GEOLOGY AND ORE

Exploration and Mining in Greenland

The Blyklippen lead-zinc mine at Mesters Vig, East Greenland

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In 1948, galena-bearing quartz veins were discovered on the west coast of Mesters Vig by members of the Danish Expeditions to East Greenland (Lauge Koch Expeditions). This initial discovery led ultimately to mining at nearby Blyklippen, where a total of 545,000 tons of ore with 9.3% Pb and 9.9% Zn was produced between 1956 and 1962. Teams from Koch's expeditions had been in the area in 1936-1938 but acting on instructions from Danish Prime Minister Th. Stauning, finding of valuable metals was not permitted because of the political situation in Europe at that time.

Aerial view of Blyklippen from the south-east, August 2001. The open pit and the site of the mining camp are arrowed. Photo: GEUS.

Mesters Vig is a small branch of Kong Oscar Fjord on the east coast of Greenland at c. 72°10´N lat., 270 km north of the nearest Greenlandic settlement Illoqqortoormiut (Scoresbysund). It was named after the chief engineer ('mester') of a Swedish expedition, the first Europeans to sail these waters in 1899. The Mesters Vig area consists of up to 1100 m high mountains intersected by valleys partly covered by dwarf shrub heath. The climate is arctic with an annual average temperature of ÷10°C, snow cover for 9-10 months and permafrost to a depth of about 100 m, and with two month's polar night. Due to extensive sea ice, the summer sailing period is restricted to 4-8 weeks with ice-strengthened ships.

Geology

The Mesters Vig area is underlain by Carboniferous, Permian and Triassic sediments intruded by Palaeogene dolerite sills and dykes. Towards the south, the area is bordered by the Palaeogene Werner Bjerge alkaline complex, in the west, it is bordered by a major regional fault beyond which is the Caledonian fold belt.

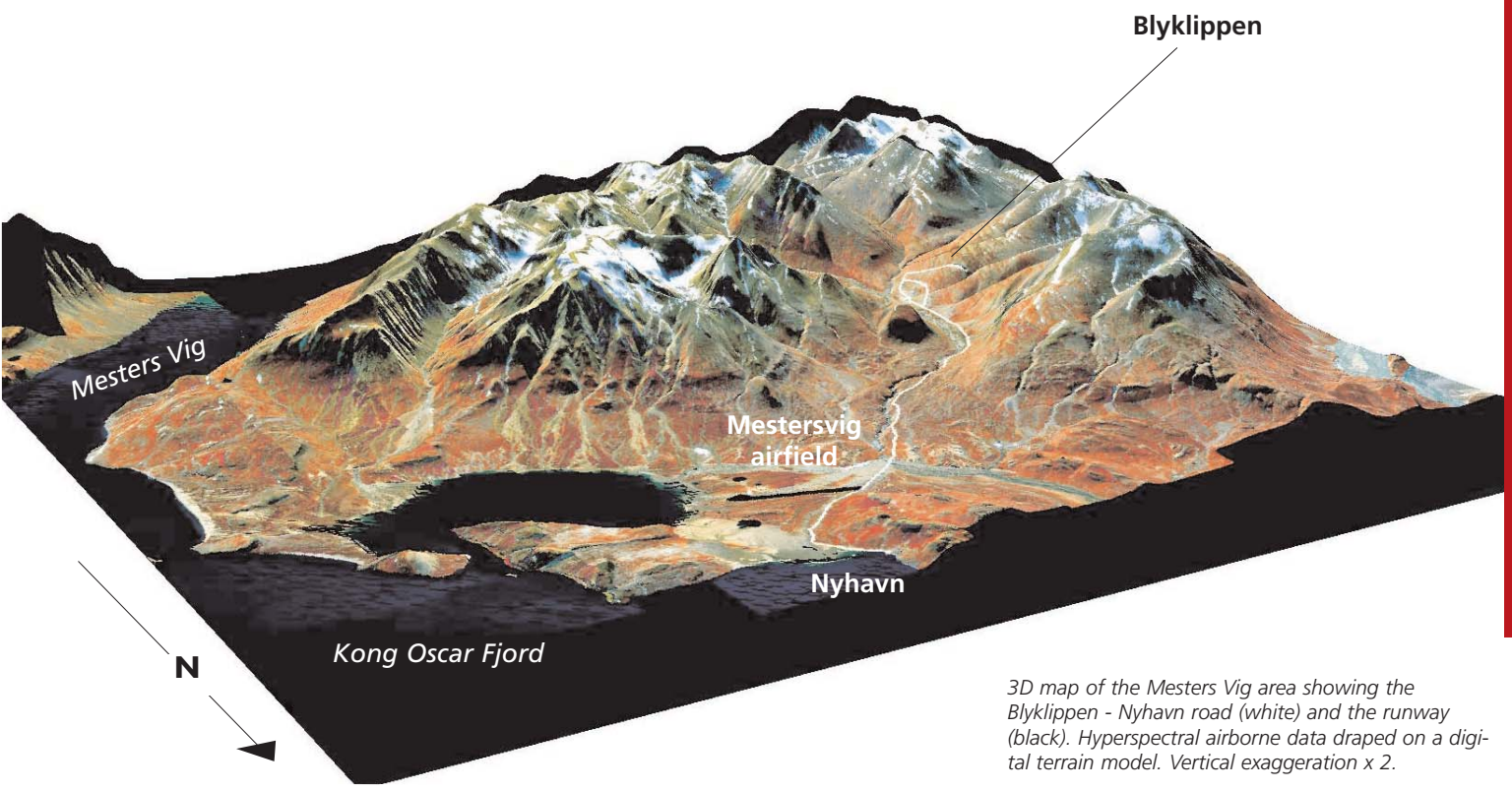
Most of the area is made up of continental syn-rift deposits of Late Carboniferous to Early Permian age deposited in an N-S-orientated system of west-tilted half grabens. They form a 2-3 km thick unit of alluvial and fluvial sediments dominated by cross-bedded arkosic sandstones and conglomerates, with subordinate intercalations of lacustrine, calcareous and carbonaceous shales and mudstones with plant and fish fossils. This sequence dips about 20° towards the north and east and it is unconformably overlain by 250 m of Upper Permian marine sediments comprising a basal conglomerate, marginal marine evaporites and carbonates, bituminous shale and a variegated clastic unit. Lower Triassic silty shales overlie the Upper Permian sequence. The entire sedimentary package is intruded by Palaeogene dolerite sills up to 100 m thick, two sets of dolerite dykes striking NNW and NNE, and lamprophyric dykes.

