The mineralization and operation of the Nalunaq Gold Mine, Southern Greenland

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Introduction

The Nalunaq Gold Mine is located in southern Greenland in the Kirkespirdalen in the vicinity of the town Nanortalik. Nalunaq can be translated "to the place which is hard to find" or "the place that deceives".

The gold occurrence was discovered in 1992 (Gowen *et al.* 1993) and the mine opened in 2004 and produced until 2008. The reasons for the mine closed were a combination of a drop in gold prize, grade of the remaining ore and increasing operating cost. Gold provinces occur in several areas in Greenland, but Nalunaq was the first and only mine to produce gold in Greenland. This paper gives a short introduction to the geology, mineralogy and mining method of this remote gold ore deposit.

Geological Setting

The Nalunaq gold mine is situated in the south Greenland basement, where the Palaeoproterozoic Ketilidian juvenile orogen evolved during northward subduction of an oceanic plate under the southern margin of the Archaean craton from 1850 Ma to 1725 Ma (Garde *et al.* 2002). The Ketilidian orogen is subdivided into four domains; Border Zone, the Julianehåb Batholith, and the Psammite and Pelite Zones, which forms the fore arc (Fig. 1).

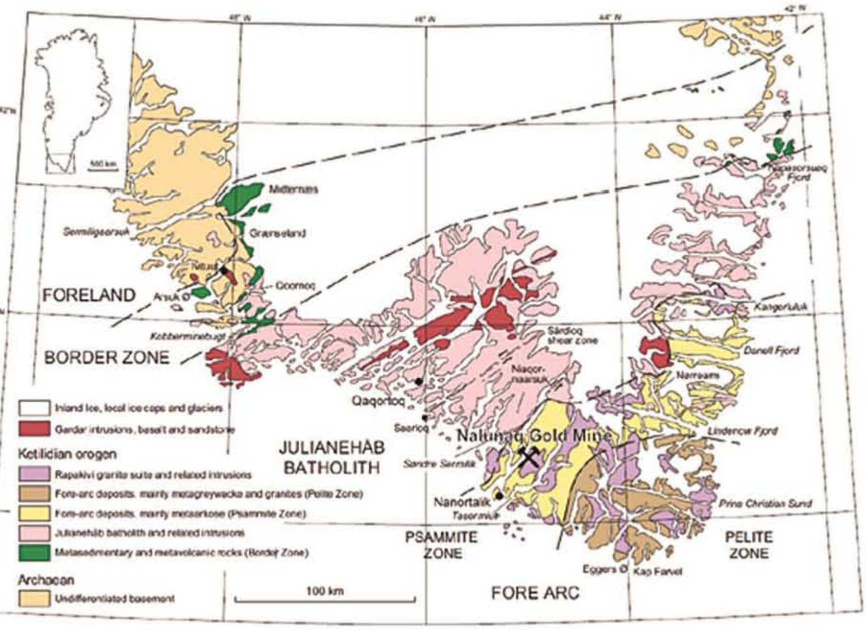

Fig. 1. *Geological map of Southern Greenland with the location of the Nalunaq Gold Mine (Secher et al. 2008).*

The Nalunaq gold mine is situated within the Psammite zone. The Foreland border zone consists of reworked Archaean basement of the craton and unconformable overlaying Ketilidian supracrustal rocks. The central part is dominated by the Julianehåb batholith, a calc-alkaline batholith which intruded along the southern margin of the North Atlantic craton over a north-dipping subduction zone. The Psammite Zone is composed of basic volcanic rocks, metamorphosed sandstone protoliths, migmatised pelitic and semi-pelitic rocks, calcareous metasediments, bedded massive-pyrrhotite/graphitic-cherts, dolerites, syn- to post-kinematic appinite dykes as well as post-kinematic rapakivi granites. The psammites represents intra- and fore-arc sediments, which are eroded from the Julianehåb batholith and deposited in fluvial to shallow marine environments to the south of the batholith. The basic volcanic rocks are associated with gold, as observed at the Nalunaq Gold Mine. The Pelite Zone to the south consists of pelitic rocks originally deposited as turbidites in an offshore environment distally to the Psammite zone.

Mineralization

The Nalunaq gold deposit is a high-grade orogenic-type gold mineralisation associated with quartz veins in a narrow ductile shear zone in the Palaeoproterozoic amphibolite facies and metavolcanic rocks (Kaltoft *et al.* 2000). The thickness of the largest gold hosting quartz vein, the so-called Main Vein, is generally around 0.5 m but can be up to 2.1 m and often display pinch and swell structure. Occasionally, quartz is not present at the pinches but then tension gashes often indicate the presence of the Main Vein. The Main Vein has an azimuth of ~50° with an inclination of around 35° and is only displaced by few faults (Fig. 2).

