# ENVIRONMENTAL MONITORING AT THE FORMER SEQI OLIVINE MINE IN SOUTHWEST GREENLAND 2011-2018

Scientific Report from DCE – Danish Centre for Environment and Energy No. 319 2019

AARHUS UNIVERSITY
DCE – DANISH CENTRE FOR ENVIRONMENT AND ENERGY

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# Data sheet

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Abstract: The olivine mine at Seqi in Southwest Greenland operated between 2005 and 2009. This report contains the results from monitoring studies conducted after mine closure between 2011 and 2018. The studies included sampling of lichens, blue mussels and seaweed, supplemented with sampling of surface soil and freshwater in 2018. Contamination (mainly with chromium and nickel) had decreased since mine closure and elevated concentrations of contaminants could only be detected in lichens within a distance of 1 km from the pit area and former ore crushing facility. Elevated concentrations of contaminants could neither be measured in blue mussels nor seaweed during the latest sampling in 2018. The results indicate that there is still minor dust dispersion and deposition in close vicinity to the mine but no significant dispersion of contaminants to the marine environment. Overall, DCE assesses the impact from the former mining activities at Seqi as insignificant to the environment at Seqi. Consequently, DCE considers the Seqi olivine mine to serve as an example of how a mine can be operated with minimum environmental impact by establishing adequate environmental requirements and conditions as part of the license and through detailed environmental monitoring and regulation during mine operation.

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# Eqikkaaneq

Svenskit aatsitassarsioqatigiiffiat Minelco A / S (Siornagut tassaasoq Seqi Olivine A / S) Niaqunngunami Seqinnersuusaami olivinemik suliffissuarni atorneqartartumik piiaanissamut 2005-imi akuerineqarpoq. Misissuinerit aallarniutaasut sanaartornerillu 2005-ip naanerani 2006-imilu ingerlanneqareermata 2007-mi upernaakkut olivinimik piiaaneq aallartippoq. 2009-illi naanerani aningaasaqarneq pissutigalugu piiaaneq unitsinneqarpoq, aatsitassarsiorfillu matuneqarluni.

2004-imiilli ukiut tamangajaasa Seqinnersuusaami avatangiisit misissuiffigineqartarput aatsitassarsiorneq sioqqullugu aammalu kingorna avatangiisit qanoq sunnigaasimanerat malinnaavigisinnaajumallugu. Nalunaarusiaq manna 2011-imiit 2018-imut avatangiisit misissuiffigineqartarnerannik imaqarpoq. Misissuiffigineqartunut ilaapput orsuaasat, qeqqussat uillullu, taakkulu nunami imaanilu avatangiisit malinnaavigineqarneranni uuttuutitut atorluartuupput. 2018-imi katersinermi kingullermi nunap qaaniit imermiillu aamma misissugassanik tigooraanerit ilanngunneqarput.

Aatsitassarsiorfiup matuneraniit ukiut ingerlaneranni sananeqaatit avatangiisini takornartaasut annikilliartorsimapput, pingaartumillu tassaallutik krom (Cr), savimineq (Fe), kobolt (Co) aammalu nikkeli (Ni). Misissugassanik tigooraanermi kingullermi 2018-imi pisumi tamakku ima annikillisimatigipput taamaallaat aatsitassarsiorfimmit 1 km-inik ungasissusillup iluani uuttorneqarsinnaalersimallutik. Aatsitassarsiorfimmiit 1 km iluanni piffissap tamatuma tamarmi iluani orsuaasani sananeqaatit tamakku qaffasialaartarnerat uuttortarneqarsinnaavoq. Paasisat takutipaat pujoralaat siammarternerat unerarnerallu aatsitassarsiorfiup matuneraniit malunnaqisumik appariarsimasoq, ullumikkullu (2018-imi) taamaallaat aatsitassarsiorfimmiit 1 km missaannik ungasitsigisup iluani uuttorneqarsinnaalersimallutik. Uuttukkat qaffasinnerpaat aatsitassarsiorfiusimasup eqqannguani uuttorneqarput.

Imaani avatangiisini sananeqaatit takornartaasut pingaarnerit, Cr aamma Ni, 2018-imi qeqqussani uillunilu ittut pinngortitami nalinginnaasumik qaffasissuserisartakkamissut qaffasissuseqalersimapput. Tamatumuunakkut malunnarpoq sananeqaatit avatangiisini takornartaasut arrorsimasut pujoralanniittullu Seqinnersuusaami aatsitassarsiorfimmiit imaani avatangiisinut siammmartarnerat annikitsuararsuaannanngorsimasoq.

Ataatsimut isigalugu misissuinerit takutippaat sananeqaatit avatangiisini, nunami immamilu, takornartaasut aatsitassarsiornerup 2009-imi unitsinneqarneraniilli malunnaqisumik appariarsimasut. Cr aamma Ni nunami avatangiisini aatsitassarsiorfimmiit 1 km ungasitsigisup iluani qaffasialaarnerat 2018-imi uuttorneqarsinnaavoq, immamili naamik. Paasisat taaneqareersut tunngavigalugit Danmarkimi Avatangiisinik Nukissiutinillu Misissuisoqarfik naliliivoq Seqinnersuusaami aatsitassarsiorfimmiit avatangiisit massakkut sunnigaanerat soqutaajunnaarsimasoq.

Aatsitassarsiorfiup matunerata kingorna Seqinnersuusaami avatangiisit misissuiffigineqartarnissaannik pilersaarutigineqartut nalunaarusiakkut ugguuna naggataarneqarput. Paasisat siuliani taaneqartut tunngavigalugit misissueqqinnissaq pisariaqanngitsutut Danmarkimi Avatangiisinik Nukissiutinillu Misissuisoqarfimmiit isigineqarpoq. Qaquguli talittarfik peerneqassagaluarpat avatangiisitigut misissuinissaq naliliisoqassappat pisariaqalersinnaavoq. Taamaammat naleqquttunik avatangiisit pillugit piumasaqaasiornikkut kiisalu avatangiisit malinnaavigiuarnerisigut aqunneqarnerisigullu annikitsuinnarmik avatangiisinut sunniilluni aatsitassarsiortoqarsinnaaneranut Seqinnersuusaami olivenisiorfik assersuutissaqqissutut Danmarkimi Avatangiisinik Nukissiutinillu Misissuisoqarfimmiit isigineqarpoq.

# Sammenfatning


Det svenske mineselskab Minelco A/S (tidligere Seqi Olivine A/S) fik i 2005 en udnyttelsestilladelse til brydning af industrimineralet olivin ved Seqi i Niaqunngunaq (Fiskefjord) i Sydvestgrønland. Efter indledende undersøgelser og konstruktionsarbejde i slutningen af 2005 og i 2006 startede den egentlige brydning af olivin i foråret 2007. I slutningen af 2009 blev brydningen imidlertid stoppet af økonomiske årsager, og minen blev lukket ned.

Siden 2004 er der næsten hvert år blevet gennemført studier af miljøet ved Seqi for at følge miljøpåvirkningen fra mineaktiviteterne under og efter minedriften. Denne rapport indeholder resultater af miljøstudier fra perioden 2011 til 2018. Miljøprogrammet inkluderede lav, tang og blåmuslinger, der er nøgle-moniteringsarter i hhv. land- og havmiljø. Ved den sidste indsamling i 2018 blev programmet suppleret med prøver af overfladejord og ferskvand.

I landmiljøet aftog koncentrationerne af miljøfremmede stoffer relateret til minen, særligt krom (Cr), jern (Fe), kobolt (Co) og nikkel (Ni), i årene efter nedlukningen af minen. Ved den seneste indsamling i 2018 var koncentrationerne i lav faldet til et niveau, hvor en påvirkning kun kunne måles indenfor en afstand af 1 km fra mineområdet. I området indenfor 1 km's afstand til minen kunne svagt forhøjede koncentrationer måles i lav i hele perioden. Resultaterne indikerer, at spredning og deponering af støv relateret til minen er faldet markant siden nedlukningen, og i dag (2018) kan det kun måles meget lokalt indenfor en radius af ca. 1 km fra mineområdet. De højeste værdier blev målt i umiddelbar nærhed af bruddet.

I havmiljøet var koncentrationerne af de primære miljøfremmede stoffer fra minen, Cr og Ni, i 2018 faldet til baggrundsniveauet i tang og blåmuslinger ved alle målestationer. Dette indikerer, at spredning af både opløste og partikelbundne miljøfremmede stoffer fra mineområdet til det marine miljø ved Seqi nu er ubetydelig.

Samlet set viser undersøgelserne, at koncentrationerne af miljøfremmede stoffer i både det terrestriske og marine miljø er faldet markant, siden minedriften stoppede i 2009. Svagt forhøjede koncentrationer af Cr og Ni kunne kun måles i det terrestriske miljø indenfor en afstand af 1 km fra minen i 2018 og ikke i det marine miljø. På baggrund af ovenstående resultater vurderer DCE derfor den nuværende miljøpåvirkning relateret til minedriften ved Seqi som værende uden miljømæssig betydning for området.

Denne rapport afslutter det planlagte miljøarbejde ved Seqi efter nedlukningen af minen. Baseret på ovennævnte resultater vurderer DCE ikke, at der er behov for yderligere undersøgelser. Skal kajanlægget på et tidspunkt fjernes, kan der dog blive behov for yderligere miljøundersøgelser til evaluering af dette. DCE betragter derfor olivinminen ved Seqi som et godt eksempel på, hvordan en mine i Grønland kan drives med minimal miljømæssig påvirkning ved bl.a. fastsættelse af hensigtsmæssige miljøkrav og vilkår samt løbende miljøovervågning og regulering.

# Summary

The Swedish mining company Minelco A / S (formerly Seqi Olivine A / S) was in 2005 granted permission to exploit the industry mineral olivine at Seqi in Niaqunngunaq (Fiskefjord) in Southwest Greenland. After initial test work and construction in late 2005 and 2006, the production began in spring 2007. In late 2009, the mining was stopped due to economic reasons and the mine site closed.

Since 2004, environmental studies have been conducted at Seqi almost every year to monitor the environmental impact from mining during and after the mining operation. In this report, the results from the sampling campaign from 2011 to 2018 are presented and discussed. The sampling programme included lichens, seaweed and blue mussels, which serve as key monitoring species in terrestrial and marine environments, respectively, supplemented with surface soil and fresh water samples during the latest sampling in 2018.

In the terrestrial environment, results from collection and analyses of lichens showed that concentrations of mine-related contaminants, mainly chromium (Cr), iron (Fe), cobalt (Co) and nickel (Ni), had decreased since the mining period. During the last year of the monitoring, 2018, the concentrations had decreased to baseline levels more than 1 km away from the mining area. Within 1 km of the mine pit / former ore crusher site, slightly elevated contaminant concentrations were observed in lichens during the entire period. The results indicate that dust dispersion and deposition from the mine have decreased markedly since the mine closure. There is still (2018) some minor dust dispersion and deposition within a 1 km area of the mine, highest in immediate vicinity to the mine pit.

In the marine environment, collection of seaweed and blue mussels showed that the concentrations of the main contaminants Cr and Ni had decreased to background level in 2018 at all stations. This indicates that dispersion of both dissolved and particle-bound metals from the mining area into the marine environment at Seqi, as measured during the latest sampling in 2018, is negligible.

