Dispersion and bioaccumulation of elements from an open-pit olivine mine in Southwest Greenland assessed using lichens, seaweeds, mussels and fish

Jens Søndergaard

Received: 1 August 2012 / Accepted: 3 January 2013
© Springer Science+Business Media Dordrecht 2013

Abstract This study investigated dispersion and bioaccumulation of mining-related elements from an open-pit olivine mine at Seqi in Southwest Greenland (64°N) using lichens (*Flavocetraria nivalis*), seaweeds (*Fucus vesiculosus*), mussels (*Mytilus edulis*) and fish (*Myoxocephalus scorpius*). The mine operated between 2005 and 2009, and samples were taken every year within a monitoring area 0–17 km from the mine during the period 2004–2011. A total of 46 elements were analysed in the samples. After mining began, highly elevated metal concentrations, especially nickel (Ni), chromium (Cr), iron (Fe) and cobalt (Co), were observed in lichens relative to pre-mining levels (up to a factor of 130) caused by dust dispersion from the mining activity. Elevated metal concentrations could be measured in lichens in distances up to ~5 km from the mine/ore treatment facility. Moderately elevated concentrations of Ni and Cr (up to a factor of 7) were also observed in seaweeds and mussels but only in close vicinity (<1 km) to the mine. Analyses of fish showed no significant changes in element composition. After mine closure, the elevated metal concentrations in lichens, seaweeds and mussels decreased markedly, and in 2011, significantly elevated metal

concentrations could only be measured in lichens and only within a distance of 1 km from the mine.

Keywords Olivine · Mining · Dispersion · Bioaccumulation · Greenland

Introduction

Dispersion of elements from the mining industry is a well-known environmental concern. Mine-related elements such as metals may pose a threat to the environment due to their bioaccumulation and potential toxicity to biota (Josefson et al. 2008; Torres et al. 2008). Furthermore, dispersion of mine-related elements as dust or as aqueous dissolved or particle-bound metals may last for decades after mine closure (Søndergaard et al. 2011a, b; Zimmer et al. 2011). Assessment of element dispersion and bioaccumulation near mines, both in the terrestrial and marine environment, is therefore important to evaluate the mine-related pollution sources and, if needed, to address measures to reduce them.

As biological indicator species: lichens, seaweeds, mussels and sedentary fish such as shorthorn sculpins have been used in a number of studies related to mining activities (Gibb et al. 1996; Johansen et al. 1991; Naeth and Wilkinson 2008). Lichens are extensively used as bio-indicators of terrestrial dust deposition due to their widespread abundance and their ability to accumulate and concentrate elements deposited from the air (Nash

J. Søndergaard (✉)
Department of Bioscience, Aarhus University,
Frederiksborgvej 399,
DK-4000 Roskilde, Denmark
e-mail: jens@dmu.dk

1996). Seaweeds, mussels and sedentary fish such as shorthorn sculpins accumulate most metals and reflect different bioavailable metal sources within the marine environment (Rainbow 1995). Adjacent to mining activities in Greenland, environmental monitoring programmes typically focus on the above-mentioned four bio-indicators to evaluate the dispersion of elements in the surrounding area (Johansen et al. 2010; Glahder et al. 2010).

In late 2005, a mine was opening at Seqi in Southwest Greenland by the Swedish company Minelco with the purpose of mining the mineral olivine (Fig. 1). Olivine is a low-value industrial mineral primarily used in steel production as slag former, for sand blasting and as foundry sand (Minelco 2012). Besides that, olivine is recognized as a promising cost-effective CO₂ sequestration agent, which may help to reduce the anthropogenic impact on climate as olivine is widely abundant, easily extractable and weathers quickly on the earth's surface, storing the CO₂ in environmentally safe and stable bicarbonates (Lackner 2003). At the olivine mine at Seqi, a total of 1.7 million tons of olivine were extracted from 2005 to 2009 when the mining was stopped due to economic reasons (BMP 2010).

This study evaluates the spatial and temporal trends of dispersion and bioaccumulation of elements related to the mining activities at Seqi. The study is based on continuous samplings of lichens (*Flavocetraria nivalis*), seaweeds (*Fucus vesiculosus*), mussels (*Mytilus edulis*) and fish (*Myoxocephalus scorpius*) conducted before, during and after the mining activities from 2004 to 2011. According to the knowledge of the author, this is the first study to evaluate element contamination from olivine mining, and hopefully, it will serve as an important case study for future activities.

