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Sigurður H. Magnússon and Björn Thomas

Unnið fyrir Alcoa Fjarðaál

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ABSTRACT

As a part of the UN-ECE International Cooperative Programme on vegetation and air borne pollution, moss samples of *Hylocomium splendens* were taken all over Iceland in 2005 and analysed for heavy metals (As, Cd, Cr, Cu, Fe, Hg, Ni, Pb, V, Zn) and sulphur (S). Additionally, the areas around the aluminium smelter site at Reyðarfjörður, aluminium smelter at Straumsvík, and ferro-silicon plant and aluminium smelter at Grundartangi, were sampled intensively. This report uses the data of the 2005 and previous 2000 survey for identifying the baseline for future monitoring of airborne deposition in the Reyðarfjörður area.

In general, most of the measured elements show higher concentration close to the aluminium smelter site, especially at the shore of the fjord. Nevertheless, most values are low and do not differ significantly from the background concentration in eastern Iceland. Furthermore, some of the elements (Cd, Cu, Fe, Ni, and V) increased between 2000 and 2005 which may reflect increased soil dust from areas of active soil erosio and dust from the aluminium building site. Lead (Pb) and sulphur (S) showed a decreasing trend which is consistent with other areas in Iceland and probably related to a decline in long-distance transport.

The moss surveys of 2000 and 2005 provide a good baseline for future monitoring of heavy metal deposition in the Reyðarfjörður area.

Lykilorð	**Yfirfarið**
heavy metals, sulphur, deposition patterns, mosses, industrial sites, aluminium smelter, Iceland	BM, PH, SB

ÁGRIP

Sumarið 2005 fór fram á Náttúrufræðistofnun Íslands rannsókn á þungmálmum og brennisteini í mosa á Íslandi í samvinnu við Umhverfisstofnun og fleiri aðila. Rannsóknin er liður í fjölþjóðlegu verkefni sem hefur það markmið að fylgjast með loftmengun og að finna helstu uppsprettur hennar. Í þessum tilgangi hefur tildurmosa (*Hylocomium splendens*) verið safnað víðs vegar um land á 5 ára fresti allt frá árinu 1990 og þungmálmar greindir. Árið 2000 var mosa einnig safnað til mælinga á þungmálmum á allmörgum stöðum við álverið í Straumsvík og í nágrenni fyrirhugaðs álvers í Reyðarfirði. Var það hugsað sem upphaf vöktunar á þungmálmum við álverin. Sumarið 2005 voru rannsóknir við álverin endurteknar og vöktun einnig hafin í nágrenni verksmiðjanna á Grundartanga.

Við rannsóknirnar árið 2005 voru tekin 11 mosasýni í Reyðarfirði á tveimur sniðum í mismunandi fjarlægð frá álverinu og styrkur As, Cd, Cr, Cu, Fe, Hg, Ni, Pb, V, Zn og S ákvarðaður með ICP-tækni. Við úrvinnslu voru notaðar niðurstöður úr þeim sýnum sem safnað var á landinu öllu árin 2000 og 2005. Styrkur þungmálma og brennisteins var kannaður eftir fjarlægð frá álverinu í Reyðarfirði: a) <3 km, b) 3–100 km og c) >100 km og einnig borinn saman við styrk efna við álverið í Straumsvík (<3 km) og við iðjuverin á Grundartanga (<3 km). Til þess að lýsa dreifingu efna í Reyðarfirði nánar voru teiknuð kort sem sýna styrk efnanna á einstökum söfnunarstöðum. Árið 2005 var álverið enn í byggingu en það mun hefja framleiðslu 2007.

Árið 2005 reyndist styrkur flestra efnanna vera hæstur um miðjan fjörð, þ.e. við verksmiðjusvæðið.

Þótt dreifingarmynstur flestra efnanna sé svipað má greina þau í eftirfarandi fjóra flokka eftir styrk:

1. Arsen og sink – styrkur reyndist vera hæstur nálægt álverslóðinni, einkum næst sjónum beggja vegna fjarðar.
2. Króm, járn, kopar, nikkel og vanadíum – sýndu svipað útbreiðslumynstur. Styrkur þessara efna var hæstur á allstóru aflöngu svæði nálægt álverslóðinni beggja vegna fjarðar með sjónum. Útbreiðsla þeirra virðist ná nokkru lengra inn í fjörðinn en efni í 1. og 3. flokki.
3. Kadmíum, kvikasilfur og blý – voru í einna hæstum styrk beggja vegna fjarðar nálægt álverslóðinni, en styrkur þeirra virðist ná hærra upp í hlíðar sunnan fjarðar en efni í flokkum 1–2.
4. Brennisteinn – sýndi ekkert greinilegt útbreiðslumynstur í firðinum.