A pre-Upper Permian, 15-20 km-long, anticlinal fold structure occurs along Mesters Vig and Deltadal. Faulting is widespread with the so-called Mesters Vig Graben as the most conspicuous structure. This graben is 4 km wide and 12 km long and bordered by normal faults orientated NNW-SSE. Another dominant fault orientation is N-S. Upper Permian and Triassic sediments preserved inside the graben are down faulted c. 1000 m. It is evident that faulting has taken place at different times because displacement of the Upper Permian sediments is greater than that of the Palaeogene sills.

The Mesters Vig Pb-Zn veins

Fault-controlled epithermal lead-zinc veins are abundant over some 300 km^2 in the Mesters Vig area. Two major vein zones are associated with the border faults of the Mesters Vig Graben but other veins occur outside the graben.

The Sortebjerg-Blyklippen vein zone forms a discontinuous vein system 15 km long along the western border fault of the graben. At Sortebjerg, five outcrops occur over a distance of 4 km, each being a silicified, quartz-vein zone orientated 150°/80°E, 20-200 m long and up to 20 m wide. Galena and sphalerite occur as



3D map of the Mesters Vig area showing the Blyklippen - Nyhavn road (white) and the runway (black). Hyperspectral airborne data draped on a digital terrain model. Vertical exaggeration x 2.

irregularly distributed pods and lenses which are generally concentrated along the hanging wall. The largest lens consisting of massive galena is 13 m long and 0.75 m wide. Based on a few diamond drill holes along one of the outcrops, a resource of 220,000 tons with 9.3% Zn, 2.1% Pb and 0.7% Cu has been indicated over a length of 250 m. *The Deltadal - Rungsted Elv vein zone* is a discontinuous, 8 km-long vein system along the eastern border fault of the graben. It hosts 150°/80°W-orientated, strongly silicified and quartz-veined zones up to 50 m wide with lenses of massive galena up to 0.3 m thick. Metal concentrations in mineralised vein intervals, as indicated by 10 m chip sample profiles, average about 4.2% Pb, 0.5% Zn and 0.3% Cu.

Vein mineralogy is dominated by quartz, baryte, galena and sphalerite, with minor calcite, pyrite and chalcopyrite, and traces of tetrahedrite. Sphalerite and galena occur as massive, coarse-grained lenses up to m-size but the minerals are rarely found together. Sphalerite and quartz often display rhythmic growth. The Pb/Ag ratio varies from 2,000 to 10,000 and there is a tendency for the ratio to decrease with increasing copper content. In some of the veins, there are indications of a vertical zonation involving upwards enrichments from quartz to baryte and from copper through zinc to lead, but no regional zonational pattern is evident. Wall-rock alteration of the Permo-Carboniferous sandstones comprises silicification and kaolinisation. Where the veins intersect Upper Permian sediments, extensive barytisation and silicification of the lowermost limestone unit may occur. In Oksedal south of Mesters Vig, the lower 5-9 m of the limestone sequence along a quartz vein is replaced by alternating mm-thick layers of grey and white baryte ('zebra-baryte') over a distance of up to 150 m from the vein. A resource of some 330,000 tons with 95% baryte has been indicated in a near-surface part of this area by a few drill holes.