Methods and instrumentation

Study area

The Seqi olivine mine is located in Southwest Greenland in the bottom of the fiord Fiskefjord (64°59'N; 51°33'W), approximately 90 km north of the capital Nuuk (Fig. 1). The nearest settlement is Atammik situated at the inlet of the fiord, 40 km southwest of the mine. The climate is low Arctic with average summer temperatures around 5 °C for July and winter temperatures around

Fig. 1 Location of the Seqi olivine mine in Southwest Greenland (64°N) with the sampling stations marked. Station C1 to C16 are coastal stations (lichens, seaweeds and mussels sampled), and I1 to I8 are inland stations (only lichens sampled). Shorthorn sculpins were sampled at the inner part of the fiord within an area 5 km from the mine. The lower detailed map shows the location of the open-pit mine, the roads, the ore treatment facility (crushing, sieving and loading of ore) and the port area

−7 °C for January (Priestley 2004). Precipitation is moderate, averaging 60 mm per month during summer and 40 mm during winter. Winds are predominantly east–north–easterly, and the mine is accessible for ships most of the year due to limited sea ice cover in the fiord. Vegetation in the area is sparse and consists mainly of grasses and low scrub.

Geologically, the Seqi olivine deposit is a dunite-type deposit, and the olivine is contained in igneous, ultramafic rocks (Zuo 2006). The olivine ((Mg, Fe)₂SiO₄) in the deposit is contained in a mixture of

two minerals, forsterite and fayalite, which are the Mg- and Fe-rich end members, respectively. The deposit is characterized by a very homogeneous composition with low variation in the MgO/FeO ratio and contains more than 90 % forsterite and less than 8 % fayalite components. The bulk composition of the olivine has an average of more than 48 % MgO, making it ideal for industrial purposes (Zuo 2006). Besides MgO, the olivine contains on average 42 % SiO₂, 7.9 % Fe₂O₃, 0.76 % Al₂O₃, 0.27 % Cr₂O₃ and 0.36 % NiO. The deposit is exposed at the ground surface and was estimated to contain 150 million tons of olivine prior to the mining operation. Surrounding the deposit are peridotites and gabbro/norites in varying amounts, which could largely be avoided using an open-pit mine type. In late 2005, an open-pit mining operation was initiated. Following excavation, olivine ore was crushed, sieved and sorted according to grade at an ore treatment facility near the port area. Olivine was subsequently stored in piles before being shipped out in bulk carriers. During the period from 2006 to 2009, a total of 1.7 million tons of olivine was produced from the mine, and the largest quantities were produced in 2007 (620,000 tons) and in 2008 (420,000 tons) (BMP 2009). In 2009, the mine was stopped, and a closure plan was initiated in early 2010 (BMP 2010). The location of the open-pit mining area, the roads, the ore treatment facility and the port area can be seen in Fig. 1. After the mining stopped, the area was remediated according to the mine closure plan, and excess olivine situated in piles near the ore treatment facility was removed and placed in the open pit.

To study the environmental impact of the mine operation, an environmental monitoring programme was initiated in 2004 by the former National Environmental Research Institute in Denmark (Asmund et al. 2009), and a number of sampling stations were positioned within an area with a radius of 17 km from the mine (Fig. 1). This paper contains the most important results from the monitoring programme (Søndergaard et al. 2009; Søndergaard and Asmund 2010).

Sampling

Lichens

F. nivalis lichens were sampled at a total of 24 stations in the area around Seqi (Fig. 1). Out of these stations, 16 of the lichen stations were situated at the coastline

(C1–C16), and eight of the stations were located inland near the mine site (I1–8). During the entire period from 2004 to 2011, lichens were sampled every year at all stations except C5, C8–9 and C12, where lichens were only sampled in 2008. In the period from 2004 to 2008, only resident lichens from the stations were collected. From 2009 to 2011, lichens transplanted from an uncontaminated site the previous year were collected at stations C1–4, C6–7 and C10, and I1–8. Transplantation of lichens to selected sites near the mine was done to ensure that any observed changes in element concentrations were due to atmospheric deposition during the last year and not a result of the previous year's depositions and accumulations in the lichens (Søndergaard et al. 2011b).

Resident lichens were collected as bulk samples within an area of 100×100 m at the sampling stations. Fresh living lichens growing on dead organic matter were selected while lichens growing directly on soil or rocks were excluded. This was done to maximize the probability that elements accumulating in the lichens originated from deposition of particles from the air and not from underlying soil or rocks. Lichens for transplantation were collected near station C16, located 17 km from the mine. At the sampling sites, transplanted lichens were placed on the ground on organic matter and covered with a 1×1-cm-mesh nylon net held in place by some flat pieces of rock. This was done to avoid removal of the lichens by the wind. Three 15×15 patches of lichens were made at each site. The lichen transplants were collected the following years, and new lichens were placed at the same spot. When sampling, lichens were collected in polyethylene bags. Transplanted lichens from the three patches were pooled together as a bulk sample. Later in the laboratory, lichen samples were sorted using stainless steel tweezers, and only the green/yellow thalli were kept and subsequently dried at 60 °C for 24 h. The weights of the bulk samples of both resident and transplanted lichens after sorting and drying were typically 2–3 g. The lichens were not washed in order to avoid the leaching of soluble substances (Carreras and Pignata 2002).