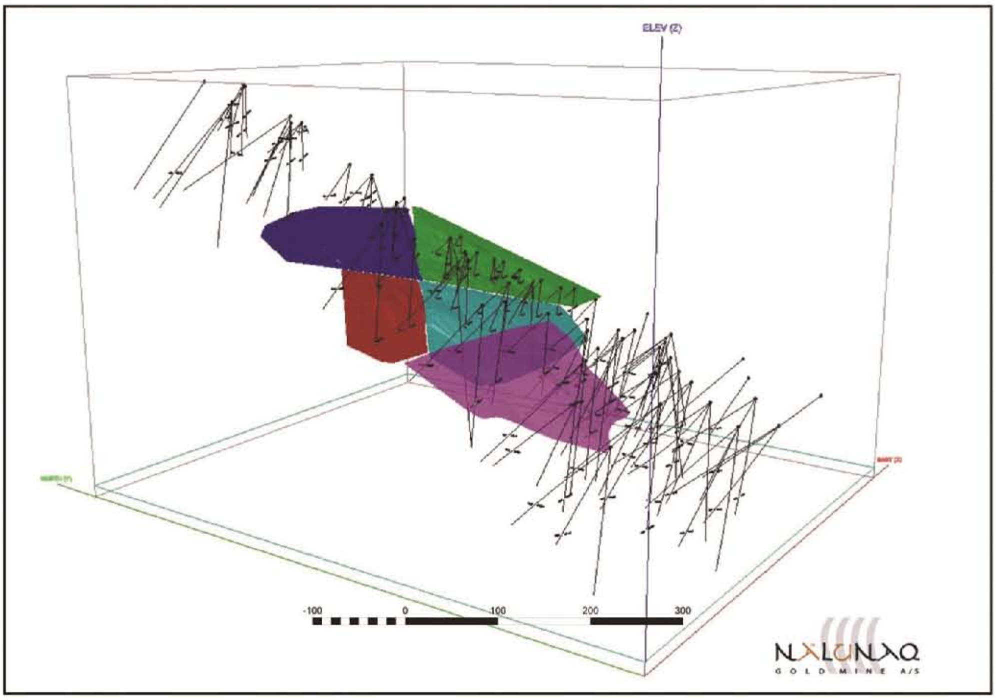

Fig. 2. *Illustration of the Main Vein and drill holes. The colours indicate different fault blocks (Nalunaq Gold Mine 2006).*

The Main Vein occasionally split into several veins, which was linked to a decrease in gold grade. This made it difficult to follow one specific vein, thus it was attempted to keep several of these visible in the adit. However, the grade rarely became very good again after the splits. The split was then interpreted to roughly mark the outer boundary of the gold mineralization.

Mineralogical, the Main Vein is composed mainly of quartz and gold with accessory diopside, plagioclase, muscovite, pyrite, arsenopyrite and scheelite. Diopside is clearly associated with calc-silicate alterations of the metavolcanic hostrocks. The gold primarily occurs in the quartz vein as visible gold flakes up to 2 mm, and as a brownish mass of very fine-grained gold (Fig. 3). When quartz was not present, i.e. in the pinches, the accessory minerals could be used to infer the presence of the Main Vein. Scheelite was particularly helpful because of its fluorescence in UV-light.

Fig. 3. *Gold flakes in quartz with greyish to brownish parts containing fine grained gold (Foto: H. Buus Madsen).*

The highest concentration of gold of more than 4000 g/t was recorded in a well on top of Nalunaq Mountain. However, gold concentrations of up to 200 g/t were occasionally also present in calc-silicate alterations. The average grade of the deposits was 13.3 g/ton with large variation in gold concentration indicating a nugget distribution.

Most of the gold occurs as native gold and sometimes as alloys with silver, but also as maldonite (Au_2Bi). The presence of maldonite in Nalunaq is the first occurrence of this mineral in Greenland. Gold also occurs together with bismuth and antimony grains in a delicate skeletal network. Chemically, the gold grains are composed of 85–95% gold and 5–15% silver with accessory Bi of 0.3% and Sb of 0.01% (Kaltoft *et al.* 2000). The gold occurs as inclusions in quartz, dioside, plagioclase, muscovite, arsenopyrite and löllingite, which may indicate that gold precipitated at the same time as these minerals (Kaltoft *et al.* 2000). Additionally, gold flakes were also observed to occur inside 1–2 mm pyrite cubes. Gold is also concentrated within fractures in the quartz vein, which indicate that gold was deposited/remobilized after the host minerals crystallized.