The paragenetic sequence for the Mesters Vig veins has three phases. The initial and main mineralising phase comprises quartz

"Gustav Holm", Lauge Koch Expedition's ship, on its way to Mesters Vig 1949. Photo: Fin Kløve Lassen, 'Blyminen i Mesters Vig', published by Atuagkat, 2005.

Icelandic ponies used for transportation at Mesters Vig in 1949. Photo: Fin Kløve Lassen, 'Blyminen i Mesters Vig', published by Atuagkat, 2005.

veining with major concentrations of sphalerite and galena, after which shearing and brecciation took place. The second phase embraces silicification and quartz cementing of the breccias and formation of baryte-bearing quartz veinlets, with minor amounts of sphalerite and galena, which intersect the main mineralisation. Finally, calcite veinlets were formed. The age of all mineralisation is assumed to be Palaeogene with the mineralising phases correlated with the intrusion of the Werner Bjerge alkaline complex. However, it should be noted that quartz veins have not been observed in rocks younger than Upper Permian and a Late Permian age for especially the early phase of mineralisation cannot be excluded.

Blyklippen Pb-Zn deposit

The Blyklippen lead-zinc deposit ('The Lead Rock') that is now exhausted, is part of the Sortebjerg-Blyklippen vein zone. It is the only deposit in East Greenland that has been mined. The original deposit formed a sulphide lens at 300 m to 490 m a.s.l. within a major quartz-vein zone orientated 150°/40°-90°E and developed

Typical Mesters Vig vein with brown sphalerite and white quartz in Permo-Carboniferous sandstone, Sortebjerg. Photo: GEUS.

along a normal fault in Permo-Carboniferous sandstones. The 1000 m long zone is cut at the northern end by a transverse fault (040°/50° SE) and it gradually disappears to the south. Due to pinch and swell, its thickness varies from a few metres up to 50 m. The quartz-vein zone is sharply delineated to the east (along the hanging wall) by the fault. The western limit (the footwall) is less sharp, being a transitional zone with decreasing intensity of quartz veining and kaolinisation. Small-scale, late-stage, west-dipping faults intersect and brecciate the main quartz-vein zone. The main sulphide lens occurred close to the footwall of the zone within a swell structure at the northern end of the vein. There is no correlation between thickness of the quartz-vein zone and the sulphide lens.

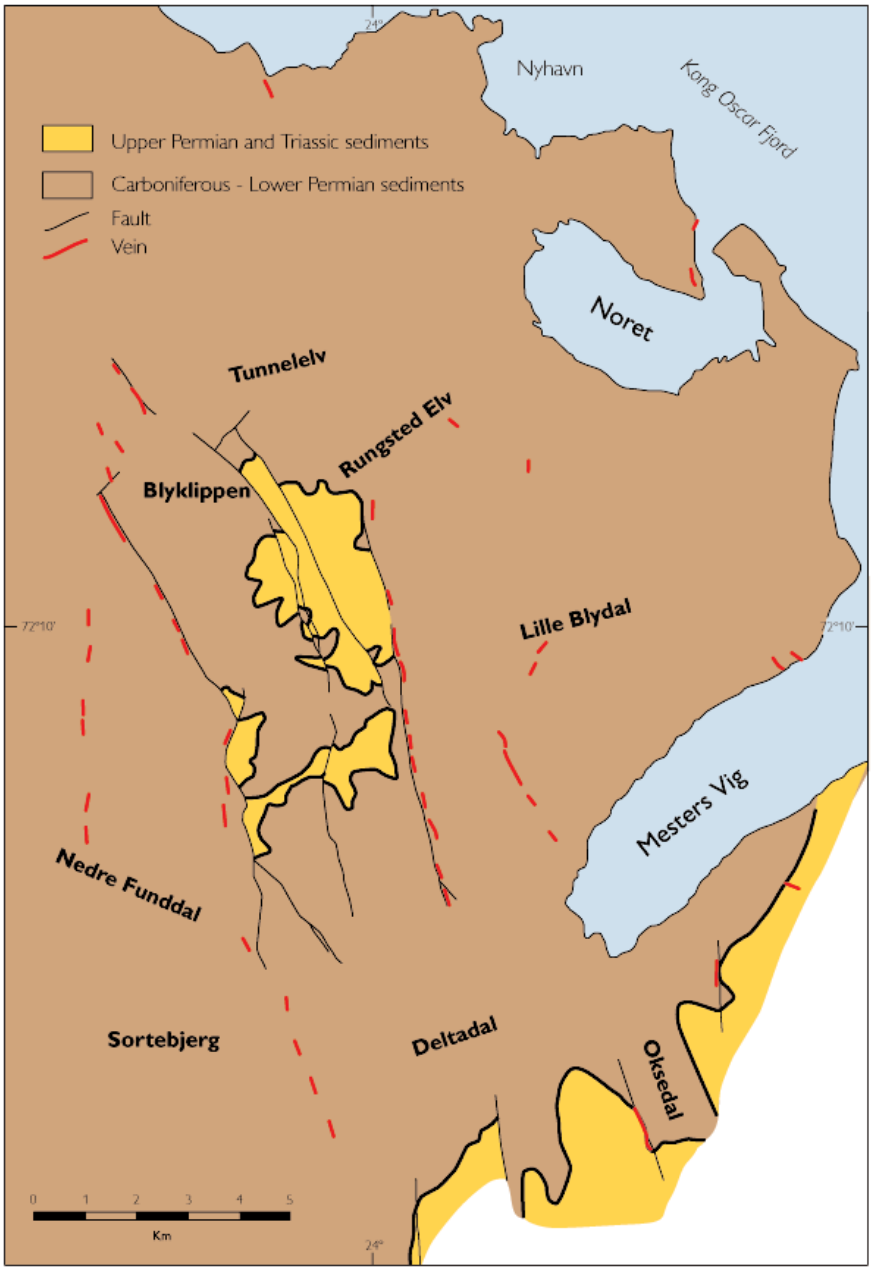
The mined-out sulphide lens was 2-10 m thick, 300 m long and 160 m high. It consisted of 65% quartz, 15% sphalerite, 10% galena, 5-10% baryte with trace amounts of pyrite, chalcopyrite and tetrahedrite. Copper and silver contents were 120 ppm and 15 ppm, respectively. Across the lens galena- and sphalerite-enriched sections alternated. In general, sphalerite was enriched in the lower and the northern part of the lens whereas galena was enriched near the surface and in the southern part. The 040° transverse fault delimiting the sulphide lens to the north, hosts sheared and mylonitised ore lenses in the fault plane. The age of the faulting

