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Minerals from the the Sulitjelma Copper Mines, North Norway

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The Sulitjelma Copper Mines (1891-1991) ranks as the largest mining enterprise in Norway in the 20th centrury. During the mining operations and also later, fine mineral specimens have been collected in the district.

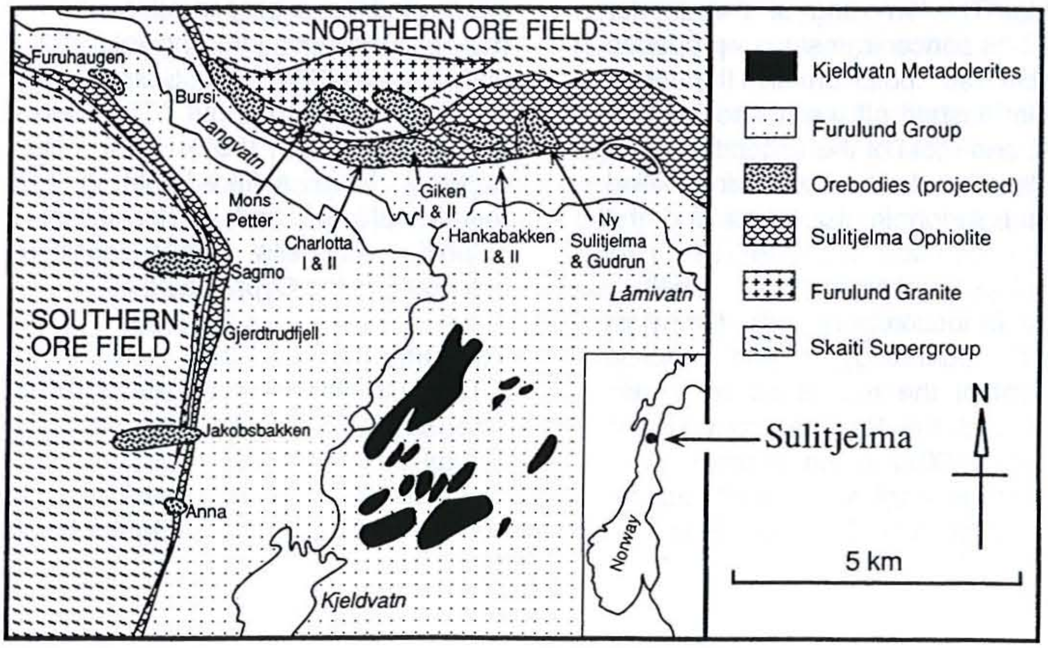
Introduction

Copper has been mined in Norway for several hundred years, the first documented copper mine being the Verlohrne Sohn Mine in Kongsberg 1490. Several types of copper ore deposits have been exploited, but the major ore type has been the Caledonian, massive, strata-bound sulphide deposits. Vigsnes, Stordø, Folldal, Røros, Løkken, and Grong are other well-known ore districts with deposits of this type. In this paper, however, the Sulitjelma district will be focused on. It is situated about 80 km east-southeast of the town Bodø in Nordland county.

Mining history

The first deposit discovered in Sulitjelma was found by a lapp, Mons Petter, about 1858. The Swedish consul Nils Persson was granted a mining lease in 1886, and after investigations and preliminary mining from 1887 he established a mining company, the Sulitelma Aktiebolag, in 1891. The Sulitjelma mines became the largest mining enterprise in Norway in the 20th century, with an estimate of 75 000 man years of labour. The largest number of employees was reached in 1913, amounting to 1 737. The company was reorganized in 1933, under the name of A/S Sulitjelma Gruber, and from 1937 the major shareholders were Norwegians. The mining operations ended June 28, 1991.

Figur 1. Simplified geological map of the Sulitjelma area with the location of the most important sulphide deposits (after Cook et al. 1993).



Sulitjelma was a very isolated mining society, in a remote valley, about 35 km from the nearest public road and the coast to the west, and 10 km from the Swedish border to the east. The transport took place partly by a railway line (built by the mining company) and partly by boats (on the lakes) from the coast. In the winter some supplies were transported by horse wagons on the ice-covered lakes. The railway was completed in 1956. In 1972, after more than 80 years of mining, a road was finally finished, and the railway was closed down.

