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Ni,Co-mineralizations in the Valberg quarry, Kragerø, South Norway: a progress report

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Introduction

The Valberg quarry in Kragerø, Telemark, has been known for decades as a rewarding collecting site for well crystallized species of prehnite, albite, scapolite, calcite, quartz, epidote, among others. These minerals are located in hydrothermal veins and alteration zones within a hyperite (gabbroic) complex. The interesting geology of the complex has been treated by several authors (Forbes 1857, Brøgger 1934, Bugge 1943, Bugge 1965). Recently, geologist Ulrik Søvegjarto has carried out detailed geological mapping within and around the quarry on the instructions of Franzefoss Bruk A/S. However, no thorough investigation of the mineralogy of the mineralized veins, lenses and altered rocks have been reported.

During quarrying in the late 1990s, excellent samples of Ni,Co-bearing sulphide ores and minerals became available through systematic search by local mineral collectors, especially Vegard Evja, Trond Spilhaug and Aslak Jensen. A closer look at these ores and minerals was initiated, in order to evaluate the complexity of the sulphide mineralizations, and to establish the correct nomenclature of the arsenosulphides. The sulphide minerals have been investigated by X-ray diffraction, ore microscopy, electron microprobe and scanning electron microscopy. This article is a progress report with special emphasis on the Ni-Co-mineralizations.

The history of the Valberg quarry

A test production of 200 tons of hyperite from Valberg was shipped to England in 1913. Already the next year regular quarrying was started by the landowner, George Dahll, nephew of the more well known geologists and mining entrepreneurs Johan and Tellef Dahll, in co-operation with English interests. The main product was macadam gravel for road construction, for an international market. Dahll maintained the company *Valberg Macadam* A/S until 1948, when the ownership was transferred to Raffineringsverket AS in Kristiansand under a new name, *Valberg Hyperite A/S*. The first 40 years of the Valberg quarry's history has been treated in detail by Midgaard & Tande (1953). The property and rights were in 1973 taken over by a new company, *Norsk Hyperit A/S*, owned by the Danish company Faxe Kalk. In 1995 the quarry was bought by Franzefoss Bruk A/S, and is now named *Franzefoss Valberg*. The quarry has been in operation for 86 years, with only short periods of stagnation.

Present working

Franzefoss Valberg is a crushing plant intended for export and with a capacity of 900 000 tons annually. The plant is a 5-step crusher built to manage the strongest demands of quality for asphalt in Germany. The loading capacity is 800 tons an hour, and it is possible to load ships up to 10 000 tons. The plant is worked by 2 shifts in the period March - December, while in the winter necessary maintenance takes place. Franzefoss Valberg has only 9 permanent employees, including the manager, Egil Rundsag, the quarry overseer, Frode Jørgensen, and the shop foreman, Ove Skogvold. The company Selmer ASA is leased to take care of drilling and blasting, and Farsjø Steintransport to manage transport, uncovering, block sorting and loading of blocks for coastal protection.

Products are hyperite sand, gravels and crushed stones for concrete, asphalt, road constructions, and railway ballast, and large blocks of gabbro for coastal protection and harbour works. During

recent years about 400 000 tons have been produced annually, of this 65 000 tons have been used locally.

Geology

The gabbroic rocks (hyperites) of the Valberg intrusive body constitutes a major part of the Valberg peninsula. The intrusive body is 2.5 km long and 1-1.5 km wide (Fig. 1). The Valberg quarry is situated at Delingsåsen in the southern part of the area. The gabbroic rocks occur as a lense-shaped body which have intruded a series of older quartzites, mica shists and amphibolites. The regional metamorphism in the area has reached at least amphibolite grade. Within a few small areas of the Valberg intrusive body the olivine hyperite is quite fresh with only incipient signs of recrystallization. Recryst-allization increases, however, in the other parts of the intrusive, through hornblende hyperite, to more or less schistose amphibolite and hornblende schists (Forbes 1857, Bugge 1965).

Lenses of massive, nickel-rich sulphide ore occasionally occur in the hyperites. A multitude of late, hydro-thermal veins and hydrothermally altered rocks are also present, often concentrated to certain areas. Scapolite, albite, clinochlore, amphibole and mica are characterstic minerals in altered rocks; while quartz-albite-chlorite-pyrite-calcite and albite-prehnite-epidote-calcite-clino-chlore are characteristic minerals in two common types of hydrothermal veins and lenses. Many other minerals have also been found. A preliminary list of minerals reported from the Valberg quarry is shown in Appendix 1.