Seaweeds

Brown seaweeds (*F. vesiculosus*) were sampled in the tidal zone directly from shore at all the coastal stations every year between 2004 and 2010. In

2011, samples were only taken at stations C1–3 and C15–16. Ten to 15 individual seaweed plants were collected at each site. After sampling, the seaweeds were rinsed three times in clean water, and only the fresh growth tips were kept in order to measure the most recent element uptake. The growth tips were cut from the rest of the plants using stainless steel scissors and kept in polyethylene bags at freezing temperatures until freeze-dried and homogenized to powder in an agate mortar in Denmark prior to the chemical analyses.

Mussels

Resident blue mussels (*M. edulis*) were sampled in the tidal zone directly from shore at all the coastal stations every year between 2004 and 2010. In 2011, samples were only taken at stations C1–C3 and C15–C16. After collection, the lengths of the mussels were measured in the laboratory, and mussels were divided into two size classes according to their shell lengths: 4–5 and 5–6 cm. A sample consisting of 20 individual mussels was taken from each size class. The adductors of the mussels were cut using a stainless steel scalpel, and the shells were opened and allowed to drain for a few minutes before the soft parts were removed from the shells. The soft parts of each size group were pooled into a polyethylene bag and frozen before being transported to Denmark. Here, the mussels were freeze-dried and homogenized to powder in an agate mortar prior to the chemical analyses. Sample water content was determined by weighting the samples before and after freeze-drying.

Fish

Shorthorn sculpins (*M. scorpius*) were sampled within an area 5 km from the mine during the period 2004–2010. Shorthorn sculpins were not sampled in 2011. The fish were caught by angling close to shore, and approximately 20 individuals were caught each year. In the laboratory, the fish were measured and weighted, and their sex determined. The livers were then cut out using a stainless steel scalpel, packed in a polyethylene bag and frozen before being sent to Denmark. In Denmark, the dry weight percentages of the samples were determined by drying a 2–3-g subsample in a porcelain crucible at 105 °C until constant weight.

Chemical analyses

Subsamples of lichens, seaweeds, mussels and fish were taken out for analyses. For lichens, seaweeds and mussels, one to three subsamples of 300 mg (dry weight) were taken from each sample. For shorthorn sculpins, one subsample of 1 g (wet weight) of the liver was cut out from the inner part of the liver. The subsamples were digested using 4 ml Merck Suprapure HNO₃ and 4 ml MilliQ water in Teflon bombs under pressure in a microwave oven (Anton Paar Multiwave 3000). After digestion, solutions were transferred to polyethylene bottles with MilliQ water, and element analyses were performed directly on these solutions using an Agilent 7500ce ICP-MS at the Department of Bioscience, Roskilde, Denmark. The following 46 elements were analysed: Li, Be, Na, Mg, Al, P, K, Ca, Sc, Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, Ga, Co, As, Se, Rb, Sr, Y, Zr, Mo, Rh, Pd, Ag, Cd, Sn, Sb, Cs, Ba, La, Ce, Nd, Ta, W, Au, Hg, Tl, Pb, Bi, Th and U. The analytical quality was continuously checked by analysing blanks, duplicates and the certified biological reference materials TORT-2, DORM-3 and DOLT-3 from the National Research Council Canada (www.nrc-cnrc.gc.ca) and BCR-482 from European Commission–Joint Research Centre (www.irmm.jrc.be). Element-specific detection limits were defined as 3 standard deviations (SD) on blank samples. The laboratory at the Department of Bioscience in Roskilde is accredited for analyses of Ni, Cr, Cu, Zn, As, Cd, Hg and Pb in biota with precisions (2 SD) of 15–20 % and participates biannually in the international laboratory inter-calibration programme QUASIMEME organized by the European Union (www.quasimeme.org).

Data treatment

Results from elemental analyses of resident and transplanted lichens, seaweeds and fish liver were used directly for comparison of element concentrations between sites and years without further data treatment. For blue mussels, the average of the measured element concentrations for the two size classes, 4–5 and 5–6 cm, were used. Differences in element concentrations in lichens, seaweeds, mussels and fish liver before, during and after the mining started were tested statistically using Microsoft Excel 2010 software. Lichen stations were grouped according to the distances from the mining area/ore crushing facility (0–1 km:

stations I1–8 and C1–3; 1–5 km: C4, C6–7 and C10). A two-sample t test with a significance level of 5 % was used. Prior to the t test, data were tested for equal variances using an F test.