In the hills around Sulitjelma about twenty five massive, stratabound copper deposits were prospected, and eighteen were worked (see sketch map). The Jacobsbakken mine (1896-1968), the largest deposit, produced 4.5 million tons of sulphide ore; the Giken I mine (1892-1973), the second lagest, produced 3.2 million tons. Altogether 26 million tons of sulphide ore have been mined in the district (Ellingsen et al. 1996).

The ore was processed and smelted to blister copper in Sulitjelma. The copper ingots contained about 99% copper and 600 grams of silver and 6-8 grams of gold per ton. The mine for many years also produced a zinc concentrate and a pyrite concentrate. The smelting of the copper sulphide concentrates produced considerable air pollution in the deep valley. Paint flashed off the houses after a short time, and most of the vegetation died. Acidic, polluted water from the mines killed the fish population in the lakes and the river.

The mining, processing and smelting took place in accordance with the most advanced technology, and some improvement of the processes were also developed, e.g. the Knutsen converter in the smeltery (1902) which needed much less external energy as it used sulphur from the ore as fuel. The world's largest Elmore processing plant was built in 1909. The first of three smelteries was built in 1894, and the last one closed down in 1987. The copper smeltery was the first one ever to be based on copper smelting by electric power (Quale 1975).

Only about 900 people are now living in Sulitjelma all the year. Many of the old houses serve as holiday homes, while others are used by organizations and tourist enterprises focusing on wild life activities. A small enterprise (Saulo) takes out drill cores of sulphide ore, using polished ore and brass to make different gift objects. There is also a small, nice mining museum (founded in 1977), and a part of the Giken mine is open to visitors by a mine train through the Grunnstoll adit. Since the smeltery closed down in 1987 a rapid return of vegetation has taken place.

Geology

The sulphide deposits are situated at the contact between submarine basalts and overlying sediments of Upper Ordovicium age. The deposits are interpreted to have been formed by volcano-exhalative sedimentary processes at sea floor in a fault-controlled basin during ocean closure. The present sequence of basalts, gabbros, ultramafics and sheeted dykes has been interpreted as a preserved ophiolite suite (as a part of an ancient sea floor plate)(Boyle 1989). The Sulitjelma gabbro has been dated to about 437 million years (Pedersen et al. 1991). The rocks and deposits have suffered strong regional metamorphism and deformation. The sulphide deposits are classified as belonging to the Cyprus type.

The sulphide deposits

The Sulitjelma district is about 100 km^2 in size. About 25 individual ore deposits with a total sulphide mass of some 35 million tons have been discovered. The sulphide bodies are tabular and elongated in shape, reaching 1200 m in length and 300 m in width. They rarely exceed 5 m in thickness, the average being about 2 m.

Massive pyritic ore (with some chalcopyrite, pyrrhotite, sphalerite and galena) (60-90% sulphides) accounts for at least 80% of the total mass of sulphides (Cook 1996).

There is also some *semi-massive banded ore and disseminated ore*, besides also some *rich, remobilized pyrite-pyrrhotite-chalcopyrite ore and massive chalcopyrite ore.*

On an average the mined ores contained about 20% sulphur, 1.8% copper, 0.4% zinc, 0.5 grams per ton of gold and 30 grams per ton of silver.

Veins are also present, which Cook (1996) divides into two types: *Chalcopyrite-pyrrhotite ore veins* with the gangue minerals quartz, actinolite, titanite and kyanite, and *sulphate-bearing veins* with anhydrite, quartz, calcite and minor celestine and barite.

A chemically and mineralogically distinct zone of hydrothermal alteration surrounds each sulphide body, containing chlorite and albite and sometimes biotite and/or actinolite.

Ore minerals

The sulphide ore consists mainly of *pyrite, pyrrhotite, chalcopyrite and sphalerite. Galena, arsenopyrite, cubanite, molyb-denite and tetrahedrite* are present in minor amounts.