Í Reyðarfirði urðu allmiklar breytingar á styrk nokkurra efna frá 2000 til 2005. Styrkur nikkels og kadmíums jókst og svipaða tilhneigingu sýndu einnig kopar, járn og vanadíum. Þessar breytingar má að öllum líkindum rekja til aukins áfoks. Einnig er líklegt að framkvæmdir við byggingu álversins með tilheyrandi jarðraski hafi haft nokkur áhrif.

Styrkur kvikasilfurs og brennisteins minnkaði hins vegar með tíma í Reyðarfirði eins og víðast hvar annars staðar á landinu. Lækkandi styrk þessara efna má að öllum líkindum rekja til minnkandi loftborinnar mengunar erlendis frá.

Þrátt fyrir heldur hærri styrk flestra efnanna nálægt fyrirhuguðu álveri er styrkur þeirra í Reyðarfirði lágur og ekki verulega frábrugðinn bakgrunnsgildum á Austurlandi. Þessar niðurstöður eru góður grunnur fyrir áframhaldandi vöktun við álverið.

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1 INTRODUCTION

In Europe carpet forming mosses have been widely used since the late 1960's for assessing regional and temporal variability of atmospheric heavy metal deposition (Rühling and Tyler 1969). In Iceland concentration of heavy metals has been systematically monitored since 1990 at a five year interval as a part of the UN-ECE International Cooperative Programme on vegetation (Rühling et al. 1992 , Rühling and Steinnes 1998, Buse et al. 2003).

The moss technique for monitoring of heavy metal depositions has several advantages (see e.g. Rühling and Steinnes 1998, Buse et al. 2003). Mosses lack a cuticle and transport tissue and therefore absorb whatever is around them. In addition particles are adsorbed on their surface. This results in accumulation of heavy metals in the moss both from dry and wet deposition (Rühling and Steinnes 1998). As moss sampling is relatively simple and the concentration of heavy metals is generally much higher in the moss than in the air, analysis of the moss tissue is both a cheap and easy way to identify pollution of the environment and their sources.

As in any indirect method there are factors other than pollution that influence the concentration of heavy metals in mosses (Berg et al. 1995, Steinnes 1995, Zechmeister 1995 and Reimann et al. 2001). Input from marine environment is known to affect the metal concentration; metals can be transported from the soil to root of plants and subsequently can later reach the mosses from living or dead plant tissue. In wet areas, especially after snowmelt, contact between the soil and water can transport metals from the soil to the mosses. Furthermore windblown dust from soil can affect the metal content of mosses.

The results of the 1990s and 1995s moss surveys in Iceland indicated an increased concentration of some heavy metals in the vicinity of the aluminium smelter in Straumsvík south-western Iceland (Rühling et al. 1992, Rühling and Steinnes 1998). In the 2000 survey additional samples were taken around the Straumsvík smelter but also around the proposed aluminium smelter in Reyðarfjörður. The purpose was to obtain a clearer spatial picture of the heavy metal concentration around the smelter in Straumsvík but also to act as first step in monitoring the discharge of heavy metals from these smelters (Magnússon 2002a and 2002b). In the survey 11 elements were analyzed, 10 heavy metals (As, Cd, Cr, Cu, Fe, Hg, Ni, Pb, V and Zn) and sulphur (S).

In the 2005 survey, sampling at these sites was repeated. The industrial site at Grundartangi, western Iceland, was also added to the study. Heavy industries in this area are a ferro-silicon (iron alloy) plant that has been running since 1979 and an aluminium smelter which has been in operation from June 1998 (Íslenska járnblendifélagið 2007, Norðurál 2007).

Construction of the aluminium smelter in Reyðarfjörður began in July 2004 and operation begin in 2007 (Fjarðaál 2007).

This report focuses on the heavy metal and sulphur concentration in mosses around the aluminium smelter site in Reyðarfjörður and compares the findings with the Grundartangi and Straumsvík sites. The aim is to display and explain the spatial distribution of heavy metal concentrations around the smelter site. In the discussion, the values from Iceland and Europe are considered. In the future this and the previous study (Magnússon 2002b) will serve as a baseline for continued monitoring of the impacts of the new aluminium smelter.