Results and discussion

Lichens—bioaccumulation of elements related to the mine

Element concentrations in lichens before, during and after the mining period can be seen in Table 1. A total of 46 elements were analysed. After the mining activity started, significantly (t test; $p < 0.05$) elevated concentrations of the following elements were observed in lichens relative to pre-mining levels: Li, Mg, Al, V, Cr, Fe, Ni, Co, Rb, Y, Ag, Cs, La, Ce, Nd, Pb and Th. Of these, Cr, Ni, Co and Fe were especially elevated. Concentrations of Cr, Ni, Co and Fe in the lichens were observed up to 45, 96, 4.1 and 1,720 mg kg^{-1} dry wt., respectively, near the mining area (at St. I1). In contrast, pre-mining concentrations (mean $\pm$ SD) of Cr, Ni, Co and Fe in lichens were 0.35 ± 0.36 , 1.1 ± 1.7 , 0.20 ± 0.19 and 123 ± 77 mg kg^{-1} dry wt., respectively. Thus, concentrations of Cr, Ni, Co and Fe in lichens were elevated by factors up to 130, 87, 21 and 14, respectively. Elements that were above the detection limits but not significantly elevated in the lichens were: Be, Na, P, K, Ca, Sc, Ti, Mn, Cu, Zn, Ga, Zr, Sr, Cd and Ba. The following elements: As, Se, Mo, Rh, Pd, Sn, Sb, Ta, W, Au, Hg, Tl, Bi and U were consistently below the limits of detection. Lichens accumulate particles from the air, and the elevated element concentrations in lichens after the mining started is related to dust dispersal from the mining activities. The results indicate that Cr, Ni, Co and Fe are the main elements of concern with respect to the mine. The extracted olivine was reported to contain roughly 0.27 % Cr_2O_3 , 0.36 % NiO and 7.9 % Fe_2O_3 (Zuo 2006), and dispersal of these elements as dust is considered to originate directly from mining of the olivine ore. Cobalt and the rest of the elements found in moderately elevated concentrations in the lichens are also likely to origin from the olivine ore, either contained in minor mineral fractions or as mineral impurities. The dominant sources of dust dispersal in the area during the mining period were blasting, excavation and loading of ore material from the mining area, road traffic and ore crushing at the ore treatment facility.

Lichens—spatial and temporal trends of bioaccumulation and dispersion of elements

Concentrations of elevated elements in resident lichens peaked during the mining period in 2008 (Table 1), and Cr and Ni concentrations in lichens at each station versus distance from the mining area or ore treatment facility (the nearest of the two) is shown in Fig. 2. Relations were well described using power functions with negative exponents ($r^2 = 0.79\text{--}0.83$; $p < 0.05$). Dotted horizontal lines mark the upper limit for the 95 % confidence intervals for the pre-mining conditions. No naturally elevated concentrations of Cr or Ni were observed near the mining area prior to mining. As shown, elevated concentrations of Cr and Ni (above the 95 % confidence lines) were found in resident lichens in 2008 at stations located up to approximately 5 km from the mine/ore treatment facility.

Figure 3 shows the temporal trends in Cr and Ni concentrations in resident and transplanted lichens during the period from 2006 to 2011. Lichen sampling stations are grouped according to distances from the mine/ore treatment facility (0–1 and 1–5 km, respectively). From 2006 to 2008, resident lichens from the stations were collected, and from 2009 to 2011, samplings consisted of lichens transplanted from an uncontaminated area to the stations the previous year. The application of lichen transplants was done to evaluate the recent annual dust dispersion as resident *F. nivalis* lichens have been shown to concentrate metals over time and may contain a fraction of the previous year's metal deposition (Søndergaard et al. 2011b). Thus, while results from resident lichens may not reflect the year-to-year variation in dust dispersion and accumulation, results from lichen transplants collected each year are good indicators for that (Søndergaard et al. 2011b). The results shown in Fig. 3 indicate a marked decrease in dust dispersion from when the mining stopped in 2009 and until 2011. In 2011, significantly elevated Cr and Ni concentrations were only observed in lichen transplants located within 1 km from the mine/ore treatment facility.