Ore minerals are found in three different mode of occurrences: A) As accessory minerals in the hyperite rocks, B) in regular, plate-shaped sulphide lenses, apparently of traditional liquid magmatic origin, similar to the nickel ores which have been mined in the area (Bugge 1922, Ellingvåg-Pettersen 1979, Jerpseth 1979, Brickwood 1986), and C) in altered rocks and in lenses and veins formed during the penetration of hydrothermal solutions.

Primary nickel sulphide ore

In some places in the quarry regular, platy, massive sulphide lenses have appeared. The lenses have been up to 15 cm in width and 15-20 m in length. The lense borders were regular, smooth and distinct.

The ore was visibly dominated by coarse-grained **pyrrhotite**, but with some clusters of coarse-grained **chalcopyrite** and scattered, small grains of **pyrite**. Large (up to10 cm long and 3.5 cm wide), gray, idiomorfic crystals of **apatite** crystals were often floating in the sulphides, and, at other places, large (up to 6 cm long and 2 cm wide), black **hornblende** crystals, now almost completely altered to **chlorite** (pseudomorphic crystals). These ores are probably of the classic type of immiscibilty sulphide magma emplaced as ore schoots along fissures in early crystallized silicate magma.

Microscopic study of polished ore sections gave further information: The coarse **pyrrhotite** grains frequently contained distinctive **pentlandite** exsolutions bodies up to 0.1 cm in size. Electron micro probe analyses of the pentlandite gave quite even results, with an average weight-% of 36.7 Ni, 0.7 Co and 30.1 Fe (Table 1, No. 1-2), corrresponding to a formula of $(Ni_{0.53}Co_{0.01}Fe_{0.45})_9S_8$.

The coarse **chalcopyrite** grains in some places contained thin plates or lamellaes (exsolution bodies) of **mackinawite** oriented in three directions. The mackinawite contained Fe, Ni, and Co, but the lamellaes were too thin to give complete analyses. The chalcopyrite also had some tiny exsolution bodies of sphalerite, while large **sphalerite** grains contained a number of minute chalcopyrite exsolution bodies. The scattered **pyrite** crystals show colour zonation, visualizing Ni,Co-zonation.

Hydrothermal Ni-Co minerals

Gersdorffite is the most remarkable and most common hydrothermal Ni-Co mineral at the Valberg quarry. Remarkable in the sense that it has been found as well developed, cubic crystals up to 6 cm

across, and thus ranks among the worlds largest gersdorffite crystals. It has also been found as coarsely crystalline aggregates up to 10-15 cm across. The gersdorffite crystals always occur "frozen" in matrix, and due to their fragile and cleavable properties they usually breaks in parts during blasting or hammering of the rock. Smaller crystals have, however, been collected almost undamaged. Macroscopically gersdorffite is associated with chalcopyrite, microscopically also with cobaltite, siegenite and Ni,Co-bearing pyrite.

The gersdorffite from Valberg seems to have a fairly narrow range in chemical composition. The results of the electron micro probe analyses are shown in Table 1 (No. 3-5), and a compositional plot in the CoAsS-NiAsS-FeAsS system is shown in Fig. 2. Included here is an approximate composition of a 3 cm crystal of gersdorffite, marked G.

The cubic unit cell dimension of gersdorffite (with chemical composition approximately $(Ni_{0.49}Co_{0.16}Fe_{0.33})As_{1.00}S_{1.00}$, marked G in Fig. 2) found by least squares refinement from powder diffraction data is a = 5.6335(2) Å.

Cobaltite more rarely occurs at the Valberg quarry. The mineral has a colour and lustre very similar to gersdorffite. It is therefore difficult to visually distinguish between those two minerals. Gersdorffite, however, has a slightly more greyish hue compared to cobaltite.
Cobaltite has been found as well developed crystals up to 1.1 cm across. The mineral also occurs microscopically as a thin zone around large gersdorffite grains.

Chemical analyses from this zone are shown in Table 1 (No. 6-7), and a compositional plot in the CoAsS-NiAsS-FeAsS system is shown in Fig. 2. Included here is an approximate composition of a 5 mm crystal of cobaltite, marked C.

The cubic unit cell dimension of coarsely crystalline cobaltite (with chemical composition approximately $(Co_{0.68}Ni_{0.19}Fe_{0.13})As_{1.00}S_{1.00}$, marked C in Fig. 2) found by least squares refinement from powder diffraction data is a = 5.5931(4) Å.