Typical lead and zinc ores from Blyklippen: Top: Grey galena and white quartz. Bottom: Brown sphalerite and white quartz. Sample length: 15 cm. Photo: GEUS.

relative to the ore has been a matter of debate: either the transverse fault is pre-ore and thus the channel for the mineralising solutions, or it post-dates ore formation thus indicating the existence of a blind, transposed part of the ore body.

Nordisk Mineselskab A/S

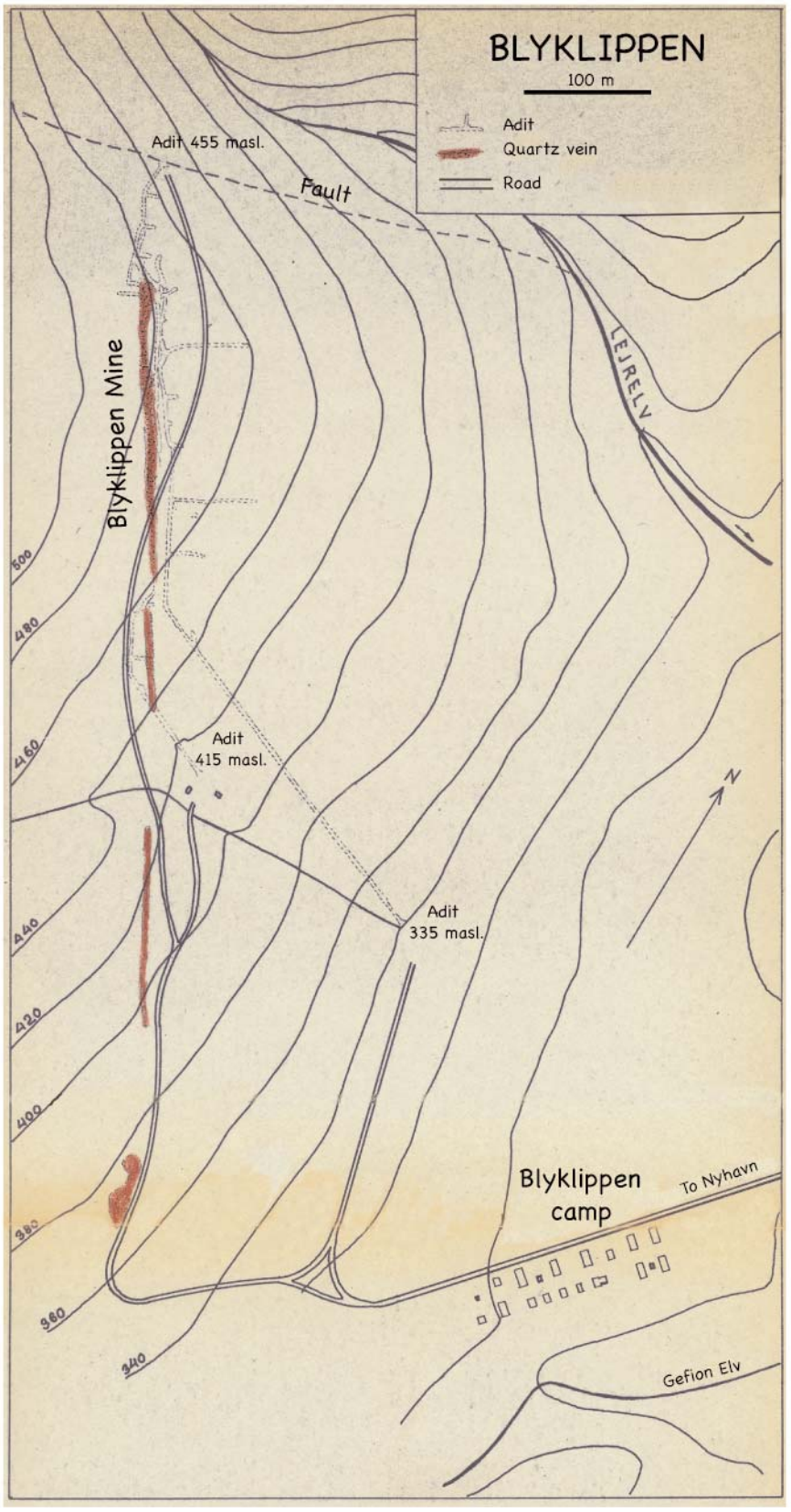
The initial lead discovery in 1948 stimulated investigations in 1949 that led to the finding of most of the lead-zinc-bearing veins presently known, including the two most important occurrences, Blyklippen and Sortebjerg. Detailed mapping and deposit investigations were undertaken at Blyklippen by the Lauge Koch Expeditions in summers 1950 and 1951. In 1952, a new company, Nordisk Mineselskab A/S (Northern Mining Company Ltd. or 'Nordmine'), was established to continue investigations and to mine the Blyklippen deposit. The share capital was 15 million DKK, the owners being the Danish State (27½%), private Danish enterprises (27½%), two Swedish companies Boliden Mining Co. (15%) and Store Kobberbergs AB (15%) and Ventures Ltd. of Canada (15%). As no mining law existed for Greenland at that time, the company was granted the rights by a special law for



