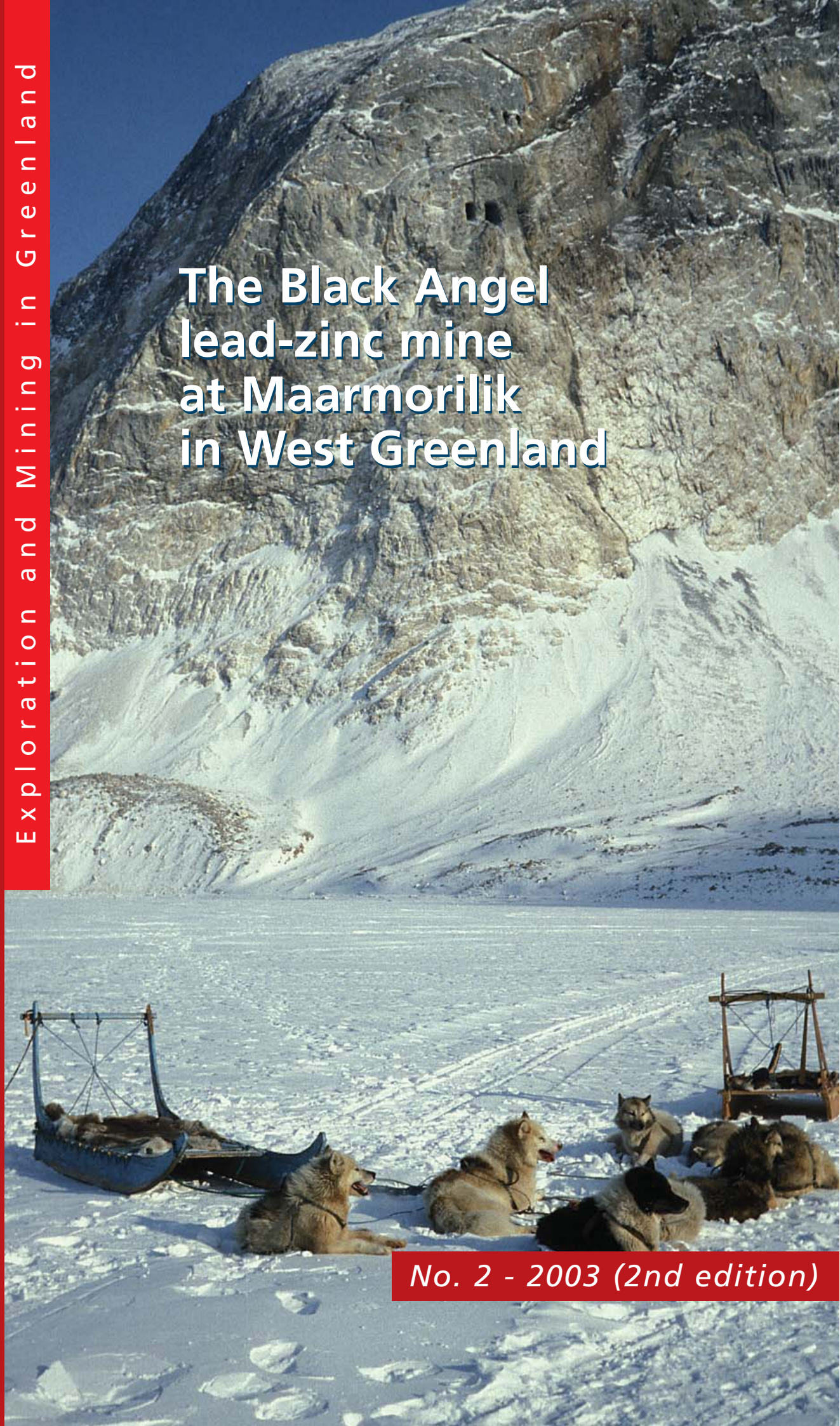
GEOLOGY AND ORE

Exploration and Mining in Greenland

The Black Angel lead-zinc mine at Maarmorilik in West Greenland



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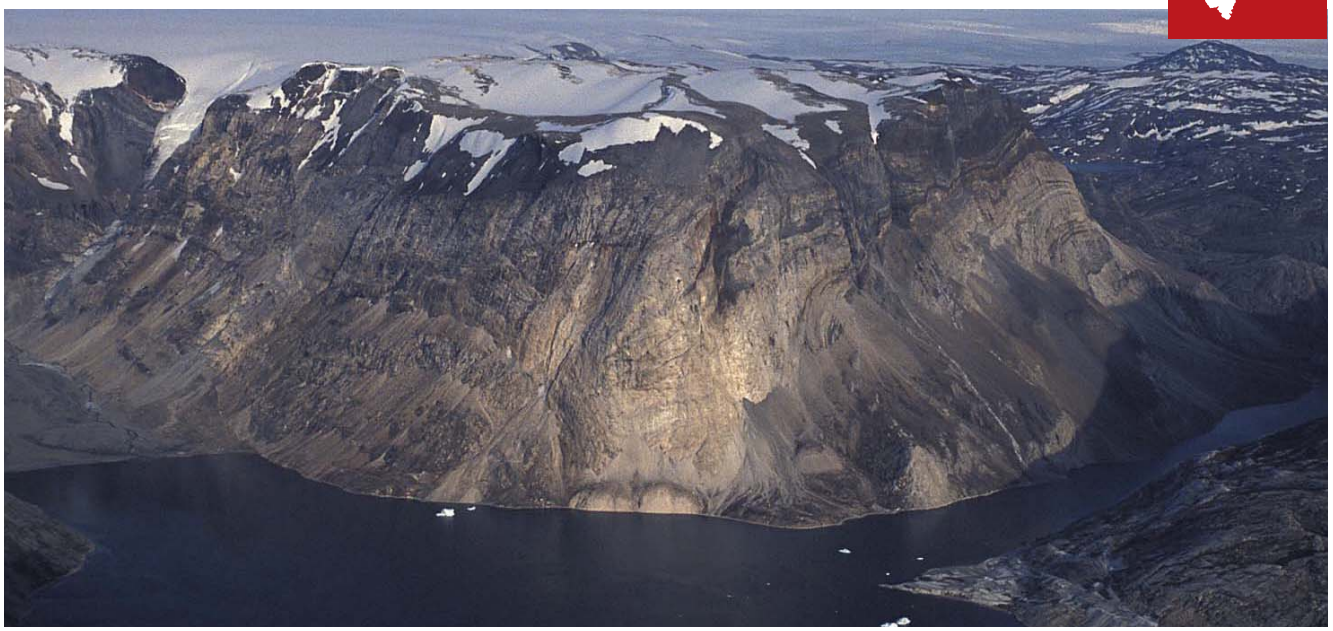
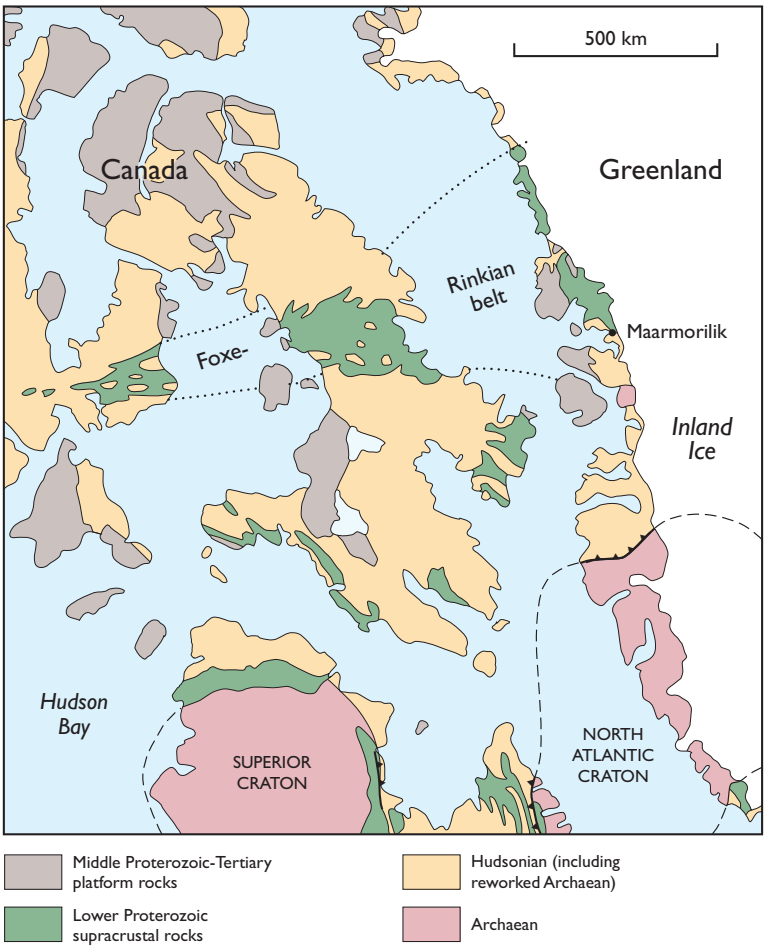


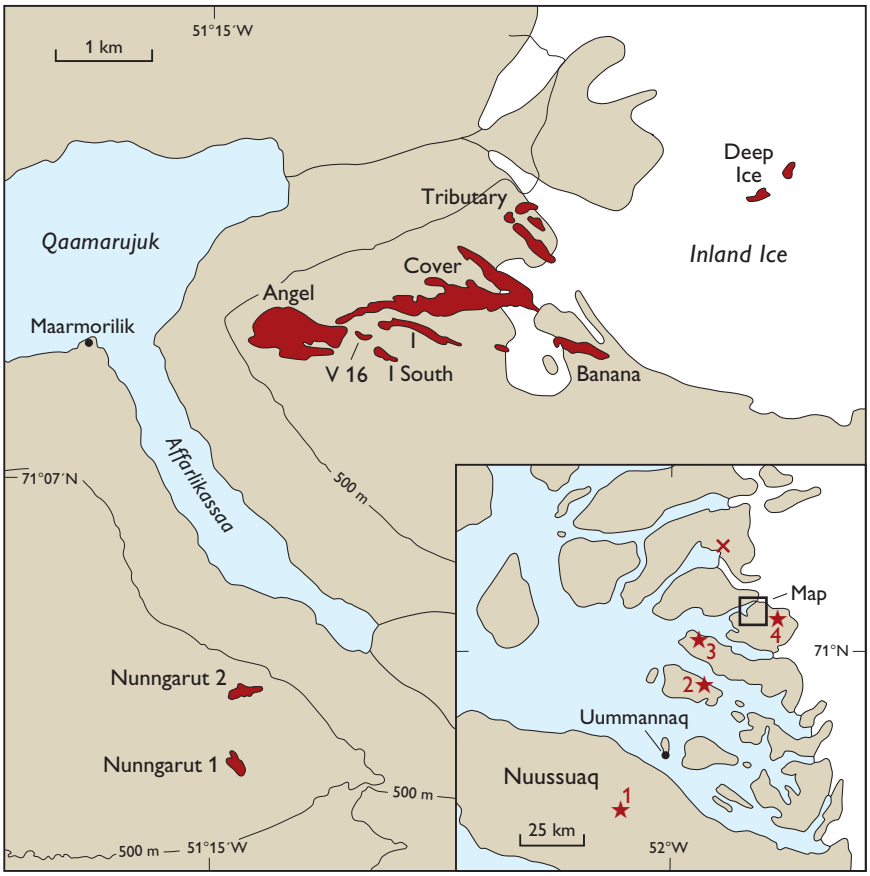
View from north-west of the Angel mountain with the Greenland Inland Ice in the background. The former mining town of Maarmorilik was situated on the peninsula to the right. Summer 1992.

The Black Angel mine took its name from a pelite outcrop that forms a dark angel-like figure on a precipitous cliff face of marble above Affarlikassaa fjord. The mineralised zone actually crops out just above the angel figure about 700 m above fjord level. The 1100 m high Angel mountain is situated at the margin of the Greenland ice cap at 71°N lat. on the west coast of Greenland, about 500 km north of the Arctic Circle, where there is two months of winter darkness. The peninsula across the fjord housed the mining camp, concentrator and all services and received its name Maarmorilik from a former marble quarry situated there from the 1930s. The only access to the mine from these facilities was by two aerial tramways.