Investigations with reflected light microscopy and electron microprobe have yielded a large number of accessory ore minerals (Cook 1996). They are almost exclusively found in the rich, remobilized ores and the veins. These minerals are usually only visible in microscope by high magnitude and are merely listed here. Many contain antimony, bismuth, lead, silver, gold and/or tellurium (Tabel 1). The association between antimony and gold/silver is significant (Cook 1992).

Macroscopic minerals

Fine ore samples

Sulitjelma is famous for its rich chalcopyrite (+ pyrrhotite) ore with a number of scattered, rounded pyrite crystals. Blocks of this ore type are found in many museums. The pyrite crystals are usually around 1-2 cm, but may reach several centimetres. Most of this ore comes from the Charlotta-Giken area.

Pyrite

Crystals of pyrite are widespread in the ores and the chlorite schists. Rounded crystals loosened from chalcopyrite ore are up to 10 cm in diameter. Pyrite in cavities and in chlorite schists usually have sharp edges, and cubes up to 5-10 cm have been collected. Cube is by far the most common habitus, but also pentagon-dodecahedrons and (in Ny-Sulitjelma) octahedrons are present. Some cubic pyrite crystals are elongated. Some pyrite porphyroblasts have surrounded other pyrite crystals during growth. The cobalt content of pyrite has been measured within the range 180-2400 ppm.

Arsenopyrite

Arsenopyrite crystals, often twinned, are commonly found as porphyroblasts up to 3 mm in pyritic ore (Cook 1996). They have a generally low content of cobalt and a quite low content of nickel (n.d. to 0.75%). In Jakobsbakken, porphyroblasts of cobaltian arsenopyrite ("danaite") crystals up to 2 cm occur in remobized ore or ore veins rich in galena, chalcopyrite, and sulphosalts. Cook (1996) reports a cobalt content in the range 0.86 - 2.51 weight %. These crystals were first decribed by Stelzner (1891) and Fletcher (1904), and later by Ramdohr (1938). Occasionally numerous, idiomorphic arsenopyrite crystals up to 1-1.5 cm in length have been found in chlorite rich layers (H.Chr. Olsen pers. comm. 1998).

Quite large crystals have also been observed from other deposits, e.g. Charlotta and Giken.

Chalcopyrite and pyrrhotite

The two minerals are present in smaller or larger amounts in most ores, and are sometimes found in massive lumps or aggregates. Chalcopyrite is also found in cavities, but usually as small irregular aggregates. Crystals have not been reported.

Native copper

The mineral was sometimes found along thin fractures, as small plates or dendritic crystal aggregates up to 7 cm in length in the Hankabakken mine. It is most likely of supergene origin.

Calcite

The mineral is commonly associated with zeolites and sulphates, usually in quite small quantities. The crystals most often have rombohedral or scalenohedral forms, with size from 0.05 to 3-4 cm, but larger crystals have also been found. Sometimes the crystals show phantoms.

Aragonite(?)

Aragonite has been reported (Garmo 1983), but all X-rayed specimens have so far turned out to be calcite.

Parisite(?)

A specimen collected in the Charlotta mine by W.C. Brøgger in 1901 is labelled parisite (the MGM collection). The mineral has not been further examined. The specimen contains heulanditt, stilbite, chalcopyrite, biotite and magnetite, but parisite was not recognized in this study.

Fluorapophyllite

Fluorapophyllite and stilbite are the most common minerals of the zeolite stage of mineralization in Sulitjelma. Thick tabular apophyllite crystals occur single or as clusters of a few crystals, but often as sheeted aggregates occurring at pocket walls. The crystal size is up to 3 cm in length and 1.3 cm in thickness, and the colour is white to watercoloured. The mineral is commonly associated with calcite, quartz, stilbite and scolecite. It is reported from Giken, Charlotta, Mons Petter and Hankabakken. Larsen (1980) analysed three different apophyllites from Sulitjelma and found that the composition varied from approximately 50 mol% to 90 mol% fluorapophyllite.