Seaweeds and mussels

Concentrations of selected elements in seaweeds and blue mussels before, during and after the mining period can be seen in Tables 2 and 3, respectively. For seaweeds, significantly elevated element concentrations (t

Table 1 Concentrations of selected elements in resident and transplanted *F. nivalis* lichens sampled during the period from 2004 to 2011 (in milligram per kilogram dry wt.). Mean element concentrations and SD for lichens collected prior to mining in 2004–2005 are listed together with mean values for resident and transplanted lichens after 1 year of transplantation grouped according to the distances from the mine/ore treatment facility (0–1 and 1–5 km, respectively). Italicized values show elements that are significantly elevated in lichens after the mining began (t test; $p < 0.05$)

Year of sampling Distance from mine (km) Resident/transpl. lichens (R./T.) Element	Pre-mining period			Mining period			After mining								
	2004–2005		SD	2006		2007		2008		2009		2010		2011	
	0–17	R.		1–5	0–1	1–5	0–1	1–5	0–1	1–5	0–1	1–5	0–1	1–5	0–1
Li	0.049	0.031	0.028	0.074	0.065	0.122	0.050	0.112	0.080	0.110	0.097	0.080	0.080	0.035	0.049
Mg	1,650	600	940	1,740	1,220	2,170	–	–	–	–	–	–	–	–	–
Al	222	111	142	223	283	317	251	338	529	492	310	256	191	210	
V	0.26	0.15	0.19	0.45	0.38	0.65	0.23	0.38	0.71	0.89	0.45	0.46	0.25	0.30	
Cr	0.35	0.36	0.44	2.72	1.97	9.91	2.58	18.21	1.87	7.08	0.98	5.13	0.43	1.30	
Mn	71	69	61	75	51	50	48	108	36	49	38	23	14	19	
Fe	123	77	103	251	156	578	111	727	356	662	188	299	88	134	
Ni	1.1	1.7	1.0	6.9	4.1	20.8	4.6	48.3	4.2	19.8	1.5	13.3	0.8	3.2	
Cu	0.93	0.55	0.55	0.66	0.82	0.60	0.71	1.16	0.91	0.97	0.57	0.56	0.50	0.52	
Zn	22	12	23	20	14	18	23	26	17	16	10	9	9	8	
Co	0.20	0.19	0.12	0.33	0.32	1.18	0.33	2.20	0.38	1.09	0.20	0.71	0.10	0.20	
Rb	2.3	1.2	2.3	3.6	3.7	6.6	3.5	5.7	3.1	3.0	1.8	2.0	1.4	1.2	
Y	0.076	0.037	0.057	0.101	0.112	0.217	0.091	0.174	0.177	0.202	0.123	0.109	0.056	0.063	
Ag	0.015	0.012	0.007	0.013	0.021	0.038	0.037	0.055	0.045	0.048	–	–	–	–	
Cd	0.081	0.035	0.064	0.070	0.089	0.091	–	–	–	–	–	–	–	–	
Cs	0.037	0.023	0.036	0.069	0.052	0.114	0.083	0.143	0.057	0.071	–	–	–	–	
Ba	12	15	10	10	12	16	9	13	16	17	7	6	4	3	
La	0.33	0.40	0.19	0.48	0.39	0.75	–	–	0.60	0.58	0.28	0.29	0.17	0.21	
Ce	0.61	0.68	0.37	0.93	0.72	1.44	–	–	1.16	1.15	0.59	0.58	0.35	0.43	
Nd	0.24	0.19	0.19	0.47	0.24	0.48	0.22	0.42	0.43	0.45	0.26	0.25	0.15	0.18	
Pb	0.60	0.22	0.54	0.52	0.92	0.68	0.78	0.89	1.58	2.04	0.53	0.52	0.34	0.38	
Th	0.020	0.024	0.014	0.068	0.013	0.059	–	–	–	–	0.060	0.061	0.022	0.053	

– indicates that the element was not determined

Fig. 2 Chromium (Cr) and nickel (Ni) concentrations in resident *F. nivalis* lichens sampled in 2008 versus distances from the mine/ore treatment facility. Points are mean values for each sampling station. The solid horizontal lines represent the mean value for Cr and Ni for the entire monitoring area observed prior to mining in 2004–2005 (baseline). Dotted horizontal lines mark the upper 95 % confidence interval of the baseline (2 SD from mean). The shown trend lines are best-fitting power functions

test; $p < 0.05$) compared to pre-mining levels were only observed at station C1, closest to the mine, and only for the elements Cr and Ni. Significantly elevated Cr and Ni concentrations were measured in 2007 and 2009, and concentrations were up to $2.6 \text{ mg Cr kg}^{-1}$ dry wt. and $5.6 \text{ mg Ni kg}^{-1}$ dry wt. Pre-mining levels (mean $\pm$ SD) of Cr and Ni in seaweeds were 0.4 ± 0.4 and $2.3 \pm 1.2 \text{ mg kg}^{-1}$ dry wt., respectively, and so concentrations were elevated up to a factor of 7 for Cr and 2 for Ni. After the mining stopped in 2009, no significantly elevated concentrations of Cr and Ni were observed in seaweeds.