The Black Angel deposit comprised ten ore bodies totalling 13.6 million tons grading 12.3% Zn, 4.0% Pb and 29 ppm Ag. Of these 11.2 million tons were extracted in the period 1973–90. The mining operations ceased when the extractable ore reserves were exhausted, leaving 2.4 million tons of ore tied up in pillars and other areas inaccessible to mining.



Pre-drift map of West Greenland and NE Canada showing the Foxe-Rinkian mobile belt and Maarmorilik. Modified from Grocott & Pulvertaft (1990).



Map of the Maarmorilik area with ore bodies shown in red. Stars in inset map show main prospects of Black Angel type; the cross marks a shale-hosted zinc prospect.

Regional geology

The ores are hosted in the Mârmorilik Formation of the Palaeoproterozoic Karrat Group. This Group belongs to the Foxe–Rinkian mobile belt of NE Canada and central West Greenland, which constitutes a component of the Trans-Hudson Orogen of North America. In Greenland, exposures of the Karrat Group are known over a north–south distance of c. 550 km covering some 10,000 km^2. The Group, that rests unconformably on an Archaean gneiss complex, is intruded by a major 1860 Ma syn-tectonic granite complex and is overlain by Cretaceous–Tertiary sediments and volcanics. The Karrat Group, several kilometres thick, is composed of lower shelf units of carbonates and quartzites, and an upper unit of deep-water turbidites and minor volcanic rocks. The basement and the cover sequence were subjected to several phases of strong folding and thrusting during the Hudsonian orogenesis and variably affected by regional metamorphism.

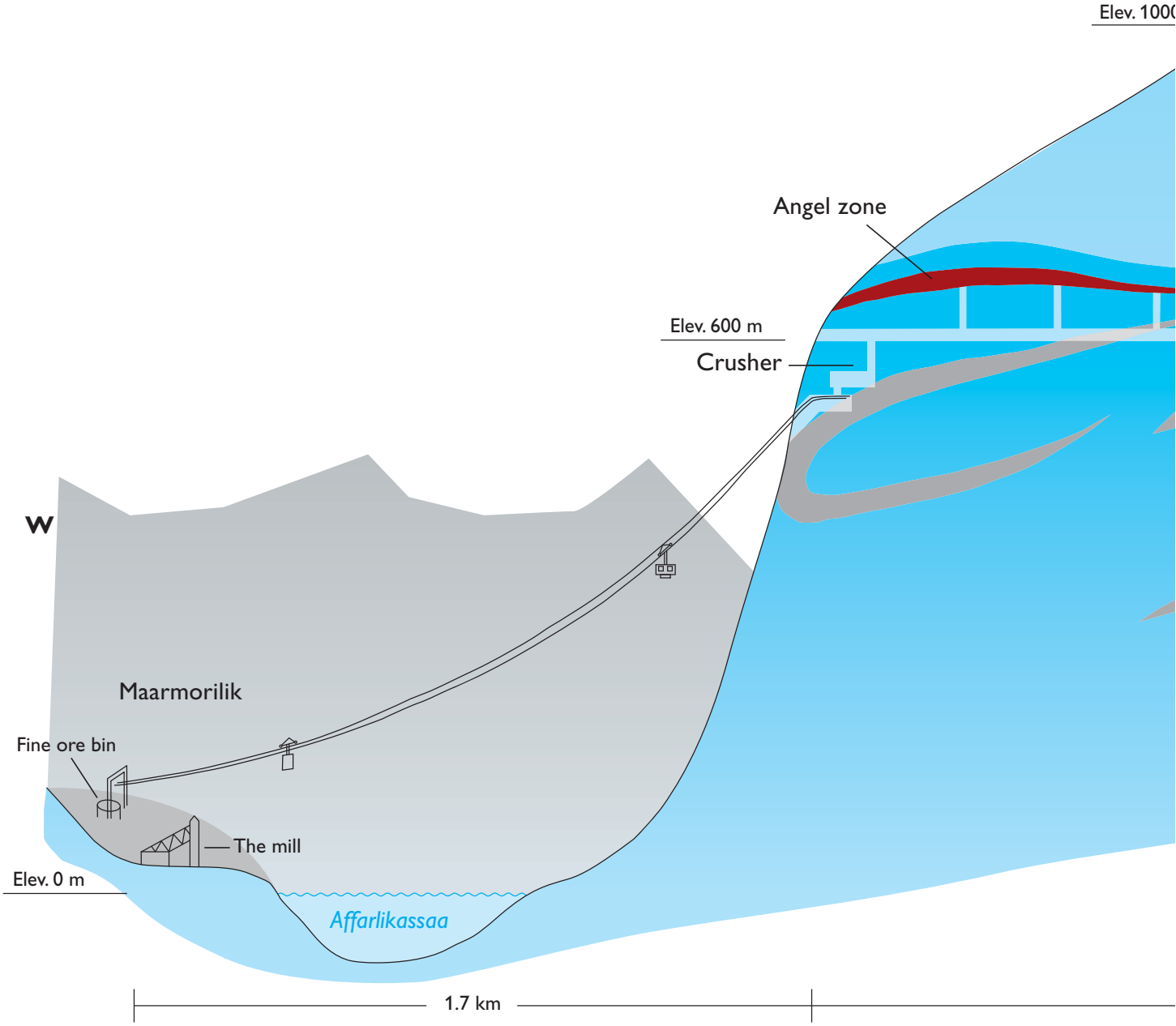
The Mârmorilik Formation consists of calcitic and dolomitic marbles with a basal quartzitic unit and intercalations of anhydrite-bearing marbles and semipelitic schists. The formation is believed to have been deposited on a carbonate shelf in an epicontinental marginal basin c. 2 Ga ago. In the mine area, where the formation has been tectonically thickened to c. 1000 m, three main phases of folding and thrusting have been distinguished, and metamorphism reached upper greenschist facies.