In conclusion, the monitoring campaign showed that the concentrations of contaminants in both the terrestrial and marine environment had decreased since the mining activities stopped in 2009. Only slightly elevated levels of Cr and Ni could be measured in the terrestrial environment within 1 km from the mine during the latest sampling event and not in the marine environment. Consequently, DCE assesses the current environmental impact from the mining activities at Seqi as insignificant to the environment at Seqi.

This report finishes the planned environmental studies at Seqi after mine closure. Based on the conclusions above, DCE assesses that further studies are not required at this stage. However, in case the pier is to be removed at some point in the future, additional environmental studies may be required to evaluate the potential effects of this. Overall, DCE regards the olivine mine at Seqi as an example of how a mine can be operated in Greenland with minimum environmental impact by establishing adequate environmental requirements and conditions as part of the license and through detailed environmental monitoring and regulation during mine operation.

# 1. About the Seqi olivine mine

The Seqi olivine mine is located at a place named Seqi in the bottom of the long and narrow fjord Niaqunngunaq (in Danish: Fiskefjord) in Southwest Greenland (Figure 1 and 2). The nearest settlement is Atammik at the mouth of the fjord.

The Niaqunngunaq Fjord is characterised by strong tidal currents due to its shape and topography and is only navigable for larger ships during a short period of time around high tide. The mine is accessible for ships during most of the year due to limited sea ice cover.

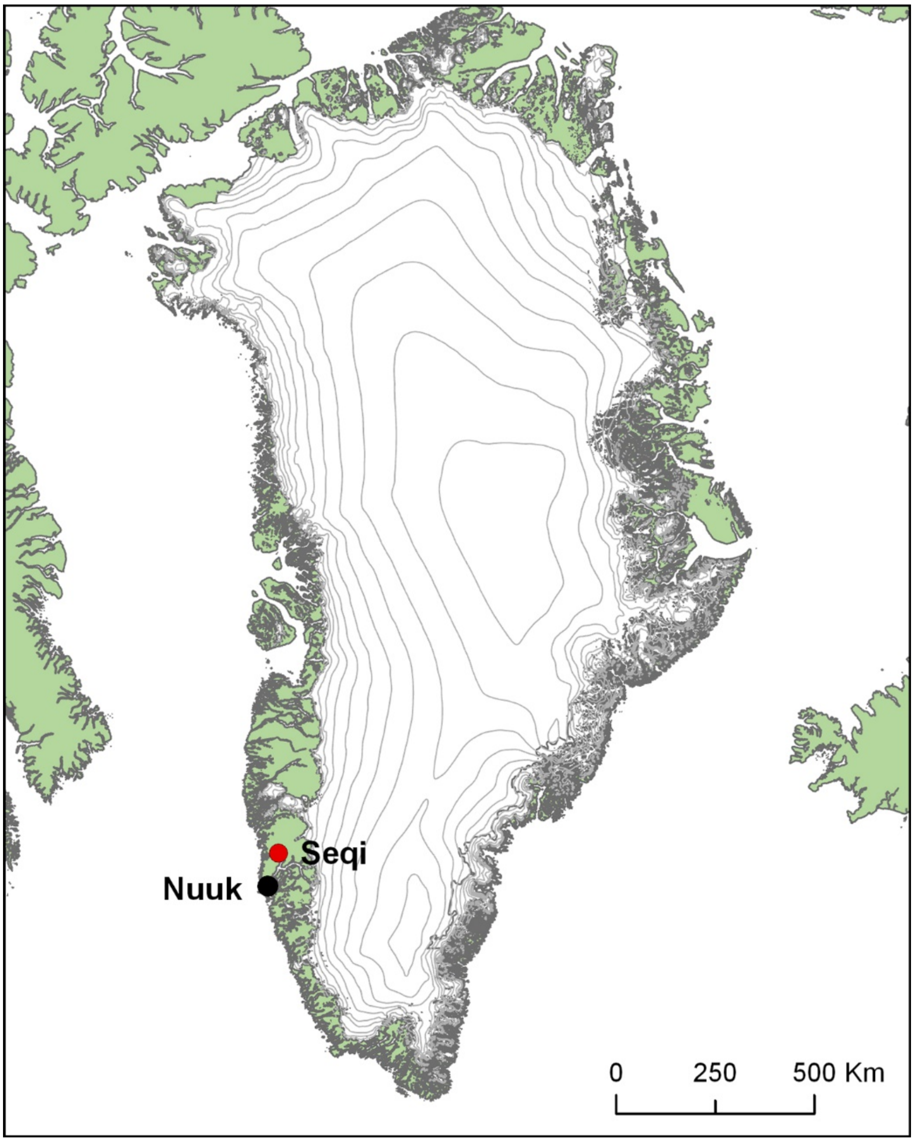


**Figure 1**. Map of Greenland showing the location of Seqi and Nuuk.

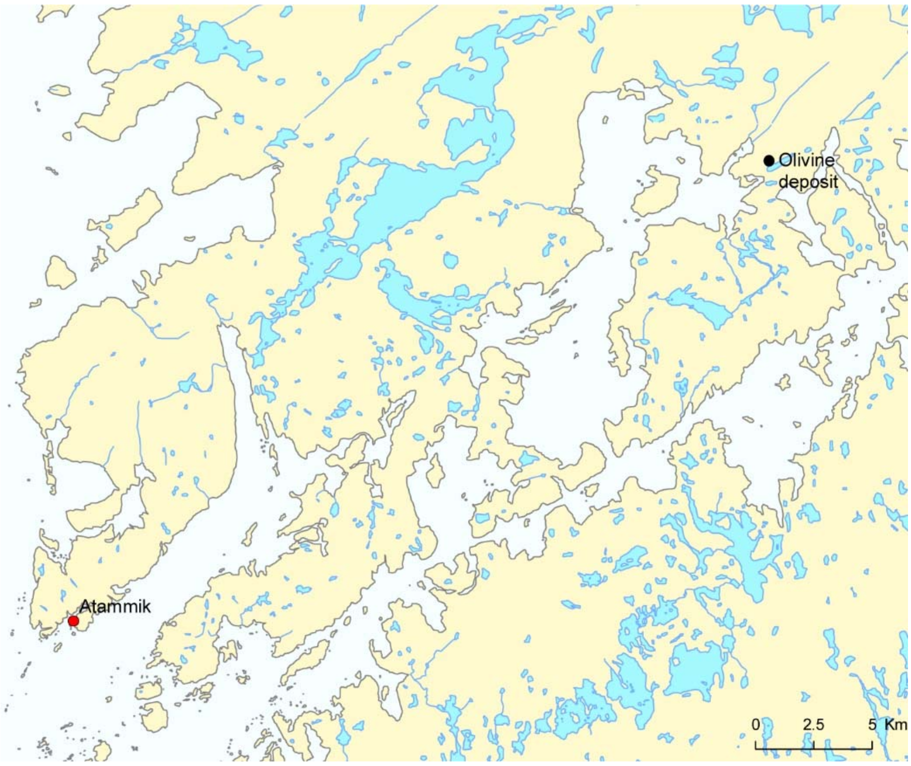


**Figure 2**. Map of Fiskefjord and the olivine deposit at Seqi.

The olivine deposit at Seqi has been known for a long time and is described in geological detail (Nielsen, 1976). The deposit expectedly contains roughly 150 million tons of olivine (Råstofdirektoratet, 2009). Olivine is a common mineral on earth and is mined in several countries today, for instance in Norway. It is an industrial mineral with the composition $(Fe,Mg)_2SiO_4$ and is mainly used in the steel industry. Olivine is used as foundry sand, for sand blasting and as a slag conditioner.

In 2005, the company Seqi Olivine A/S was granted concession for mining at Seqi (Licence 2005/26). In 2006, the company conducted a drilling campaign to estimate the size of the deposit and in spring 2007, the construction of mining facilities and associated infrastructure was finished and production was initiated. In 2007, the mining company changed its name from Seqi Olivine A/S to Minelco A/S. Minelco A/S is a daughter company of Swedish LKAB, which is owned by the Swedish state.

The deposit was mined as an open pit and the ore was crushed and stored at the coast before being shipped out in bulk carriers. These bulk carriers had a capacity of up to 50,000 tons. Approximately 30 persons were employed at the mine during operation (Råstofdirektoratet, 2009). An overview of the mining area with roads, buildings and quay areas is shown in Figure 3.

DCE has been involved in the advisory work regarding the mining project since its beginning, providing recommendations and advisory services, including specific recommendations on: 1) characterisation of the ore and waste rock in terms of chemical composition and potential leaching of contaminants; 2) establishing baseline conditions of potential contaminants in the environment; 3) designing the environmental monitoring programme according to the potential risks. The subsequent advisory work included recommendations for setting environmental requirements and conditions for the project as part of the licence. Based on DCE's recommendations, it was decided not to use low-grade olivine as fill material in roads, in the quay area or left in contact with seawater. Later, the results of the environmental monitoring programme showed significant dust dispersion due to the mining activity, and, based on DCE's recommendation, the company was required to use calcium chloride for dust control on the ground surface to reduce dust generation.

In October 2009, the production was stopped due to economic reasons, including high costs of transportation (Råstofdirektoratet, 2009). In 2010 and 2011, the mine was closed and the area was cleaned up (removal of buildings, machines, stock piles of olivine etc.) (Photos 1 and 2). It was decided to leave the pier in place for potential future use (Photo 3).

**Figure 3**. Roads, quays and the location of the former buildings and mining area at Seqi.

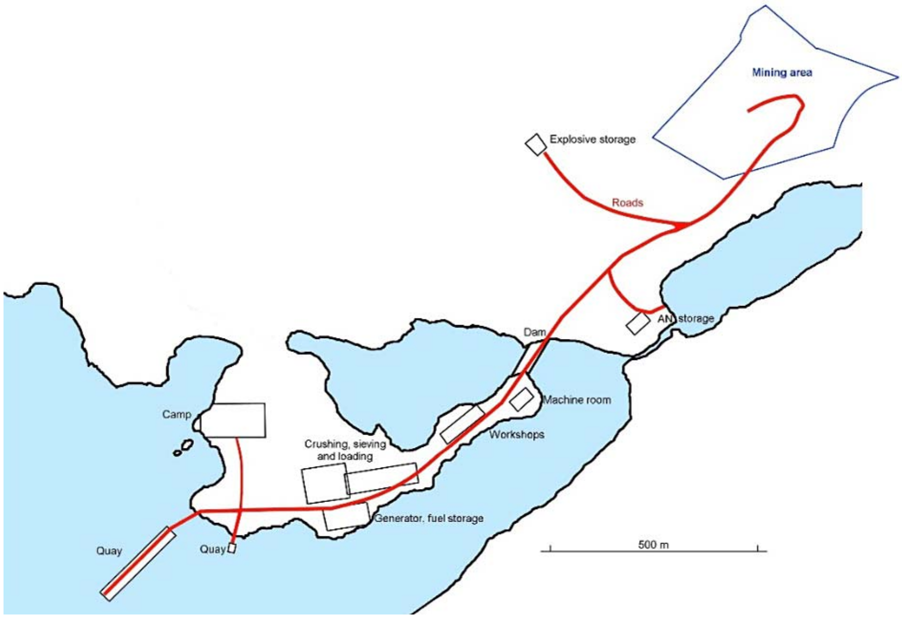


**Photo 1.** Overview of the abandoned mine site in 2018. Photo: Jens Søndergaard.

**Photo 2.** The abandoned pit area (grey area in the centre) and the exposed olivine ore body from the opposite side of Long Lake in 2018. Photo: Jens Søndergaard.

