

MINING MITIGATION IN NORWAY AND FUTURE IMPROVEMENT POSSIBILITIES¹

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Abstract: Norway has a long history of mining dating back to the Akersberg silver mine in Oslo about 1000 years ago. Larger-scale mining for copper and sulfur became common in the early 1600s. There is no active mining of massive sulfide deposits in Norway today; but the operations have left behind tailings, waste rocks and adits that in many cases discharge low-pH, metal-laden waste streams. Three of the Norwegian sulfide mines (Røros, Råna, and Sulitjelma) where mitigation has taken place, but metal release is still evident are discussed in this paper.

The Røros Mining District consists of many massive sulfide deposits mined primarily for Cu with minor lead and zinc. Some of the tailings dams have been reclaimed, while others have been left open exposed to weathering. Evidence of oxidation appears in the upper ½ meter in one of the uncovered tailings dams, closed 30 years ago, where pH is 2.5 at the surface increasing to a pH 6 at 70 cm depth. These tailings contain silicate minerals that most likely have a neutralizing potential.

The Råna mining area consist of a few smaller massive deposits and a recently closed (2002) nickel deposit associated with a mafic intrusive. Tailings from the nickel mine were emplaced along the shore line. Closure of the tailings included a soil cover 10-20 cm thick. Preliminary investigations indicate that this cover is not efficiently reducing the oxidation of sulfide minerals. Magnesium silicate minerals are most likely, however, neutralizing the acid generated from pyrrhothite, the main sulfide in the ore.

The Sulitjelma Mining District also consists of many massive sulfide deposits mined until 1991. Reclamation of the mining district includes a one meter cover on the tailings dam and the discharge of ARD into old underground mine workings. This has resulted in a mass loading reduction of 80-90%.

Characterization of these sites has primarily focused on surface water quality, and in some instances, groundwater quality. The water quality data combined with mineralogical, geochemical, and hydrogeological data of the ore deposit and waste material can be used to improve mitigation, resulting in better control of metal release.

Additional Key Words: Røros, Råna, massive sulfide deposits, Sulitjelma, ARD, nickel, silicate mineral neutralization

¹ Poster paper presented at the 7th International Conference on Acid Rock Drainage (ICARD), March 26-30, 2006, St. Louis MO. R.I. Barnhisel (ed.) Published by the American Society of Mining and Reclamation (ASMR), 3134 Montavesta Road, Lexington, KY 40502

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7th International Conference on Acid Rock Drainage, 2006 pp 1952-1960

DOI: 10.21000/JASMR06021952

<https://doi.org/10.21000/JASMR06021952>

Introduction

Norway has a long history of mining, dating back to the Akersberg silver mine in Oslo almost 1000 years ago. Larger-scale mining for Cu and S became common in the early 1600s. The focus was on massive sulfide deposits primarily associated with ophiolite and island arc complexes (Grenne et al., 1999). The Løkken, Folldal/Hjerkinn, Sulitjelma, and Røros mines are large mines that operated for over 300 years. There is no active mining of massive sulfide deposits in Norway today; but these operations have left behind tailings, waste rocks and adits that in many cases discharge low-pH, metal-laden waste streams. The Norwegian Mining Authority and the Norwegian Environmental Protection Agency (SFT) have, in some cases, together with the mining companies, worked to mitigate the environmental problems at many of the sites. These mitigations include tailings flooding, surface water discharge into the mine workings, dry cover, wet covers and wetlands, and metal precipitation in treatment plants. This has reduced metal loading 80 – 90% in down-gradient lakes and rivers. However, contaminant leach is starting to increase at some of these sites (GEO, 2005). Additional characterization, to include more detailed mineralogical, geochemical, and hydrogeological data of the ore deposit and waste material, can be used to evaluate and better predict the ARD and neutralizing potential of minerals within the mine waste, thus improving mitigation efforts, resulting in better control of metal release. This paper reviews three of these mining sites, Røros Mining District, Sulitjelma Mines, and Råna Deposit.