Mineralisation and ore

Carbonate-hosted lead-zinc mineralisation is common in the Mârmorilik Formation and in the mine area stratabound sulphide mineralisation occurs at various levels. The main ore bodies are located 600–700 m a.s.l. in the upper part of the sequence which is dominated by calcitic marble, whereas the satellite ores of Nunngarut to the south are hosted in the lower part of the sequence dominated by dolomite marble. The distribution of ore bodies is controlled by a major z-fold with a 070°-striking near-horizontal axis. The ore forms flat-lying, highly deformed, massive lenses up to 30 m thick, of which ten reach economic size and were mined. The massive

Key economic figures for the Black Angel mine

	Pb concentrate 1000 t	*Zn concentrate 1000 t*	*Gross sales mill. DKK*	*Taxes mill. DKK*	*Net earnings mill. DKK*
1973	8	46	-	-	-4
1974	37	168	336	1	76
1975	32	153	429	6	91
1976	38	143	478	11	97
1977	39	132	387	11	33
1978	42	148	332	2	16
1979	45	151	592	11	128
1980	42	151	520	22	85
1981	38	140	683	63	109
1982	37	141	653	37	71
1983	31	136	754	56	79
1984	26	122	723	33	71
1985	26	119	542	3	-231
1986	24	105	456	-32	55
1987	30	120	440	1	53
1988	34	136	779	59	149
1989	36	129	843	157	184
1990	25	87	507	99	92
1996	-	-	-	16	-
Total	***590***	***2,327***	***9,454***	***556***	***1,154***



ore consists of pyrite, sphalerite and galena, with abundant rotated marble fragments and quartz inclusions. The main accessory ore minerals are pyrrhotite, chalcopyrite, tennantite and arsenopyrite. Cherty horizons and disseminated graphite are quite common in the wall rocks whereas minor fluorite and baryte are restricted to a few of the ore bodies. Various ore tectonites have been distinguished – massive ore, banded ore, porphyroclastic ore or "buck shot ore" and remobilised ore.

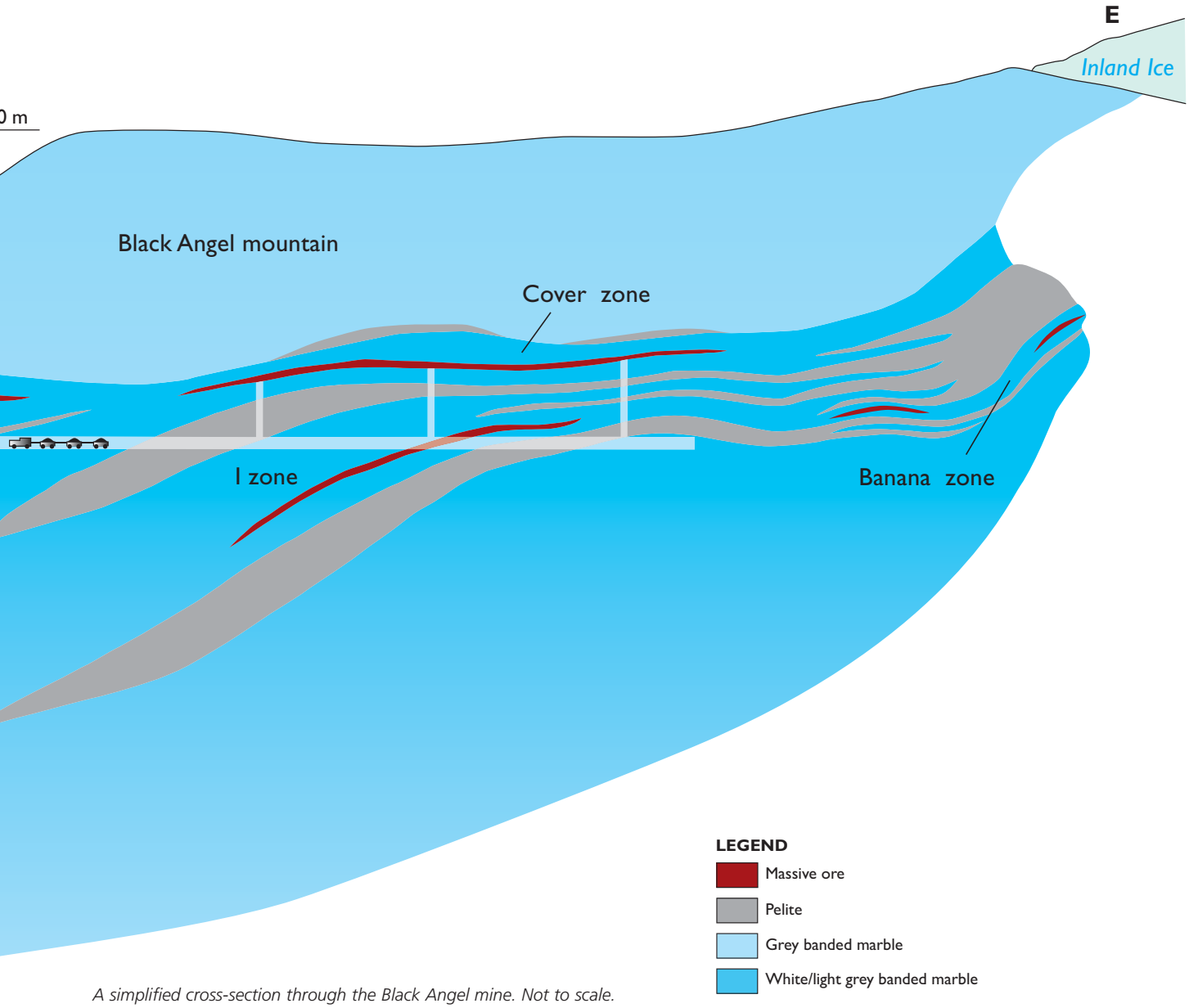
The sulphides are strongly tectonised and metamorphosed and the origin of the ores is uncertain; their present distribution is structurally controlled. It is perhaps most likely that the ores have been formed by sedimentary-exhalative processes on the sea floor (SEDEX-type) but they could also have formed at a later stage (Mississippi Valley-type).

Sphalerite-galena-pyrite occurrences of the Black Angel type are known from marble outcrops in four areas south of Maarmorilik. It appears that this type of sulphide deposit only occur in areas of intense folding and major structural thickening of the marbles.

Zinc mineralisation is also known from the clastic metasediments of the Karrat Group. At one locality north of Maarmorilik, stratabound sphalerite-galena-pyrrhotite mineralisation occurs over a strike-length of some 9 km near the base of the turbidite sequence. The clastic rocks also have a potential for epigenetic 'turbidite–hosted gold deposits'.