**Photo 3.** The pier in 2018. Photo: Jens Søndergaard.

# 2. Environmental studies

## 2.1 Background

Prior to mining, thorough baseline studies were conducted in 2004 and 2005 in the Seqi area by DCE (formerly National Environmental Research Institute (NERI)). The first background studies were carried out in May 2004 with the research vessel Adolf Jensen. Thereafter, studies were performed with assistance from mining company employees using smaller boats. The baseline studies in 2004 and 2005 included sampling of blue mussels, seaweed, snow crabs, Greenland cod, shorthorn sculpin, lichens and marine sediments as well as freshwater from the river running out of Long Lake near Seqi. In addition, a general survey of fish and shellfish was conducted in the inlet of Tasiussarsuaq and bird observations were made.

During the mining period from 2006 to 2009, and in 2010, samples of selected types of biota identified as key monitoring organisms (lichens, blue mussels, seaweed and sculpins) as well as of freshwater were collected and the environmental impact of the mining activity was evaluated. The evaluation was based on a comparison between concentrations of a long list of elements measured in the samples from 2006 to 2010 with the baseline samples. There were no measurable natural elevations of element concentrations originating from the olivine deposit. The spatial extent of environmental impact was evaluated by analyses of samples collected from a range of sites within the Fiskefjord area. Full descriptions of the sampling performed and the results obtained between 2004 and 2009 and in 2010 are given in Asmund et al. (2009), Søndergaard et al. (2009) and Søndergaard and Asmund (2011).

After mine closure, an environmental monitoring programme was established to evaluate the environmental impacts of the mining activities. This programme was run in the period 2011-2018 during the years 2011, 2012, 2013, 2014, 2015 and 2018. The environmental monitoring was a reduced version of the programme conducted during the mining period and was focused on selected key monitoring organisms and sites, taking the results from 2004 to 2010 into account. During the last year with planned environmental monitoring, 2018, the programme was extended from the samplings in 2011-2015 to cover also resident lichens, surface soil and freshwater in order to obtain a more thorough description.

The field work in 2011 was conducted by Lene Bruun and Sigga Joensen and from 2012 to 2015 by Anna Marie Plejdrup and Sigga Joensen (all from DCE). The field work in 2018 was done by Anna Marie Plejdrup (DCE), Josephine Nymand (Greenland Institute of Natural Resources) and Jens Søndergaard (DCE).

From 2011 to 2018, the monitoring programme at Seqi was focused on three species of biota: lichens (*Flavocetraria nivalis*), blue mussels (*Mytilus edulis*) and brown seaweed (*Fucus vesiculosus*). These species were selected because they are well suited as key monitoring organisms of mining contamination in the terrestrial and marine environment, respectively, as described below. They are also widely used in other monitoring programmes at mine sites in Greenland (Johansen et al., 2008 and 2010; Bach et al., 2014; Bach and Larsen, 2016).

Lichens are known as bioaccumulators of atmospheric contaminants such as metals and are abundant in the Arctic. Their lack of roots, a large surface area and a long life span enable lichens to effectively bioconcentrate air contaminants. A number of studies have shown lichens to be adequate and sensitive monitors of contaminants from mining activities (Naeth and Wilkinson, 2008; Søndergaard et al., 2011a). The lichen specie *Flavocetraria nivalis* is the preferred species for monitoring at Greenland mine sites since it is abundant, easy recognisable and has been shown to effectively accumulate mining contaminants (Søndergaard et al., 2011a and 2013; Søndergaard, 2013a and b). Since the lifetime of *Flavocetraria nivalis* spans several years and due to a limited ability of lichens to excrete the bioaccumulated contaminants again, transplanted lichens have often been used as a supplement to or instead of resident lichens to assess the year-to-year variation in dust deposition. Transplanted lichens are collected from uncontaminated reference sites and typically placed at the monitoring sites for one year.

**Photo 4.** The lichen *Flavocetraria nivalis* frequently used to assess dust deposition of contaminants from Greenland mine sites. Photo: Jens Søndergaard.

Blue mussels are suitable as monitoring organisms since they are widely distributed and bioconcentrate metals in their tissue due to their feeding strategy based on filtration of large volumes of seawater (Rigét et al., 1997; Søndergaard et al., 2011b). The contaminants in mussels are considered to be derived from both contaminants bound to particles and contaminants dissolved in the seawater (Rainbow, 1995). The timespan of blue mussels can be 10-15 years for a typical 4-6 cm mussel (Theisen, 1973). Due to a limited ability to excrete accumulated contaminants once they are taken up (Rigét et al., 1997), the concentrations of contaminants in resident blue mussels may continue to be elevated for some years after a contamination event.

Brown seaweed also effectively accumulates contaminants such as metals, but in contrast to blue mussels the contaminants accumulated in seaweed are considered to reflect only contaminants dissolved in the seawater (and not contaminants bound to particles) (Rainbow, 1995). When sampling only the annual fresh growth tips of the seaweed, the concentration of contaminants in the seaweed can be considered a proxy for the year-to-year variations in dissolved contaminants at the sampling sites.

## 2.2 Sampling

In the area around Seqi, a total of 26 tidal stations (St. 1-26; Figure 4) were established before mining for environmental monitoring purposes, with the highest density of stations located closest to the mine site. The stations furthest away from the mine, St. 17-23, acted as reference stations not impacted by mining activities. In addition to the tidal stations, 10 stations were established for lichen sampling on land close to Seqi (Lav 1-10; Figure 5).

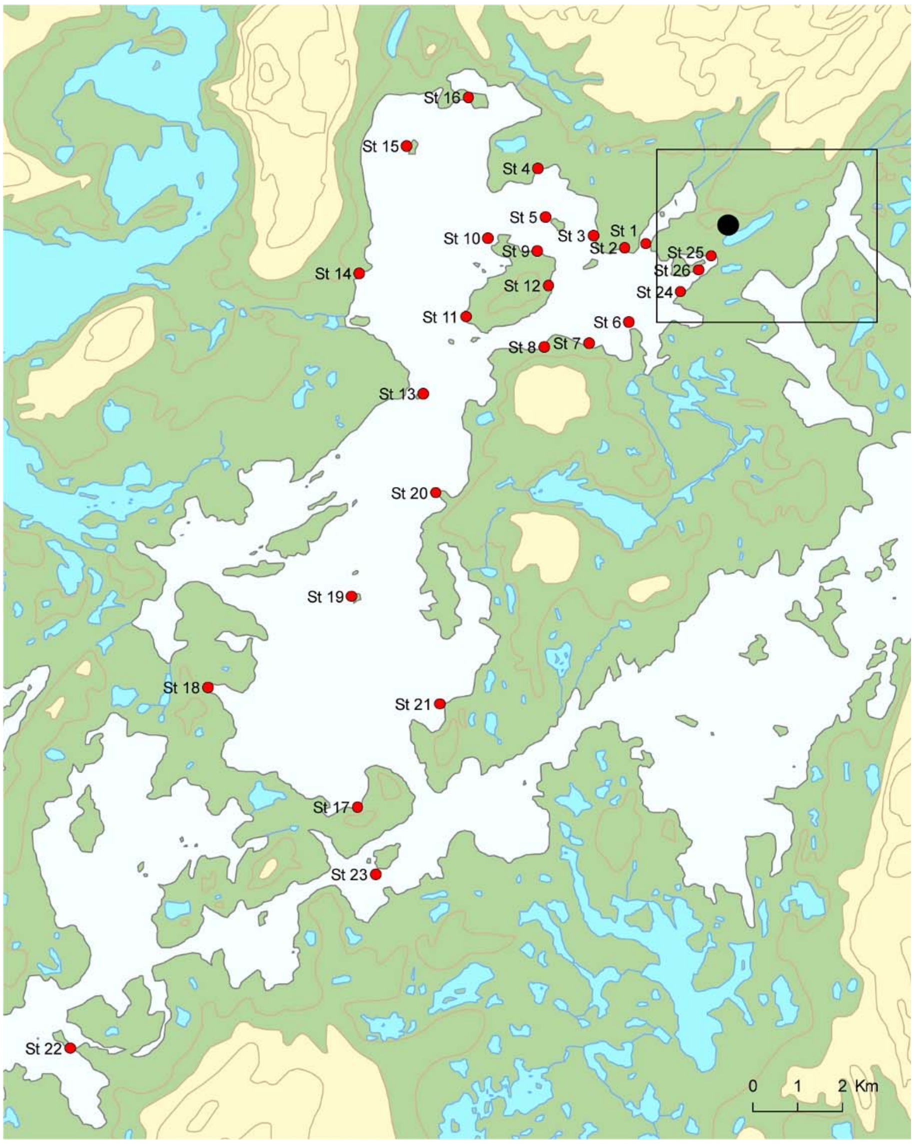


**Figure 4.** Map showing the area around the mine site (black dot) and the tidal stations (St. 1-26) where blue mussels, seaweed and lichens were sampled. The box indicates the area where additional lichen stations were established (see also Figure 5).

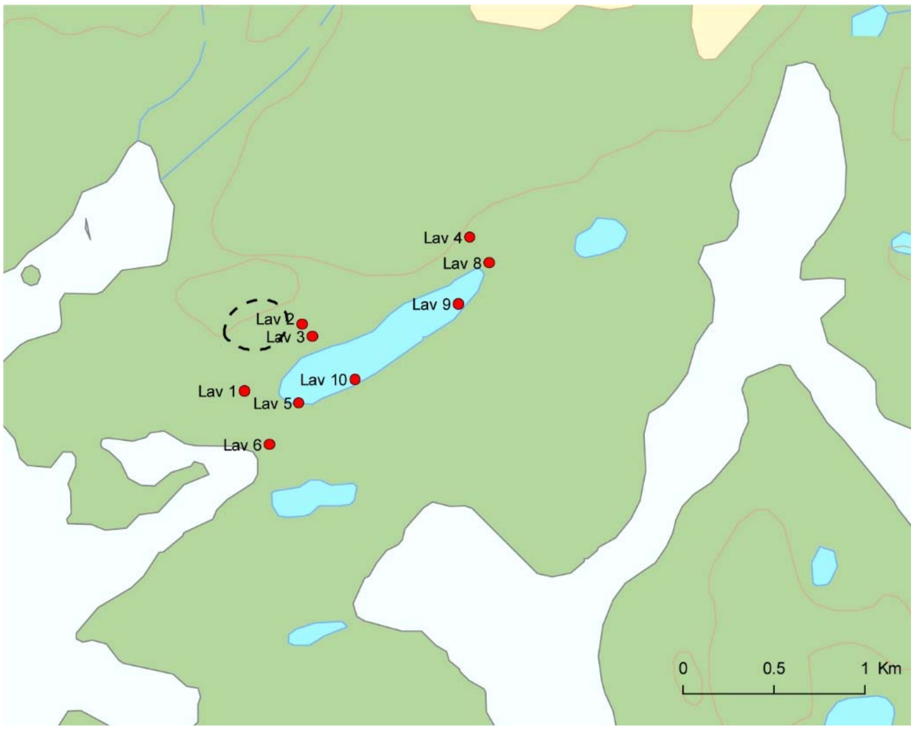


**Figure 5.** Map showing the lichen stations (Lav 1-10) around the Seqi mine site. The circle displays the mining area.

The coordinates of all the tidal stations and lichen stations are listed in Table 1.

