in the southern part. The stromatolites along with the siliceous interbeds have provided excellent marker horizons for identifying bedding and for determining stratigraphic younging direction. For a more detailed description of the stromatolitic textures the reader is referred to the ‘lithologies’ section.

Mapping of bedding and interpretation of old mine plans (e.g. Forselles, 1818) show that Sala Mine appears to be confined within a syncline with perhaps a dome and basin fold interference pattern; a basin may exist in the centre. It is not however entirely clear if there is a basin in the centre as the attitude of the bedding in NW part of the mine is unknown at present. It is also possible that the fold-interference pattern is more akin to refolded fold interference pattern in the area of Sala Mine as suggested by Ripa et al. (2002). It can be noted that there is a thickening of the ore zone between the Queen Christina Shaft and Gustav III shaft which at least on NE side of the mine corresponds to the maximum width of the NE side of the ‘basin’ in this part of the mine. Likewise can a concentration of ore be seen between the Queen Christina Shaft and Gustav III shaft be observed on all levels (Figure 14). The structure will be referred to as the Sala Syncline from here on in this report even though it is not strictly a syncline, but rather a folded syncline as will be outlined below.

It is justified to use the term Sala Syncline since all observed way-up indicators show that bedding young upwards and generally towards the centre of the mine. There appears to have been no significant amount of overturning of strata (at least not in the southern-well-exposed half of the mine) during folding and the stratigraphy of the collapsed part of the mine appears to be right way up (Figure 18). This does not rule out that overturned strata exist elsewhere in the mine but none have been observed.
Figure 17 – A wall in the Ventilatorn Gallery (155 m) showing draped stromatolitic textures in marble directly beneath the Sandrymning Level. The stromatolites show a transition from domal stromatolites to flat-laminated desiccated microbial mats. The stromatolites young upwards and suggest that the stratigraphy is right way up in the southern part of the mine. The stromatolites are included in the graphic log in Figure 18.
Figure 18 – The Ventilatorn gallery (155 m). The log shows the stratigraphy below the now inaccessible Sandrymning Level which is part of the collapsed mine. The scale is in meters. The stratigraphic succession suggests that the stratigraphy is right-way-up in the southern part of the mine.
In the central part of the Sala Syncline, the N-NW striking Storgruvan Shear Zone is situated with a general strike parallel to the length of the mine and dip of ~ 70° towards WSW. The strike of the shear zone curves from approximately N-S in the south to roughly NW in the northern part of the mine. The width of the Storgruvan Shear zone is generally between 0.5 and 4 meters. Several other shear zones occur in the mine and these are generally quite narrow and seldom over 0.5 m in width. Most of these minor shear zones are parallel to the Storgruvan Shear Zone as seen on the 155 m map (Appendix 3). The shear zones mainly consist of chlorite-serpentine phyllonites, massive talc\(^7\), dolomitic breccia and dolomite-chlorite/serpentine augen mylonite. They often have sharp boundaries towards the surrounding rock and shearing appears to have been relatively localized. The shear zones only carry minor amounts of sulphides.

The Storgruvan Shear Zone splits into at least two distinct branches between the Queen Christina Shaft and the Makalös Shaft on the 155 m level. The two emergent branches have on the 155 m map been named Storgruvan Shear Zone 1 (SSZ1) and Storgruvan Shear Zone 2 (SSZ2), respectively south of the branching point. While SSZ1 still dips ~ 70° WSW south of the branching point, SSZ2 dips ~ 80° NE. North of the branching point, the central shear zone will just be referred to as the Storgruvan Shear Zone (SSZ) in the description.

It has been difficult to trace marker beds as these are relatively few, seldom laterally continuous and often much disrupted in the mine. Instead, interpreted bedding traces have been added to the geological maps to highlight the tectonic patterns. Comparison has been made with older mine plans of Sala mine when drawing the bedding traces as these sometimes show the distribution of ‘skölar’ on different levels of the mine (e.g. Forselles, 1818). It has sometimes been possible to interpret these ‘skölar’ as bedding or shear zones from comparisons with the field observations done during this project.

\(^7\) Mining of talc has been under consideration (Sundius & Zensén 1942) but has to knowledge of the author never occurred in the Sala Mine.
It was not possible to locate the fold hinge to the Sala Syncline in the central or in the northern part of the mine during this project. Instead, it appears that the SSZ is the major divider between the two oppositely dipping limbs of the Sala Syncline. A large synclinal fold however appears to exist between SSZ1 and SSZ2 and it is for this reason that the hinge of the Sala Syncline has been placed here on the 155 m level (see appendix 3). The NW part of the mine on the SW side of the SSZ is current poorly known so there is a possibility that hinge re-appears in the NW part of the mine. This would then fit with the regional picture of the Sala area according to Ripa et al. (2002).

The localisation of Sala Mine in a syncline has been suggested by earlier observers. Grip et al. (1983) suggested that the ore deposit is regulated along the middle or on the western flank of a syncline or/and a ‘sköl-system’ which transects the mine ~ parallel to the mineralization itself. Ripa et al. (2002) placed the Sala Mine in a N-NW trending syncline whose hinge curves westwards just north of Tistbrottet.

The observations of bedding during this project are consistent with the suggestions by Ripa et al. (2002) and Grip et al. (1983). The most prominent marker horizons dip towards the centre of the mine as can be seen on the map of the 155 m level. Moreover, even though showing a lot of scatter, an equal area plot of all bedding measurements from the 155 m and 60 m levels of the mine would yield a calculated fold hinge close to the rake of the mine itself.

Figure 20 – Poles to 128 measurements of bedding from the 155 m, 85 m and 55-60 m levels of Sala Mine. The approximate rake of the Sala Mine (325° 35) has been added as a diamond. The calculated fold hinge for the poles to bedding would lie close to the rake of Sala Mine. The scatter in data is most likely due to that the Sala Syncline is refolded.

To further test the relationship between the fold hinge of the Sala Syncline and the rake, a large parasitic fold plunging down into the ore body of Johan & Liljenberg (55 m) was studied in detail. This ore body belongs to the upper parts of the Halfway Ores which follow the general rake of Sala Mine according to Sjögren (1910). This fold has a hinge which is also strikingly has the same trend as the rake of Sala Mine.

8 The ‘sköl-system’ of Grip et al. (1983) most likely refers to the Storgruvan Shear Zone and sub-parallel shear zones.
Figure 21.1 - Profile of a fold (F1) on a wall along 200°, seen towards the ESE, 55 meter level. The ore body of Johan & Liljenberg is behind and the ore body of Baron Hermelin 10 meters to the right. White: dolomitic marble, grey: skarn and phyllosilicate altered siliceous interbed. The siliceous interbed displays both folding and boudinage. The style of the left fold hinge indicates that the siliceous interbed acted as less competent relative to the marble while the opposite is true for the style of the boudinage. Also notice boudinaged vein of pyrite and serpentine to the right. No vertical exaggeration.

Besides the folds whose hinges parallel the rake of Sala Mine, there are also several folds whose hinges are at a high angle to the rake of the mine. The largest example exists in the central part of the mine. It corresponds well with the local thickening of the ore zone in the centre of Sala Mine. Following the classification of fold attitudes from Twiss & Moore (1992), all the observed folds are generally upright to moderately inclined with sub-horizontal to moderately plunging fold hinges.
5.3.4 Structural history

The structural pattern which arose during the project was interpreted in terms of the sequence of events which may have given rise to the identified major structures. From the observed types of deformation and their cross-cutting relationship, a structural history scheme for Sala Mine was produced:

D0 Deposition of the host rock (carbonate and minor volcanics) in shallow water environment. Dolomitization of the carbonate. Volcanic activity in the Sala area and syn-volcanic Mg-alteration of the metavolcanic interbeds. Epigenetic ore formation giving rise to stratabound ore bodies. S0 fabric defined by stromatolitic bedding and siliceous interbeds.

D1 F1 folding around upright ~ NNW-SSE striking axial planes. Formation of the Sala Syncline with an axial planar S1 foliation. Formation and boudinage of veins sub-parallel to F1 axial planes. Ore bodies are folded and concentrated in F1 hinge zones.

Boudinage of siliceous interbeds and thrusting possibly coeval with folding or earlier.

D2 F2 folding around upright NE-SW striking axial planes with a sub-horizontal regional fold axis. The Sala Syncline is folded and a local thickening of the ore zone is established in the centre of the mine. Formation of axial planar S2 foliation.

D3 Semi-ductile shearing along the Storgruvan Shear Zone and complementary shear zones. Mainly reverse dip-slip but with a small horizontal component (dextral?) The ore zone is cut and displaced. Remobilization?

D4* Intrusion of Trappskölen Dolerite Dyke (probably before D4 – see discussion below)

D4 Brittle strike-slip displacement along minor faults and the shear zone boundary of the SSZ.

The following section will now provide an interpretation of the tectonic history of the ore and its host rock from the oldest to the youngest events.
The early formation and evolution of the host rock has already been made subject for inquiry. As for ore genesis, this will be discussed in a separate chapter later. For now, it is enough to say that everything points to that ore had already been introduced into the host rock before ductile deformation commenced in Sala.