History of the mine

Sulphide samples leading to the discovery of the Black Angel deposit were found in connection with marble quarrying in the 1930s and investigated by Danish geologists in the 1930s and 1940s. Commercial investigations including diamond drilling were carried out in the 1960s by a syndicate led by Cominco Ltd. of Canada. In



A simplified cross-section through the Black Angel mine. Not to scale.

1971 the Danish mining company Greenex A/S (established in 1964 and 62.5% owned by Cominco Ltd. through the subsidiary Vestgron Mines Ltd.) obtained a 25-year exploitation concession. Financial terms were favourable at that time, with a 45% resource tax of yearly earnings to be paid after recovery of all pre-production costs and capital investments. The investment of c. 333 mill. DKK had been recovered in 1977, after which the company started to pay concession fees.

Underground exploration in 1971–72 indicated a probable ore reserve of 4.1 million tons grading 15.0% Zn, 5.0% Pb and 28 ppm Ag. Based on this and after a hectic construction period of only 15 months, production started in 1973. During the mine's 17-year lifespan, it was possible to more than triple the original minable reserves. In 1985 a major operating loss was incurred, and due to growing financial losses and dwindling ore reserves, Cominco scheduled Black Angel mine for closure in early 1986. Boliden Mineral AB took over Greenex from Cominco in mid-1986. Boliden managed to keep the mine in operation and ensure sufficient mill throughput for profitable operation until mid-1990. Boliden cut operation costs, which peaked at about 1,700 DKK/t in 1985 by about 30% to 1,200 DKK/t. Among other things, personnel were reduced from 335 at the end of 1984 to around 250 in late 1987. Greenex was liquidated in 1995.

Infrastructure and personnel

The Maarmorilik townsite comprised a storage hall for stockpiles, workshops, harbour and shipping facilities, offices, residences, dining hall, heliport and hangar, as well as medical facilities. Recreational facilities included a radio/TV station, library, sports hall, post office, recreation centre and guest apartments. An 8.4-MW diesel generator station pro-

Mining town seen from the mine portal. Summer 1990.

vided all the power needed for the mine's operations and the community. By desalinating the fjord water through use of waste heat from the diesels, the power plant also produced all the fresh water required. The saline-enriched water from the desalination plant was used as drilling fluid in the mine; strong brine would not freeze when drilling in permafrost. The brine for drilling had to be transported in tanks up to the mine via the aerial tramway, as had all other equipment.

Supplies had to be shipped in and concentrate shipped out during the 6 months ice-free period from June to November. Personnel were ferried by helicopter between the mine and the nearest airport at Ilulissat, 200 km to the south.

The Black Angel mine provided employment opportunities and was important to the local economy. Of the c. 350 employees, up to 44% were Greenlanders, the rest mainly Danes and Swedes. The employees worked a 10-hour shift, with 2 shifts a day, six days a week. Four working months at the mine earned one month's vacation, travel included.

When mining was discontinued, Greenex undertook in 1990–91 an extensive clean-up, partly of buildings, plant, installations etc. and partly targeting the sources of heavy-metal contamination in the area. Final abandonment involved the removal of all surface structures (except two) and the cable ways. Very little infrastructure was removed from the mine.

Exploration in the mine area

In the period 1966–85, 17 major surface drilling programs were conducted around Maarmorilik and a total of 160,000 m was drilled in 400 holes. Most of the drilling was on top of the Angel mountain where it was performed systematically in a grid along the 070° corridor hosting the ores. Much of this was through the ice cap, so that 200–300 m of ice had to be penetrated and then several hundred metres of rock to intersect the target areas. New ore bodies located by surface drilling were investigated further by underground drilling. Primary exploration drilling was also accomplished underground, thus continually adding new tonnage to the ore reserves.

High-grade ore intersections below the ice cap were encountered in three areas. Only the westernmost of these, the Deep Ice zone, was reached by primary development and mined, whereas the two easternmost targets remain. This was partly due to delays created by water inflow due to the lack of permafrost below the ice cap.

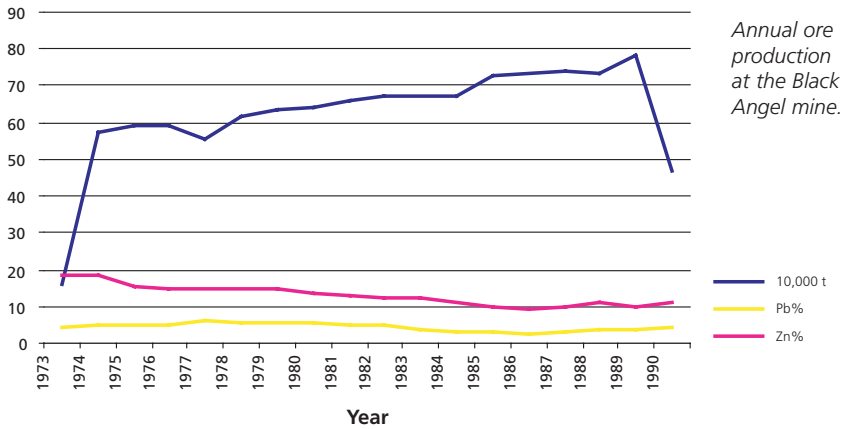
Immediately south of the mine area, several lead-zinc prospects of Black Angel type exist, and farther away, lead-zinc prospects of the same type occur in three areas. Some of these were drill tested but all were rejected as viable prospects by Greenex. However, the zinc prospects in the turbidite basin north of Maarmorilik were found after the mine closure and never drilled.

Car on foot-wall ramp in marble below mined-out stopes in ore dipping to the left.