2 METHODS

In the vicinity of the aluminium smelter site in Reyðarfjörður the moss *Hylocomium splendens* was sampled on September 4th and 5th, 2005, at 11 points located along two transects (I and II). The samples R37-2, R38-2 and R43-2 had to be taken at new points close to the former R37, R38 and R43 of the 2000 survey (Magnússon 2002b), as construction work at the site had disrupted the previous sampling points. In order to get a better picture of the distribution pattern of heavy metals around the smelter site, two additional samples to the previous survey were obtained, R35-B and R42-B, (Figure 1). Transect I consists of 6 samples along the northern coast of the fjord. Transect II intersects the first at the smelter site and extends across the fjord towards southeast, with three samples on the northern side and two on the southern side of the fjord. Transect I has samples further away from the smelter than was possible for Transect II due to topography of the fjord. In the 2000 survey the main characteristics of the sample points were described (Magnússon 2002a). The new and displaced sample points in the 2005 are described in Table 1.

The sampling was conducted according to the monitoring manual of the European heavy metal deposition monitoring program (Harmens 2005). At every sampling point, 5–10 sub-samples of the moss *Hylocomium splendens* were taken within a 50 x 50 m plot and placed together in a plastic bag. The locations of the sampling points were determined by GPS. Sampling was carried out at the same sampling points as in 2000 unless they had been disturbed by the construction operations around the smelter site.

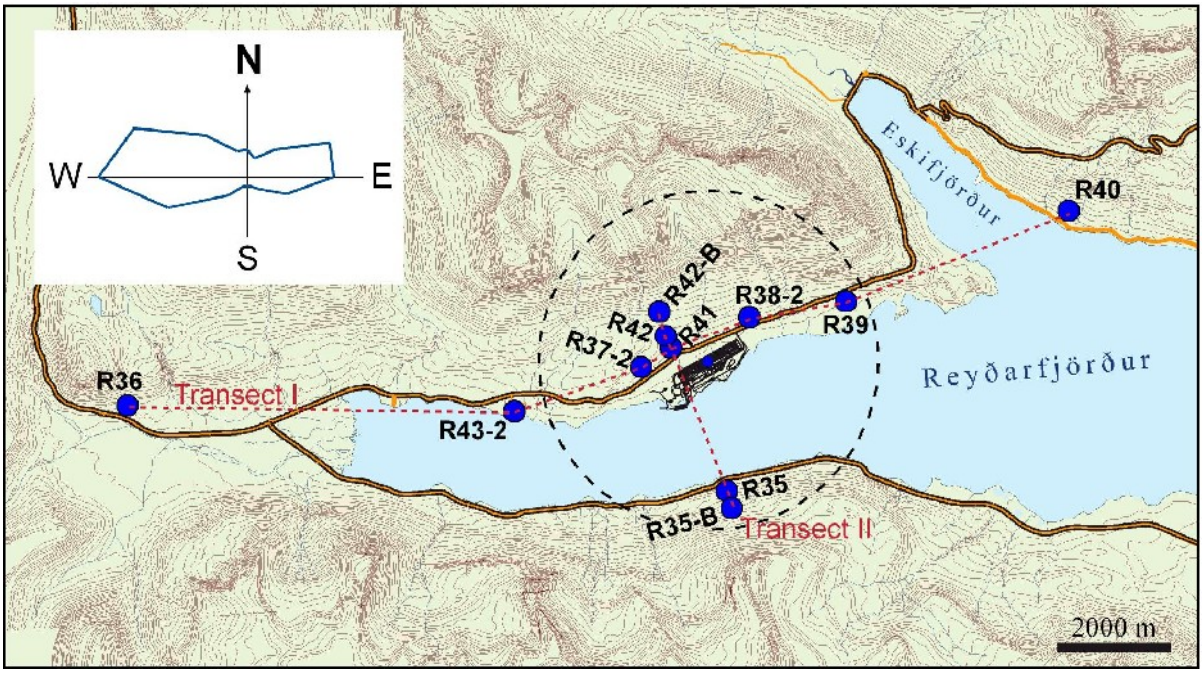


Figure 1. The aluminium smelter site in Reyðarfjörður and adjacent area. Locations of transects and points where moss samples were collected in 2005 are marked with blue dots. The relative frequency of wind directions in 2005 is also shown (average of weather station 2 and 3, 3 km west and east of the smelter). The dashed circle defines the area with a radius of 3 km from the smelter and the centre is marked by a small blue dot. - Iðnaðarsvæðið í Reyðarfirði og nágrenni. Staðsetning álvers er sýnd með litlum bláum punkti, en sýnatökustaðir mosa árið 2005 eru táknaðir með svörtum punktum. Sýnd er tíðni vindátta árið 2005 (meðaltal mælistöðva 2 og 3 sem eru 3 km austan við og vestan við verk-smiðjuna. Brotin lína afmarkar það svæði sem er innan við 3 km frá miðju álvers.