Simplified geological map of the Mesters Vig area showing the distribution of hydrothermal veins. Modified from Witzig (1954).

mineral exploration and mining for 50 years in a c. 100,000 km² concession area in East Greenland between 70° and 74½°N lat.

The company conducted year round investigations between 1952 and 1954 from a new camp connected to the Nyhavn harbour site by a 12 km road, and serviced by a new airport with a 1,800 x 45 m gravel runway. This airport facility was built and maintained by the Danish State. The deposit was investigated by driving three adits at the 455, 415 and 335 m levels, totalling about 2,500 m, accompanied by surface and underground diamond drilling of 110 holes, totalling c. 5,000 m. Total cost for the investigations was about 29 million DKK. Subsequent calculations showed a resource of 560,000 tons mineable ore with 11.1% Pb and 8.6% Zn. This tonnage was



Map of Blyklippen showing quartz vein outcrops, underground workings and mining camp.

Improvised housing built of beer boxes at Nyhavn. Photo: Niels Pugholm, 'Blyminen i Mesters Vig', published by Atuagkat, 2005.

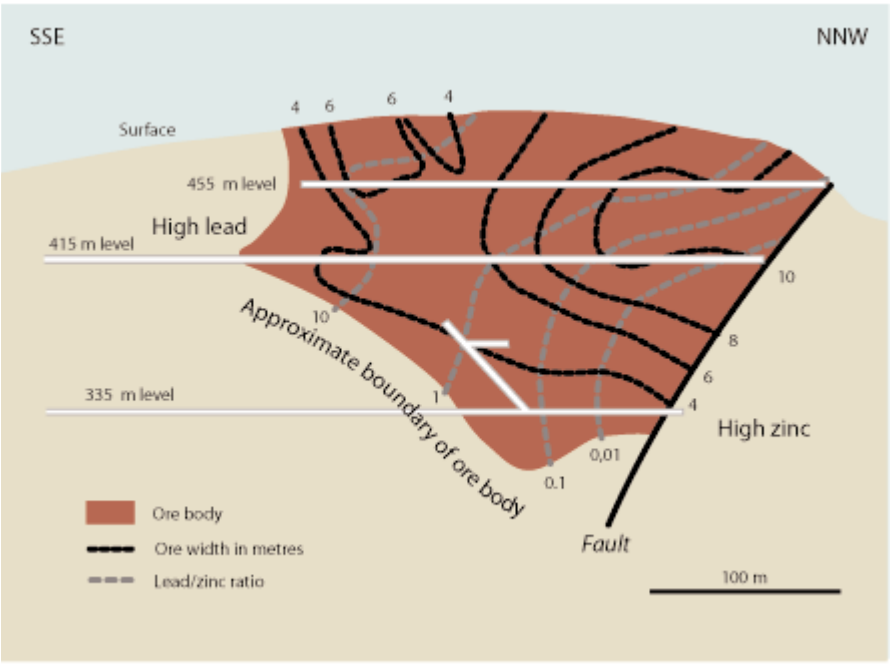
regarded as insufficient for commercial exploitation but the Danish State stepped in with financial support (a loan and a bank guarantee), after which it was decided to proceed with mining and at the same time continue mineral exploration in the hope of finding additional ore. Preparations for mining, including the building of a mill and a shallow water pier at Nyhavn, were carried out between 1954 and 1956, and production started in March 1956. The deposit was exhausted in March 1962. The financial statement after six years of mining showed a total income of 107 million DKK and expenditures of 99 million DKK with 6.5 million DKK used for exploration but with no dividends for the shareholders.