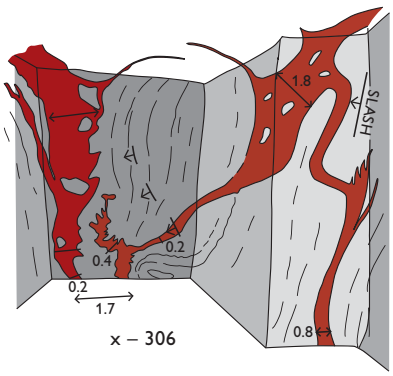
Mining and ore treatment

The main mining equipment was electro-hydraulic 2 and 3 boom jumbos, front-end loaders (scooptrams) and trucks, and the mine housed an underground workshop for repair and maintenance. After drilling by hydraulic jumbos and blasting, the broken ore was hauled by truck to ore passes and then by locomotive haulage to the primary crusher bin just inside the tramway portal. Parts of the Angel zone near the portal were declared off limits to mining to protect major access and transport routes in this area from possible damage from rock instability.

The crushed ore was skipped across the fjord to the ore dressing plant by an aerial tramway with a free span of 1500 m. The tramway had a capacity of 12 skips per hour; skip capacity was 10 tons. One skip was fitted with a cabin to transport personnel. There was a second, smaller tramway for transportation of material.



Annual ore production at the Black Angel mine.



Sketch of thin irregular ore which must be mined selectively.

Ore from Nunngarut was trucked directly to a crusher in Maarmorilik.

The concentrating process was conventional selective flotation of galena and sphalerite using sea water. In most years the recovery was c. 96% for zinc, 90% for lead and 75% for silver. Annual production averaged 135,000 tons of 57.6% zinc concentrate and 35,000 tons of 69.7% lead, 420 ppm silver concentrate. Tailings were discarded through a pipeline

Maarmorilik after the removal of the mining town. Summer 1997.

to the bottom of the adjacent Affarlikassaa fjord. The concentrate was stored under cover and shipped to West European smelters, normally by three shipments between June and November.

For the ore reserve calculations – computerised from the early 1980s – a diluted cut-off grade of 8% combined lead and zinc was used. The ore was mainly mined by the room-and-pillar method; only smaller steep ore bodies were mined by cut-and-fill methods. In thin parts of the ore, selective mining (resuing) was practised. The full face was drilled over, keeping the ore horizon in the top of the face. The lower part of the face containing the waste was blasted and mucked out first. The upper ore section was then mined. Ore bands down to 0.4 m thick were mined by this method.

Tonnage and production of individual ore bodies of the Black Angel mine

	Tonnage			Production			Recovery %	
Ore zone	in 1000 t	Pb%	Zn%	in 1000 t	Pb%	Zn%	Ore	Metal
Angel	6,645	4.8	14.2	5,283	5.0	14.6	83	85
Cover	3,992	2.8	10.5	3,343	3.0	11.0	84	88
Tributary	767	2.0	9.1	683	2.0	9.2	89	90
I	684	4.6	12.3	622	4.7	12.7	91	94
Banana	450	2.9	8.3	335	3.2	9.1	73	82
Nunngarut 1	347	3.8	8.7	327	3.8	8.8	94	95
Deep Ice	316	5.5	14.8	312	5.5	14.9	99	99
Nunngarut 2	197	3.1	7.2	150	3.2	7.5	76	79
I South	119	4.3	11.1	112	4.4	11.2	95	95
V 16	36	1.9	5.3	28	2.0	5.4	79	81
Total	13,557	4.0	12.3	11,196	4.1	12.6	83	85

View of the mining town and the Angel mountain from the west. Summer 1985.

Remnant mining – guided by a careful registration of metal contents in the pillars aiming at maximal metal recovery and supervised by an extensive rock mechanics programme – led to a high metal extraction rate of 85%. In one section of the Angel zone, the stopes were totally backfilled with waste and a number of high-

Typical face to be mined selectively: ore on top of white marble.

grade pillars were recovered by long hole mining from drifts underneath the ore horizon.

All ten ore zones, except the Deep Ice zone, are in permafrost. On the whole, the permafost proved to be an asset for mine stability and it contributed to the high extraction rate. Close to the surface the rock temperature is minus 4°C and this rises by 1°C per 150 m from surface. However, under the ice cap, the temperature rises more rapidly so that the eastern part of the mine is not in permafrost – hence water flows in from fissures in the marble. During development of the access ramp to the Deep Ice zone, drifting was stopped in 1984 for more than a year because of high water inflow. It was finally continued through the water-bearing zone under cover of grout injection and draining of the water.