After the host rock and ore had formed, the Finntorp formation experienced F1 folding around upright approximately NW-SE striking axial planes. F1 folding created an upright open-close syncline with a (currently) moderately NW plunging fold hinge in the area of Sala Mine. The scale of this syncline is such that it is referred to as the Sala Syncline as it confines the entire mine. The hinge of the syncline has a similar plunge as the rake of the Sala Mine (Figure 20) and it is undoubtedly the structure which is inferred on the profile of Forselles (1818) (Figure 16).

The siliceous interbeds appear boudinaged and pinched in the F1 folds. The boudin lines and neck lines generally parallel the hinges of minor F1 folds observed (Figure 33). Though it is possible that the extension recorded by the boudins is the result of an earlier phase of deformation, the boudinage and folding may also very well be coeval and belong to a single deformation phase (Hemin Koyi, 2007 – personal communication). It is however safe to say that the boudinage of the siliceous interbeds of Sala Mine didn’t post-date D1.

The style of boudinage shows that the siliceous interbeds generally acted as competent units relative to the marble, yet there appears to have been differences in the competence not only related to the thickness of the competent layers. When not completely separated, the siliceous interbeds display clear pinching with well developed necks. The thickest portions of the boudins and swells are often rich in silica or skarn (commonly tremolite) while the neck zones are rich in phyllosilicates.

Some of the siliceous interbeds display class 3 F1-fold geometry in the hinge zones, indicating that parts of the siliceous interbeds acted as incompetent relative to the dolomitic marble during D1. This contrasts with other observations that the siliceous interbeds are generally boudinaged prior to or during D1. Possibly this may be due to initial lateral heterogeneity in the competence of the sedimentary beds (e.g. due to sedimentary reworking, hydrothermal alteration or lateral facies variations) or to changes in relative competence during deformation and metamorphosis. However, the siliceous interbeds generally appear to have acted as competent units relative to the dolomitic marble.

Besides F1 folding, it is locally seen that some of the earliest shortening has been accommodated by thrusting (Figure 22). The best example of this is found in the Ventilatorn Gallery (155 m) where a quartz-rich bed appears to be over-thrust from the N-NW, causing a local duplication of the thickness of the bed. Mining has excavated a 3D-view of this low-angle thrust and the thrust is seen to have a wide fault-bend fold. The scale of the thrust is approximately 2-3
meters long so it is a minor structure compared to the mine itself. As for thrusts in general in the Sala area, imbricate beds and stratigraphic repetition was noted in the area north of Sala Mine by Grip et al. (1983).

The thrusting may very well belong to the same phase of deformation as F1 (Hemin Koyi, 2007 – personal communication). It could also belong to a separate phase of deformation predating D1. However, since only a few thrusts were recognised in Sala Mine, there is insufficient data to resolve this issue with certainty. Therefore, the thrust seen in the Ventilator Gallery will be referred to as a D1 structure for now.

Profile along 150-330
Location: Ventilator gallery - 155 m level
Date: 20070426

Following F1, the F2 fold hinges and boudin lines were refolded around sub-vertical axial planes trending NE-SW. This deformation phase is referred to as D2 and mainly involved F2 folding. The F2 folding established local reversals of F1 fold hinges and boudin lines as well as gentle curving of the Storgruvan Shear Zone. The predominant plunges of F1 fold hinges are however still moderately towards the N-NW as seen in the lineation plot below (Figure 33). F2 established a local thickening of the ore zone in the central part of Sala Mine on the NE side of the Storgruvan Shear Zone. Moderately plunging F2 fold hinges have been measured on both limbs of the syncline and the F2 fold hinges plunge towards the centre of the Sala Syncline.

The interpretation that NE-SW folding post-dated D1 is based on the fact that all fold hinges of observed F2 folds lay within or close to the NE-SW striking to the S2 foliation observed in the
mine (Figure 31). The F2 fold hinges yield different values of plunge which is an ideal behaviour for the younger generations of fold in a refolded area (Twiss & Moore, 1992). The variation in the plunge of F2 fold hinges is thus an effect of the different attitudes of already folded layers being folded again during F2. In general, F2 folding appears to have been relatively gentle on the scale of Sala Mine.

It was not possible to establish with complete confidence if the SSZ formed before or after D2. It is however believed that the observed shearing occurred after D2. The shear zone is roughly parallel to a series of NW striking shear zones west of Sala Mine. These were identified as D3 structures by Ripa et al. (2002) who also suggested that the SSZ may be related to this phase of deformation. There is also an interesting NNW-SSE striking dolerite dike seen on Figure 3, suggested to have an age of ~ 950 Ma BP by Ripa et al. (2002). This dike looks as if it could pass through Sala Mine but it has not been observed underground. It has however been observed on mine maps of the Bronäs Mine nearby (Locality 1 on Figure 3). The dolerite dike is parallel to the SSZ. If it is assumed that the dolerite dike intruded along an earlier plane of weakness resulting from D3 shearing, a NNV continuation of the SSZ north of Sala Mine and a post D2 origin is indicated. The mineralogy of the shear zones also suggests post-D2 shearing. Though hydrous Mg-silicates such as talc, chlorite and serpentine are abundant throughout Sala Mine, they are especially abundant in the SSZ. These hydrous Mg-silicates are of very fine grainsize in the SSZ. If the shearing occurred before D2, it would be expected that these Mg-silicates were metamorphosed and attained a coarser grain-size. A dragfolded spaced S1 foliation defined galena in carbonate has moreover been observed in the Grisen gallery (55 m).
The style of the shear zones imply that the dolomitic marble acted competent while the Mg-silicates acted incompetent during shearing. In the most carbonate-rich sections of the shear zones, highly flattened fine-grained chloritic schists commonly anastomoses around strained clasts of carbonate. The carbonate clasts show various degrees of strain, being more rounded and sheared in the augen mylonite while being more angular in the dolomitic breccia. The least brecciated parts of the dolomite marble commonly define shear pods bound by thin minor shear zones rich in hydrous Mg-silicates. Thinner shear zones are generally observed to branch and join at low angles (20-30°) and on the whole, an impression of a system of anastomosing shear zones is given.

Kinematic indication in the shear zones was provided by observations of asymmetrically winged objects of carbonate, imbricate clasts, S-C shear bands, S-C’ shear bands as well as trains of carbonate clast in a Mg-silicate matrix. For the Storgruvan Shear Zone, it was concluded during the field work that slightly oblique (dextral) reverse movement had occurred, causing a relative shift of the Western block upwards.

Constructed S-C intersections acquired during the late-stage of the project does however show a considerable spread in the in the S-C intersections. Some values even suggest a small sinistral horizontal component though most suggest a dextral component. The measurements were done in the Liljenbergs Försökningsort gallery (55 m) which is one of the best exposures of the SSZ. The constructed S-C intersections were produced by measuring S- and C-type shear bands and plotting them in a stereonet to find the line of intersection. The S-C intersections line-up along the shear plane of the SSZ.

The constructed values show that pure visual field inspection of S-C fabrics in Sala Mine may be insufficient for determining the movement direction in the SSZ. A strong stretching lineation does however occur in the carbonate at the shear zone boundary. This lineation plunges steeply towards the SW and if this lineation parallel to the movement direction, it suggests a mainly reverse movement but possibly with a minor sinistral component.

Figure 24 – Constructed S-C intersections (black circles), stretching lineation (black squares) and shear plane (great circle) from the SSZ in Liljenbergs Försökningsort (55 m).
There are however some features in the shear zone which may suggest a link to D2 deformation or pre-D2 activity along the SSZ.

1: The stretching lineation roughly lays in the axial plane of the F2 folds.

2: The axis of curvature in the shear zone also lay in the axial plane of the F2 folds and have similar trends as the L2 lineation measured in the mine

3: A Dragfolded bed over-printed by a foliation striking 082 72 has been observed in the Grisen gallery (55 m). (It is however not sure if this foliation really is a S2 foliation)

The second point could indicate that the shear zone has been gently folded during F2 which would suggest a pre-D2 origin. An alternative explanation is however that the shear zone may have followed the folded axial plane of the Sala Syncline. The shear zone may simply have propagated along a mechanical plane of weakness established during D1 deformation.

*Figure 25 – SSZ1 viewed towards SE close to the Bergenstierna ore body (155 m). S-C and S-C’ fabrics along with sheared asymmetric objects indicate that the western block (right) has been displaced upwards. At the shear zone boundary there are sub-horizontal slickensides. Notebook for scale is 15 cm long.*
It was noted above that there is a significant branching point of the SSZ between the Makalös Shaft and the Queen Christina Shaft on the 155 m level. While SSZ1 still show slightly oblique reverse uplift of the SW block (Figure 25), SSZ2 yield an unambiguous sense of shear due to a complex shear fabric yielding different kinematics. The combined effect of SSZ 1 & SSZ 2 appears to have caused a relative displacement of the southern block which host the earliest mined deposits of Sala Mine. Moreover, observations of shear zones in the vicinity of the collapsed mine suggest that the shape of the collapse to some extent follow the shear zone boundaries.