Mining and ore treatment

The mining of the Blyklippen deposit was a pioneer enterprise in a remote, harsh area lacking infrastructure. Due to the severe climate, it was decided to place the mill with all processing facilities (crushing, grinding, flotation, thickeners, filters, drying furnaces), as well as the diesel power plant and air compressors, underground in chambers excavated in the sandstone below the ore body, and below the permafrost. The latter reached a depth of 120 m. The mill was designed for a daily production of 350 tons ore corresponding to an annual production (10 month) of about 90,000 tons.

Mining took place from the three adits at the 335, 415 and 455 m levels by the cut-and-fill method: the width of the stopes being the same as the vein width. The filling material was taken from surface scree in summertime and from the hanging wall. The uppermost part of the ore was

mined in open pit during the summer. As rock temperatures were below zero in much of the mine, it was necessary to use pre-heated water for drilling. The broken ore in the cut-and-fill stopes was scraped with 45-inch scrapers to the ore passes and then hauled on the main level, 415 m, in Granby dump cars to an underground crushing plant. This consisted of a jaw crusher and a cone crusher which reduced the ore to <25 mm. The crushed ore was stored in an ore pass raise with a 24-hour mill capacity. From here, it was led to a conventional type flotation plant installed in a 65 m-long and 7 m-wide room inclined 18° for gravity flow with two mills for grinding highest up. Eleven double cells were used for both lead and zinc flotation, the recovery being 95% for lead and 92% for zinc. The tailings with 0.15% Pb and 0.75% Zn were discharged to the surface where they ended up in the local stream bed. Water was pumped from a local stream and during winter water shortage could be a problem. The concentrates were pumped on to filtering and drying furnaces, heated by the exhaust gases from the diesel engines. The diesel power plant with four 350 kw generators was installed in a 60 m-long rock hall. At first, the concentrate was packed in 60 kg canvas sacks, later it was compressed into large blocks containing 4 tons Pb-concentrate or 2.5 tons Zn-concentrate each. The concentrate was then trucked to the pier at Nyhavn and stored in open air on pallets, to await transport on barges to ships in the sailing period.



Longitudinal section of the Blyklippen ore body. Modified from Harpøth et al. (1986).

Miners ready to go underground. Photo: Jørgen Christensen, 'Blyminen i Mesters Vig', published by Atuagkat, 2005.

Lead and zinc concentrate at Nyhavn ready for shipment. Photo: Fin Kløve Lassen, 'Blyminen i Mesters Vig', published by Atuagkat, 2005.

The Blyklippen camp

The mining camp (Minebyen) comprised 22 wooden buildings including accommodation and administrative barracks, workshops, warehouses, as well as a hospital, chemical laboratory and a canteen. Most buildings were erected on poles to avoid damage from permafrost that during surface thawing in summer has the potential to crack foundations. The site also hosted oil tanks and a short airstrip for the company's STOL aeroplane that was used for local transportation. The mine operated 10 months a year, February to November, with a staff of about 90 persons, mainly Danes and Swedes. Twice as many were employed in the summer months. There was no mining in the two months of polar night, December and January, and this period was used for holidays and repairs. Access for personnel mainly on 10 month contracts was by aeroplane between Mestersvig airfield and Reykjavik, Iceland, the nearest international airport. Supplies had to be shipped in and concentrate shipped out during the 4-8-week ice-free period in August and September.

After mine closure, the diesel generators were removed from their underground chamber but the remaining plant was left within the mountain. In 1974, the best preserved barracks of the mining camp were transferred to a new exploration base camp at Nyhavn and in 1983, all but two of the remaining buildings were burned as part of a cleaning up agreement with Greenlandic/Danish authorities.