Table 1. *Location and characteristics of the sampling points near the aluminium smelter site in Reyðarfjörður (revised from Magnússon, 2002b and extended).* - Staðsetning og helstu einkenni sýnatökustaða í Reyðarfirði og nágrenni (endurskoðaðar upplýsingar frá Sigurði H. Magnússyni (2002).

Tran-sect *Snið*	No. *Númer*	Distance to smelter, m *Fjarlægð frá álveri, m*	m asl *Hæð yfir sjó, m*	Slope [°]/ direction *Halli [°]/ Hallastefna*	Vegetation type *Gróðurgerð*	Dominant vascular plants	Ríkjandi háplöntutegundir
I	R36	10400	80	7/S	Grassy openings in birch	*Agrostis capillaris*	Hálíngresi
						Empetrum nigrum	Krækilyng
						Campanula rotundifolia	Bláklukka
I	R43-2	3500	80	5/S	Sloping heathland	*Agrostis capillaris*	Hálíngresi
						Empetrum nigrum	Krækilyng
						Deschampsia flexuosa	Bugðupuntur
I	R37-2	1200	80	5/S	Sloping heathland	*Vaccinium uliginosum*	Bláberjalyng
						Empetrum nigrum	Krækilyng
						Carex bigelowii	Stinnastör
						Betula nana	Fjalldrapi
I	R38-2	1100	60	20/SE	Sloping grassland	*Vaccinium uliginosum*	Bláberjalyng
						Deschampsia caespitosa	Snarrótarpuntur
						Agrostis capillaris	Hálíngresi
						Empetrum nigrum	Krækilyng
I	R39	2700	20	3/S	Grassy heath	*Vaccinium uliginosum*	Bláberjalyng
						Agrostis capillaris	Hálíngresi
						Festuca vivipara	Blávingull
I	R40	6900	30	10/SW	Grassy heath	*Festuca vivipara*	Blávingull
						Galium verum	Gulmaðra
						Equisetum arvense	Klóelfting
						Juncus trifidus	Móasef
II	R41	700	60	16/SE	Sloping grassland	*Agrostis vinealis*	Týtulíngresi
						Equisetum pratense	Vallelfting
						Festuca vivipara	Blávingull
						Deschampsia caespitosa	Snarrótarpuntur
II	R35-B	2600	160	12/NW	Heathland	*Vaccinium uliginosum*	Bláberjalyng
						Empetrum nigrum	Krækilyng
						Carex bigelowii	Stinnastör
						Deschampsia flexuosa	Bugðupuntur
II	R35	2300	80	15/N	Sloping grassland	*Carex bigelowii*	Stinnastör
						Juncus trifidus	Móasef
						Festuca vivipara	Blávingull
						Thalictrum alpinum	Brjóstagras
II	R42	900	80	5/SE	Sloping mire	*Carex nigra*	Mýrastör
						Juncus arcticus	Hrossanál
						Equisetum palustre	Mýrelting
						Hierochloe odorata	Reyrgresi
II	R42-B	1200	160	12/SE	Sloping grassland	*Agrostis capillaris*	Hálíngresi
						Deschampsia caespitosa	Snarrótarpuntur
						Deschampsia flexuosa	Bugðupuntur

After sampling, the moss samples were kept frozen until February 2006. Then they were thawed and cleaned of dead material and attached litter. Segments from the 2005 growing season were separated and discarded and only the growth segments of 2002, 2003 and 2004 kept for analysis. The separated material was then put into paper bags and dried at room temperature. The samples were sent to the Section of Plant Ecology and Systematics of the University of Lund, Sweden for analysis. Before analysis the samples were dried at 40 °C and wet ashed with nitric acid. From each sample, 1g of moss was used for the analysis. Cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), nickel (Ni), lead (Pb), vanadium (V) and zinc (Zn) were measured with inductively coupled plasma emission spectrometry (ICP-ES) and arsenic (As), mercury (Hg) and sulphur (S) with inductively coupled plasma mass spectrometry (ICP-MS) technique. The quantification limits are listed in Appendix 1. The remaining part of each moss sample was dried at room temperature and will be stored for possible future investigations.