Table 1. Positions of tidal stations (St. 1-26) and lichen stations (Lav 1-10).

| **Station** | **Position** | | **Station** | **Position** | |
|---|---|---|---|---|---|
| | **64 N + min.** | **51 W + min.** | | **64 N + min.** | **51 W + min.** |
| | Tidal stations | | St. 19 | 54.604 | 43.767 |
| St. 1 | 59.082 | 35.489 | St. 20 | 55.846 | 41.395 |
| St. 2 | 58.922 | 35.981 | St. 21 | 53.292 | 41.252 |
| St. 3 | 59.342 | 37.292 | St. 22 | 49.124 | 51.672 |
| St. 4 | 59.747 | 39.142 | St. 23 | 51.264 | 43.094 |
| St. 5 | 59.172 | 38.428 | St. 24 | 58.354 | 34.767 |
| St. 6 | 57.922 | 35.789 | St. 25 | 58.839 | 33.617 |
| St. 7 | 57.721 | 37.699 | St. 26 | 58.594 | 34.107 |
| St. 8 | 57.584 | 38.449 | | Lichen stations | |
| St. 9 | 58.839 | 38.564 | Lav 1 | 58.932 | 33.665 |
| St. 10 | 59.007 | 39.838 | Lav 2 | 59.125 | 33.206 |
| St. 11 | 58.048 | 40.587 | Lav 3 | 59.096 | 33.195 |
| St. 12 | 58.021 | 38.815 | Lav 4 | 59.392 | 32.099 |
| St. 13 | 57.030 | 42.073 | Lav 5 | 58.898 | 33.281 |
| St. 14 | 58.554 | 43.561 | Lav 6 | 58.774 | 33.486 |
| St. 15 | 60.037 | 42.334 | Lav 7 | 58.326 | 34.596 |
| St. 16 | 60.527 | 40.556 | Lav 8 | 59.317 | 31.965 |
| St. 17 | 52.056 | 43.592 | Lav 9 | 59.196 | 32.174 |
| St. 18 | 53.415 | 47.788 | Lav 10 | 58.972 | 32.890 |

The 2011-2018 environmental monitoring programme focused on collection and analyses of the key monitoring species – lichens, seaweed and blue mussels – from selected stations. The programme was reduced from that conducted during the mining period because of the relatively low level of contamination observed when the mine was active. The programme was conducted during the years 2011, 2012, 2013, 2014, 2015 and 2018. During the last year of the monitoring, 2018, the programme was extended to include also samples of freshwater and surface soil and more samples of lichens at selected stations for the purpose of obtaining data for a thorough evaluation of the environmental status of the area before cease of monitoring.

### 2.2.1 Soil

Surface soil was sampled in 2018 at all stations, where lichens were also collected (St. 1, 3, 6, 9, 10, 13, 15, 19, 23, 24, 25 and 26 (Figure 4) and Lav 1, 2, 3, 4, 6, 9 and 10 (Figure 5)), a total of 19 stations. In addition, a sample of olivine sand exposed at the ground surface at station Lav 1 was taken for source characterisation (Photo 5).

**Photo 5.** Olivine sand originating from weathering of the ore body was sampled near the mine pit for source characterisation. Photo: Jens Søndergaard.


**Photo 6.** Samples of surface soil below the organic litter layer were collected at all sites in 2018. Photo: Jens Søndergaard.

Surface soil was sampled by first removing the upper organic litter layer and then sampling the upper c. 1 cm of the mineral soil (Photo 6). Three samples were collected from each site and pooled into a polyethylene bag.

### 2.2.2 Lichens

From 2011 to 2015, resident *Flavocetraria nivalis* lichens were collected at St. 10, 13, 15, 19 and 23 and transplanted *Flavocetraria nivalis* lichens were collected at St. 1, 3, 6, 9, 24, 25, 26 (Figure 4) and Lav 1, 2, 3, 4, 6, 9 and 10 (Figure 5) (Photo 7). The latter had been transplanted from an area near St. 19/23 the year before (Photo 7).

In 2018, resident *Flavocetraria nivalis* lichens were collected at all the sites listed above and *Flavocetraria nivalis* lichens transplanted three years before, in 2015, from an area near St. 19/23 were collected at St. 6, 9 and 26 and Lav 1, 2, 3, 4, 6 and 9.

The lichen samples were collected by hand, put into polyethylene bags and frozen until further preparation (sorting and freeze-drying).

**Photo 7.** Both resident and transplanted *Flavocetraria nivalis* lichens were used for assessment of dust deposition of contaminants. The transplanted lichens were collected from a reference site far from the mine (St. 19/23) and transplanted to monitoring sites near the mine and typically left there for one year. This technique enables assessment of the dust deposition from year to year. The photo shows how the transplanted lichens were left at the site supported by a net and pieces of rock. Photo: Jens Søndergaard.

### 2.2.3 Seaweed and mussels

From 2011 to 2015 and in 2018, seaweed (*Fucus vesiculosus*) and blue mussels (*Mytilus edulis*) were collected at five stations in the Seqi area (St. 19, 23, 24, 25 and 26 (Figure 4)). Collection was done by hand at low tide (Photo 8).

The seaweed and blue mussel samples were prepared at the laboratory at Greenland Institute of Natural Resources in Nuuk.

For seaweed, the tips of the seaweed distal to the bladders (representing the recent summer's growth) were cut off with a pair of stainless steel scissors. The tips were then washed three times with milliQ water, packed in polyethylene bags and frozen.

Blue mussels with 4-6 cm shell length were selected. Approximately 20 mussels were cut open and left for drainage for a few minutes. Thereafter, the soft parts were scraped out with a scalpel into a polyethylene bag and the pooled samples were frozen.

**Photo 8**. Seaweed (*Fucus vesiculosus*) and blue mussels (*Mytilus edulis*) were sampled at five selected sites during 2011-2018. Photo: Jens Søndergaard.

### 2.2.4 Freshwater

Freshwater was sampled at three locations in 2018: 1) at the inflow to Long Lake at the NE end near station Lav 8; 2) at the inflow to Long Lake from the pit area near station Lav 2; 3) at the outflow from Long Lake near station Lav 5 (Figure 5).

At each station, samples of both unfiltered and filtered freshwater were taken and stored in 15 ml polyethylene vials. Duplicate samples were taken at all stations. Filtered samples were filtered in the field using a syringe and a 0.45 µm nylon filter.

**Photo 9**. The outflow of freshwater from Long Lake where water was sampled in 2018. The pit area is visible in the background. Photo: Jens Søndergaard.

# 3. Analytical methods

All samples were analysed at the accredited Environmental Trace Element Laboratory at Department of Bioscience, Aarhus University in Roskilde, Denmark.

## 3.1 Soil, lichens, seaweed and blue mussels

Soil samples were sieved to less than 2 mm in size and freeze-dried.

Lichen samples were sorted by hand using plastic tweezers and only fresh looking green / yellow parts of the lichens were selected and freeze-dried.

Seaweed and mussel soft parts were also freeze-dried and the samples homogenised in an agate mortar.

Subsequently, 300 mg of freeze-dried sub-samples of soil, lichens, seaweed and mussels were digested in a mixture of 4 ml concentrated Merck Suprapure nitric acid and 4 ml milliQ water in Teflon bombs in an Anton Paar Multiwave 3000 Microwave Oven (following the DS259 method).

Finally, the solution was diluted to 60 grams with milliQ water and stored in polyethylene bottles until analysis.

## 3.2 Freshwater

Freshwater samples (both filtered and unfiltered) were stored cool in 15 ml polyethylene vials.

Prior to analysis, 15 µl of concentrated Merck Suprapure nitric acid was added to the samples and the acidified samples were left for a minimum of 24 hours.

### 3.2.1 Chemical analyses

All samples were analysed for element composition by Inductively Coupled Plasma Mass Spectrometry (ICP-MS) using an Agilent 7900 ICP-MS.

A total of 61 elements were analysed in the samples: lithium (Li), beryllium (Be), sodium (Na), magnesium (Mg), aluminium (Al), phosphorus (P), potassium (K), calcium (Ca), scandium (Sc), titanium (Ti), vanadium (V), chromium (Cr), manganese (Mn), iron (Fe), cobalt (Co), nickel (Ni), copper (Cu), zinc (Zn), gallium (Ga), arsenic (As), selenium (Se), rubidium (Rb), strontium (Sr), yttrium (Y), zirconium (Zr), niobium (Nb), molybdenum (Mo), ruthenium (Ru), palladium (Pd), silver (Ag), cadmium (Cd), antimony (Sb), tellurium (Te), caesium (Cs), barium (Ba), lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), lutetium (Lu), hafnium (Hf), tantalum (Ta), wolfram (W), rhenium (Re), platinum (Pt), gold (Au), mercury (Hg), thallium (Tl), lead (Pb), bismuth (Bi), thorium (Th) and uranium (U)) using the following elements as internal standards: germanium (Ge), rhodium (Rh), indium (In) and iridium (Ir).

Detection limits for the measured elements on the day of analysis were determined based on measurements of blank solutions and calculated as three times the standard deviation on these. Blank solutions are the digestion solutions alone without the samples, treated in the Teflon bombs and diluted in the same way as the samples. At least one blank solution was prepared for every series of digestion (16 vials). Detection limits on the day of analysis are reported in the data tables in the present report.

In addition to the blank solution, one duplicate sample (same sample ID but two different digestions) and at least one sample of Certified Reference Material (CRM) were analysed per series of digestion. The duplicate sample was analysed to check the repeatability of the measurements and the CRMs were analysed to check the accuracy. The CRMs used were: DORM-4, TORT-3, DOLT-5, MESS-4, PACS-2 and SLRS-6 (www.nrc-cnrc.gc.ca).

The laboratory at the Department of Bioscience is accredited by the Danish Accreditation Fund, DANAK, for the analyses and parameters listed in Table 2 with the shown detection limits and precisions.

The quality of the methods is further checked by participation in the international QUASIMEME laboratory inter-calibration programme twice a year.