The branching of the SSZ may account for the fact that the hinge of the Sala Syncline is difficult to find in the central and northern part of the mine. The segment of the Sala Syncline which hosted the hinge appears to be confined within the southern block. Therefore, the displacement of the block holding the hinge of the Sala Syncline during shearing may have caused a juxtaposition of the two blocks holding the two limbs of the Sala Syncline (Figure 25). Thus, the shear zone became the dividing plane between the two limbs of the Sala Syncline in the mine’s central part just as is observed. This would predict that the hinge of the Sala Syncline may re-emerge in NW part of the mine on the NW side of the SSZ. From observations of shear zones in the mine in general, it seems shearing has mainly caused uplifts of SW lying segments.

**Figure 26** – Schematic diagram showing how shearing during late D1 or afterwards may have caused a displacement within of the hinge of the Sala Syncline. 3a and 3b represent different scenarios depending on the sense of shear in SSZ2. In 3a and 3b, the SSZ has become the dividing plane between the oppositely dipping limbs of the Sala Syncline. Note that the relative amounts of displacement are unknown.

A stereonet plot of shear zones of different dip direction close to the branching point at 155 m depth yield an intersection line plunging ~ 35° towards the NW. However, old mine maps suggest that the plunge of this intersection may in fact be much steeper and that the intersection may surface between the Makalös Shaft and the Sandrymningen Level.
It is of course far from certain that all the observed shear zones in the mine formed at the same time or that the shear zone has only been active once. A phase of reactivation under more brittle conditions is indicated by that lineations on slickensided surfaces binding the shear zones are often sub-horizontal on both SSZ 1 and SSZ 2. This contrasts with the S-C and S-C' fabrics, which indicate a more steep but oblique reverse dip-slip movement. The lee sides of some slickensides line-up sub-vertically and indicate that sub-horizontal movement has occurred and that the relative movement was mainly dextral. Most likely, this represent a strike-slip reactivation along narrow
(cm-scale) faults at the shear zone boundaries under more brittle conditions. The deformation phase is referred to as D4.

The amount of displacement still remains to be determined, both for the brittle strike-slip movement and the reverse dip-slip shearing. The main difficulty lies in the lack of major lithological boundaries and marker horizons which would be useful when estimating the offset if they are cut by the shear zones. There are however some interesting features in Sala Mine worth discussing when estimating the amount of displacement.

One is the Trappskölen Dolerite Dike. Though it must be emphasised that nowhere could the intersection between the Storgruvan Shear Zone and Trappskölen Dolerite Dike be visited during this survey, the late reactivation with brittle strike-slip movement re-invokes the possibility that the dike has been displaced along the shear zone, yet under more brittle conditions. If the Trappskölen Dolerite Dike belongs to a generation of dikes intruded around 1530 Ma BP, the dike provides an indication of a dextral displacement of 18.5 m after 1530 Ma BP. Yet again, it must be emphasised that the dike has not been dated and the intersection has not been available for inspection.

It was noted by Sjögren (1910) that there are large differences in the distribution of ore bodies on the two different sides of the Storgruvan Shear Zone. From 40 m down to a depth of ~180 m, most of the ore bodies occur on the SW side (e.g. the Halfway Ores) while below, most of the ore bodies are situated on the NE side (e.g. the Ore Levels). An important exception is the eastern part of the Halfway Ores between 85 and 155 m depth, which is laterally bordered by the shear zone.

Figure 29 – Trappskölen Dolerite Dike on a plan map of the 190 meter level of the mine. Note the en echelon style of the dike and that it ‘jumps’ dextrally at the contact to the Storgruvan Shear Zone. If this jump is the result of relatively late strike-slip movement along the Storgruvan Shear Zone, it indicates a dextral displacement of ~ 18.5 m after emplacement of the dike.

9 Gumaelius (1873) inspected the locality on Figure 29 and interpreted the ‘jump’ at the contact with the Storgruvan Shear Zone as possibly being due to faulting. Sjögren (1910) dismissed this idea on the basis that dolerite is the youngest lithology in the mine and he interpreted the Storgruvan Shear Zone to be coeval with ore formation. Sjögren (1910) did however never visit the locality on Figure 29.
towards the SW. It has not been able to check if another shear zone is laterally bordering this ore body on the NE side.

If it is assumed that the Halfway Ores (excluding the eastern part) and the Ore Levels originally constituted a single coherent mineralized segment which was cut and displaced by SSZ, it provides a rough estimate of the displacement along this zone. Such a value would be an apparent vertical displacement of around 100 m (this estimate does however not consider movement along the southern segment). The fact that the ore occurs on both sides of the Storgruvan Shear Zone in the area of the Halfway Ores does however show that the displacement along the shear zone doesn’t need to have been this large. There is nothing to say that the Sala ore started of as a single ore zone and the Halfway Ores and the Ore Levels may very well have formed as two different ore zones. There appear to have been differences between the ores of the Halfway Levels and the Ore Levels. For example, Sjögren (1910) noted that the ore was richer in silver in the Ulrika Eleonora Level (155 m) and the Halfway Ores while the ores of Ore Levels are only half as rich in silver and contain more sphalerite. Thus, for now it is difficult to estimate the displacement along the shear zone with confidence.

Figure 30 – 3D perspective view of Sala Mine looking upwards from the sub-surface towards the SSW, sub-perpendicular to the rake. The major ore zones of Sala Mine are divided by at which side of the SSZ they occur. Green denotes ore bodies on the NE side of the SSZ, orange denotes ore bodies on the SW side and red denotes ore bodies confined within the two branches SSZ1 and SSZ2. The blue lines do not strictly denote F1 fold hinges but rather concentration of ore in the hinge zone of the Sala Syncline. The red lines are arbitrary lines showing the approximate locations of the axial planes of F2 folds interpreted from mine maps. It illustrates the idea that the ore zones were folded during F2 (compare with Figure 14).
5.3.5 Fabrics

The marble and siliceous interbeds show fabrics ranging from penetrative grain-shape to compositional fabrics to a preferred orientation of fine-grained skarn aggregates. There is a variation with lithology in terms of the fabric (Figure 31). Besides the foliations, the impure marble and skarn-rich lithologies show stretching and mineral lineations which cluster in the SE-quadrant of the lineation plot (Figure 33). The most homogeneous fine-grained siliceous interbeds however show multiple vague foliations but no lineation except for intersection lineations.

In the phyllosilicate-rich siliceous interbeds, the foliation appears to be mainly expressed by the preferred orientation of phyllosilicates such as chlorite, sericite and phlogopite (Figure 31). The foliation is usually rather vague due to the fine grain size and the crenulative relationships between the foliations are not always apparent, not even in thin-section. Very often, two foliations can be discerned and these have been possible to correlate with the two phases of folding observed in the mine. A third foliation has locally been observed but this foliation has not been possible to correlate with any structure and may simply be sedimentary (e.g. bedding).

The foliation pattern seen in Figure 31 is not entirely conclusive. It can however be noted that there is a vague tendency towards a cluster of foliations in the NW and SE quadrants. Here it is seen that the grain-shape fabric in the marble cluster ~ in the area expected for the fabric to the S2 folds. If it assumed that the grain-shape fabric in marble is the most easily reset fabric during deformation due to a low strain-memory of carbonate, it lends further support to the age-relationship between D1 and D2.
S1 is correlated with the F1 phase of folding from the fact that it is observed to be axial planar to F1 folds. It is best developed in the siliceous interbeds in the form of a parallel alignment of platy minerals. Interestingly, galena occurs as 2-3 mm veins in a spaced S1 foliation in the carbonate rich siliceous interbed in Liljenbergs Försökningsort (55 meter). The galena is hosted by a matrix of very homogeneous white carbonate which in turn is surrounded by more siliceous material rich in skarn and phyllosilicates. The style is a spaced foliation with galena occurring as 2-3 mm veins in a carbonate matrix. This very conspicuous bed traverses the Johan & Liljenberg ore body (55 m) and provides an indication that galena ore was already introduced into the host rock prior to F1 and that galena was mobile during D1 deformation.

The S2-foliation is the most conspicuous fabric seen in the marble and it appears as a grain-shape fabric in marble, parallel orientation of platy minerals in mica rich interbeds (e.g. chloritic drapes) and as elongated lenses of fine-grained serpentine and chlorite in white marble. The S2-foliation as seen in the serpentine spotted marble is not strictly an S-fabric but rather a compositional L > S foliation. This becomes clear when viewing these rocks at different angles. The maximum direction of stretch of the green lenses of serpentine are elongate in a sub-vertical direction while the intermediate is generally trending NE-SW.

Apart from a correlation with the relative ages of foliations suggested by Ripa et al. (2002), there are several indications that the SW-NE striking foliation is younger than S1. The best example can be seen in the southern part of the 155 level near the hinge of the Sala Syncline. Here the S2 foliation remains relatively consistent and overprints the hinge of the Sala Syncline at a
high angle. Moreover, the foliation shows a great consistency throughout the mine. It is notable however that at some localities, the S2-foliation displays a more E-W direction.

Most of the lineations measured in the L > S fabric of the serpentine spotted marble plot in the opposite field of the F1 fold hinges and boudin lines. This is taken as an indication that the D1 movement direction has been recorded by the serpentine lenses. Four measurements of stretching lineation also plot along the axial plane of the F2 folds in the SW quadrant and are most likely L2 lineations. L2 is perhaps related with the strong stretching lineation of 30-50° towards the SW in the Sala area reported by Allen et al. (2003b).