3 DATA ANALYSES

For the analyses, data from the 2000 and 2005 surveys were used. The data set was divided into three parts according to the distance from the smelter site in Reyðarfjörður; <3 km, 3–100 km, >100 km. In addition, sampling points within 3 km of the industries at Grundartangi (aluminium smelter and ferro-silicon plant) and the aluminium smelter at Straumsvík were grouped respectively and used for comparison to the Reyðarfjörður data. The mean for each distance class was calculated together with standard error (SE) and presented in graphs. Comparison of the elements between sites and distance classes were made with one-way ANOVA on log transformed values for each survey respectively. Comparisons of site means were then made with the Tukey-Kramer HSD test (JMP 2005).

Comparison between years (2000 vs. 2005) was done on paired samples with a paired t-test (JMP 2005) on log transformed values for each site or distance class separately; Reyðarfjörður < 3 km (n=4), 3–100 km (n=16), >100 km (n=82), Straumsvík <3 km (n=11). The sampling points close to Grundartangi (<3 km) were excluded from this test due to few samples (n=2).

The results are also presented with maps showing the metal concentration at each sampling point, thus giving an overview of the spatial distribution of heavy metal concentrations near the Reyðarfjörður smelter site. In accordance with the European moss sampling program (Buse et al. 2003) the legend of the maps is adapted to the colours generally used in their presentation of overall results. This ensures a more objective view on the data, as only highest values in the European context are highlighted in red or orange. In addition the samples from the Icelandic surveys of 2000 and 2005 are ranked in order to make their relative comparison more easy (Appendix 2).

4 RESULTS AND DISCUSSION

The prevailing winds in 2005 at the smelter site came from west and northwest, as measured at the two nearby weather stations. East and north-eastern winds were also frequent (Figure 1).

4.1 Arsenic (As)

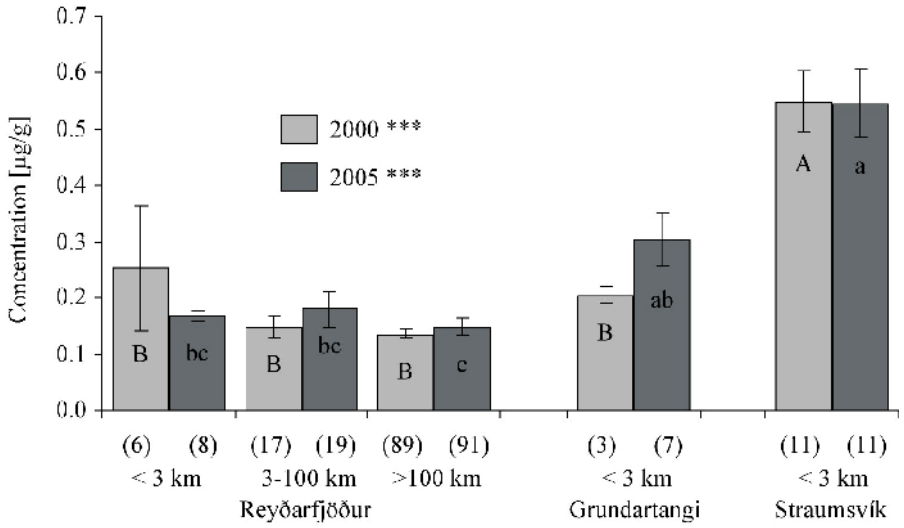
In the 2005 survey, arsenic concentration in mosses in Reyðarfjörður (11 samples) showed only little variation (0.12–0.20 µg/g) and did not reveal any clear distribution pattern (Figure 2). The samples within 3 km of the aluminium smelter site were comparable to other distance classes and to the Grundartangi site, but were found to be significantly lower than in Straumsvík for both the 2000 and 2005 surveys (Figure 2). Comparison of paired values did not show any significant change in arsenic concentration with time except for the distance class 3–100 km. There the concentration increased from 2000 to 2005 (from 0.15 to 0.18 µg/g; $P<0.01$, $n=16$).

Even though the sample from R39 had a relatively high concentration in 2000 (0.81 µg/g), all samples in 2005, close to (<3 km) the smelter site, had medium concentrations compared to other samples in Iceland (Appendix 2).

Samples in Reyðarfjörður had lower values than densely populated areas of Central Europe but were similar to rural areas of Scandinavia (Buse et al. 2003).

Arsenic (As)

A.



B.