For blue mussels, significantly elevated concentrations of Cr, Ni and V were observed at the two stations

closest to the mine, station C1 and C2 (<1 km from mine; Fig. 1). No significant changes were observed for the other elements analysed. Concentrations of Cr, Ni and V were measured up to 9.7 , 16.7 and 1.4 mg kg^{-1} dry wt., respectively. Pre-mining levels of Cr, Ni and V in blue mussels were 1.4 ± 0.8 , 2.7 ± 0.9 and $0.6 \pm 0.4 \text{ mg kg}^{-1}$ dry wt., respectively. Thus, Cr, Ni and V concentrations in blue mussels near the mine were elevated up to a factor of 7 for Cr, 6 for Ni and 2 for V. Similarly to seaweeds, no significantly elevated concentrations of Cr, Ni or V were observed in blue mussels in 2010 and 2011 after the mining activity ceased.

The dominant source for the observed contamination in seaweeds and blue mussels is considered an outwash of dissolved and particle-bound Cr, Ni and V from land, originating from olivine ore dust dispersed during the mining process.

Fish and other samples

Element concentrations measured in fish liver from shorthorn sculpins before, during and after the mining period can be seen in Table 4. Shorthorn sculpins are relatively sedentary fish, and all fish were caught within an area 5 km from the mine. Fish liver is known to accumulate and concentrate contaminants such as metals (Johansen et al. 1991). However, no significant changes were observed in the element compositions in shorthorn sculpins after the mining started (Cr, Ni and V were below or close to detection limits during the entire period).

Other samples that were collected near the mining area include freshwater samples from Long Lake (Fig. 1) and liver samples from Arctic char caught in Long Lake (Asmund et al. 2009; Søndergaard et al. 2009). None of these showed any significant changes in element composition as a result of the mining activity.

Conclusions

This study investigated dispersal and bioaccumulation of elements related to an open-pit olivine mine at Seqi in Southwest Greenland. Studies using lichens, seaweeds, mussels and fish as biological indicator organisms showed that dispersion and bioaccumulation of especially Cr, Ni, Co and Fe as

Fig. 3 Chromium (Cr) and nickel (Ni) concentrations in resident and transplanted *F. nivalis* lichens after 1 year of transplantation during the period from 2006 to 2011. Points are mean values. Results are grouped according to the distances from the mine/ore treatment facility (0–1 and 1–5 km, respectively). Prior to transplantation, lichens had Cr and Ni concentrations of 0.2–0.5 mg kg⁻¹ dry wt. for both metals. The solid horizontal lines represent the mean value of Cr and Ni for the entire monitoring area prior to mining observed in 2004–2005 (baseline). Dotted horizontal lines mark the upper 95 % confidence interval of the baseline (2 SD from mean)

Table 2 Concentrations of selected elements in *F. vesiculosus* seaweeds at St. C1, located close to the mine, sampled during the period from 2004 to 2011 (in milligram per kilogram dry wt.). Mean element concentrations and SD for seaweeds

collected prior to mining in 2004–2005 are listed together with mean values for seaweeds at St. C1 from 2006 to 2011. Italicized values show elements that are significantly elevated in seaweeds at St. C1 after mining began (*t* test; *p* < 0.05)

Year of sampling	Pre-mining period		Mining period				After mining	
	2004–2005		2006	2007	2008	2009	2010	2011
Element	Mean	SD	Mean	Mean	Mean	Mean	Mean	Mean
Li	0.45	0.22	0.30	0.43	0.29	0.40	0.57	0.35
Mg	8,250	640	8,150	6,770	–	–	–	–
Al	32	32	30	65	30	74	3	9
V	0.40	0.34	0.33	0.47	0.31	0.53	0.16	0.17
Cr	0.40	0.39	0.40	2.62	1.03	0.97	0.11	0.12
Fe	69	73	79	181	94	197	36	38
Ni	2.3	1.2	1.4	5.6	4.5	5.4	1.5	1.9
Zn	12	4	13	16	10	17	13	14
Co	0.59	0.34	0.35	0.77	0.66	0.67	0.25	0.46
Cd	1.9	0.6	1.0	0.9	–	–	–	–
Pb	0.051	0.030	0.026	0.040	0.025	0.066	0.046	<0.030

– indicates that the element was not determined

Table 3 Concentrations of selected elements in *M. edulis* mussels at St. C1 and C2, located close to the mine, sampled during the period from 2004 to 2011 (in milligram per kilogram dry wt.). Mean element concentrations and SD for mussels collected

prior to mining in 2004–2005 are listed together with mean values for mussels at St. C1 and C2 from 2006 to 2011. Italicized values show elements that are significantly elevated in mussels after mining began (t test; $p < 0.05$)