Ongoing exploration

Simultaneously with the investigations and mining at Blyklippen, summer exploration was performed in Nordisk Mineselskab's concession area. After 1958, the work concentrated on a major molybdenum occurrence at Malmbjerg, some 25 km south of Blyklippen, and up to 1962 comprehensive investigations in various joint ventures included 1329 m drifting and *c.* 22,000 m diamond drilling. However, feasibility studies showed that the indicated resource of 119 million tons with 0.25% MoS_2 was not profitable given the molybdenum price of the time, and it was decided to resume the regional mineral exploration while waiting for a better molybdenum market price. Mineral exploration was carried out in the period 1968-1984 and a large and diversified number of new mineral occurrences were found and investigated. However, the company

Concentrate production:

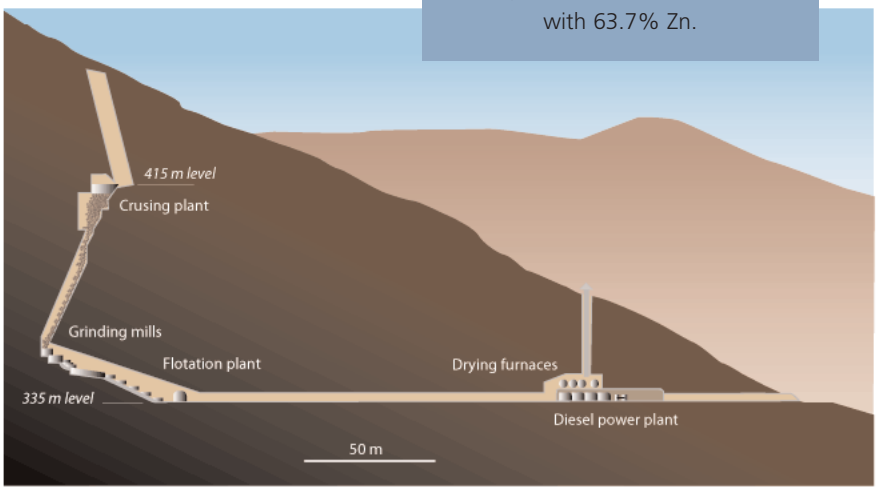
58,500 tons Pb-concentrate with 82.7% Pb and 115 ppm Ag.

74,600 tons Zn-concentrate with 63.7% Zn.

did not succeed in bringing any into production. In 1984, mineral exploration was abandoned and effort was concentrated in a joint venture exploring for oil in Jameson Land to the south. This ceased in 1990 without tangible results and in the following year the company was liquidated.

Pollution and environmental monitoring

At the time the Blyklippen deposit was mined, environmental issues were not of particularly high priority. The first comprehensive environmental studies were initiated in 1979 and high levels of lead, zinc and cadmium were documented in water and sediments of the local stream, Tunnelelv. It was also shown that beach sand, seaweed and sculpins from Kong Oscar Fjord were affected by pollution from the former mine. Later investigations (1996) have shown a marked decrease in the marine pollution. The main sources of the pollution are the tailings in the streambed at the foot of Blyklippen, and the Nyhavn harbour area. In 1979, 85% of the original *c.* 411,000 tons tailings had been washed out into Tunnelelv. The distribution of zinc along the stream was clearly demonstrated by a pollution monitoring project in 2000-2001 using airborne hyperspectral data. In Nyhavn, spilling had occurred when the concentrate sacks were loaded on barges for transport to ships, and on several occasions whole barge loads of canvas sacks with concentrate were dropped accidentally into the sea.



Schematic section through Blyklippen showing the processing plants.