Stilbite

The mineral often occurs as sheafshaped crystal aggregates, and sometimes almost ballshaped. The crystals are usually white and up to 3-4 cm in length. Yellowish white to orange crystals up to 2 cm were found (in blocks at surface) in 1996, together with actinolite and small, watercoloured heulandite crystals. Stilbite is the most common zeolite in Sulitjelma.

Heulandite

Greyish white to watercoloured heulandite crystals up to 2.2 cm in hight, 1,5 cm in length, and 1.0 cm in width are found associated with stilbite and scolecite.

Scolecite

The mineral is common in the zeolite-bearing veins, and it is often found in fine specimens, espesially in Mons Petter. Balls of radiated crystals up to 2,5-3,0 cm in length, have been collected in pockets together with calcite, apophyllite and stilbite crystals. The crystals are from colourless to white.

Okenite

The mineral is reported by Vogt (1935, 1938), and the presence has been verified by X-ray study at MGM. Balls of radiated crystals up to 0.7 cm in length have been observed in small pockets together with apophyllite. At Sulitjelma Mining Museum balls of radiated needles up to 1.5 cm in diameter occur on a large specimen together with chabazite.

Chabazite

Chabazite from Charlotta has been identified by X-ray at MGM. Sulitjelma Mining Museum has a platy specimen with an area of about 2 dm^2 with chabazite crystals, with a size of 0.2-0.6 cm, occurring together with okenite.

Gyrolite

Greyish white, ballshaped crystals up to 1.6 cm were collected by T.T. Garmo in 1985 at waste heaps from Charlotta at the shore of Langvann, and tentatively labelled gyrolite. This has now been verified by X-ray diffraction. The mineral occurs together with scolecite, fluorapophyllite, chalcopyrite, and chlorite.

Harmotome and laumontite

These minerals are reported by Vogt (1935, 1938) as members of the zeolite stage of mineralization.

Thaumasite

The thaumasite in Sulitjelma was apparently first recognized by Fredrik Carlson around 1912-1914, and later identified and described by Vogt (1935,1938) from the Giken, Charlotta and Holmsen mines, as the youngest mineral of the zeolite stage of mineralization, and evidently younger than barite. Thaumasite is quite common in the veins, as the last fissure filling, usually occuring in up to handsize, white lenses or clusters of needleshaped grains and radiated balls, with needlesize up to more than 1 cm. Vogt (1938) descibed his largest piece of pure thaumasite to be 27x27x18 cm, weighing 7.75 kg, found in a large quartz-anhydrite-gypsum vein in the upper Giken mine.

Anhydrite

Crystals up to 5 cm in length of anhydrite are sometimes found frozen within medium-grained, massive anhydrite, but they have not been found as free crystals. Most anhydrite is found as fine- to coarse-grained masses. The colour is usually distinctly violet. It is commonly associated with quartz, pyrite, actinolite, chlorite, calcite, and gypsum. The mineral is reported by Cook (1996) as a major constituent of the sulphate veins.

Gypsum

The mineral occurs as thin fracture fillings and larger cavity fillings. It is often very coarse-grained, sometimes up to 5 - 10 cm. It is white to watercoloured.

Barite

Lumps of massive, bluish barite up to 5-7 cm with small calcite rhombohedrons and tiny needles of an antimony sulphosalt has been collected by W.C. Brøgger 1901 in the Giken mine (as found in the collection of Mineralogical-Geological Museum in Oslo). Vogt (1935, 1938) reported corroded masses of bluish grey barite within massive thaumasite from a vein in the Giken mine. Cook (1996) reported the mineral as a minor constituent in the sulphate veins.

Celestine

Vogt (1935, 1938) reported celestine, and also Cook (1996) observed the mineral as a minor constituent in the sulphate veins.

Quartz

Quartz is a major constituent in the veins and is also a quite common accessory in the ores. It is usually massive, but some rock crystals have been found.

Albite

Albite crystals completely covering the side walls of a 10 cm wide vein in the Giken mine were reported by Vogt (1938). Other minerals in the vein were thaumasite, barite, pyrite, stilbite, chlorite, and apatite.