	Pre-mining period		Mining period				After mining				
Year of sampling	2004–2005		2006	2007	2008	2009		2010	2011		
Station	All		C1	C1	C1	C2	C1	C2	C2	C1	C2
Distance from pier (km)	0–17		<1	<1	<1	<1	<1	<1	<1	<1	<1
Element	Mean	SD	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean
Li	0.76	0.31	0.62	0.70	0.47	0.66	0.87	0.73	0.86	0.51	0.45
Mg	5,120	1,610	4,520	4,470	–	–	–	–	–	–	–
Al	163	225	245	196	520	342	242	149	84	184	95
V	0.59	0.36	0.81	1.17	0.70	0.58	1.40	1.05	0.65	1.06	1.07
Cr	1.4	0.8	1.7	9.7	4.2	5.7	3.0	2.7	1.4	1.9	1.3
Fe	206	173	325	541	277	241	409	242	157	259	170
Ni	2.7	0.9	2.1	16.7	7.9	7.6	7.0	5.0	2.8	3.4	2.9
Zn	77	23	63	69	64	83	97	91	79	93	85
Co	0.47	0.23	0.36	1.03	0.52	0.59	0.68	0.56	0.44	0.55	0.52
Cd	4.0	1.1	2.1	1.5	–	–	–	–	–	–	–
Pb	0.38	0.13	0.62	0.55	0.47	0.33	0.71	0.36	0.29	0.65	0.31

– indicates that the element was not determined

dust were the main environmental concern. These elements were associated with the olivine ore, and dominant sources of dispersion were blasting,

excavation and loading of ore material from the mining area, road traffic and ore crushing at the ore treatment facility. During the mining period,

Table 4 Concentrations of selected elements in shorthorn sculpin liver sampled within 5 km from the mine during the period from 2004 to 2011 (in in milligram per kilogram wet wt.). Mean

element concentrations and SD for shorthorn sculpin liver collected prior to mining in 2004–2005 are listed together with mean values from sampling during the period 2006 to 2011

	Pre-mining period		Mining period				After mining
Year of sampling	2004–2005		2006	2007	2008	2009	2010
Element	Mean	SD	Mean	Mean	Mean	Mean	Mean
Li	<0.02	–	<0.02	<0.02	<0.01	<0.01	<0.02
Mg	169	20	167	136	–	–	–
Al	<16	–	<16	<16	–	<1	<5
V	0.02	0.02	0.06	0.09	0.05	<0.01	<0.06
Cr	<0.15	–	<0.15	<0.15	<0.02	<0.02	<0.09
Fe	144	117	73	180	235	244	132
Ni	<0.3	–	<0.3	<0.3	<0.3	<0.3	0.08
Zn	35	7	25	32	–	32	33
Co	0.08	0.11	0.02	0.16	0.17	0.10	0.13
Cd	0.37	0.25	0.28	0.60	–	–	–
Pb	<0.03	–	<0.03	<0.03	<0.01	<0.01	<0.04

– indicates that the element was not determined, < indicates a result below the limit of detection

dust dispersion of mine-related elements was observed in distances up to 5 km from the mine. After mine closure, the dust dispersion decreased markedly, and 2 years after mine closure, dust dispersion could only be measured within 1 km from the mine/ore treatment facility. Highly elevated concentrations of mine-related elements could be observed on land in lichens, but only moderate changes in element compositions were observed in seaweeds and blue mussels in the marine environments. Furthermore, elevated element concentrations in seaweeds and mussels were only observed very locally near the mine and not after the mining activity ceased. This is in contrast to previous mining operations in Greenland (especially the Pb–Zn mine in Maarmorilik and the cryolite mine in Ivittut) where significant contamination of the marine environment can still be measured decades after mine closure. In conclusion, the dispersal and bioaccumulation of elements from the olivine mine operation at Seqi was relatively low and is not considered to affect the adjacent marine ecosystem showing this to be a low-environmental-impact type of mining operation.

Acknowledgments The author wishes to thank Gert Asmund for chemical advice and for performing some of the chemical analyses, and Sigga Joensen and Lene Bruun for assistance in the field and in lab; all are from the Department of Bioscience, Aarhus University, in Roskilde. Also, the mining company Minelco A/S is thanked for providing the logical facilities on site.