**Table 2.** Accredited elements, detection limit (DL) and precision (2 SD) for ICP-MS analyses of sediment, freshwater and biota at the Department of Bioscience, Aarhus University.

| | Sediment (mg $kg^{-1}$) | | Freshwater (µg $l^{-1}$) | | Biota (mg $kg^{-1}$) | |
|---|---|---|---|---|---|---|
| **Element** | **DL** | **Precision** | **DL** | **Precision** | **DL** | **Precision** |
| Li | 1.6 | 15% | 1.0 | 15% | - | - |
| Be | 0.3 | 15% | 0.2 | 5% | - | - |
| Na | 200 | 15% | 55 | 10% | - | - |
| Mg | 15 | 15% | 10 | 10% | - | - |
| Al | 1000 | 30% | 10 | 10% | - | - |
| P | 30 | 15% | 15 | 15% | - | - |
| K | 650 | 20% | 25 | 10% | - | - |
| V | 0.2 | 15% | 0.2 | 5% | - | - |
| Cr | 0.5 | 35% | 0.2 | 5% | 0.4 | 20% |
| Mn | 5.5 | 20% | 2.5 | 15% | - | - |
| Fe | 70 | 15% | 10 | 5% | - | - |
| Co | 0.2 | 10% | 0.2 | 8% | - | - |
| Ni | 0.3 | 15% | 0.5 | 10% | 0.3 | 15% |
| Cu | 2.5 | 15% | 0.8 | 10% | 2 | 15% |
| Zn | 1.0 | 15% | 10 | 15% | 5 | 15% |
| As | 0.6 | 35% | 1.0 | 20% | 2 | 20% |
| Se | 1.0 | 25% | 0.5 | 10% | 1 | 20% |
| Sr | 0.4 | 50% | 0.5 | 5% | - | - |
| Mo | 0.7 | 25% | 2.0 | 15% | - | - |
| Ag | - | - | - | - | 0.2 | 40% |
| Cd | 0.3 | 15% | 0.1 | 10% | 0.1 | 15% |
| Sn | 0.2 | 20% | 2.0 | - | - | - |
| Sb | 0.9 | 20% | 2.0 | 40% | - | - |
| Cs | 0.2 | 10% | 0.1 | - | - | - |
| Ba | 0.5 | 10% | 1.0 | 5 | - | - |
| Pb | 1.4 | 20% | 0.3 | 10% | 0.3 | 20% |

# 4. Results and discussion

## 4.1 Soil

The aim of the soil sampling was to: 1) identify elements of potential environmental concern present in elevated concentrations in the olivine compared with typical surface soil, 2) evaluate if these elements were present in elevated concentrations in the surface soil near the mine due to dispersion and subsequent deposition as dust on the ground surface.

Surface soil was collected at 19 locations in the Seqi area in 2018 and its chemical composition was compared with that of crushed olivine sampled from the mine pit as well as between sites. A total of more than 60 elements were analysed in the samples.

Figure 6 shows concentrations of selected elements in olivine compared with surface soil at increasing distances from the mine.

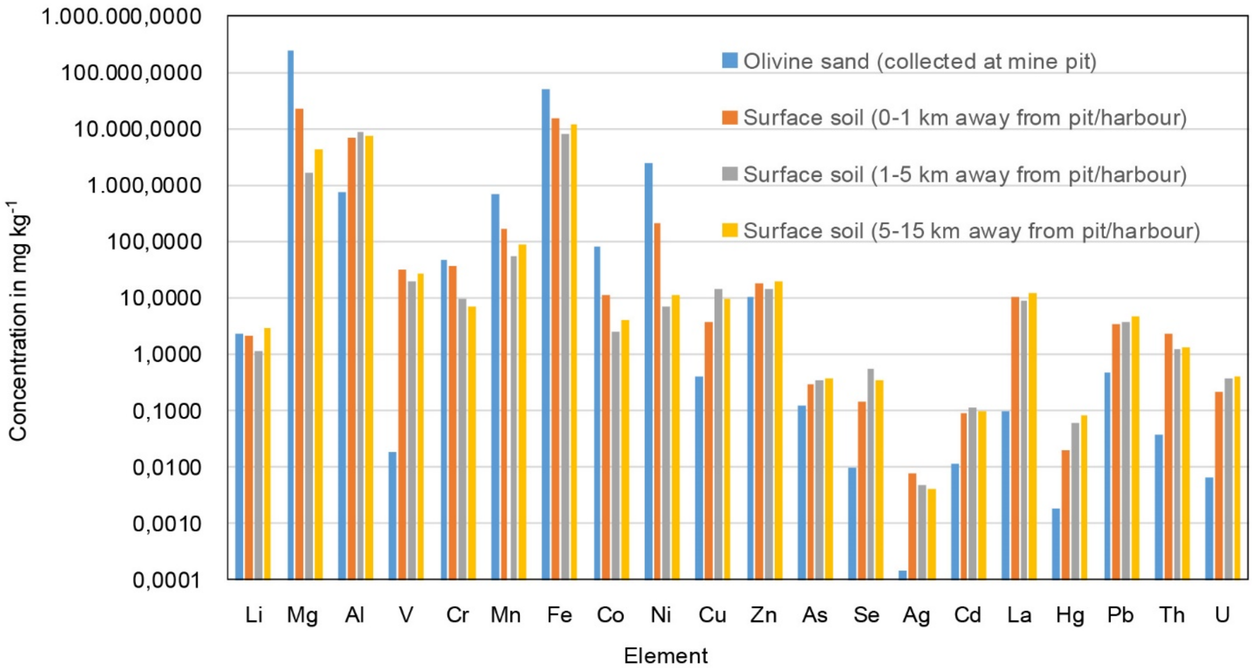


**Figure 6.** Selected elements measured in olivine sand (collected at the mine pit) and in surface soil collected at different distances to the pit/harbour area (0-1 km away: sites Lav 1-10 and St. 24-26; sites 1-5 km away: St. 1, 3, 6 and 9; sites 5-15 km away: St. 10, 13, 19 and 23). The bar represents the mean value. More than 60 elements were evaluated in total.

In the following statistical evaluation, element concentrations in olivine and in surface soil near the mine (i.e. 0-1 km away) were compared with the concentrations (mean ± 2 standard deviation (SD), i.e. the 95% confidence interval) in surface soil furthest from the mine (i.e. 5-15 km away). Of the more than 60 elements evaluated in total, Mg, Cr, Mn, Fe, Co and Ni were elevated in olivine or in surface soil close to the mine pit. The term 'elevated' here refers to concentrations above the mean + 2 SD of the concentration level in surface soil 5-15 km from the mine. Concentrations of elevated elements in surface soil are listed in Table 3.

Consequently, Mg, Cr, Mn, Fe, Co and Ni along with Cu, Zn, Cd and Pb (traditional elements of concern near mining areas) were the targeted elements in the evaluation of the remaining environmental samples.

**Table 3.** Selected elements measured in olivine sand (collected at the mine pit) and in surface soil collected at different distances to the pit/harbour area (0-1 km away: sites Lav 1-10 and St. 24-26; sites 1-5 km away: St. 1, 3, 6 and 9; sites 5-15 km away: St. 10, 13, 19 and 23). Mean and standard deviation (SD) are given. Concentrations are in mg $kg^{-1}$ dry weight. More than 60 elements were evaluated and the selected elements represent those elevated in olivine sand or in surface soil close to the mine compared with surface soil more than 5 km from the mine site.

| | Olivine sand (collected at mine pit) | | Surface soil (0-1 km away from pit/harbour) | | Surface soil (1-5 km away from pit/harbour) | | Surface soil (reference stations; 5-15 km away from pit/harbour) | |
|---|---|---|---|---|---|---|---|---|
| **Element** | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** |
| Mg | 240000 | - | 23100 | 61800 | 1600 | 587 | 4390 | 5280 |
| Cr | 46.5 | - | 37.4 | 25.8 | 9.3 | 12.2 | 7.0 | 10.9 |
| Mn | 676 | - | 165 | 197 | 56 | 16 | 88 | 93 |
| Fe | 48300 | - | 15000 | 11100 | 8060 | 3620 | 11700 | 13300 |
| Co | 82.2 | - | 11.5 | 23.2 | 2.4 | 1.5 | 3.8 | 5.3 |
| Ni | 2370 | - | 210 | 613 | 7 | 8 | 11 | 22 |

## 4.2 Lichens

Resident lichens were sampled during the baseline studies in 2004-2005, during the first years of the mining operation in 2006-2008 and in the last year of monitoring in 2018. Transplanted lichens were sampled from 2009 to 2018. The results are shown in Table 4.

**Table 4.** Selected element concentrations (mg $kg^{-1}$ dry weight) in resident and transplanted *Flavocetraria nivalis* lichens at different distances to the mine site before, during and after mining. Underlined values are elevated compared with the baseline (pre-mining) level for the area (here defined as higher than mean + 2 SD of the baseline level). ND=Not Determined. Transplanted lichens had been placed for one year at the sites, except for 2018 when the lichens had been placed at the sites for three years.

| | **Pre-mining period** | **Mining period** | | | | **After mine closure** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Year of sampling | 2004-2005 | 2006-2008 | | 2009 | | 2010-2015 | | 2018 | | | |
| Distance from mine (km) | 0-15 (all stations) | 0-1 | 1-5 | 0-1 | 1-5 | 0-1 | 1-5 | 0-1 | 1-5 | 0-1 | 1-5 |
| Resident/ Transplanted lichens (R./T.) | R. | R. | R. | T. | T. | T. | T. | T. | T. | R. | R. |
| Element | Mean ± SD | Annual mean | Annual mean | Annual mean | Annual mean | Annual mean | Annual mean | Annual mean | Annual mean | Annual mean | Annual mean |
| Mg | 1650 ± 600 | 1740-2170 | 942-1220 | ND | ND | 1480-2400 | 1340-1790 | 1560 | 1320 | 1380 | 992 |
| Cr | 0.35 ± 0.36 | 2.72-18.2 | 0.44-2.58 | 7.08 | 1.87 | 0.88-5.13 | 0.32-0.98 | 0.50 | 0.28 | 1.41 | 0.25 |
| Mn | 71 ± 69 | 50-108 | 48-61 | 49 | 36 | 15-35 | 14-38 | 24 | 19 | 40 | 80 |
| Fe | 123 ± 77 | 251-727 | 103-156 | 662 | 356 | 117-299 | 88-188 | 107 | 90 | 89 | 69 |
| Co | 0.20 ± 0.19 | 0.33-2.20 | 0.12-0.33 | 1.09 | 0.38 | 0.19-0.71 | 0.10-0.30 | 0.27 | 0.22 | 0.19 | 0.14 |
| Ni | 1.07 ± 1.66 | 6.91-48.3 | 0.99-4.60 | 19.8 | 4.19 | 1.64-13.3 | 0.71-1.54 | 2.55 | 0.92 | 2.40 | 0.75 |
| Cu | 0.93 ± 0.55 | 0.66-1.16 | 0.55-0.82 | 0.97 | 0.91 | 0.52-0.72 | 0.50-0.73 | 0.66 | 0.61 | 0.59 | 0.52 |
| Zn | 22 ± 12 | 18.2-26.0 | 14.5-23.2 | 16.5 | 16.5 | 8.4-13.3 | 9.0-13.2 | 12.7 | 13.8 | 15.2 | 19.3 |
| Cd | 0.081 ± 0.035 | 0.070-0.091 | 0.064-0.089 | ND | ND | 0.015-0.066 | 0.019-0.097 | 0.058 | 0.080 | 0.049 | 0.048 |
| Pb | 0.60 ± 0.22 | 0.517-0.886 | 0.540-0.925 | 2.04 | 1.58 | 0.383-0.784 | 0.275-0.867 | 0.535 | 0.473 | 0.309 | 0.336 |

As shown in Table 4, the elements Cr, Fe, Co and Ni were elevated in lichens up to 5 km from the mine site during the mining period. After the mine closed in 2009, concentrations decreased, and in 2018 only Cr was slightly elevated in resident lichens and only within 1 km from the mine.