Locally it can be observed that the elongate lenses of fine-grained chlorite and serpentine in the marble correlate with the column interspace textures of domal and columnar stromatolites. A possible explanation for the relationship between the two may be that stretching in the sub-vertical movement direction during folding has been especially well recorded by these originally sub-vertical sedimentary features.

Figure 33 – Equal area lineation plot constructed from 46 lineation measurements in Sala Mine. The great circle has an attitude of ~ 225 85. This is similar to the S2 foliation observed in the mine. The rake of Sala Mine has been added for comparison.

In the structural history section, it was noted that the F2 fold hinges plot along S2. This is seen in Figure 33 where the hollow circles line-up in a NE-SW direction parallel to the S2 foliation.
5.3.6 Veins

The F1 folds locally show development of axial planar veins. The veins are found in the marble and mainly carry serpentine and chlorite. They are seen to originate from the folded siliceous interbeds and sometimes carry sulphides with them (particularly pyrite). The observed veins are cm-thick and axial planar to small parasitic F1 folds (wavelengths less than 10 meters). The veins are locally seen to be boudinaged in a similar strain-regime as the F1 folds to which they are axial planar.

![Figure 34](image)

*Figure 34 – A F1 folded skarn- and phyllosilicate-rich bed in Liljenbergs Försökningsort (55 m) seen towards the south. Notice the small cm-wide vein which is axial planar to the fold and the boudinaged axial planar vein to the right of the scale bar. Fold axis and boudin lines are approximately 320° 35°.*

The marble is moreover locally intersected by cm-size veins of sparry calcite (possibly of multiple generations) which are especially conspicuous in the green-coloured marble. At several locations it is clearly seen that these calcitic veins cut ductile structures. They are thus a relatively late phenomenon though they may have utilised pre-existing zones of weakness during their formation.

Thin straight veins of fibrous serpentine (probably *chrysotile asbestos*) were locally seen in the siliceous interbeds. In thin-section it was observed for one such vein that the serpentine occurs as a fracture-fill and that the fractures cut euhedral crystals of diopside. The diopside crystals moreover showed signs of retrograde alteration leading to the formation of serpentine and talc in the vicinity of the serpentine vein. Similar serpentine veins with up to cm thickness are seen in a sample from the tourist mine’s mineral collection.
5.4 Metamorphism

Not much is known about the metamorphic history of Sala Mine at present. According to Ripa et al. (2002), the ores of Sala have been affected by a syn-metamorphic phase of deformation which is D1 according to the terminology of this article. Due to the high degree of partitioning of Mg into skarn minerals associated with galena, Ripa et al. (2002) suggested that the Sala ore was introduced into the host rock before regional metamorphism in Bergslagen. This is in agreement with what can be observed in the mine and the metamorphic event is here referred to as M1.

The abundance of hydrated magnesium silicates in both the shear zones and the siliceous interbeds indicate a later phase of retrograde alteration and hydration. Talc can persist in upper greenschist-lower amphibolite facies (Simandl & Paradis, 1999) but diopside and tremolite have locally been found to be completely altered to carbonate, chlorite and talc in Sala Mine (Kieft et al., 1987). Thus, though some of the talc may have persisted since M1, it is likely that some of the talc observed in the mine is derived from retrograde alteration of minerals such as tremolite and diopside.

It is also possible that serpentine is derived from retrograde alteration reactions of peak metamorphic assemblages. Serpentinisation of diopside, forsterite, tremolite and plagioclase has been reported from the Proterozoic carbonate-skarn hosted Oranga galena-chalcopyrite-sphalerite ore in central India by Patel et al. (2004). The authors attributed the serpentinisation to fluid-rock interactions after peak metamorphosis. Two thin-sections of a siliceous interbed produced for this project revealed that talc and serpentine at least locally appears to be growing at the expense of diopside and tremolite in the siliceous interbeds of Sala Mine.

Figure 35 – Thin section capture of skarn-rich interbed from Nedstigningsorten (14 m). The picture is taken with crossed nicols and show a vein of serpentine cutting across porphyroblasts of tremolite. Serpentine growth furthermore appears not to be localised to the vein but to grow at the expense of the tremolite. Talc can also be observed to grow along the cleavage planes of the tremolite crystal near the centre.
As for the metamorphic evolution in general terms, it may be expected that the M1 prograde metamorphic event lead to a relative dehydration (not necessarily complete) of the silicate minerals occurring in the mine. Likewise, a decarbonation of the carbonates is expected. This is as both tremolite and diopside have been observed as important metamorphic minerals in the mine and the formation of both yields a fluid phase during prograde metamorphosis (Yardley, 1989).

\[
\begin{align*}
3\ \text{dolomite} + 4\ \text{quartz} + 1\ \text{H}_2\text{O} & \rightarrow \ 1\ \text{talc} + 3\ \text{calcite} + 3\ \text{CO}_2 \\
5\ \text{talc} + 6\ \text{calcite} + 4\ \text{quartz} & \rightarrow 3\ \text{tremolite} + 2\ \text{H}_2\text{O} + 6\ \text{CO}_2 \\
2\ \text{talc} + 3\ \text{calcite} & \rightarrow \ 1\ \text{tremolite} + 1\ \text{dolomite} + 1\ \text{CO}_2 + 1\ \text{H}_2\text{O} \\
1\ \text{tremolite} + 3\ \text{calcite} + 2\ \text{quartz} & \rightarrow \ 5\ \text{diopside} + 1\ \text{H}_2\text{O} + 3\ \text{CO}_2
\end{align*}
\]

Perhaps there exist a relationship between the emission of a fluid-phase during M1 with the formation of veins which are axial planar to the F1 folds. Likewise may there be a relationship between shearing and retrogression.
5.5 Ore Geology

5.5.1 General characteristics

The ore of Sala Mine is characterised by a high percentage of elements Zn, Pb, Ag, Sb and Hg as noted by several earlier observers (Kieft et al., 1987; Tegengren, 1924; Sjögren, 1910; Sjögren, 1900). Moreover, it is characterised by poorness in Cu, Bi (Per Nysten, 2007 – personal communication) and Au (Tegengren, 1924). Some general zonation patterns have been recognised, for example that mercury phases such as amalgam, cinnabar and native mercury are especially abundant in the southernmost and uppermost parts of the mine, e.g. the area around the Torg Shaft. A decrease in silver grade with depth has also been noted (Sjögren, 1910).

Three ore grade analyses were done for this project, two from well-known localities in Sala Mine and one from the Bronäs Mine nearby (Locality 1 on Figure 3) which is believed to belong to the same ore field. These analyses are found in the appendix section in the end of the report. Just as in Sala Mine, the ore of the Bronäs Mine show high grades of the elements Zn, Pb, Ag, Sb and Hg.

5.5.2 Ore mineralogy

In hand-specimen, the view of the ore from Sala Mine is dominated by sphalerite and galena, sometimes occurring together, sometimes occurring one by itself. Besides these two sulphides, pyrite, pyrrhotite and arsenopyrite are sometimes found and cinnabar and molybdenite occur more rarely. The presence of antimony is expressed by the occurrence of phases such as tetrahedrite, geocronite and boulangerite which may be found in sizes allowing identification without a hand-lens. Also occurring, yet much more rarely are mesoscopic native silver, native mercury (Sjögren, 1910; Zakrzewski & Burke, 1987) and native antimony.

It has been suggested that ores holding mesoscopic pyrargyrite were mined in the early history of the mine in Herr Sten’s Level but these ores are poorly known and no reference sample is known to exist. Grip et al. (1983) reported that the ore of the oldest part of the mine (marked in red on Figure 3) was exceptionally rich in argentite (acanthite?), pyrargyrite, faehlerz and dyscrasite though it is debatable whether significant degrees of argentite ever occurred in the mine. Even though Sjögren (1900) suggested that the principal argentiferous mineral of Sala Mine was

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10 In the discussion on mineralogy, chemical formulas for different minerals have been omitted. A table with general chemical formulas is found as an appendix in the back of the report.

11 Sala Mine is the type-locality for native antimony as first described in the 18th century (Swab, 1748)
Acanthite, later studies have revealed that acanthite is only a minor phase in the Sala ore (Kieft et al., 1987; Johan Holmgren, 2007 – personal communication). Kieft et al. (1987) reported that the most common carriers of silver were pyrargyrite, Ag-Pb-Sb sulphosalts and freibergite in the older parts of the mine where antimony was especially abundant.

On a microscopic scale, it is seen that the mesoscopic ore minerals host a more complex mineralogy involving the elements antimony, silver and mercury (Kieft et al., 1987). These occur as small blebs in their native state or as antimonides, amalgams and sulphosalts etc. Microscopic phases found in the Sala ore include amalgam, dyscrasite, allargentum, tetrahedrite, pyrargyrite and gudmundite (Kieft et al., 1987). The occurrence of these microscopic inclusions is the mineralogical manifestation of the silver richness (as well as the mercury and antimony richness) of the Sala ore rather than the acanthite of Sjögren (1900) (Kieft et al., 1987; Johan Holmgren, 2007 – personal communication).