The Røros Mining District

The Røros Mining District consists of many smaller massive sulfide deposits. The first deposit was discovered in 1645 but was mined for only three months. Shortly after, the Røros Copper Works was established to mine the Old Stortvart deposit. A systematic search between 1650 and 1700 resulted in many discoveries. Several deposits were also discovered in the 1900s by detailed geological mapping, geophysical prospecting, and drilling. The last operation in the central Røros District (the Lergruvebakken Mine) closed in 1977, while the Killingdal Mine, located 50 km north of Røros, closed in 1986 after 312 years of operation. The main products from these mines were Cu and pyrite, with minor amounts of Zn.

Geology

The Røros District is a part of the Norwegian Caledonides fold belt. Cambro-Silurian metamorphosed rocks are tightly folded in a deep depression in a sub-Cambrian basement. The Cambro-Silurian strata of the Røros District represent a series of marine sediments mixed with submarine volcanics. The strata underwent a complex deformation history, with several stages of folding, thrusting, and late faulting.

The ore deposits in the Røros District are massive sulfides, presumably formed from black smokers on the ocean floor (Oftedahl, 1958). The deposits can be divided into *pyrite deposits* and *pyrrhotite deposits*, both with various amounts of chalcopyrite, sphalerite, and accessory minerals: magnetite, limonite, rutile, galena, arsenopyrite, mackinawite, cubanite, argentite, and molybdenite (Bugge et al., 1975; Segalstad, 2000).

The pyrite deposits consist of 60 – 80% pyrite with minor pyrrhotite; the ores contain 1 - 2% Cu, and 1 – 6% Zn. The gangue consists of quartz, chlorite, and muscovite/sericite.

The *pyrrhotite deposits* have large amounts of green silicate fragments of hornblende, chlorite, and biotite. Magnetite is common, and pyrite may occur as disseminations. The Cu grade is at least 1% in these ores.

Wall rocks are strongly chloritized with K-rich micas (biotite or muscovite). Some deposits show a quartz – sericite – pyrite zone.

Mine Drainage and Reclamation

The floatation plant at the Kongens Gruve (the King’s Mine) was the last to operate in the northern Røros Mining District, discharging tailings into Orvsjøen Lake and into a tailings dam. Most of the original waste dumps were later reprocessed with the new ore; therefore, few waste rock dumps are left in the area. The tailings dam has been covered with till and revegetated.

The Storwartz Mine, located in the eastern Røros Mining District, has the largest waste dumps and tailings in this district. There is a tailings dam down-gradient of the mine. Prior to the construction of the tailings dam, the tailings were discharged into Prestbekken Creek. There is an area where this creek discharged into Djupsjøen Lake, depositing tailings material as a sand bank. Field observations indicate that these tailings are oxidized from the surface to a depth of ½ – 1 m, characterized by a red-orange color and a low pH. The pH increases below this zone, which is characterized by gray colored material.

Water quality analyses have been performed for the creek up gradient of the mine, and down gradient where the creek discharges into Djupsjøen Lake. Prestbekken Creek has a pH of 3.3 – 3.7 with 0.5 – 3 mg/l Cu, 1 – 10 mg/l Zn, 0.002 – 0.02 mg/l Cd, and from not detected up to 0.058 mg/l dissolved Pb (Iversen, 2004a).

The color on the surface of the main Storwartz tailings is orange brown with a soil pH of 2.52 (Table 1). The tailings pH changes with depth to a pH of 6.1 at a depth of 70 – 80 cm. These tailings were emplaced more than 30 years ago, and have not been reclaimed.

Table 1. Tailings profile from the Storwartz Mine tailings in the Røros Mining District.

Depth (cm)	pH	Color
0	2.52	Orange brown
10	2.73	Light brown
15	2.77	Light brown gray
20	3.05	Light brown gray
30	4.09	Medium gray
70 - 80	6.1	Medium-dark gray

The Råna Mining Area

A few deposits were mined approximately 20 km south of Narvik, in the Råna mining area in northern Norway. The Bruvann Deposit was mined as an open pit and underground mine from 1989 until 2002, when the ore ran out. The mine entrance was located approximately 400 m above sea level. The extraction process (crushing, milling, and flotation) was located near the mine entrance. The Bjørkåsen Mine, another massive sulfide deposit 3 km further south, was mined between 1917 and 1964. Effluents from these two mines drain into an arm of the Ofotfjorden. Tailings from Bjørkåsen were discharged on the tidal flat in the inner part of the fjord arm. A large part of the tailings from the Råna Mine was placed on top of the tailings from the Bjørkåsen Mine.