References

- Asmund, G., Boertmann, D., Johansen, P. (2009). Baseline and monitoring studies at the Seqi olivine mine 2004 to 2007. NERI Technical Report 715. National Environmental Research Institute (NERI), Aarhus University, 90 p. <http://www2.dmu.dk/Pub/FR715.pdf>. Accessed 15 June 2012.
- BMP (2009). Annual report 2008. Nuuk: Bureau of Minerals and Petroleum (BMP). http://www.bmp.gl/images/stories/about_bmp/publications/annual_report_2008_high.pdf. Accessed 15 June 2012.
- BMP (2010). Annual report 2009. Nuuk: Bureau of Minerals and Petroleum (BMP). http://www.bmp.gl/images/stories/about_bmp/publications/annual_report_2009_high.pdf. Accessed 15 June 2012.
- Carreras, H. A., & Pignata, M. L. (2002). Biomonitoring of heavy metals and air quality in Cordoba City, Argentina using transplanted lichens. *Environmental Pollution*, 117, 77–87.
- Gibb, J. O. T., Allen, J. R., & Hawkins, S. J. (1996). The application of biomonitors for the assessment of mine-derived pollution on the West Coast of the Isle of Man. *Marine Pollution Bulletin*, 32(6), 513–519.
- Glahder, C., Søndergaard, J., Asmund, G., Rigét, F. (2010). Environmental monitoring at the Nalunaq Gold Mine 2010. NERI Technical Report 811. National Environmental Research Institute (NERI), Aarhus University, 32 p. <http://www2.dmu.dk/Pub/FR811.pdf>. Accessed date 15 June 2012.
- Johansen, P., Hansen, M. M., Asmund, G., & Nielsen, P. B. (1991). Marine organisms as indicators of heavy metal pollution—experience from 16 years of monitoring at a lead-zinc mine in Greenland. *Chemistry and Ecology*, 5 (1–2), 35–55.
- Johansen, P., Asmund, G., Rigét, F., Johansen, K., Schledermann, H. (2010). Environmental monitoring at the former lead-zinc mine in Maarmorilik, Northwest Greenland, in 2009. NERI Technical Report 775. National Environmental Research Institute (NERI), Aarhus University, 32 p. <http://www2.dmu.dk/Pub/FR775.pdf>. Accessed 15 June 2012.
- Josefson, A. B., Hansen, J. L. S., Asmund, G., & Johansen, P. (2008). Threshold response of benthic macrofauna integrity to metal contamination in West Greenland. *Marine Pollution Bulletin*, 56, 1265–1274.
- Lackner, K. S. (2003). A guide to CO₂ sequestration. *Science*, 300, 1677–1678.
- Minelco (2012). <http://www.minelco.com/en/Products-applications/Products/Minelco-Olivine/>. Accessed 15 June 2012.
- Naeth, M. A., & Wilkinson, S. R. (2008). Lichens as biomonitors of air quality around a iamond mine, Northwest Territories, Canada. *Journal of Environmental Quality*, 37, 1675–1684.
- Nash, T. H., III. (1996). Nutrients, elemental accumulation and cycling. In T. H. Nash III (Ed.), *Lichen biology* (pp. 136–153). Cambridge: Cambridge University Press.
- Priestley, E. (2004). Environmental due diligence desk study of the Seqi Olivine Project Greenland for Crew Development Corporation. Consultant Report, Voaden Sandbrook Limited, UK, 29 p.
- Rainbow, P. S. (1995). Biomonitoring of heavy metal availability in the marine environment. *Marine Pollution Bulletin*, 31(4–12), 183–192.
- Søndergaard, J., Asmund, G. (2010). Environmental monitoring at the Seqi olivine mine 2010. NERI Technical Report 813. National Environmental Research Institute (NERI), Aarhus University, 36 p. <http://www2.dmu.dk/Pub/FR813.pdf>. Accessed 15 June 2012.
- Søndergaard, J., Schiedek, D., Asmund, G. (2009). Environmental monitoring at the Seqi olivine mine 2008–2009. NERI Technical Report 753. National Environmental Research Institute (NERI), Aarhus University, 48 p. <http://www2.dmu.dk/Pub/FR753.pdf>. Accessed 15 June 2012.
- Søndergaard, J., Asmund, G., Johansen, P., & Rigét, F. (2011). Long-term response of an arctic fiord system to lead-zinc mining and submarine disposal of mine waste (Maarmorilik,

- West Greenland). *Marine Environmental Research*, 71, 331–341.
- Søndergaard, J., Johansen, P., Asmund, G., & Rigét, F. (2011). Trends of lead and zinc in resident and transplanted *Flavocetraria nivalis* lichens near a former lead-zinc mine in West Greenland. *Science of the Total Environment*, 409, 4063–4071.
- Torres, M. A., Barros, M. P., Campos, S. C. G., Pinto, E., Rajamani, S., Sayre, R. T., et al. (2008). Biochemical biomarkers in algae and marine pollution: a review. *Eco-toxicology and Environmental Safety*, 71, 1–15.
- Zimmer, L. A., Asmund, G., Johansen, P., Mortensen, J., & Hansen, B. W. (2011). Pollution from mining in South Greenland: uptake and release of Pb by blue mussels (*Mytilus edulis* L.) documented by transplantation experiments. *Polar Biology*, 34, 431–439.
- Zuo, G. (2006). Industrial applications of SeqiOlivine. Internal Report, Minelco, Sweden, 14 p.