According to Kieft et al. (1987), the occurrence of silver-rich blebs in both galena and sphalerite results from exsolution and segregation during cooling and low-temperature equilibration of the primary assemblage. The authors suggested that this phase of exsolution may be related to the development of the shear zones in the mine. Except for occurring within the sulphide matrix itself, the Ag-Hg-Sb minerals occur as remobilisates in later veins (Kieft et al., 1987; Zakrzewski & Burke, 1987).

As for non-sulphides, magnetite has very locally been observed to occur as aggregates or even more rarely, as cm-size crystals in skarn-pods and veins. The magnetite has been found together with 0.1-5 mm large flakes of chlorite or in ~ 2 mm wide veins in the dolomitic marble.

### 5.5.3 Gangue

Directly adjacent to some of the ore bodies, the ore mineralization is accompanied by skarn which occurs dispersed in the marble, in pods or veins. The most common gangue minerals are tremolite, diopside, calcite, dolomite, chlorite, serpentine, talc and phlogopite. Barite has been reported from sphalerite ore bodies in the southern part of the mine (Sjögren 1910) while dravite was found in the Namnlösen ore body (155 m) together with galena during this survey. Especially skarn-rich sections have been marked on the geological maps.

### 5.5.4 Ore types

Observations of larger ore mineralizations were few during this project as these were generally mined out when the mine was still in operation. Instead, observations have been done at the fringes
of mined ore bodies where ore locally can be found as disseminations, vein networks, stringers, pods and small veinlets. Nevertheless, according to Kieft et al. (1987), the Sala ore only locally occurred as massive galena and sphalerite ores. Sjögren (1910) noted that the bulk of the ore consisted of dressing ore which had to be enriched before smelting. Thus, a significant part of the Sala ore appears to have been semi-massive. A broad division has here been made between sphalerite dominated ores and galena dominated ores even though a gradational relationship between the two exist (Sjögren, 1910).

The sphalerite ores of Sala Mine generally hold about 12 % Zn, 2 % Pb and 150-200 ppm Ag according to Tegengren (1924). When the mine was in operation, they were generally regarded as poor relative to their galena counterpart and as a rule had to be subjected to dressing before they could be smelted for any profit (Sjögren, 1910). Gangue occurring with sphalerite as seen in the mine’s mineral collection include tremolite, serpentine, phlogopite, diopside, barite, calcite and dolomite. Other ore minerals associated with the sphalerite include galena, geocronite, boulangerite, tetrahedrite and amalgam. Vogt (1905) reported that the sphalerite ores of Sala Mine contain minor amounts of native silver, silver amalgam, native mercury and cinnabar.

The sphalerite ores appear to at least locally have been extremely rich in mercury. During the processing of sphalerite ores in the early 20th century, amalgam was often discovered in the processing plants, for example in the drains. Moreover, smelting of the sphalerite ore to zinc oxide yielded considerable amounts of liquid mercury that could be collected as a by-product (Granström, 1940). This is in accord with the fact that reports of mercury phases, native silver and amalgam cluster in the southern, sphalerite dominated part of the mine, for example the Torg Shaft section (Sjögren, 1900 & Sjögren 1910).

Observations of sphalerite ores during this survey were mainly done in the vicinity of the ore body Rödstjärten in the southern part of the 155 m level. The ore left on the walls occur as networks of veins enclosing white dolomitic marble. Where the vein networks are dense, the texture is reminiscent of a breccia with variably sized elasts of dolomitic marble in a matrix of sphalerite. However, at the fringes of these “breccias”, it is seen that the outermost veins are not really defining a breccia. Thus, the term ‘vein network’ is preferred rather than ‘ore breccia’ to avoid putting any genetic connotations on this ore type.

The sphalerite has a dark-brown colour, metallic-vitreous lustre and a brown weathering surface indicative of slight iron content. Skarn occurring with this type of ore is generally tremolite occurring as ~ 5 mm long thin shiny needles and prisms dispersed in the sphalerite mass. The needles appear to have no common orientation. There are moreover 2 mm flakes of brownish-yellow phlogopite within the sphalerite mass.
The boundaries between the sulphides and the host rock are compositionally distinct but their interface is structurally complex. Commonly, the sphalerite occurs as networks of anastomosing veins enclosing relatively pure segments of carbonate. It is possible that the vein-systems graded into more massive sphalerite occurrences in sections of the ore bodies that are now mined out.

The way of occurrence of the sphalerite ores indicates epigenetic formation after lithification of the carbonate but prior to ductile deformation. Further evidence for an epigenetic origin can locally be observed, for example in Figure 37 where flat-laminated stromatolitic layering with cumulate stromatolites is cut by pre-cleavage veins carrying sphalerite and skarn.

After deposition, the ore has been subjected to ductile deformation to generate minor folds, boudinage and mullions. It is difficult to tell if sphalerite acted as competent relative to the marble or not. Some observations suggest that the dolomitic marble have been competent while others suggest the opposite.

The vein systems are overprinted by penetrative foliations and flattened along the S2 axial plane. The elongate carbonate clasts in Figure 36 are moreover parallel to the L2 stretching lineation. Thus, the sphalerite ores essentially appears to have recorded the deformation of the host rock. This suggests that it was emplaced prior to the ~1850 Ma BP peak deformation and

*Figure 36 – The typical texture of the vein system sphalerite ore observed in the gallery Wallbergs Nordöstra near the Rödstjärten ore body (155 m). The dark material is sphalerite and the white material is dolomitic marble. The picture shows the ‘breccia-like’ texture of the ore. The ore shows signs of mullioning, boudinage and folding. However, in the direct vicinity of the ore, flat-laminated stromatolites are relatively well-preserved. Hanging compass for scale.*
metamorphism of the Svecokarelian orogeny. Thus, the sphalerite ore in southern Sala Mine appears to have remained essentially in-place relative to its host rock during deformation. This of course doesn’t rule out that material has been remobilized from the sphalerite ores during deformation and metamorphosis, nor does it out rule that the shape of ore bodies have changed during deformation.

A chemical analysis ore major and trace elements performed for this project revealed some extraordinary results for the sphalerite ore seen in Figure 37. The sphalerite ore was found to be very poor in the elements Ag (12 ppm), Sb (18 ppm) and Pb (0.02 &%) while being very rich in Zn (25.3 %). Moreover, the grades of Cd and Hg were above the detection limits for these elements (1000 ppm and 100 ppm respectively). Except for the grades of Hg and Zn, these results (though based on only one analysis) are anomalous for Sala ore. This is as they are exceptionally poor in Sb and Ag. For a full list of the analytical results, the reader is referred to appendix 6.

The relatively well preserved stromatolitic textures and siliceous interbeds in the vicinity of the sphalerite ores have revealed that the workings where sphalerite was mined on the 155 m level grossly follow bedding and appear to have been folded along with the strata. This indicates that there may have been a stratigraphic control on the formation of sphalerite ores, e.g. that ore formation preferentially occurred within certain stratigraphic units. For Rödstjärten (155 m), it can moreover be seen that the ore body is located in an F1 anticline which plunges NW down to its

Figure 37 – Wallberg Fältort (155 meter), just NW of the Rödstjärten sphalerite ore body. The lower right part of the picture shows a small cumulate stromatolite in a laminated section of dolomitic marble, defining a steeply dipping bedding plane. Cumulate stromatolites are characteristic of cryptagal laminites (Wanke & Melezhik, 2005). Texturally destructive veins of sphalerite and tremolite cut the cryptagal laminate at a low angle. Two foliations are visible: S1 = 153/56 and S2 = 041/63. Both overprint the skarn and the sphalerite. This indicates epigenetic ore formation and that the sphalerite ores were emplaced prior to D1. Pen for scale.
continuation Röda Sänkningen (160 m). Thus, this sphalerite ore body occur in the hinge of a F1 anticline and is elongate along the fold hinge.

An inspection of the walls of Herr Sten’s Level at the surface revealed sphalerite vein systems very similar to the ones observed at the 155 m level. From these observations, the sphalerite ore bodies appear to be stratigraphically underlying the galena ore bodies further to the north in the mine. The fact that recognisable stromatolites and sphalerite ore occur directly adjacent to each other is moreover taken as evidence that the formation of sphalerite ore was not a completely texturally destructive process in Sala. In fact, there is little difference in the degree of preservation between the stromatolites of southern Sala Mine and Finntorpsbrottet.

The Ag-richness of the galena ore in Sala Mine is extreme with grades of 1 500-10 000 ppm (Tegengren, 1924; Grip et al., 1983; Kieft et al., 1987). Grip et al. (1983) reported that the galena ore hold about ten times as much silver as the sphalerite ore. Other mesoscopic phases found with galena in the mine’s mineral collection include geocronite, idiomorphic pyrite, sphalerite, boulangerite, calcite, dolomite, diopside, garnet (rarely), serpentine, tourmaline (probably dravitic), chlorite, talc and tremolite.

Samples of massive galena ore from Sala are only known from museum collections. The most striking samples of galena ore commonly contain large (> 1 cm) euhedral crystals of diopside (‘salite’) or more rarely < cm-size garnets or tourmaline in a galena matrix. The porphyroblasts may occur as fragments or be veined or replaced by galena under the microscope (Tegengren, 1924).