Geology

The Bruvann Deposit is associated with the Råna mafic intrusion (Boyd and Mathiesen, 1979). The chemical composition of the Råna intrusion indicates that it formed through fractional crystallization of a tholeiitic gabbroic magma. The intrusive complex consists of peridotites, olivine norite, norite, and quartz norite surrounded by calciferous and garnet shists and marble horizons (Foslie, 1921; Gustavson, 1969). The nickel deposits are associated with peridotites and the noritic gabbros.

The deposits consist of pyrrhotite, pentlandite, chalcopyrite, and pyrite; occurring interstitially with olivine and orthopyroxene. The average nickel grade is 0.55%. Locally, the sulfides have been remobilized, generating massive sulfide areas with nickel grades up to 5%.

Mine Drainage and Reclamation

Following closure of their mining operation in 2002, the Nikkel & Olivin A/S mining company reclaimed the property. Sand from settling ponds was deposited underground in the mine tunnels. Tailings dams and some of surrounding waste rocks deposited in the open pit area were reclaimed with 10 – 20 cm of soil. The drainage has been monitored since the start of the mining operation. The recipient environment, the Ballangs Fjord is also being monitored.

A preliminary evaluation of the tailings in the settling pond indicates that the sulfides are oxidizing under the soil cover. However, the tailings seem to maintain a high soil pH of 6 – 8. Nickel concentration is relatively high in water leach analyses (first step of sequential analysis described by Dold, 2001) performed on the settling pond material, together with a high magnesium content, 1-10 mg/l and 0.01-0.13 wt.%, respectively. The total magnesium concentration in these samples are little less than 20 wt. percent, while Ca constitute approximately 1 wt.%. The final extraction step, which uses a four acid mix to dissolve feldspars leached most of the Ca (Fig. 1).

The receiving environment, the Ballangen Fjord, has increased in Ni and As concentrations according to SFT (Pers. Com.O. Bjertnæs, 2005). The sources to this contamination are poorly understood.

Table 2. Average, minimum and maximum total element concentrations from the settling pond material based on sequential extraction analysis (Dold, 2001). Concentrations are in wt.%. nd=not detected. Average (Avg.) is based on 20 samples).

Element	Avg,	Min.	Max.
Na	0.29	0.16	0.51
Mg	18.26	6.08	22.10
Al	1.53	0.79	2.81
P	0.0055	nd	0.02
K	0.21	0.17	0.3
Ca	1.07	0.59	1.85
S	0.1	0.06	0.36

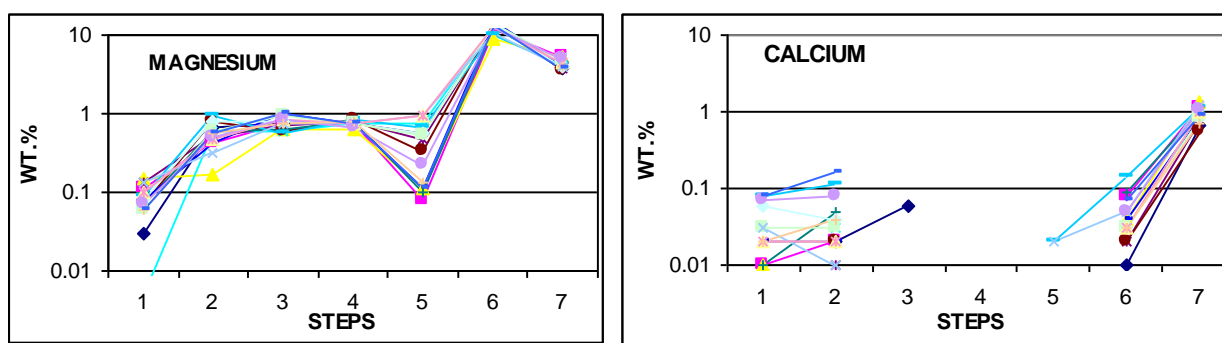


Figure 1. Results from seven step sequential extraction (Dold, 2001) analysis for Mg and Ca performed on settling pond samples.