A coarsegrained, slightly yellowish brown aggregate associated with quartz and anhydrite consist of albite, as verified by X-ray diffraction at MGM. The feldspar is also found in other specimens, sometimes as small, greyish white crystals.

Other primary minerals

Reported in association with the ores and veins are also the silicates: *chlorite*, *actinolite*, *hornblende*, *amphibole asbestos*, *biotite*, talc(?), *titanite, kyanite, epidote, clinozoisite*, and *almandine garnet*, besides the phosphate *apatite*. *Staurolite, diopside and tourmaline* has not been reported with certainty in association with the ores, although it has been found several places in the region.

Secondary minerals

As for most mines in Norway the secondary minerals on the waste heaps have not attracted much attention, and they have not been systematically collected and studied. *Goethite* is of course widespread. *Chalcanthite* has also been identified (Søyland Hansen, pers.comm. 1997). Three secondary minerals are observed on the native copper; two of them are tentatively identified as *cuprite* and *tenorite*, while the third has a bluish green colour. Probably there are several others.

Minerals recently collected at other localities in the area

A few years ago two pockets were discovered side by side within a tunnel of the Sulitjelma road. They yielded several hundred titanite crystals, many twinned. Most of them were lying loose in chlorite masses, but also fine matrix specimens appeared. The nicest has about 55 crystals, up to about 3 cm long. The largest, twinned, single crystal is 6.7 cm long. The crystals show colours from yellow to brown, and most crystals contain more or less inclusions of chlorite.

The pockets also contained calcite crystals up to 10 cm and a few, somewhat irregular, waterclear quartz crystals up to 30 cm. The largest weighing 22 kg.

A few small pockets in road cuts at the Sulitjelma road not far from Fauske contained small siderite, dolomite, calcite, rutile ("sagenite"), quartz, and pyrite crystals.

During the construction work of water power tunnels north of Sulitjelma (Siso water power plants) many years ago, yellowish green prehnite crystals of very good quality were found by the workers. Some of the prehnite was covered by small apophyllite crystals.

Vein paragenesis

Vogt (1938) states that thaumasite is the youngest mineral in the zeolite stage of mineralization. Stilbite seems to be older than the other three common minerals of the zeolite stage in Sulitjelma: fluorapophyllite, scolecite and heulandite. Okenite is younger than fluorapophyllite.

A generation of calcite is younger than the four common minerals of the zeolite stage. But calcite probably occurs in more than one generation. Quartz crystallized early, may be earliest of the vein minerals. But quartz is quite often not present.

Sulphates and zeolite stage minerals are rarely present in the same specimens, but from Vogt's descriptions they are often present in the same veins. Thaumasite belongs to the zeolite stage, but contains sulphate.

Minor sulphides are commonly present. Chalcopyrite is by far the most common, but also pyrite, galena and trace ore minerals are quite often observed in zeolite stage specimens. Visually it has been difficult to recognize other ore minerals, but a microscopical study would probably yield many.

Table 1.
List of trace ore minerals recorded from the Sulitjelma copper sulphide deposits (after Cook 1996):

allargentum, Ag_{1-x},Sb_x
altaite, PbTe
antimony, Sb
argentite, $Ag2_S$
arsenic, As
aurostibite, $AuSb_2$
bismuth, Bi
bismuthian antimony, (Sb,Bi)
bismuthinite, Bi_2S_3
bornite, Cu_5FeS_4
boulangerite, $Pb_5Sb_4S_{11}$
bournonite, $PbCuSbS_3$
breithauptite, NiSb
chalcostibite, $CuSbS_2$
clausthalite(?), PbSe
costibite, CoSbS
dyscrasite, Ag_3Sb
electrum, (Au,Ag)
empressite, AgTe
geocronite, $Pb_{14}(Sb,As)_6S_{23}$
gudmundite, FeSbS
hessite, Ag_2Te
jamesonite, $Pb_4FeSb_6S_{14}$
jordanite, $Pb_{14}(As,Sb)_6S_{23}$
kongsbergite, (Ag,Hg)
löllingite, $FeAs_2$
mackinawite, Fe_9S_8
meneghinite, $Pb_{13}CuSb_7S_{24}$
nisbite, $NiSb_2$
pyrargyrite, Ag_3SbS_3
realgar, AsS
seligmannite, $PbCuSbS_3$
silver, Ag
stannite, Cu_2FeSnS_4
tennantite, $(Cu,Ag,Fe,Zn)_{12}As_4S_{13}$
tetradymite, Bi_2Te_2S
tsumoite, BiTe
valleriite, $4(Fe,Cu)S \cdot 3(Mg,Al)(OH)_2$