Figure 7 shows the temporal variation of Cr and Ni in resident lichens during the first years of mining operation (2006-2008) and in transplanted lichens during the rest of the monitoring period (2009-2018) at different distances from the mine.

As shown in Figure 7, the concentrations of Cr and Ni increased in resident lichens from 2006 to 2008 and decreased in transplanted lichens after 2009, and today they are near the baseline mean level at distances 1-5 km from the mine. The concentrations in transplanted lichens from sites located 0-1 km from the mine are higher than at sites located 1-5 km away but did not exceed the upper 95% confidence interval of the baseline level in 2018.

Figure 8 shows the spatial variation of Cr and Ni in transplanted lichens collected in 2018.

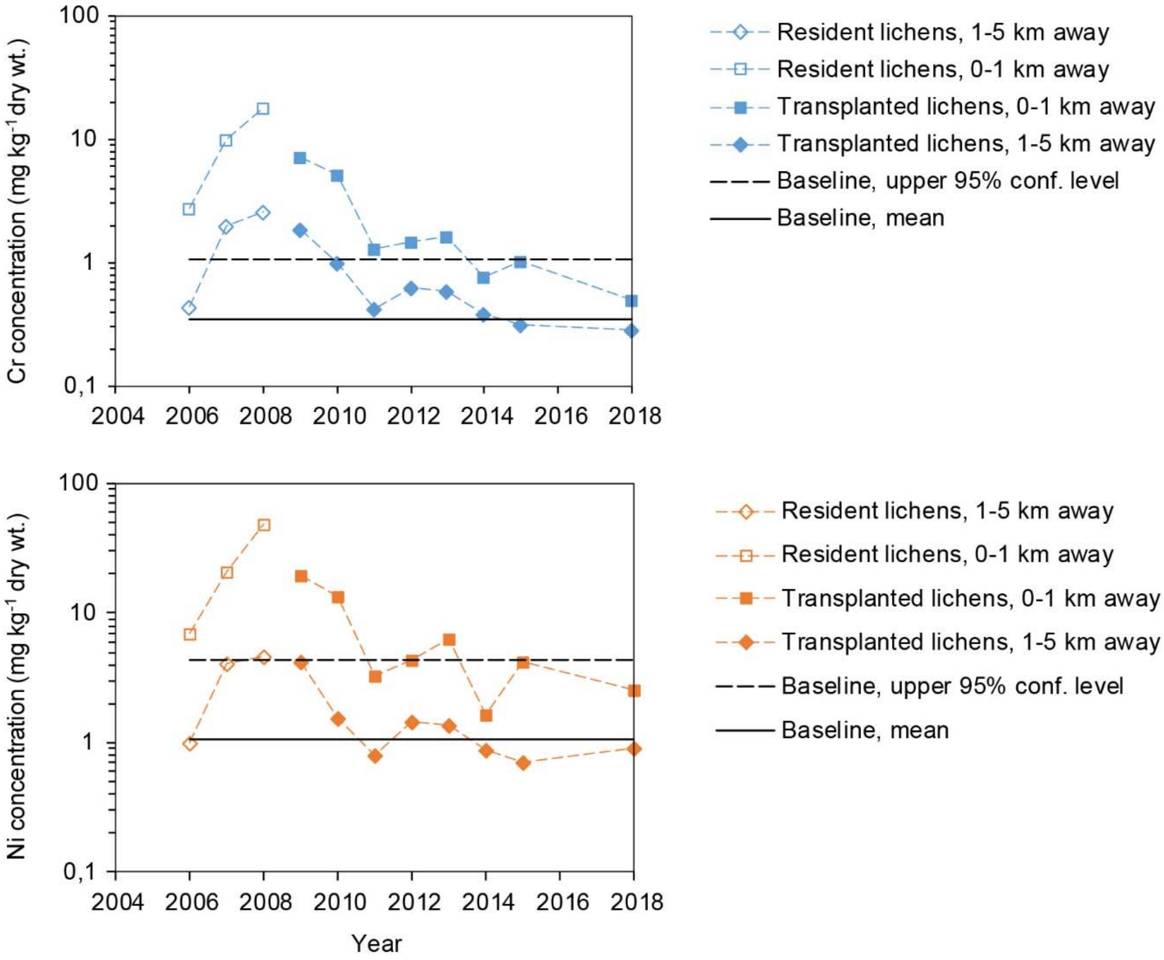


**Figure 7**. Concentrations of chromium (Cr, upper graph) and nickel (Ni, lower graph) in resident and transplanted *Flavocetraria nivalis* lichens at different distances to the mine pit/former ore crusher (0-1 km and 1-5 km, respectively) during the period 2006-2018. The mean baseline level for the entire area and the upper 95% confidence level of the baseline are also shown. Transplanted lichens were placed at the sites for one year, except for transplanted lichens collected in 2018, which were placed for three years..

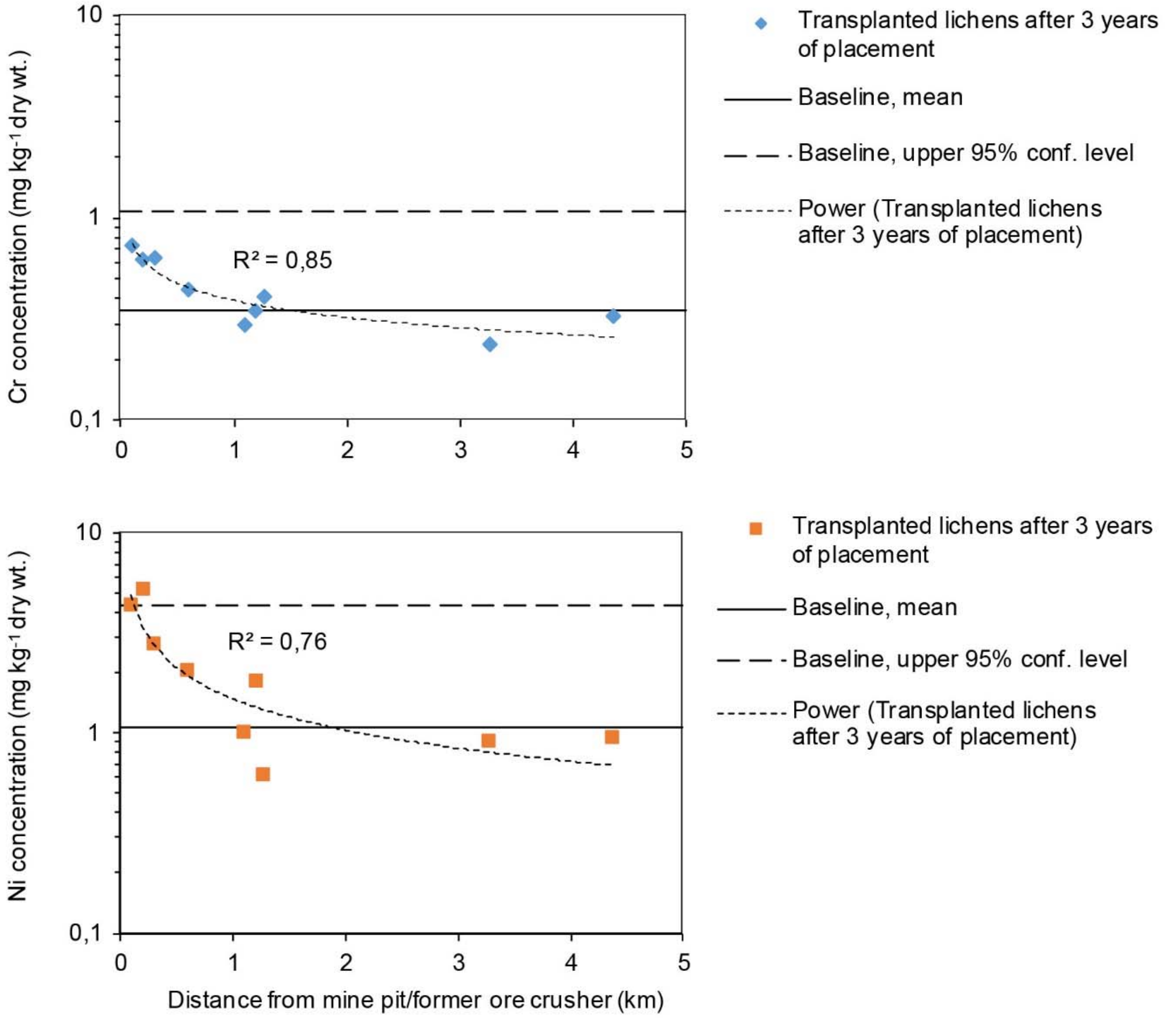


**Figure 8**. Concentrations of chromium (Cr, upper graph) and nickel (Ni, lower graph) in transplanted *Flavocetraria nivalis* lichens after three years of placement in 2015-2018 relative to distances to the mine pit/former ore crusher. The best-fitting trend line and correlation coefficient are also shown together with the mean baseline level for the entire area and the upper 95% confidence level.

As shown in Figure 8, the concentrations of Cr and Ni in transplanted lichens collected in 2018 decreased with distance to the mine pit / former ore crusher and were near the baseline mean approximately 1 km away.

The findings of the analyses of resident lichens sampled from 2006 to 2008 indicate that the dispersion and subsequent deposition of dust containing elevated concentrations of mainly Cr, Fe, Co and Ni increased as a result of the mining activities during the first years of mining operation. Elevated concentrations could be measured up to c. 5 km away from the mining area. No naturally elevated concentrations were identified in the olivine deposit during the baseline studies (Asmund et al., 2009). Subsequently, transplanted lichens were used to assess the temporal variation in dust deposition from 2008 to 2018. The results from transplanted lichens indicate that dust deposition peaked during the first monitoring year (2008-2009) and decreased thereafter. In 2018, concentrations had decreased to undetectable levels in transplanted lichens at distances more than 1 km away from the mining area. Within 1 km of the mine pit / former ore crusher site, slightly elevated concentrations were observed in both resident and transplanted lichens, indicating that there is still a minor mine-related dust dispersion and deposition within this area, most pronounced in the immediate vicinity to the mine pit.

## 4.3 Seaweed

Seaweed was sampled at three stations (St. 24, 25 and 26) in close vicinity to the harbour and at two reference sites (St. 19 and 23) located 10-15 km away from the harbour. During the mining period, slightly elevated concentrations of Cr and Ni were found in seaweed (and blue mussels) and only at sites in close vicinity to the harbour (Søndergaard et al., 2009; Søndergaard and Asmund, 2010). Consequently, the monitoring programme for 2011-2018 included only these relatively few marine sites.

Mean concentrations of selected elements in seaweed at the sites close to the harbour versus the reference sites for the different years are shown in Table 5.