The Sulitjelma Mining District

Mining in the Sulitjelma District, located in northern Norway, was once Norway's second largest enterprise. The underground train tracks stretched for a total of 880 km. The mining operation closed in 1991 after 104 years of operation. The district is divided in two areas by the elongated Lake Langvatn. The ores were discovered in 1858, but it took another 30 years before the mine was opened. The deposit was primarily mined for S from an ore containing 20% S, but Cu (1.8%) and Zn (0.4%) were also extracted, with minor amounts of Ag (600 gram/ton) and Au (8 gram/ton). The Cu ore was first roasted, emitting large amounts of SO₂; later, the operation switched to flotation and an electric Cu smelter (Segalstad, 2002).

Geology

The Cu-bearing strata-bound massive sulfide deposits are contained in basic volcanics of Ordovician age, interbedded in a thick sequence of marine sediments and submarine volcanics: greenstones, tuffs, and Na-rich keratophyres. The sediments are carbon-rich pelites, greywacke, and impure quartzites. Conglomerates and limestone occur in minor amounts. The sulfide ores are found between the major metabasic igneous complex (amphibolites and gabbro) and the Furulund Shist (Bugge, 1978; Qvale, 1975). These rocks underwent different stages of metamorphism during the Caledonian Orogeny, ranging up to 620°C and 9 – 10 kbar pressure (Cook et al., 1993).

There are both Besshi-type and Cyprus-type massive sulfides in the 20 deposits found in the Sulitjelma Mining District (Cook et al., 1990). Each ore body is associated with an intense hydrothermal alteration in the lower stratigraphic unit, and a distinct retrograde greenschist facies with chlorite, biotite, and albite.

The deposits are dominated by pyrite with subordinate chalcopyrite, sphalerite, and pyrrhotite. Galena, arsenopyrite, cubanite, molybdenite, stannite, and tetrahedrite occur in minor amounts (Cook, 1996). The ore body is cut by late faults carrying pyrrhotite, chalcopyrite, and sulfosalt minerals. Masses of anhydrite and celestite are also found in these veins, often intergrown with actinolite, biotite, chlorite, calcite, and quartz (Cook et al., 1993).

Mine Drainage and Reclamation

Metal pollution to surface water in the Sulitjelma Mining District is assumed to be from adit drainages, based on flow volumes and water quality; the pH ranges from 2.4 to 2.8, with Cu and Zn concentrations up to 500 mg/l and 250 mg/l, respectively (Iversen et al., 1991). About 50 tons of Cu/year were being released to Langvatn Lake, before several of the adits were plugged (those giving the most drainage), and water was collected and discharged into one of the larger mine tunnels. These measures have resulted in a metal loading reduction of approximately 80 – 90%, with Cu release down to about 12 tons annually (Iversen et al., 1991). As a result, fish can now live in the Sulitjelma lakes and rivers.

The largest single polluter in the area is the Mons Petter Mine (named after its discoverer). The remediation efforts have resulted in precipitation of Cu and Zn in the deeper parts of the mines, while Fe^{+2} iron is still dissolved in the water. The Fe is not considered an environmental problem but may be looked upon as an aesthetic problem; when the Fe^{+2} iron is oxidized to Fe^{+3} iron, the yellowish ocher, $\text{Fe}_2(\text{OH})_3$, precipitates along the waterways.

Alternative remediation methods have been tried in a pilot test on water from the Mons Petter Mine (Knudsen, 1995). Limestone was added as a pH regulating agent, and Fe was concentrated by reverse osmosis. Copper was precipitated using electrolysis. The pilot test showed that this remediation was costly. The Norwegian Institute of Water Research (NIVA), who conducted the project on contract with SFT, concluded that metal precipitation by adding limestone and depositing the metal precipitates would be a simpler and better method. The remaining problem would be to manage the amounts of metal precipitates.

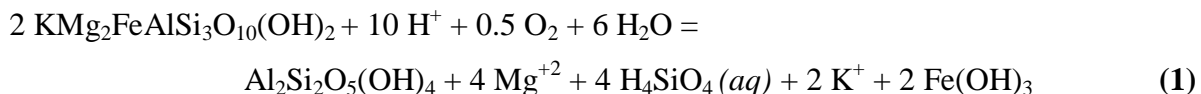
The tailings material generated after flotation was implemented in 1928 was discharged to the shore of Lake Langvatn, creating a large sand bank. After closure, this tailings area was reclaimed with a soil cover (Walder and Nilssen, 2005).