Pollution and environmental monitoring

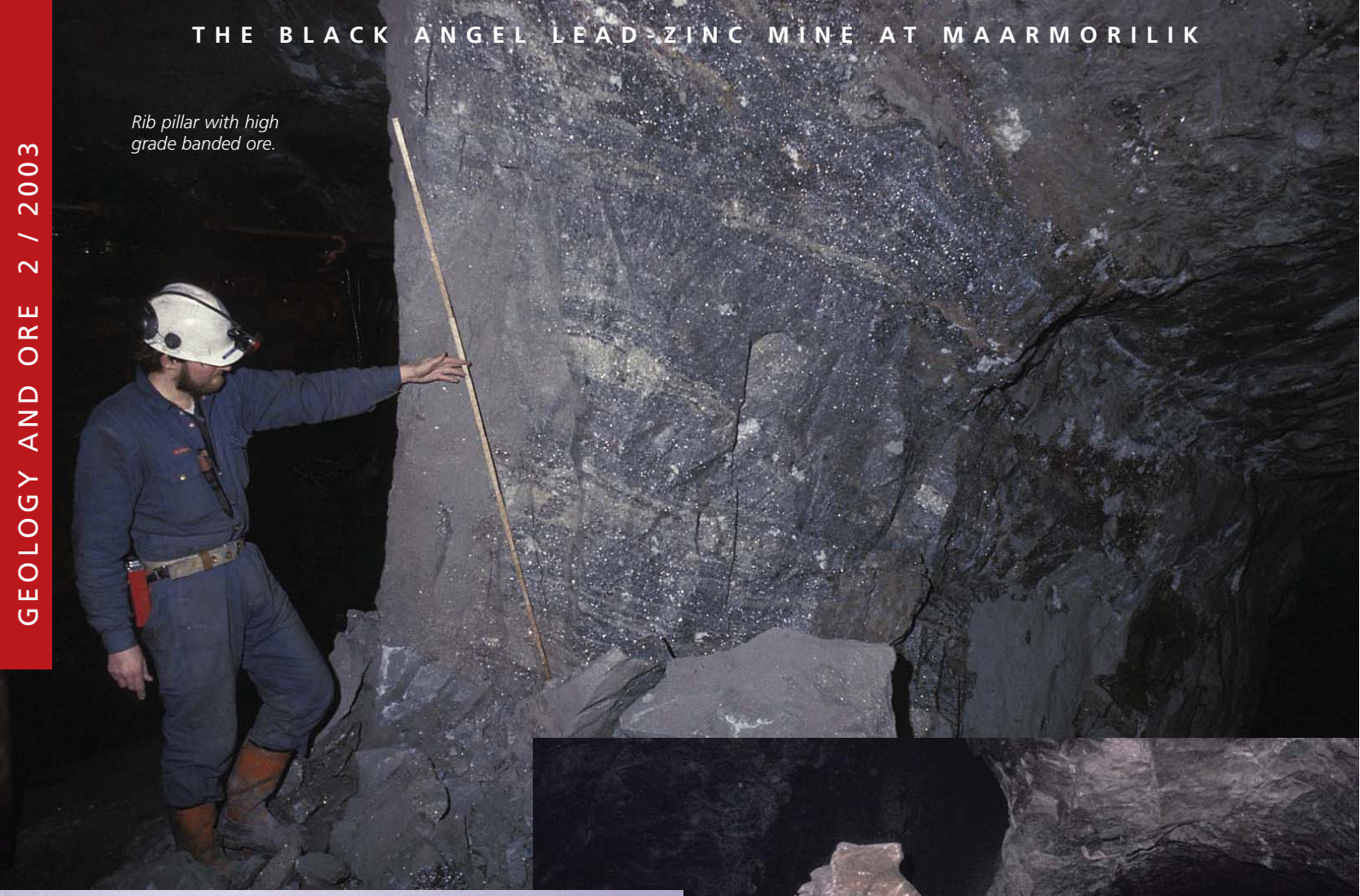
After the first few years of mining, pollution was found to be a bigger problem than anticipated. Increasing amounts of dissolved lead, zinc and cadmium were measured in the fjord water around Maarmorilik. A comprehensive monitoring of heavy metals in the biota showed that lead pollution of blue mussels and seaweed in the intertidal zone of the coastal areas near Maarmorilik was the most serious problem. As a result, the authorities requested Greenex to improve the environmental situation, the main culprits of the pollution being tailings and waste dumps.

The tailings were discharged at a depth of 30 m through a pipeline, from where they settled on the bottom of the Affarlikassaa fjord at 50–60 m. A number of measures were undertaken, and from 1978 to 1985 lead content of the tailings fell from 0.44% to 0.15%, zinc content from 1.10% to 0.23% and cadmium content from 57 to 14 ppm.

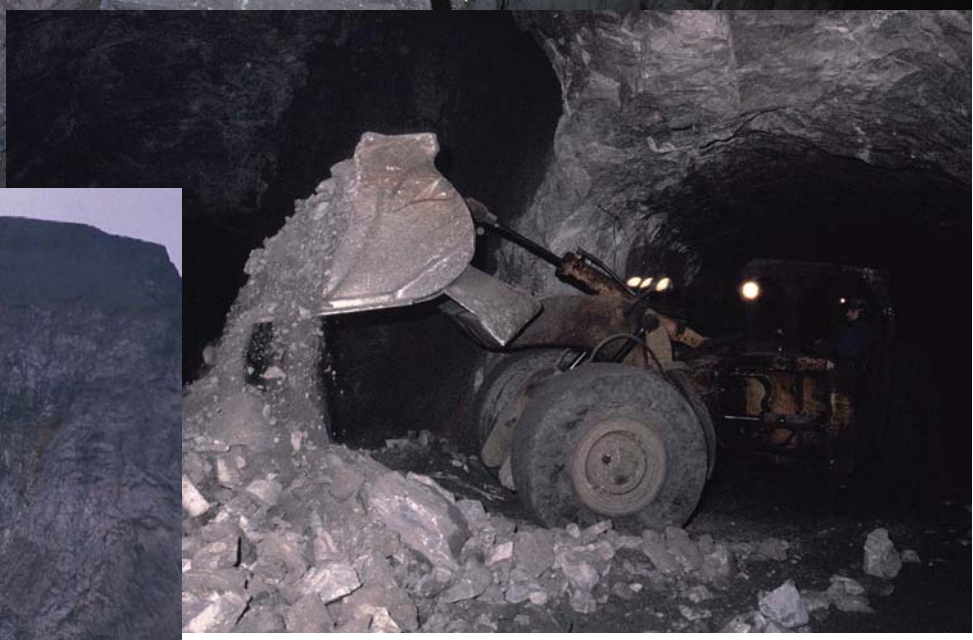
Four waste dumps totalling 2–3 million tons with 0.1–0.8% Pb and 0.3–2.3% Zn had been disposed outside the mine in its first 10 years of operation. One of these dumps of c. 400,000 tons reached into the tidal zone, and the highest lead- and zinc values in seaweed and mussels occurred in this area. After mine closure this dump was removed and partly placed on the bottom of the Affarlikassaa fjord and partly in the former concentrate storage.

"Buck shot ore" with marble rafts left in pillar.

Prior to abandonment, an environmental agreement was in place to ensure the ongoing monitoring of the fjords around Maarmorilik by the National Environmental



Rib pillar with high grade banded ore.



Scooptram shifting broken rock.

Waste dump reaching from 345 m a.s.l. into the fjord on north side of the Angel mountain, summer 1989. The ore horizon is seen just above the dump hole (arrow) in the uppermost part of the 900 m high cliff. The dump was removed after mine closure.

Research Institute (NERI). Thus, since closure the environment around the site has been monitored annually by analysing for lead and zinc in sea water, lichens, seaweed and marine animals. As anticipated, these studies show a marked decline in heavy metal concentrations compared to earlier.

Resumption of mining activity?

At mine closure, Greenex deposited important geological records at the Geological

Survey of Greenland, Copenhagen – now the Geological Survey of Denmark and Greenland (GEUS). This included data files comprising the ore reserves data base, geological sections and mine maps. A complete set of surface exploration reports was already housed at the Survey.