**Table 5.** Selected element concentrations (mg kg$^{-1}$ dry weight) in *Fucus vesiculosus* seaweed at different distances to the mine site before, during and after mining. Underlined values are elevated compared with the baseline level for the entire area (here defined as higher than mean + 2 SD of the pre-mining level).

| | **Pre-mining period** | **Mining period** | | **After mine closure** | | | |
|---|---|---|---|---|---|---|---|
| Year of sampling | 2004-2005 | 2006-2009 | | 2010-2015 | | 2018 | |
| Station | All stations | St. 24-26 | St. 19/23 | St. 24-26 | St. 19/23 | St. 24-26 | St. 19/23 |
| Distance from port (km) | 0-15 | 0-1 | 10-15 | 0-1 | 10-15 | 0-1 | 10-15 |
| Element | Mean ± SD | Annual mean | Annual mean | Annual mean | Annual mean | Annual mean | Annual mean |
| Mg | 8250 ± 644 | 6760-7670 | 6070-7740 | 8400-9910 | 8900-10300 | 9180 | 9046 |
| Cr | 0.398 ± 0.390 | 0.347-1.470 | 0.108-0.342 | 0.154-0.375 | 0.069-0.180 | 0.272 | 0.174 |
| Mn | 17.9 ± 9.8 | 25.0-64.3 | 8.63-11.3 | 19.6-32.2 | 6.89-11.2 | 24.5 | 7.13 |
| Fe | 69.1 ± 73.4 | 50.0-139 | 12.8-86.6 | 51.0-110 | 19.3-35.8 | 35.5 | 20.3 |
| Co | 0.588 ± 0.340 | 0.344-0.590 | 0.212-0.369 | 0.296-0.579 | 0.221-0.374 | 0.341 | 0.217 |
| Ni | 2.28 ± 1.19 | 1.26-3.64 | 0.997-1.25 | 0.918-3.40 | 0.785-1.17 | 1.40 | 0.960 |
| Cu | 1.93 ± 0.56 | 2.65-6.94 | 1.69-3.35 | 1.55-3.84 | 1.38-2.18 | 2.27 | 1.68 |
| Zn | 12.1 ± 3.5 | 10.6-19.1 | 5.26-9.87 | 7.01-15.2 | 5.92-13.7 | 8.34 | 9.46 |
| Cd | 1.95 ± 0.64 | 0.957-1.119 | 2.35-2.36 | 1.40-1.87 | 2.57-3.52 | 1.49 | 3.27 |
| Pb | 0.051 ± 0.030 | 0.024-0.055 | 0.044-0.056 | 0.025-0.413 | 0.015-0.355 | 0.771 | 0.301 |

As shown in Table 5, seaweed showed relatively large variations in chemical composition between years. Concentrations of Cr, Mn, Cu and Pb exceeded the baseline (pre-mining) level at the sites closest to the harbour in some years. However, the data on Mn, Cu and Pb showed no consistency between years. Further, Cu and Pb are likely not mine-related contaminants (see Chapter 4.1). Consequently, the variation observed for Mn, Cu and Pb is considered a result of natural year-to-year variations and not of the mining activities. Elevated concentrations were only consistent for Cr and Ni, and only at St. 25, which is situated closest to the harbour. The concentrations of Cr and Ni in seaweed at St. 25 in the period 2005-2018 are shown in Figure 9.

As shown in Figure 9, the concentrations of Cr and Ni in seaweed at St. 25 were elevated during the mining period and shortly after, but had decreased to the baseline level in 2018.

Since seaweed takes up metals dissolved in the seawater, dispersion of dissolved metals from the mining area into the marine environment at Seqi, measured during the latest sampling in 2018, is negligible.

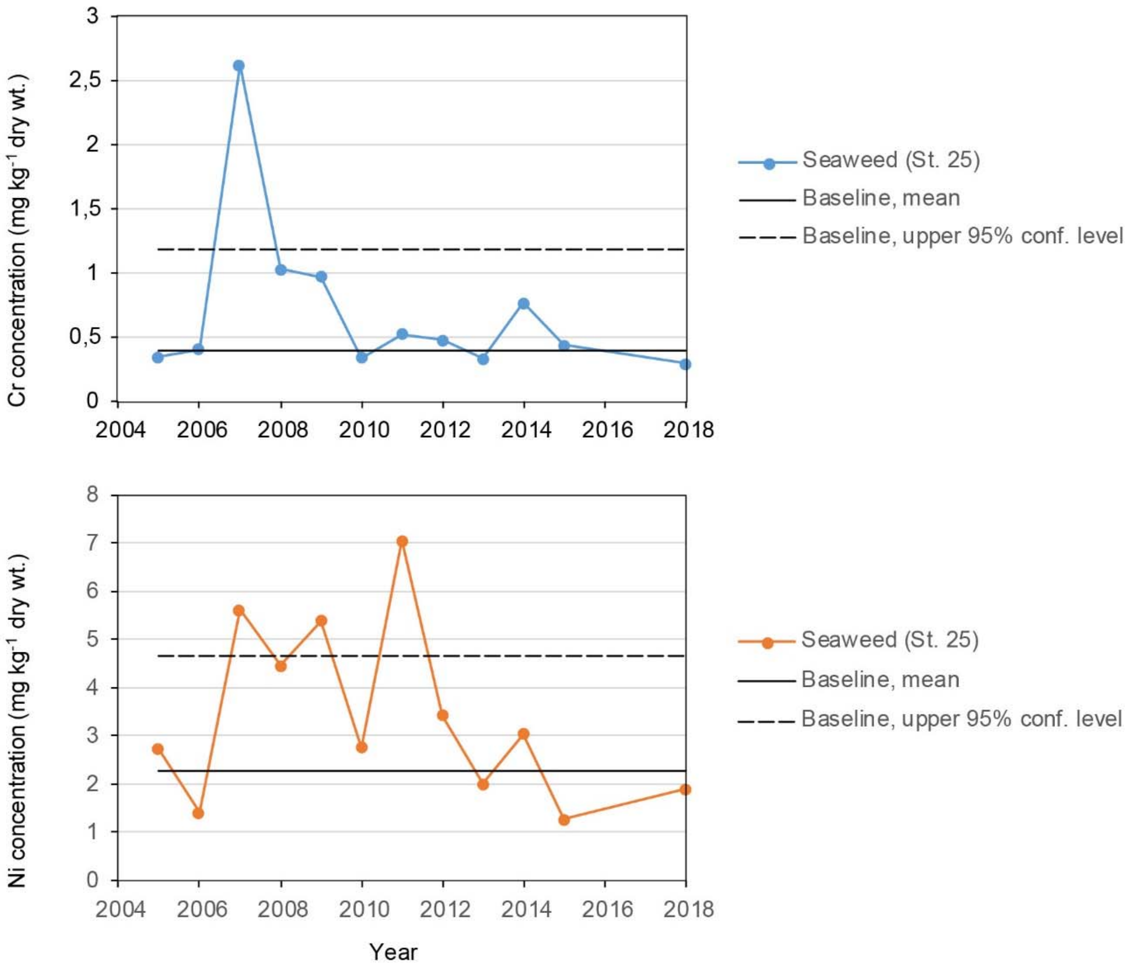


**Figure 9.** Concentrations of chromium (Cr, upper graph) and nickel (Ni, lower graph) in *Fucus vesiculosus* seaweed collected at the site closest to the harbour (St. 25) during the period 2005-2018. The mean baseline level for the entire area and the upper 95% confidence level of the baseline are also shown.

## 4.4 Mussels

Blue mussels were sampled at the same stations as the seaweed.

Mean concentrations of selected elements in blue mussels at the sites close to the harbour versus concentrations at the reference sites for the different years are shown in Table 6.

As shown in Table 6, in some years of the mining period the concentrations of Cr, Ni and Cu exceeded the baseline (pre-mining) level at the sites closest to the harbour. The concentration of Cu only just exceeded the baseline level and only in one year, and the observed variations in Cu are therefore considered to be induced by natural year-to-year variations and not the mining activities. In contrast, at St. 25, situated closest to the harbour, the elevated concentrations of Cr and Ni observed in blue mussels were consistent (see Figure 10).

**Table 6.** Selected element concentrations (mg kg$^{-1}$ dry weight) in resident *Mytilus edulis* mussels (blue mussels) at different distances to the mine site before, during and after mining. Underlined values are elevated compared with the baseline level for the entire area (here defined as higher than mean + 2 SD of the pre-mining level).

| | **Pre-mining period** | **Mining period** | | **After mine closure** | | | |
|---|---|---|---|---|---|---|---|
| Year of sampling | 2004-2005 | 2006-2009 | | 2010-2015 | | 2018 | |
| Station | All stations | St. 24-26 | St. 19/23 | St. 24-26 | St. 19/23 | St. 24-26 | St. 19/23 |
| Distance from port (km) | 0-15 | 0-1 | 10-15 | 0-1 | 10-15 | 0-1 | 10-15 |
| Element | Mean ± SD | Annual mean | Annual mean | Annual mean | Annual mean | Annual mean | Annual mean |
| Mg | 5120 ± 1610 | 3790-4520 | 3250-4380 | 5140-5990 | 4260-5430 | 6295 | 5191 |
| Cr | 1.39 ± 0.81 | 1.66-<u>5.48</u> | 0.86-1.05 | 1.57-2.44 | 0.672-1.25 | 1.44 | 0.88 |
| Mn | 5.68 ± 3.05 | 4.42-6.86 | 3.31-6.85 | 5.07-8.57 | 4.50-6.35 | 5.42 | 5.52 |
| Fe | 206 ± 173 | 217-328 | 92-172 | 168-440 | 112-175 | 272 | 123 |
| Co | 0.466 ± 0.230 | 0.358-0.679 | 0.296-0.454 | 0.444-0.660 | 0.339-0.658 | 0.522 | 0.374 |
| Ni | 3.09 ± 2.71 | 2.12-<u>9.14</u> | 1.06-2.07 | 2.80-3.68 | 1.05-5.79 | 2.67 | 1.31 |
| Cu | 5.85 ± 1.38 | 6.06-<u>8.75</u> | 5.47-8.16 | 6.63-8.15 | 6.59-8.12 | 8.17 | 7.54 |
| Zn | 77.0 ± 23.2 | 62.8-94.3 | 60.3-101 | 65.4-101 | 71.1-95.6 | 81.5 | 94.5 |
| Cd | 3.98 ± 1.15 | 2.10-2.21 | 3.14-4.47 | 3.80-4.34 | 3.54-4.87 | 4.06 | <u>6.31</u> |
| Pb | 0.382 ± 0.132 | 0.389-0.622 | 0.395-0.567 | 0.325-0.636 | 0.357-0.588 | 0.623 | 0.405 |