During this project, semi-massive galena ore was found in pods embedded in (> cm-size) crystals of sparry calcite with aggregated fine serpentine and chlorite in the Namnlösen ore body (155 m). The galena is here accompanied by minor amounts of euhedral crystals of tourmaline.
Several samples where taken and sent for analysis. The analysis yielded results which are very consistent with earlier results for Sala galena ore, namely high grades of Ag (1380 ppm) and Sb (971 ppm) while it yielded a rather low Hg-grade (28.5 ppm). Reference samples for both the analysed sphalerite ore and the galena ore may be viewed in the mine’s museum.

Galena was also rarely observed in veins with a thickness up to 2-3 cm in different parts of the mine. The attitudes of the most conspicuous galena veins are similar to the S1 fabric, indicating that galena was mobile during D1. Galena was also found disseminated in the marble and as fine-grained aggregates in veins and pods.

The current appearance of the workings where galena was mined (e.g. Namnlösen – 155 m) give the impression that the ore has occurred as large pods and lenses. However, as has already been noted, there are indications that much of the Sala ore was semi-massive and occurred as stringers and veins considerably intermingled with the host rock.

It is regrettable that the relationship between the ore and bedding in the northern part of the mine was hard to study because of the low grade of exposure and the fact that the marble appears to be homogenous with few siliceous interbeds. It is clear however that the ore bodies observed in the 155 m and 55-50 m levels of the mine almost invariably appear to laterally have at least one side defined by a shear zone or a minor fault and to be elongate parallel to the F1 fold hinges. In other words, they are elongate along the strike of the mine.

The workings of Bergenstierna (155 m), Baron Hermelin (55 m) and Johan & Liljenberg (55 m) however give an indication that the extent of the mineralization is at least partly stratigraphically controlled. The relationship to bedding is however not as apparent for the largest ore bodies which were studied during this project, namely Billow (155 m) and Hjärnes Sänkning (155 m).

Figure 39 – A view of a part of the Johan & Liljenberg ore body (55 m) seen towards SE. Note that the moderately dipping hanging wall and footwall are parallel. Both are dipping towards the left of the picture (approximately NE) and are sub-parallel to bedding. Photo: Jan Kruse
6. DISCUSSION ON ORE GENESIS AND REMOBILIZATION

6.1 Ore genesis

The picture of the genesis of the Sala ore is far from complete. The ore has been subject to a number of mineralogical studies in the past but there is a lack of data on geochemistry, fluid inclusions, isotopes, stratigraphy and structural geology etc. Some facts remain however and suggestions on the conditions of formation have been made.

Grip et al. (1983) briefly described the dimensions of the ore bodies as a result of sedimentary structures intersected by tectonic structures. It was suggested that room for hydrothermal solutions was established during a lowering of the eastern part of the mine relative to the western part. The main agent for this movement was ‘Storgruveskölen’. Grip et al. (1983) suggested the possibility that the ore elements had been deposited along with the carbonate and subsequently been mobilised during folding and faulting, possibly during the intrusion or solidification of the Sala granite. They suggested that the ‘sköl-system’ may have worked as conduits for the ore-fluids which could have accommodated movement before, during and after the emplacement of the ore.

From the observations that the Storgruvan Shear Zone is largely un-mineralized, it is uncertain if this structure really existed during ore formation. If it did, it would be expected that it became mineralized as was noted by Sjögren (1910).

Allen et al. (1996) characterised the Sala ore as an ore of the SVALS\textsuperscript{12}-type. They suggested that the SVALS-type ores of Bergslagen formed by sub-seafloor replacement in volcanic environments with carbonates. The ore was emplaced within carbonate/volcanic sedimentary sequences by hydrothermal solutions. The hydrothermal system may very well have been driven by the same volcanoes which supplied pyroclastic ejecta for the metavolcanic beds. Subsequent regional metamorphosis later gave rise to extensive skarn-mineralization adjacent to the ores. Later, Allen et al. (2003a) likened the Sala ore with the Garpenberg type ore from northern Bergslagen. This ore-type is believed to have formed from syn-volcanic stratabound replacement adjacent to stromatolite reefs prior to remobilization during deformation.

Ripa et al. (2002) suggested that the ore may have formed during the emplacement of the older intrusives around Sala. A close relationship was pointed out between the Loviseberg Cu-deposit north of Sala and a porphyry identified as a subvolcanic intrusion.

The Pehr’s Copper Mine Cu-Bi-As-Ag-Mo-W mineralization \textit{(Locality 15 on Figure 3)} \textasciitilde 1 km NW of the Queen Christina Shaft also shows a similar proximity to early subvolcanic intrusions.

\textsuperscript{12} Short for “Strata-bound, volcanic associated, limestone-skarn” Zn-Pb-Ag(-Cu-Au) sulphide deposit, approximately corresponding to the “Falun-type” deposit of older Swedish ore geological literature.
The mineralogy of the Pehr’s Copper Mine deposit contain minerals of Cu and Bi as well as Ag, W and Mo. (Per Nysten, 2007 – personal communication)

The stratigraphic relationship between Sala Mine and the Pehr’s Copper Mine is at the moment poorly constrained. The fact that Pehr’s Copper Mine occurs at the interface between metavolcanics and dolomitic marble does however provide an indication that this mineralization is deeper seated stratigraphically or more proximal relative to subvolcanic intrusions in the north.

Returning again to Sala Mine itself, the investigators of older times mostly attributed the ore formation in Sala Mine to the ‘skölar’. The importance that investigators saw in these structures has already been mentioned and to cite Sjögren (1910):

Of special interest is the connection between the ores and the ‘sköls’: this has, in fact, been the object of attention of all earlier observers, and any theory dealing with the history of the formation of the Sala deposit must depend to a large extent on the solution of this problem.

The account of Sjögren (1910) is one of the most detailed descriptions of the relationship between ‘skölar’ and ore formation in Sala. Yet, it doesn’t distinguish between shear zones and siliceous interbeds. Contrary to Sjögren (1910), J H Forselles (1818) distinguished between ‘lagerskölar’ carrying ‘hälleflinta’ (fine-grained felsic metavolcanite) and ‘Storgruvégången’ (the Storgruvan Shear Zone). Sjögren (1910) opposed Forselles idea of ‘hälleflinta’ occurring in ‘sköls’, claiming that the siliceous material of the ‘skölar’ have been confounded with hälleflinta.

The current author wish to speak in favour of Forselles (1818) as most of the ‘lagerskölar’ on Forselles cross-section of the mine parallel stromatolitic bedding and locally have preserved sedimentary features (normal grading, lamination etc.). The ‘lagerskölar’ most likely represent the hydrothermally altered and metamorphosed siliceous interbeds already described.

Forselles (1818) noted that the galena ore is commonly richest in the lowermost part of ‘lime layers’ and closest to the Storgruvan Shear Zone. The ‘lime layers’ are separated by silicate rich ‘lagerskölar’ of different sizes and Forselles (1818) noted that the silicates decrease upwards in the ‘lime layers’ until they finally diminish, as does the ore mineralization.

Sjögren (1910) states that where large 'skölar' approach each other, the ore is exceedingly rich. Most likely, this relationship is simply the effect of siliceous interbeds being cut by shear zones.

In the light of the separation of bedding and shear zones performed during this survey, the current author suggests that the mineralization was emplaced as stratabound ore bodies at depth. This occurred through flow of hydrothermal fluids along the siliceous interbeds, the ‘lagerskölar’ of Forselles (1818). The siliceous interbeds were hydrothermally altered to phyllosilicate- and skarn-rich varieties during the lifetime of the hydrothermal system. Silica was emplaced along
with ore and gave rise to the extensive skarn mineralization which accompanies the ore during metamorphism.

Thus, a stratigraphic control on the mineralizing fluids seems to have existed during the introduction of the ore. This does not rule out that syn-sedimentary/syn-volcanic faults may have posed a structural control on mineralizing fluids. Unambiguous syn-sedimentary faults have however not been recognised. Possibly, early faults have become mineralized and difficult to recognise.

Forselles (1818) noted that the bases of the intercalated marble units are preferably the most mineralized. This was verified for the Bergenstierna ore body (155 m) during this survey. With the stratigraphic younging direction constrained, the ore solutions may have rose upwards towards the free surface. Therefore, the ore solutions may have preferentially mineralized the base of the carbonate horizons above the conductive siliceous interbeds.

After ore formation, the ore bodies were subjected to at least two phases of deformation. During D1, the mineralization was concentrated as elongate bodies along F1 fold axes. The ore became especially concentrated in the hinge of the Sala Syncline and associated parasite folds. This may have been due to thickening associated with folding or remobilization. During D2, the Sala Syncline was folded and a especially wide ore zone was established in the centre of the mine. During D3, movement occurred along the Storgruvan Shear Zone and the ore mineralization was cut and displaced. It may have caused a separation of the Halfway Ores from the Ore Levels though this has not been possible to prove during this project.

The distribution of ore elements prior to the stratigraphically controlled hydrothermal event is unknown. Thus it cannot be established without complementary work if originally syngenetic ore was dissolved and re-deposited epigenetically by hydrothermal fluids, if the ore elements were leached from non ore-minerals in the stratigraphically underlying metavolcanics or if the ore elements derived directly with fluids emanated from cooling subvolcanic intrusions. Most importantly, the extreme richness in the elements Ag, Hg and Sb of the Sala ore has yet to be explained.