Siegenitt is found microscopically as a thin zone outside zones of cobaltite and pyrite around large gersdorffite grains and in contact with chalcopyrite aggregates on the outer side. Analyses are very even, and show a Ni:Co:Fe ratio of approximately 6:2:1 (Table 1, No. 8-10), giving an apparent formula of $(Co_{0.67}Fe_{0.33})Ni_2S_4$.

Millerite is found in small pockets in calcite/dolomite lenses together with calcite crystals and small crystals of quartz, albite and pyrite. The mineral occurs in bunches of tiny needles up to 2,5-3 cm in length. Millerite needles are also found in massive rock/ore, often associated with Ni-bearing pyrite and, more rarely, a little galena. Millerite needles then often occur in sprays. Chalcopyrite aggregates apparently replace millerite. Twin lamellae are observed in a few grains. The millerite is quite pure NiS (Table 1, No. 11-12).

Pyrite as small cubes within chalcopyrite aggregates associated with gersdorffite showed colour zonation on a microcopic scale. The thin more brownish zones turned out to be Ni,Co-enriched zones. Pyrite bricketed aggregates associated with millerite showed a similar Ni,Co-enrichment. A nickel content up to 5 weight-% and a cobalt content up to 3.8 weight-% was measured. Cobalt and nickel occurred in different ratios and different contents. The maximum sum content found of cobalt and nickel was 6.6 weight %.

A thin zone with pyrite between the cobaltite zone and the siegenite zone (see above) contained up to 6.3 weight % nickel, but minor cobalt only (from not detected up to 0.4 weight-%). The electron micro probe analyses of the pyrites are shown in Table 1, No. 13-19.

Conclusions

The original basic/ultrabasic magma was rich in sulphur, iron, nickel, cobalt and phosphate. A liquid immiscibillety between a silicate and a sulphide melt occurred. The sulphide magma crystallized along fissures in already frozen silicate rocks, forming Ni,Co-rich sulphide ore. At a later

stage hydrothrmal solutions penetrated fissures and parts of the gabbroic rocks, altering rocks and forming veins and lenses along fractures by disolving and precipitating minerals. The hydrothermal solutions probably brought with them dissolved material from external sources. The hydrothermal Ni,Co-minerals were, however, probably formed from material leached from pre-existing minerals in the host rocks and the Ni,Co-bearing massive ores.

Present collecting situation

Due to strict safety regulations, private mineral collecting at the Valberg quarry is usually not allowed. Any visit at the site must be approved by the mine management.

Acknowledgement

We greatly appreciate the hospitality, information and samples given by Franzefoss Bruk A/S by mining manager Egil Rundsag and overseer Frode Jørgensen, geologist Ulrik Søvegjarto, and the mineral collectors Vegard Evja, Trond Spilhaug and Aslak Jensen.

Sammendrag

Valberg steinbrudd ble startet i 1913 og har siden vært i mer eller mindre kontinuerlig drift. Nåværende eier, Franzefoss Valberg, overtok driften i 1995. Valberg hyperittkompleks er 2,5 km langt og 1-1,5 km bredt, og består av basiske/ ultrabasiske bergarter, bl.a. olivinhyperitt, hornblendehyperitt, amfibolitt og hornblendeskifer.

Sulfidmineraler opptrer makroskopisk dels som massive sulfidlinser av magmatisk opprinnelse og dels som aksessoriske mineraler i senere dannete hydrotermale årer og omvandlingssoner. *Massiv sulfiderts* består hovedsakelig av pyrrhotitt, chalcopyritt og pyritt. Pyrrhotitt inneholder betydelige mengder pentlanditt som mikroskopiske, uregelmessige eksolusjonskropper. Chalcopyritt inneholder stedvis mikroskopiske eksolusjonskropper av mackinawitt og sphaleritt. *Hydrotermale årer* inneholder gersdorffitt i kubiske krystaller opptil 6 cm i kantlengde, og aggregater opptil 10-15 cm brede. Dette er blant verdens største gersdorffitt-krystaller, men siden krystallene ligger inne i massivt materiale, blir nesten alle krystallene ødelagt ved sprengning eller sleggeslag. Koboltitt, i krystaller opp til 1,1 cm, opptrer nokså sjeldent. Milleritt er funnet som nålformede aggregater og bunter opptil 3 cm i lengde. Det er ved mikroskopiske undersøkelser observert små mengder siegenitt. Hydrotermal pyritt er i likhet med magmatisk pyritt sonert med hensyn til nikkel og kobolt.