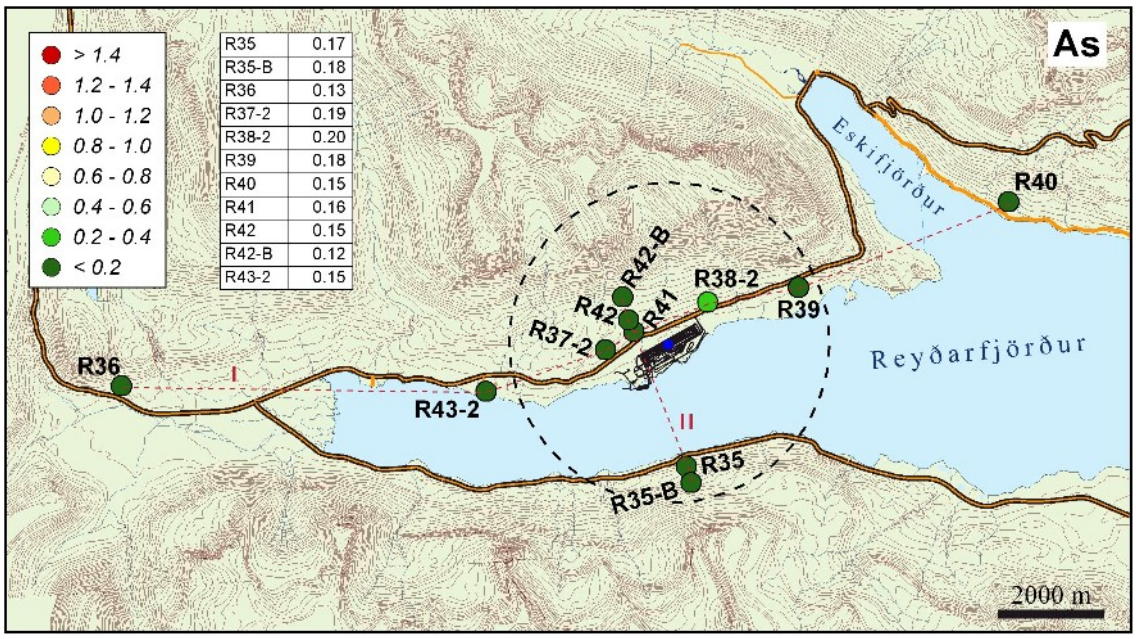


Figure 2. (**A**) Average arsenic (As) concentration at different distances (<3 km, 3–100 km, >100 km) from the aluminium smelter site in Reyðarfjörður in the 2000 and 2005 moss survey. For comparison the average arsenic concentration close to (<3 km) the industrial sites Grundartangi and Straumsvík is given. Standard error is shown with vertical lines and the number of samples is given in parentheses below. Stars denote significance between classes tested with ANOVA, NS: not significant; *: p <0.05; **: p<0.01; ***: p<0.001. Different letters in the columns denote significant difference between distance classes and site within each year, (p<0.05, Tukey test). - *Styrkur arsens í mosa í mismunandi fjarlægð frá álveri í Reyðarfirði (<3 km, 3–100 km, >100 km) árin 2000 og 2005. Til samanburðar er einnig sýndur styrkur arsens við iðjuverin á Grundartanga og í Straumsvík. Lóðréttar línur tákna staðalskekkju. Innan sviga er sýndur fjöldi sýna í hverjum flokki. Stjörnur við ártöl tákna marktækan mun á svæðum og stöðum, metið með fervikagreiningu, NS: ekki marktækt; *: p <0,05; **: p<0,01; ***: p<0,001. Mismunandi bókstafir tákna marktækan mun milli svæða innan ára, metið með Tukey prófun (p<0,05).*

(B) Spatial distribution of arsenic concentration in mosses along the sampling transects close to the aluminium smelter site in Reyðarfjörður in 2005. The dashed circle shows the area <3 km of the smelter centre (blue dot). The colour scale reflects the European range for arsenic in moss (Buse et al. 2003). - *Styrkur arsens í mosa í Reyðarfirði. Brotin hringferill afmarkar svæði innan við 3 km frá miðju álvers. Litakvarði er miðaður við skýrslu Buse o.fl. (2003).*

4.2 Cadmium (Cd)

In 2005, the cadmium concentration in Reyðarfjörður varied between 0.06 and 0.16 µg/g which is relatively high for samples in Iceland (Figure 3, Appendix 2). No clear distribution pattern was observed within the fjord although concentrations were somewhat higher close to the smelter site, especially along the coast.