Discussion and Conclusion

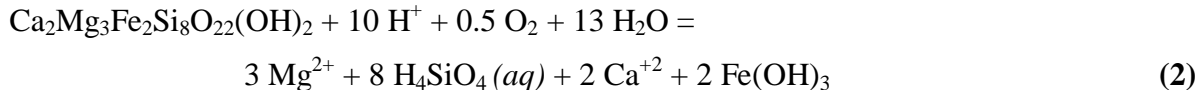
There are still considerable amounts of leaching taking place at many of the old, closed mining operations. The reclamation/remediation work that has been performed has reduced metal loading by 80 – 90%, at least for the short term. In most cases, covers were emplaced without a thorough characterization of the wastes. The covers on many of the massive sulfide deposit waste material will, with time, start to leach out more concentrated lower volume seepage, because the waste material has very little neutralizing capacity. These problems have been seen in other parts of the world (Ritchie, 1994), and are now starting to appear in Norway (Iversen, 2004b; GEO, 2005).

The characterization of these sites has primarily focused on surface water quality, and in some instances, groundwater quality. The water quality data combined with mineralogical, geochemical, and hydrogeological data of the ore deposits and their waste materials, some of which has been discussed in this paper, can be used to improve mitigation, resulting in better control of the metal releases.

The tailings at the Stortvartz Mine (in the Røros Mining District) have a high sulfide content, generating a low pH at the surface. The rapid increase in pH at a depth of 0.7 m indicates that there are neutralizing minerals in the tailings. The rocks contain biotite, which can alter to kaolinite (Appelo, 1994), thereby consuming H^+ ions according to the following chemical reaction:

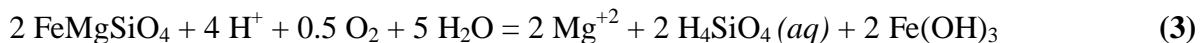


Similar dissolution reactions may take place for the clino-amphibole, most likely with a much slower reaction rate (Nagy, 1995; Brantley and Chen, 1995):



These neutralizing reactions are slower than the pyrite oxidation reactions at the surface of the tailings, but at depth, where O_2 availability is reduced, they can control the pH. However, the amount of these neutralizing gangue minerals is not known, and neither is any mobility analysis of metals released during the sulfide oxidation in the upper part of the tailings.

In the settling ponds material from Råna, olivine and clino-pyroxene comprise the main part of the gangue minerals, with smaller amounts of calcite. The sequential extraction data indicate that the amount of calcite is very small or absent in the analyzed material. Magnesium is high in the water leach, indicating that olivine is weathering in the system. Olivine may weather with consumption of H^+ ions, according to the following chemical reaction:



The high pH and pyrrhotite oxidation indicate that olivine neutralization is as rapid as the pyrrhotite sulfide oxidation.

Although the pH is neutral, nickel is mobile due to its poor sorption on metal hydroxides and the high solubility of NiO; while Cu and Co are more likely to be sorbed in the precipitating $Fe_2(OH)_3$. It is, therefore, expected that unknown quantities of Ni leach from the tailings into the fjord.

There is still considerable contamination from old waste rock piles at Sulitjelma that have not been reclaimed. Most of the reclamation measures have focused on minimizing discharges from adits, and placing a cover on the tailings discharged at the shoreline of Lake Langvatn (Iversen, 1995; Iversen, 1998). The mineralogy of surrounding rocks of the mine tunnels and possibly in the tailings indicates that there would be a neutralizing effect similar to the Stortvartz and the Råna mines. However, this has not yet been verified.

These discussions point out the importance of analyzing the mineralogy within the waste material, estimating their rates relative to the sulfide oxidation rate and the mobility of elements

released during the sulfide oxidation. To be able to upgrade reclamation procedures and perform long term prediction on future seepage, characterization work is planned on several reclaimed and un-reclaimed mine sites in Norway.

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