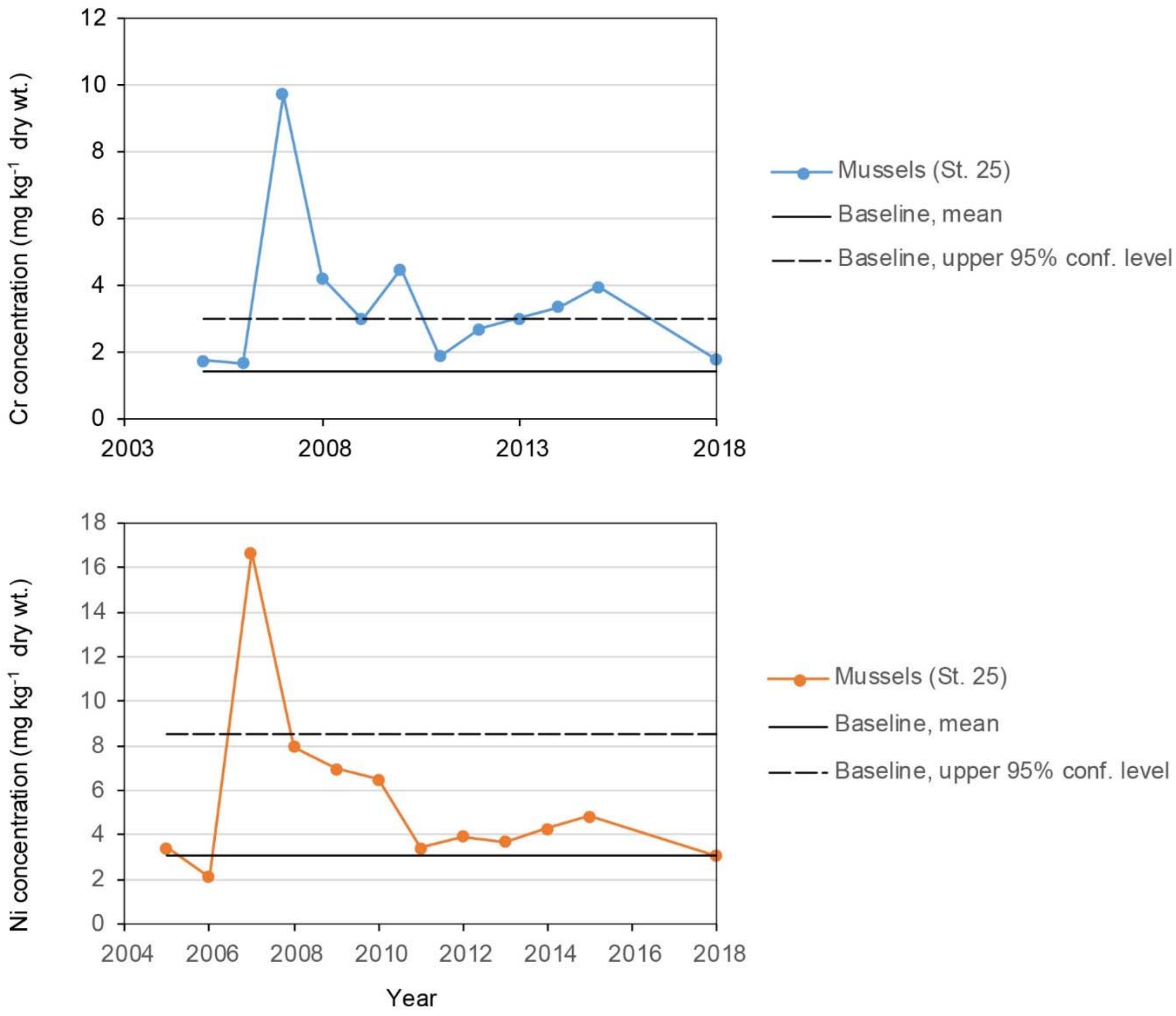


**Figure 10.** Concentrations of chromium (Cr, upper graph) and nickel (Ni, lower graph) in resident *Mytilus edulis* mussels (blue mussels) collected at the site closest to the harbour (St. 25) during the period 2005-2018. The mean baseline level for the entire area and the upper 95% confidence level of the baseline are also shown.

As shown in Figure 10, the concentrations of Cr and Ni in blue mussels at St. 25 were elevated and peaked in 2007 during the mining period, but in 2018 the concentrations had reached the baseline level.

As blue mussels take up both metals dissolved in the seawater and particle-bound metals (Rainbow, 1995), the dispersion of both dissolved and particle-bound metals from the mining area into the marine environment at Seqi, as measured during the latest sampling in 2018, appears to be negligible.

## 4.5 Freshwater

Freshwater was sampled at three locations in 2018: in the inflow to Long Lake at the NE end, in the inflow to Long Lake in the pit area and in the outflow from Long Lake.

Mean concentrations of selected elements in unfiltered and filtered water samples from the three locations are shown in Table 7 relative to the Greenland Water Quality Criteria.

**Table 7.** Selected elements measured in unfiltered and filtered (<0.45 µm) freshwater in the inflow to Long Lake (from the NE end and from the mine pit area, respectively) and outflow of Long Lake (in µg $l^{-1}$). Values for Greenland Water Quality Criteria (GWQC) for filtered water for mining activities (MRA, 2015) are also shown

| | **Inflow, NE end (near St. Lav 8)** | | **Inflow from pit area (near st. Lav 2)** | | **Outflow (near st. Lav 5)** | | **QWQC** |
|---|---|---|---|---|---|---|---|
| Element/type | Unfiltered | Filtered | Unfiltered | Filtered | Unfiltered | Filtered | Filtered |
| Mg | 1054 | 1042 | 9474 | 9471 | 1724 | 1721 | - |
| Cr | 0.412 | 0.400 | 0.242 | 0.236 | 0.175 | 0.178 | 3 |
| Mn | 1.330 | 1.250 | 0.083 | 0.056 | 0.840 | 0.185 | - |
| Fe | 48.6 | 41.8 | 5.85 | 3.56 | 20.4 | 13.1 | 300 |
| Co | 0.064 | 0.061 | 0.031 | 0.027 | 0.026 | 0.020 | - |
| Ni | 1.15 | 1.14 | 11.4 | 11.2 | 2.00 | 2.01 | 5 |
| Cu | 1.30 | 1.28 | 0.242 | 0.300 | 0.602 | 0.598 | 2 |
| Zn | 0.733 | 0.735 | 0.634 | 0.694 | 0.567 | 0.585 | 10 |
| Cd | 0.002 | 0.002 | 0.001 | 0.001 | 0.001 | 0.001 | 0.1 |
| Pb | 0.019 | 0.020 | 0.006 | 0.009 | 0.011 | 0.015 | 1 |

As shown in Table 7, the concentrations of Mg and Ni in the inflow water to Long Lake from the pit area were approximately a factor 10 higher than in the inflow water not directly affected by the pit at Long Lake's NE end. The concentrations of Cr, Fe and Co, which were higher in surface soil near the mine, were not higher in the water from the pit area compared with the inflow at Long Lake's NE end. The concentrations of Mg and Ni in the outflow of Long Lake ranged in-between the concentrations measured in the inflow to the NE end of Long Lake and the concentrations in water from the pit area. Element concentrations were almost identical in the unfiltered and filtered samples, except for Mn and Fe, whose concentrations were higher in the unfiltered samples. The water quality in the outflow of Long Lake complied with the Greenland Water Quality Criteria (GWQC).

The results above indicate that Ni and Mg are leached in run-off from the mine pit, resulting in slightly elevated concentrations of Mg and Ni in the outflow of Long Lake. The almost similar results for Mg and Ni in the unfiltered and filtered samples indicate that these elements are mainly present in dissolved form. Mg is a macronutrient to plants and animals and is not considered an environmental contaminant. Ni is known as an element of potential environmental concern (Adriano, 2001). However, the observed dissolved Ni concentration in the outflow from Long Lake of 2 µg $l^{-1}$ was well below the GWQC level of 5 µg $l^{-1}$. Consequently, the environmental impact of the increased dissolved Ni input from the mining area is considered negligible. This conclusion is supported by the results of the seaweed and mussel analyses presented above, which (in contrast to the water sampling) provide a time-integrated measure of the bioavailable Ni concentrations in the water near the outflow from Long Lake.

# 5. Conclusion

An environmental monitoring programme was conducted at the former Seqi olivine mine site from 2011 to 2018, and this report presents the results and conclusions drawn.

In the terrestrial environment, the results from collection and analyses of lichens showed that dispersion and subsequent deposition of dust from the mining activities (containing elevated concentrations of mainly Cr, Fe, Co and Ni) peaked in the mining period. During the last year of the monitoring, in 2018, dust deposition had decreased to undetectable levels in lichens at distances more than 1 km away from the mining area. Within 1 km of the mine pit / former ore crusher site, slightly elevated concentrations were observed in lichens during the entire period. This indicates that there is still (in 2018) some minor dust dispersion and deposition within this limited area, with the highest concentrations in the immediate vicinity of the mine pit.

Fresh water running in and out of Long Lake, which is located in close vicinity to the mine site, was sampled in 2018. The water showed moderately elevated concentrations of Ni in the run-off from the mine pit. However, due to subsequent dilution of the run-off in the lake, the water quality in the outflow of Long Lake into the marine environment complied with the Greenland Water Quality Criteria for mining activities.

In the marine environment, the concentrations of the main contaminants Cr and Ni in seaweed and blue mussels had decreased to baseline levels in 2018. This indicates that dispersion of both dissolved and particle-bound metals from the mining area into the marine environment at Seqi, as measured during the latest sampling in 2018, is negligible.

In conclusion, the monitoring campaign showed that the concentrations of contaminants in both the terrestrial and marine environment had decreased since the mining activities stopped in 2009. Only slightly elevated levels of Cr and Ni could be measured in the terrestrial environment within 1 km from the mine and not in the marine environment. Consequently, the environmental impact from the former mining activities on the environment at Seqi is assessed as insignificant.

DCE is not acquainted with the status and planned maintenance of the large pier left at Seqi. However, since the quay is not composed of olivine or any reactive material, it is not considered a significant environmental issue. However, in case the pier is to be removed at some point in the future, environmental monitoring studies may be relevant to evaluate this.

Based on the above, DCE assesses that further environmental studies are not required at Seqi at this stage.

DCE considers the Seqi mine an example of how a mine can be successfully operated in Greenland with minimal environmental impact. Important elements of this success was the assessment made of the potential detrimental environmental impacts prior to mining commencement, including baseline studies. Based on this assessment, adequate environmental requirements and conditions were established as part of the licensing, and environmental monitoring and regulation during the mine operation allowed mitigation of the dust dispersal detected by the monitoring.

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# ENVIRONMENTAL MONITORING AT THE FORMER SEQI OLIVINE MINE IN SOUTHWEST GREENLAND 2011-2018.

The olivine mine at Seqi in Southwest Greenland operated between 2005 and 2009. This report contains the results from monitoring studies conducted after mine closure between 2011 and 2018. The studies included sampling of lichens, blue mussels and seaweed, supplemented with sampling of surface soil and freshwater in 2018. Contamination (mainly with chromium and nickel) had decreased since mine closure and elevated concentrations of contaminants could only be detected in lichens within a distance of 1 km from the pit area and former ore crushing facility. Elevated concentrations of contaminants could neither be measured in blue mussels nor seaweed during the latest sampling in 2018. The results indicate that there is still minor dust dispersion and deposition in close vicinity to the mine but no significant dispersion of contaminants to the marine environment. Overall, DCE assesses the impact from the former mining activities at Seqi as insignificant to the environment at Seqi. Consequently, DCE considers the Seqi olivine mine to serve as an example of how a mine can be operated with minimum environmental impact by establishing adequate environmental requirements and conditions as part of the license and through detailed environmental monitoring and regulation during mine operation.

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