6.2 Remobilization

As the host rock has experienced multiple events of deformation and metamorphosis, it is inevitable to at least consider that the ore to some extent has been remobilized after formation.

At temperatures of 400°C, only slight differential stress is needed in order to mobilize galena according to Berglund (1979). Minor remobilization of galena during F1 folding has already been observed in early S1 foliation and in veins sub-parallel to F1 axial planes. Galena has also been
seen to replace tremolite skarn in samples from the mine’s museum. Whole-scale remobilization has however not been possible to prove. At present, it is not possible to decide to what extent galena may have been remobilized but it can be noted that there are concentrations of ore in the hinge zone of the Sala Syncline, at the boundary to the SSZ, in the central part of the mine as well as in the southern, now collapsed part of Sala Mine.

As for the shear zones, they certainly appear to have displaced the ore deposits along with the host rock in the central and northern part of the mine. It is however uncertain to what extent they may have contributed to remobilizing the deposit. It was earlier noted that the Storgruvan Shear Zone is poor in ore minerals. However, an interesting aspect in respect to remobilization is that the major shear zone intersection observed at the 155 m level plunges NW from the collapsed workings in the south. The branches of the shear zones confine the mined ore zone in the southern mine (Figure 30).

The southern part of the mine has long been known to have hosted an exceptionally silver-rich ore deposit (Sjögren 1910). The Torg Shaft section, which belongs to the southern part has likewise long been known for its richness in mercury in the ore deposits of Fågelburen (90 m), Juthyllsgruvan (85 m) and Penninggruvan. The ore of the last ore body is known to have held at least 100 ppm Hg and lays directly south of SSZ 1. (Tegengren, 1924; Sjögren, 1900 & Sjögren, 1910). Native antimony has also been reported from the Torg Shaft section more than once (Sjögren, 1910). Jamesonite has moreover been reported from Bjelkes Tvärort of the Torg Shaft section (Erik Jonsson, 2007 – personal communication). All of the mentioned anomalous Hg, Sb and Ag low temperature occurrences lie between or adjacent to the two major shear zones in the southern part of the mine. From this it appears that the southern block hosted an Ag-Sb-Hg anomaly.

Zakrzewski & Burke, (1987) described Ag-Hg phases occurring in druses and cavities in the mine. The samples were remarkably similar to the samples collected by Sjögren (1900) in the southern part of Sala Mine. They concluded that the formation of secondary moschellandsbergite in an area of native mercury demands that a release of Hg from some mercury rich source has to be postulated. They did however stress that the occurrence of Ag-Hg minerals in the southern part is only of minor importance for the total budget of mercury in the mine as most mercury seem to be associated with Zn-Pb ores.

Possibly, the occurrence of exotic Ag-Hg-Sb phases could be related to an event of remobilization where these elements have been mobilized during shearing and/or metamorphosis and enriched in the southern part. Tomkins et al. (2004) described remobilization of auriferous sulphide melts in the Hemlo Gold Deposit of Ontario, Canada. In this setting, auriferous sulphide
melts migrated along the Hemlo Shear Zone and were preferentially focused into extensional regions (e.g. jogs). The melts were mainly expelled at the terminus of the shear zone or at splays.

For the SSZ, any releasing bend could potentially create a conduit parallel to the shear zone intersection. This would allow remobilisates to migrate and give rise to a secondary ore zonation, namely that the ore was richest in the southern, uppermost and now collapsed part of Sala Mine.

If an event of remobilization occurred synchronously with shear zone movement, it is of course far from certain that the Ag-Sb-Hg anomaly in Sala formed from partial melts. Yet if the elements were remobilized in another fluid phase or in solid-state during shearing, they should be expected to have obeyed the permeability regime of the shear zone. This shows that there potentially is a structure which may be involved in the formation of the Ag-Sb-Hg anomaly of southern Sala Mine.

An alternative explanation for the Ag-Sb-Hg anomaly of the southern part of the mine is supergene enrichment (strictly speaking, not a remobilization process). If there were a raised structural permeability in the southern part of the deposit as a result of fracturing, shearing and development of structural conduits, it must have eased fluid percolation downwards which may have promoted an enrichment. Even though supergene enrichment is rare in Bergslagen, supergeneously enriched ores related to faults have been reported in the past, for example the Mullmalmen iron-oxyhydroxide deposit of the Stollberg Ore Field by Ripa (1996).
Just as suggested by Grip et al. (1983), the extent of the Sala deposit is controlled by sedimentary bedding intersected by tectonic structures. This report has described this relationship and provided a picture of the deposit as a multiply deformed, stratabound Zn-Pb-(Hg)-(Sb) deposit hosted by stromatolitic marble. This has been shown by an integration of data on structural geology, stratigraphy and ore geology. An integration of such data has been one of the major aims of the project as it is in the view of the author, an essential trinity when attempting to unravel the nature of an ore deposit. This study has also involved a review of historical data, largely to complement for the fact that the entire mine was not possible to study at the given time. There are still many unknowns concerning the structural geology and stratigraphy of Sala Mine. Undoubtedly these will be resolved by studying more levels of the mine. Hopefully, a small contribution to our knowledge of the geology of Sala Mine has been made.

As for now, it can be concluded that relatively well-preserved stromatolites and altered siliceous interbeds occur in direct proximity to the ores of Sala Mine. These reveal the stratigraphic younging direction and show that the ore mineralization at least locally formed as stratabound ore bodies sub-parallel to bedding. The bedding was afterwards folded to generate the Sala Syncline which confines the mined mineralization along its entire length. This lead to that initially sub-horizontal ore bodies now generally dip at moderate to high angle towards the centre of the mine.

The ore bodies are elongate along the hinge of the Sala Syncline and they appear to have been concentrated in F1 fold hinges, both locally (e.g. Rödstjärten – 155 m) and on the scale of the Sala Syncline. The Sala Syncline was later gently cross-folded by F2 folding, leading to local reversal in F1 fold hinges and ore body rakes. The result was a thickening of the ore zone in the centre of the mine. During D3, the entire mineralization was displaced along shear zones though the amount of displacement has yet to be determined. The largest shear zone is the Storgruvan Shear Zone which has previously been referred to as ‘Storgruveskölen’ or ‘Storgruvegången’. The shear zone doesn’t seem to have generated the ore of Sala Mine but it may have displaced a significant part of the ores upwards (the Halfway Ores). It may also have played an important role in enriching the ores of the southern mine. Yet, the mechanism of enrichment is at present unknown.

A late phase of brittle strike-slip movement has also been identified which have partly occurred at the shear zone boundaries. The late strike-slip movement may have offset a post-Svecokaralian dyke approximately 18.5 m dextrally.
When it comes to the significance for prospecting the Sala area, the results suggest the following:

1: The branching points of shear zones may be interesting. This as there may be a relationship between the Ag-Sb-Hg anomaly of southern Sala Mine and the branching point of the Storgruvan Shear Zone.

2: The widest ore zone on the NE side of the SSZ is where F1 and F2 synclines meet. Thus, intersections between F1 and F2 folds should be of interest as these may hold thickened ore zones.

3: The ore bodies of Sala Mine are locally sub-parallel to bedding horizons, often in the form of Mg-altered metavolcanics. Thus, siliceous interbeds may provide valuable marker horizons when tracing ore mineralizations in the Sala area.

Finally, while reading the structural geology of a mine from the shape of its workings, it is good to add some final criticism. Above all things, it is important to realize that the 3D-models and maps only show what has been mined and not was is still there to be mined. For Sala Mine, the narrow width of the mine may reflect that the ore deposit is relatively narrow. It could however also simply reflect the faith which was put in the Storgruvan Shear Zone, the siliceous interbeds (‘Lagerskölar’) and the since old known rake when following the mineralization at depth. Thus, there is nothing to say that there are no lateral extensions to the deposit. As an example, The Oscar sphalerite ore body on the 55 m level occurs at a considerable distance from the SSZ.

It must furthermore be emphasized that this study has been performed in a limited part of the Sala Mine and no complementary mapping were done in the surroundings. The number of outcrops is limited around the mine but there are other levels of lower accessibility in the mine which could be mapped.
8. SUGGESTIONS FOR FUTURE RESEARCH

The 85 and 90 m levels are of great interest for future geological studies. This is since the 90 m level is basically a girdle of galleries around the collapsed 16th century mine, which hosted an Ag-Sb-Hg anomaly. The two major branches of the SSZ are believed to be present on this level so the 90 m level would be a good target for investigating the relationship between the shear zones and the Ag-Sb-Hg anomaly.

Likewise, the 90 m level is coherent with the 85 m level where there are stromatolitic textures and siliceous interbeds in the area of the Halfway Ores. A correlation of siliceous interbeds on this level with the siliceous interbeds from the 155 m and 60 m levels could allow a determination of the displacement along the Storgruvan Shear Zone.

The SSZ could be studied in more detail to better constrain the timing of shearing, kinematics and the relationship to metamorphic events or phases of deformation. This could also establish if multiple phases of shearing has occurred along the zone.