Mining operation

Mining method

The mining method used was longhole open stoping, which involve development of horizontal sub-levels for every 11 m vertical and stopes between the sub-levels (Fig. 4). The sub-levels are driven by using the resue mining technique, where the waste rock below the inclined Main Vein is blasted and mucked first, and the ore is blasted afterwards. The stopes between the sub-levels are mined by drilling long holes from one sub-level to the other and then blast the holes with explosives. However, for an explosion to expand it needs space, so a raise was driven along the vein by handheld jackleg from one sub-level to the other, creating this space. For every 15 m a rib-pillar was left between the stopes for stability. Due to the low inclination of the Main Vein of 35° some of the ore did not fall down by itself. The ore left in the stopes had to be scraped down which, of course increased the cost of the operation. Roughly 500 t of ore was hauled to the harbor every day.

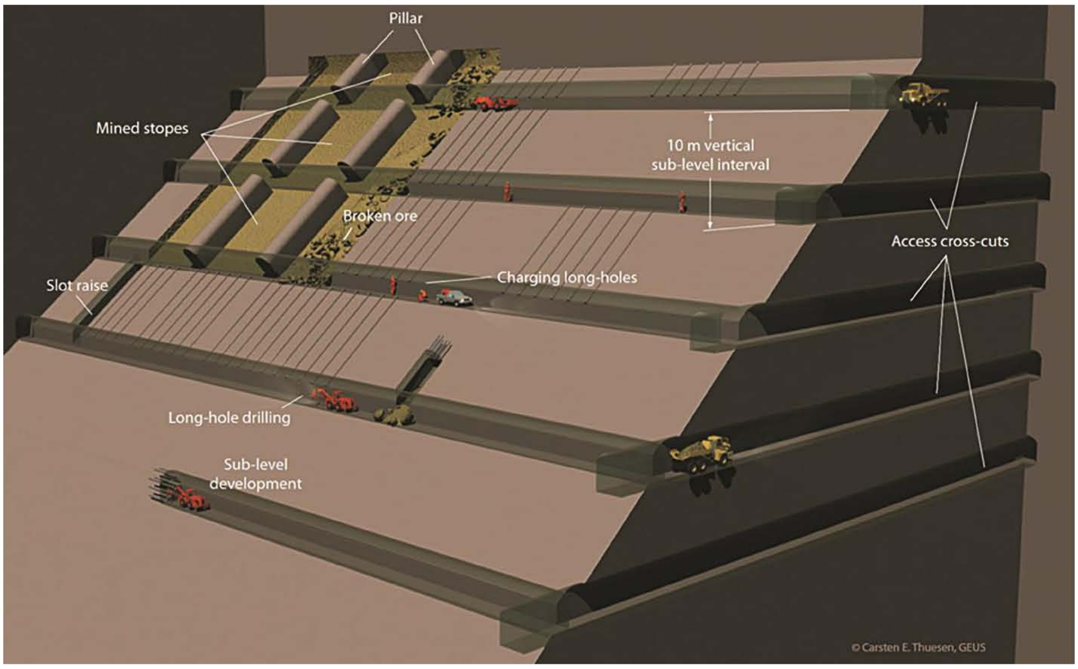

Fig. 4. *Schematic 3-D presentation of the mining method (3-D figure by Thuesen, C.E., GEUS).*

Extraction of gold

The ore was shipped to Nugget Pond, Canada for processing. First the ore was finely crushed and then sent through a gravity separation process which extracted around 75% of the gold. To extract the remaining gold a Carbon in Pulp leaching method was used. Water and cyanide was added to the finely crushed ore to form a pulp. The pulp then goes through several tanks where it is stirred to get the gold out into solution by forming gold cyanide ions. To extract the gold the solution was run through tanks with active coal where the cyanide gold ions are adsorbed onto the carbon. Then the gold was extracted from the coal by desorption and electrolysis. Finally, all the gold was melted and poured to gold bullions (Fig. 5). In the period 2004–2008 the Nalunaq Gold Mine produced 10.66 t of gold (Government of Greenland 2017), which is equivalent to a cube of 0.8×0.8×0.8 m.

***Fig.* 5.** *First gold bullion from Nalunaq Gold Mine (Foto: Nalunaq Gold Mine).*

Mother nature; friend or foe?

The Kirkespirdalen offers spectacular scenery with mountains, glaciers, flora, fauna and even aurora borealis during winter time. But this scenery offered some challenges for the mining operation. The steep slopes of Nalunaq Mountain were a major challenge when drill sites had to be chosen, where some drill site had to be hand built with rocks found on the mountain. Thus, data coverage was not evenly distributed. Obviously, snow and ice caused problems during the winter, where ice formed at the entrances to the mine making it difficult for the trucks to pass the slippery ice. Snow also had to be cleared from the roads and campsite, but what was even worse was the lurking risk of having avalanches blocking the access to mine and threatening the safety of the workers. When spring arrives one should think that all the challenges with ice are over. But then the sea ice arrives from the east coast of Greenland, blocking the harbour and making it impossible to ship out ore.

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