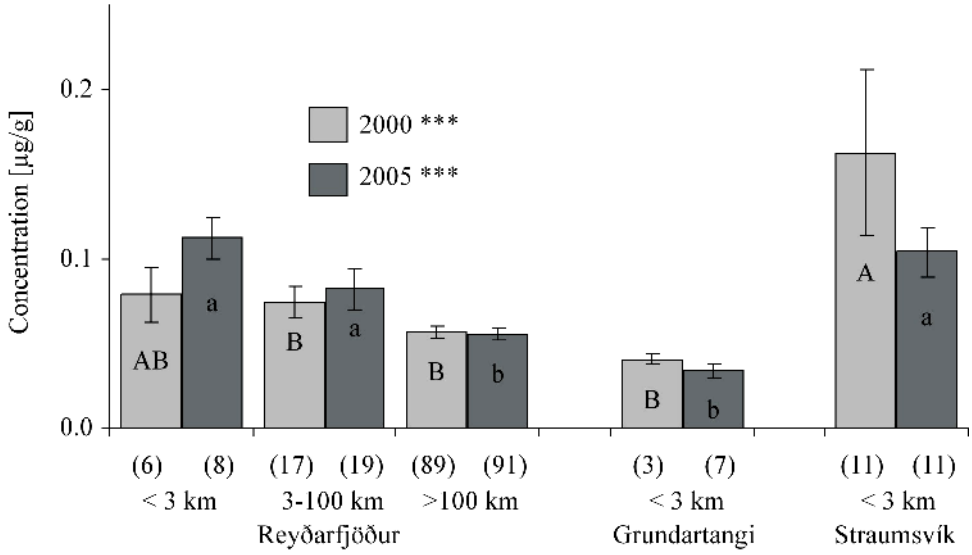
Comparison of distance classes and sites showed that for 2005 the concentration in Reyðarfjörður (< 3 km) was similar to the 3–100 km distance class and for Straumsvík. It was however significantly higher than in the >100 km distance class and at Grundartangi (Figure 3). In 2000 the Reyðarfjörður site (<3 km) did not differ from the other classes or sites.

Comparison of paired values showed on average higher concentration in Reyðarfjörður in 2005 than in 2000 (<3 km) although not significant (0.11 and 0.08 µg/g, P=0.070, n=4). Similar results was also found for the distance class 3–100 km between 2000 and 2005 (0.07 to 0.08 µg/g (P<0.05, n=16). Compared to Europe, the values in Reyðarfjörður in 2005 were low, but higher than in remote areas of Scandinavia (Rühling and Steinnes 1998, Buse et al. 2003).

Earlier studies in Iceland have shown that concentration of cadmium in moss is generally higher within areas of high erosional activity than in other places (Rühling et al. 1992, Rühling and Steinnes 1998). Therefore, the relatively high values of cadmium in Reyðarfjörður in 2005 might be related to increased soil dust in the area.

Cadmium (Cd)

A.



B.