A geochemical analysis of the siliceous interbeds in the direct vicinity of the ore bodies could be of interest. It has been proposed that the beds may have channelled hydrothermal fluids during ore formation. If so, they should have acquired a geochemical composition which would stand out in comparison with less altered beds in the Sala area.

Moreover, the author knows of no S-isotopes studies performed in Sala Mine. An S-isotope study of samples taken from the different parts of the mine could possibly shed some light on the mechanism which triggered the precipitation of ore and the source of the sulphur.

The major ore zones should be possible to further differentiate but at the moment, there is scant information in the literature on what was actually mined in many of the ore bodies of Sala Mine. Tracing back the mineralization, ore body by ore body could yield a more constrained view on the ore zonation of the Sala deposit. In order to achieve this, going through the historical archives would be necessary. There are annual reports dating back to the 1630’s written by the managing directors of the mine, describing the annual development and production of Sala Mine.

It has not been possible to determine during this survey if the bedding parallel shear observed in the Sandrymning Bed (155 m) is related to folding (e.g. flexural slip) or if it is due to shearing along folded beds synchronous with movement along the Storgruvan Shear Zone. A systematic analysis of sense of shear on beds on different limbs of the Sala Syncline could establish if the bedding parallel shear is coeval with folding. If bedding parallel shear has occurred during flexural slip, it would be expected that the sense of shear is opposite on the two limbs of the Sala Syncline.

It has been demonstrated that relatively well-preserved sedimentary textures may locally be observed in Sala Mine. This makes the mine unique in comparison with many other Bergslagen
deposits where sedimentary textures in the host rock have more or less been obliterated. A study directed on differentiating these textures and placing them into their appropriate sedimentary facies would put additional constraints on the chain of events which formed the Sala ore. It could also provide valuable information on the palaeoenvironment of Bergslagen.

Further inquiries into the stratigraphy and structural geology of the mine’s surroundings could shed more light on the stratigraphic relationship between the Sala Mine and the numerous small mines occurring within a couple of kilometres distance. These deposits involve a more diverse suite of elements such as lead, zinc, silver, copper, bismuth, molybdenum, tungsten and iron etc. Establishing whether or not these deposits are related to the same ore-forming event could significantly modify the picture of the Sala deposit and its genesis.
ACKNOWLEDGMENTS

Above all; family and friends. Special thanks go to all my friends at Sala Silvergruva AB for several great years working together. Thanks for letting me wander about freely in the tourist levels of the mine and having patience with me making the Sala Silvergruva coffee table my working space.

Prof. Hemin Koyi of Uppsala University for supervising this project and for providing valuable feed-back and criticism on the interpretations. Also thanks to Prof. Christopher Talbot for co-supervision, encouragement and for several valuable discussions. Special thanks go to both for visiting the mine with me.

David Henstridge, John Nebocat and Christina Jonsson of Tumi Resources ltd. for funding the analyses and thin-sections as well encouraging this project. Thanks also go to Peter Svensson (formerly of Tumi Resources Ltd.) for encouragement.

Per Nysten for help with identifying minerals and for sharing his observations in the Sala area with me.

Prof. Victor Melezhik of NGU for providing valuable feed-back on the interpretation stromatolitic textures.

Prof. Rodney L Allen for giving a valuable tour at the Finntorp quarry and providing a map over Bergslagen.

Bo Svärd for letting me use his drawing for the front page

Torsten Jonsson of Björka Mineral AB for letting me visit Tistbrottet.

Johan Holmgren for introducing the geology of the mine to me, several long discussions about the mine’s geology and for providing a digitalized copy of a mine map over the 155 m level.

Jan Kruse and Per Carlsson for letting me use their pictures.
REFERENCES


Forselles J H af (1818) Berättelse om Sala silfververk.


Granström G A (1940) Ur Sala Gruvas Historia. Västmanlands Läns Tidnings A,-Bs Tryckeri.

Gumaelius O (1873) Om “trappskölen” i Sala grufva. Geologiska Föreningen i Stockholm Förhandlingar Vol.1, pp. 162-166


Magnusson N H (1973) Malm i Sverige I. Mellersta och södra Sverige. Almqvist & Wiksell

Norberg P (1978) Sala Silvergruvas historia under 1500- och 1600-talen. Sala kommun


Ripa M & Persson P-O (1997) The U-Pb zircon age of the Sala-Vänge granite at Sala, south central Sweden. Radiometric dating results - SGU C 830


Sundius N & Zenzén (1942) *Sala gruva.* GDA:BRAP84109. AD: SGU berggrundsbyråns arkiv ME: papper


Tegengren F R (1924) *Sveriges ädlare malmer och bergverk.* SGU Ca 17


Vogt J H L (1905) *Om zinkmalmsforekomsterne i Sala Grube.* GDA:BRAP83731. AD: SGU berggrundsbyråns arkiv ME: papper
Wanke A & Melezhik V (2005) Sedimentary and volcanic facies recording the Neoarchaean continent breakup and decline of the positive $\delta^{13}$C$_{\text{carb}}$ excursion. *Precambrian Research Vol 140.* pp. 1-35


Appendix 1 – Mineral table

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<th>Name</th>
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<tr>
<td>Allargentum</td>
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<tr>
<td>Amalgam</td>
<td>Ag$_2$Hg$_3$ (variable)</td>
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<td>CaCO$_3$</td>
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<td>Chlorite</td>
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<td>Cinnabar</td>
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<tr>
<td>Diopside</td>
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<td>Dolomite</td>
<td>CaMg(CO$_3$)$_2$</td>
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<td>Dravite</td>
<td>NaMg$_2$Al$_2$Si$_2$O$_7$ (OH,F)$_4$</td>
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</table>

This is by no means a full list of minerals found in Sala but a list of minerals referred to in the text
The outline of the mine is based on Sjögren (1910). The bedding traces are not intended to outline the style of the Sala Syncline but to outline the pattern of folding.
Appendix 5 – Block diagram of the mine below 155 m depth

An interpretative block diagram based on field data, mine maps and the 3D-model of Sala Mine. See 155 m map for legend. Letters denote the major shafts of the mine. Orange denotes the Sandymningen Level of the collapsed part of Sala Mine. The yellow siliceous interbeds are not necessarily the same beds on the different sides of the shear zones.
Appendix 6 – Ore analyses

Analysis 1  Wallbergs Nordöstra Ort (Rödstjärten) – 155 m level
Ore type  Sphalerite vein system in marble

<table>
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<th>Procedure</th>
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Sampling procedure: Several samples were taken of sphalerite vein system ore in the small gallery Ulrikas NÖ ort (155 m) in Sala Mine. The total weight of the samples was ~ 3-4 kg and it consisted of roughly 50/50 sphalerite and gangue. Representative samples only were chosen.

The samples were sent to Lundin Mining Exploration for ore analysis preparation. The analysis for major and trace elements were performed by ALS Chemex (Canada) and the codes refer to their analytical procedures. The analysis was funded by Tumi Resourced ltd.
Analysis 2  Namnlösen - 155 m
Ore type  Semi-massive/massive galena ore hosted by dolomitic marble

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<th>Element</th>
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Sampling procedure: Several samples with a total weight of ~ 2 kg were taken of massive galena ore hosted by dolomitic marble. Gangue observed in the hand samples consisted of chlorite, serpentine, calcite and dolomitic marble. The samples were found at the bottom of an old ore body during work constructing an underground concert hall in Namnlösen (155 m) and occurred in solid rock. The samples were sent to Lundin Mining Exploration for ore analysis preparation. The analysis for major and trace elements were performed by ALS Chemex (Canada) and the codes refer to their analytical procedures. The analysis was funded by Tumi Resourced ltd.
Analysis 3  Ore from Bronäs mine dump
Ore type  Massive galena/sphalerite ore

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<th>Elemental Property</th>
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<td>&lt; 10</td>
<td>ME-ICP41</td>
</tr>
<tr>
<td>U (ppm)</td>
<td>&lt; 10</td>
<td>ME-ICP41</td>
</tr>
<tr>
<td>Bi (ppm)</td>
<td>&lt; 2</td>
<td>ME-ICP41</td>
</tr>
<tr>
<td>Sr (ppm)</td>
<td>1</td>
<td>ME-ICP41</td>
</tr>
<tr>
<td>V (ppm)</td>
<td>1</td>
<td>ME-ICP41</td>
</tr>
<tr>
<td>Sc (ppm)</td>
<td>&lt; 1</td>
<td>ME-ICP41</td>
</tr>
<tr>
<td>Be (ppm)</td>
<td>&lt; 0.5</td>
<td>ME-ICP41</td>
</tr>
</tbody>
</table>

Sampling procedure: Several samples with a total weight of ~ 2 kg were taken of massive galena/sphalerite from the mine dump of the Bronäs Mine. The ore was very poor in gangue from what could be seen in hand sample.

The samples were sent to Lundin Mining Exploration for ore analysis preparation. The analysis for major and trace elements were performed by ALS Chemex (Canada) and the codes refer to their analytical procedures. The analysis was funded by Tumi Resources ltd.

Geocronite has been reported from the same ore block (Per Nysten, 2007 – personal communication) and this probably accounts for the excess of Sb over Ag in the sample.
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