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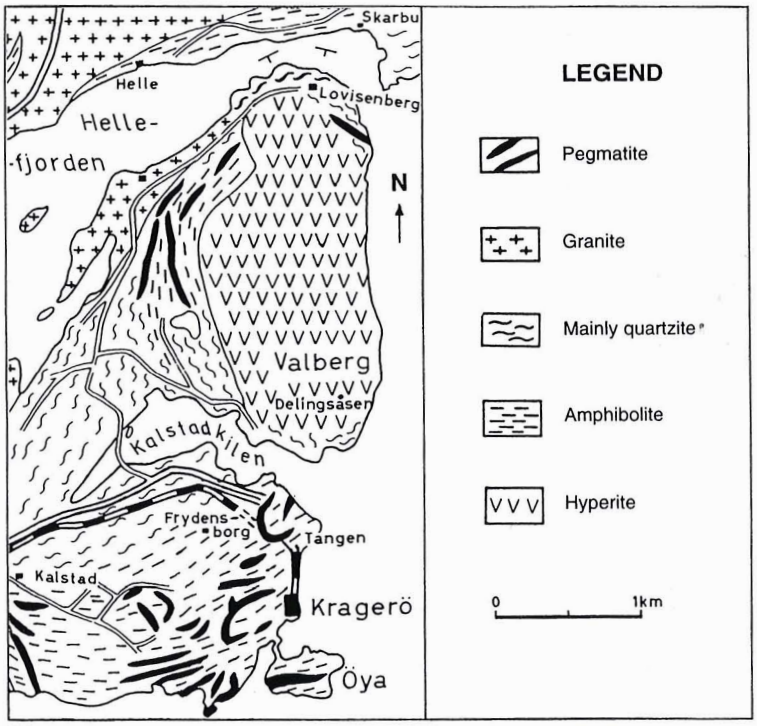

Fig. 1. The geology of Valberg and Kragerø. From Bugge (1965).

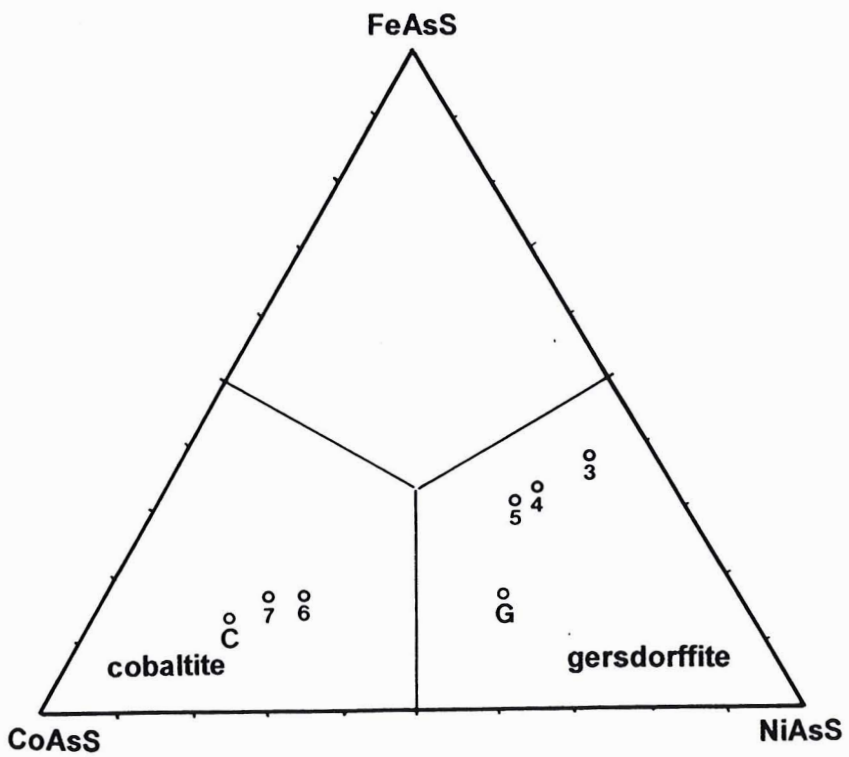

Fig. 2. Compositional plot of cobaltite-gersdorffite$_{ss}$ in the CoAsS-NiAsS-FeAsS system. The numbers refer to the analyses in Table 1. G and C refer to the coarsely crystalline samples of gersdorffite and cobaltite, respectively, used for determination of the unit cell dimentions.