Table 2.
Sulitjelma - list of minerals in addition to trace ore minerals:

actinolite
albite[1]
anhydrite[1]
apatite[1]
aragonite(?)
arsenopyrite[1]
barite[1]
biotite
calcite[1]
cassiterite
celestite[2]
chabazite[1]
chalcanthite
chalcopyrite
chlorite[1] (clinochlore?)
clinozoisite[1]
copper[1]
cubanite
cuprite
diopside[1]
dolomite
epidote
fluorapophyllite[1]
galena
garnet[1] (almandine)
gypsum
goethite
graphite[1]
gyrolite
hematite
heulandite[1]
hornblende
illite[1](?)
ilmenite
kyanite[1]
laumontite[1]
magnetite
molybdenite
montmorillonite[1]
muscovite
(natro?)jarosite[1]
okenite[1]
parisite(?)
phlogopite-2M[1]
pyrite[1]
pyrrhotite[1]
quartz[1]
rutile[1]
scolecite[1]
siderite
sphalerite[1]
stilbite[1]
tenorite
thaumasite
titanite[1]
witherite[1]

[1] verified by X-ray identification
[2] verified by electron microprobe

Table 3.
Vein minerals

Sulphates	Zeolites and associated minerals
Gypsum, $CaSO_4.2H_2O$	Stilbite, $NaCa_2Al_5Si_{13}O_{16}\cdot 14H_2O$
Anhydrite, $CaSO_4$	*Fluorapophyllite, $KCa_4Si_8O_{20}(F,OH)\cdot 8H_2O$
Barite, $BaSO_4$	Scolecite, $CaAl_2Si_3O_{10}\cdot 3H_2O$
Celestine, $SrSO_4$	Heulandite, $(Na,Ca)_{2-3}Al_3(Al,Si)_2Si_{13}O_{36}\cdot 12H_2O$
	*Thaumasite, $Ca_6Si_2(CO_3)_2(SO_4)_2(OH)_{12}\cdot 24H_2O$
	Chabazite, $CaAl_2Si_4O_{12}\cdot 6H_2O$
	*Okenite, $Ca_{10}Si_{18}O_{46}\cdot 18H_2O$
	*Gyrolite, $NaCa_{16}(Si_{23}Al)O_{60}(OH)_5\cdot 15H_2O$
	Laumontite, $CaAl_2Si_4O_{12}\cdot 4H_2O$
	Harmotome, $(Ba,K)_{1-2}(Si,Al)_8O_{16}\cdot 6H_2O$

Silicates	Sulphides	Other
Quartz	Chalcopyrite	Calcite
Chlorite	Galena	Apatite
Actinolite	Pyrite	Magnetite
Albite	Sulphosalts	
Titanite	(Pyrrhotite?)	
Kyanite	(Sphalerite?)	
Biotite(?)		

Minerals with an astrisk * are not classifed as zeolites.

Concluding remarks

The massive, the semi-massive and the disseminated pyrite ores (Cook 1996) were originally deposited by exhalative-sedimentary processes at sea floor. During a period of regional metamorphism the ores were deformed and recrystallized, and to some extent remobilized, making py-po-cp "ore" and massive cp "ore", and growth of porphyroblasts of pyrite and arsenopyrite crystals. During retrograde metamorphism cp-po ore veins and sulphate-zeolite bearing veins were formed. Sulphur isotope studies (Cook et al. 1997) strongly suggest that the sulphates formed by oxidation of pre-existing sulphides. The trace ore minerals (Table 1) mainly occur in remobilized ores and veins.

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