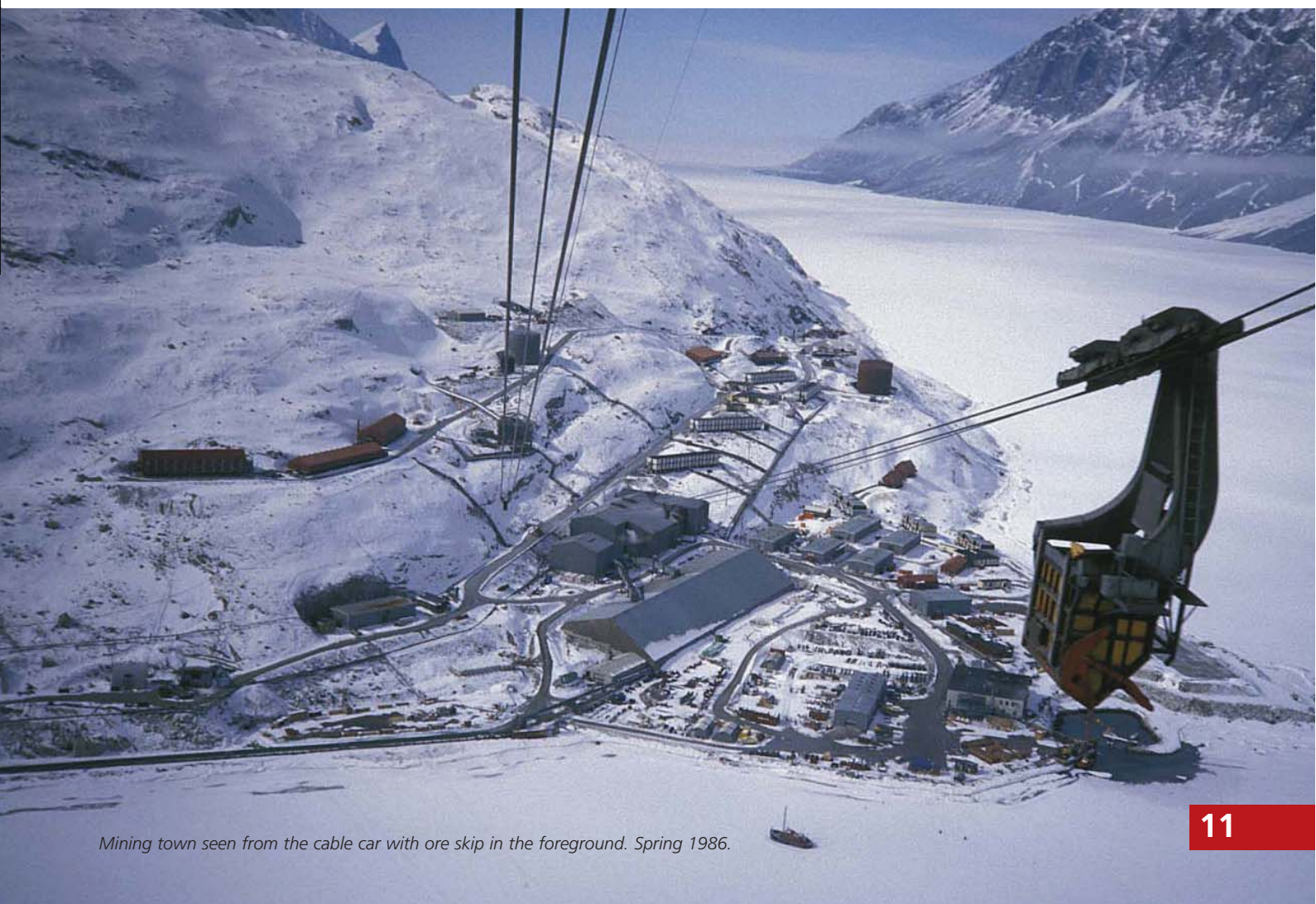
In spring 1997, Canadian company Platinova A/S was granted an exploration licence for the Maarmorilik area in order to examine the possibilities for re-opening the mine. The Platinova plan was based on mining about half of the remaining zinc from the highest value pillars in the Angel and Cover zones (800,000 tons averaging 14% Zn and 4.5% Pb). The ore was to be crushed on site and shipped by bulk ocean carrier during three shipping seasons to a concentrator for custom milling.

During a site visit in 1997, the mine was found to be completely dry with few signs of loose rock falling from the back in either stoping areas or travel ways. Measurements of previously established rock mechanical control points revealed no detectable ground movement since shutdown in 1990. Much of the equipment, including crushing facilities, was in excellent condition with virtually no signs of rust. In January 1998, however, due to low zinc prices Platinova gave up the project and the company has since abandoned its license.

Status 2006

In 2003, Black Angel Mining Ltd., a wholly owned subsidiary of British company Angus & Ross plc, obtained an exploration licence in the area. Based on the data archived at GEUS and site visits in 2005 the redevelopment of a mine and a mill on the site was investigated in a pre-feasibility study. The study (completed January 2006) is based on proven and probable ore reserves of 2.3 Mt contained largely in the pillars of the old mine. It is estimated that 80–100% of the remaining c. 1000 pillars can be mined, if the tailings are put back in the mine as a semi-dry paste, which after solidification creates extra support for the roof. The mining concept envisages a new entrance south of the Banana zone linked to a road around the Affarlikassaa fjord via the Nunngarut ramp. The road will also enable mining of the known small satellite ore bodies.

A major drilling programme carried out summer 2006 aimed at finding more ore in the vicinity of the old mine, to improve the economics of the project. The programme comprised 8675 metres of drilling in 67 holes resulting in 632 analysed samples. Four target areas were drill tested, with particular focus on the 'South Lakes Glacier' prospect, where 44 holes drilled over a lateral distance of c. 700 m have outlined a continuous, E–W orientated near vertical massive sulphide sheet to a depth of 170 m. Best intersection gave 2.7% Pb and 7.9% Zn over 13.6 metres.



Mining town seen from the cable car with ore skip in the foreground. Spring 1986.

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Typical exposure of brown, zinc-rich massive sulphides with marble rafts at 'South Lakes Glacier' prospect.

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

GEUS

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

Front cover photograph

The Black Angel mountain with mine portals and angel figure, with traditional Greenland dog sledges in the foreground. Spring 1980.

Author:
Bjørn Thomassen, GEUS

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