Table 1. Chemical composition (in weight-%) and structural formula (in atoms per fomula unit) of sulphides from the Valberg quarry: pentlandite (1-2), gersdorffite (3-5), cobaltite (6-7), siegenite (8-10), millerite (11-12), pyrite crystal in chalcopyrite (13-16), pyrite as a zone between cobaltite and siegenite (17-18), and pyrite associated with millerite (19).

	1	2	3	4	5	6	7	8	9	10
Ni	37.02	36.38	19.29	17.89	17.15	9.06	7.92	38.57	38.56	38.02
Co	0.77	0.63	3.39	6.99	8.12	20.94	22.64	13.29	12.99	12.24
Fe	29.90	30.30	13.27	10.88	10.84	6.40	6.29	6.10	6.38	7.39
Cu	0.00	0.00	0.00	0.00	0.08	0.00	0.00	0.00	0.00	0.00
Zn	0.02	0.00	0.00	0.00	0.01	0.02	0.04	0.00	0.00	0.00
As	0.01	0.04	46.70	46.71	46.83	44.21	44.95	0.00	0.00	0.03
S	33.45	33.26	19.40	19.16	19.12	20.76	20.54	41.15	41.66	41.78
Total	101.17	100.61	102.06	101.63	102.14	101.39	102.37	99.11	99.59	99.45
				Atoms per formula unit						
Ni	4.87	4.75	0.53	0.49	0.46	0.25	0.21	1.99	1.99	1.97
Co	0.10	0.08	0.09	0.19	0.22	0.57	0.60	0.68	0.67	0.63
Fe	4.08	4.16	0.38	0.32	0.31	0.18	0.18	0.33	0.35	0.40
Cu	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Zn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
As	0.00	0.00	1.00	1.01	1.00	0.95	0.95	0.00	0.00	0.00
S	7.96	7.95	0.97	0.97	0.95	1.04	1.01	3.88	3.93	3.96

	11	12	13	14	15	16	17	18	19
Ni	63.38	63.73	0.00	3.68	4.18	0.41	6.34	5.91	5.05
Co	0.45	0.55	0.00	1.41	2.43	3.85	0.00	0.32	0.24
Fe	1.35	1.35	46.33	40.16	41.14	42.84	40.26	41.00	41.84
Cu	0.00	0.00	0.20	0.00	0.13	0.00	0.00	0.00	0.01
Zn	0.01	0.00	0.00	0.06	0.00	0.00	0.04	0.05	0.00
As	0.10	0.00	0.00	0.00	0.02	0.12	0.00	0.06	0.54
S	35.59	35.59	53.90	53.93	53.53	53.37	53.31	53.81	53.28
Total	100.89	101.22	100.43	99.24	101.44	100.59	99.95	101.16	100.95
				Atoms per formula unit					
Ni	0.97	0.97	0.00	0.08	0.08	0.01	0.13	0.12	0.10
Co	0.01	0.01	0.00	0.03	0.05	0.08	0.00	0.00	0.00
Fe	0.02	0.02	1.00	0.89	0.87	0.91	0.87	0.87	0.90
Cu	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Zn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
As	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
S	1.00	0.99	2.02	2.09	1.97	1.98	2.01	2.00	1.99

Appendix 1.

Preliminary list of minerals found at the Valberg quarry, Kragerø. Minerals in brackets indicate unverified species.

Elements
Copper, graphite,

Sulphides
Chalcopyrite, cobaltite, galena, gersdorffite, mackinawite, millerite, molybdenite, pentlandite, pyrite, pyrrhotite, siegenite, sphalerite,
(covellite, bornite, arsenopyrite)

Oxides
Hematite, ilmenite, magnetite, rutile, uraninite, spinel

Carbonates
Ankerite, calcite, dolomite, malachite

Phosphate
Apatite

Arsenates
(Erythrite)

Silicates
Actinolite, albite, allanite, almandine, biotite, clinochlore, cordierite, dravite, epidote, heulandite, hornblende, illite, laumontite, montmorillonite, muscovite, natrolite, palygorskite, phlogopite, plagioclase, prehnite, pumpellyite-(Mg), quartz, scapolite [= marialite], stilbite, stilpnomelane, titanite,
(apophyllite, diopside, kaolinite, schörl, serpentine, talc)