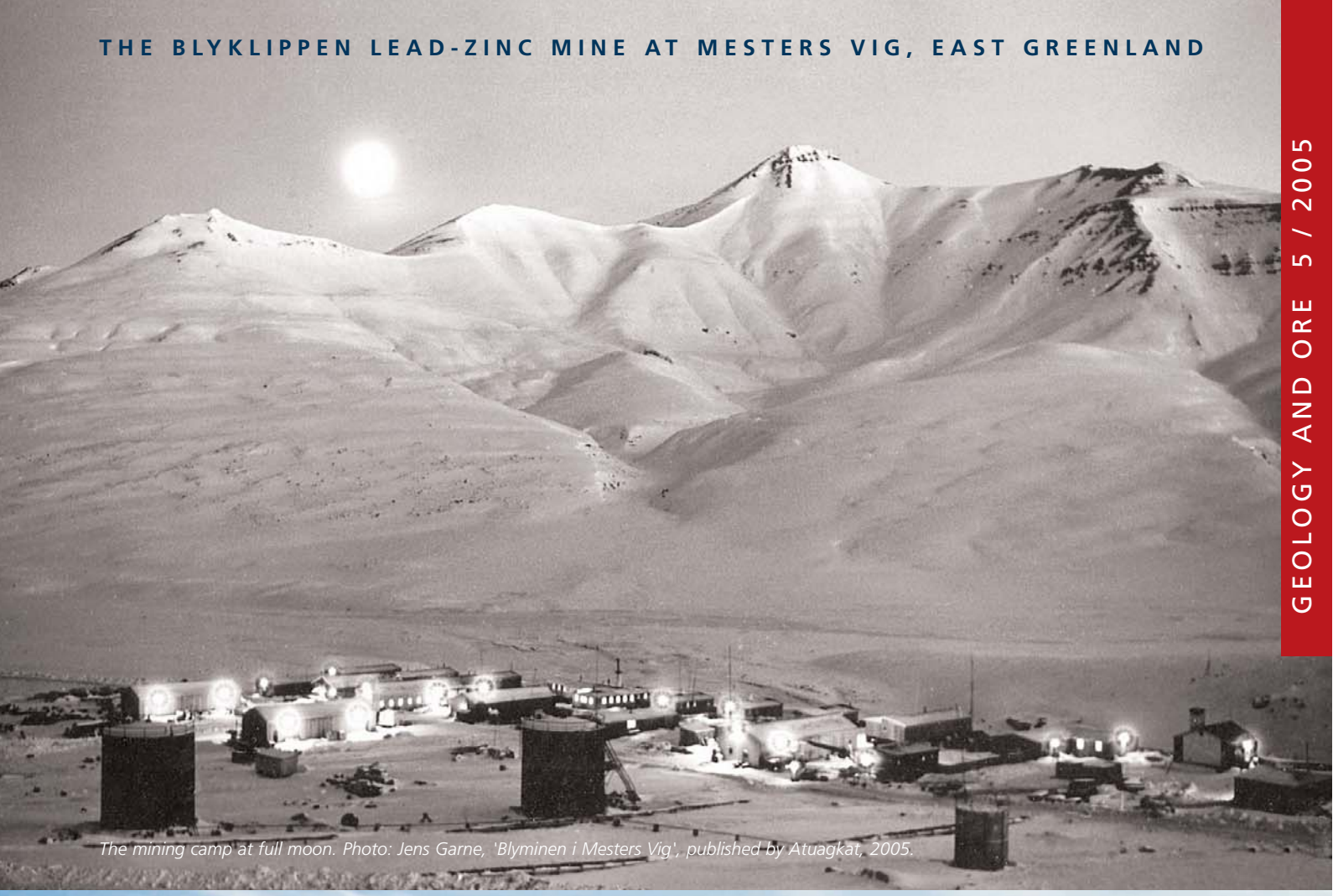
The flotation plant located underground in a 67 x 7 m chamber. Lead and zinc cells are on opposing sides with eleven cells in each circuit. Photo: Bent Sørensen, 'Blyminen i Mesters Vig', published by Atuagkat, 2005.

Diesel power plant installed in a 60 m-long rock hall. Photo: Bent Sørensen, 'Blyminen i Mesters Vig', published by Atuagkat, 2005.

Drilling. Photo: GEUS.

Driller. Photo: GEUS.

Miner. Photo: Jørgen Christensen, 'Blyminen i Mesters Vig', published by Atuagkat, 2005.



The mining camp at full moon. Photo: Jens Garne, 'Blyminen i Mesters Vig', published by Atuagkat, 2005.

View to the east from Blyklippen with remnants of the mining camp to the right and white tailings to the left. The three fuel tanks are also visible in the upper scene. August 2005. Photo: GEUS.

Annual ore production from the Blyklippen lead-zinc deposit

Period (1/10-30/9)	Tonnage	Lead (%)	Zinc (%)
1955-1956	45,000	8.2	10.5
1956-1957	87,400	8.5	10.7
1957-1958	90,200	10.0	8.0
1958-1959	92,500	12.0	10.0
1959-1960	86,000	8.0	12.0
1960-1961	101,500	10.7	8.7
1961-1962	41,800	3.8	10.3
Total	544,600	9.3	9.9

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Sikorsky S 51 helicopter used in mineral exploration 1956. Lauge Koch is in the foreground to the right. Photo: GEUS Archive.

Front cover photograph:

Driller at the 415 m level in the Blyklippen mine. Photo: GEUS.

Bureau of Minerals and Petroleum (BMP)
Government of Greenland
P.O. Box 930
DK-3900 Nuuk
Greenland

Tel: (+299) 34 68 00
Fax.: (+299) 32 43 02
E-mail: bmp@gh.gl
Internet: www.bmp.gl

G E U S

Geological Survey of Denmark and Greenland (GEUS)
Øster Voldgade 10
DK-1350 Copenhagen K
Denmark

Tel: (+45) 38 14 20 00
Fax.: (+45) 38 14 20 50
E-mail: geus@geus.dk
Internet: www.geus.dk

Author:
Bjørn Thomassen, GEUS

Editor:
Karsten Secher, GEUS

Graphic Production:
Henrik Klinge Pedersen, GEUS

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