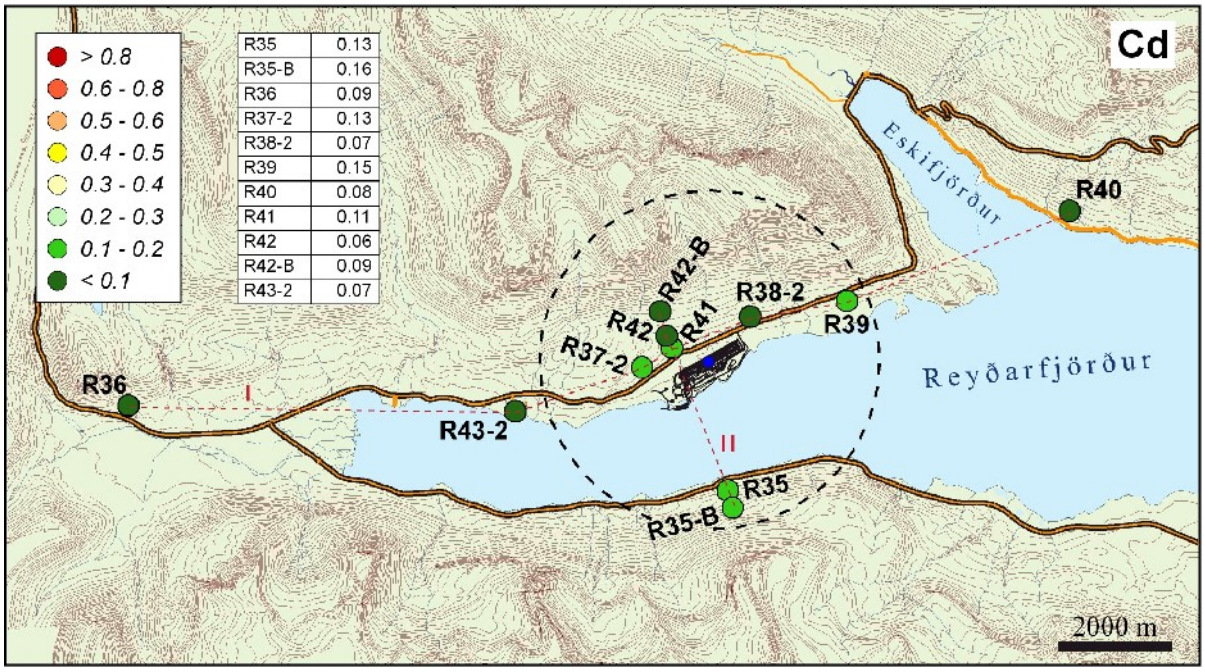


Figure 3. **(A)** Average cadmium (Cd) concentration at different distances (<3 km, 3–100 km, >100 km) from the aluminium smelter site in Reyðarfjörður for the 2000 and 2005 survey and at the industrial sites at Grundartangi and Straumsvík. - *Styrkur kadmíums í mosa í mismunandi fjarlægð frá álveri í Reyðarfirði (<3 km, 3–100 km, >100 km) árin 2000 og 2005. Til samanburðar er einnig sýndur styrkur kadmíums við iðjuverin á Grundartanga og í Straumsvík.*

(B) Spatial distribution of cadmium concentration in mosses along the sampling transects close to the aluminium smelter site in Reyðarfjörður in 2005. For details see also Figure 2. - *Styrkur kadmíums í mosa í Reyðarfirði og nágrenni. Nánari skýringar á 2. mynd.*

4.3 Chromium (Cr)

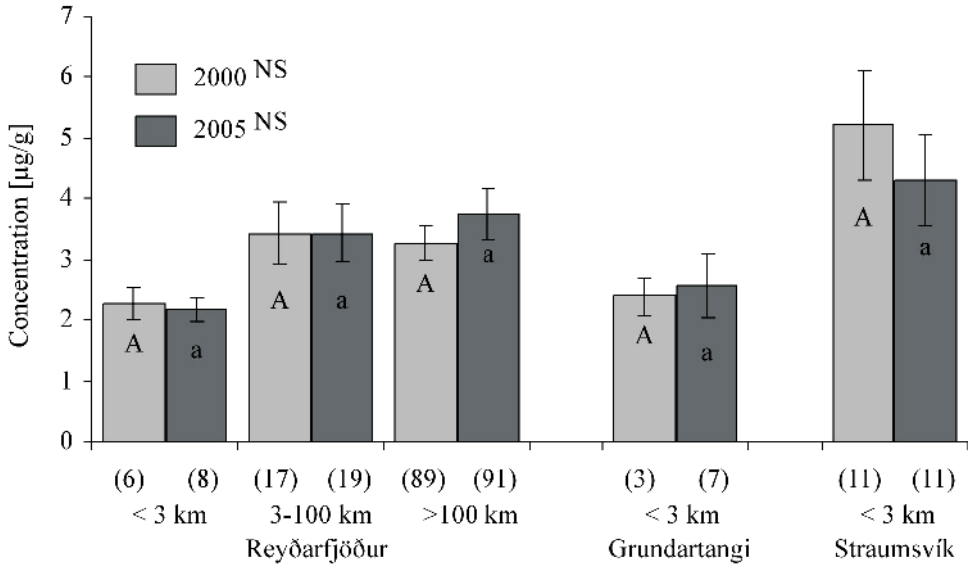
In 2005, chromium ranged from 1.56 to 3.23 µg/g in Reyðarfjörður which is in the medium range of samples from Iceland (Figure 4, Appendix 2). The moss samples along the shoreline of the fjord and close to the smelter site showed somewhat higher concentrations than other samples within the fjord.

No significant differences between the distance classes or sites could be found for either the 2000 or 2005 surveys. Comparison of paired values did not reveal any significant change with time, except for the Straumsvík site. There the average concentration changed from 5.2 to 4.3 µg/g between 2000 and 2005 ($P<0.01$, $n=11$).

For Iceland, chromium levels are higher than the European background of less than 2 µg/g (Rühling and Steinnes 1998) which is related to the high erosion activity in Iceland (Rühling et al. 1992, Rühling and Steinnes 1998). The reason for the relatively high concentration values of chromium along the coastline of the fjord and close to the smelter site is not clear but may be linked to soil dust.

Chromium (Cr)

A.



B.

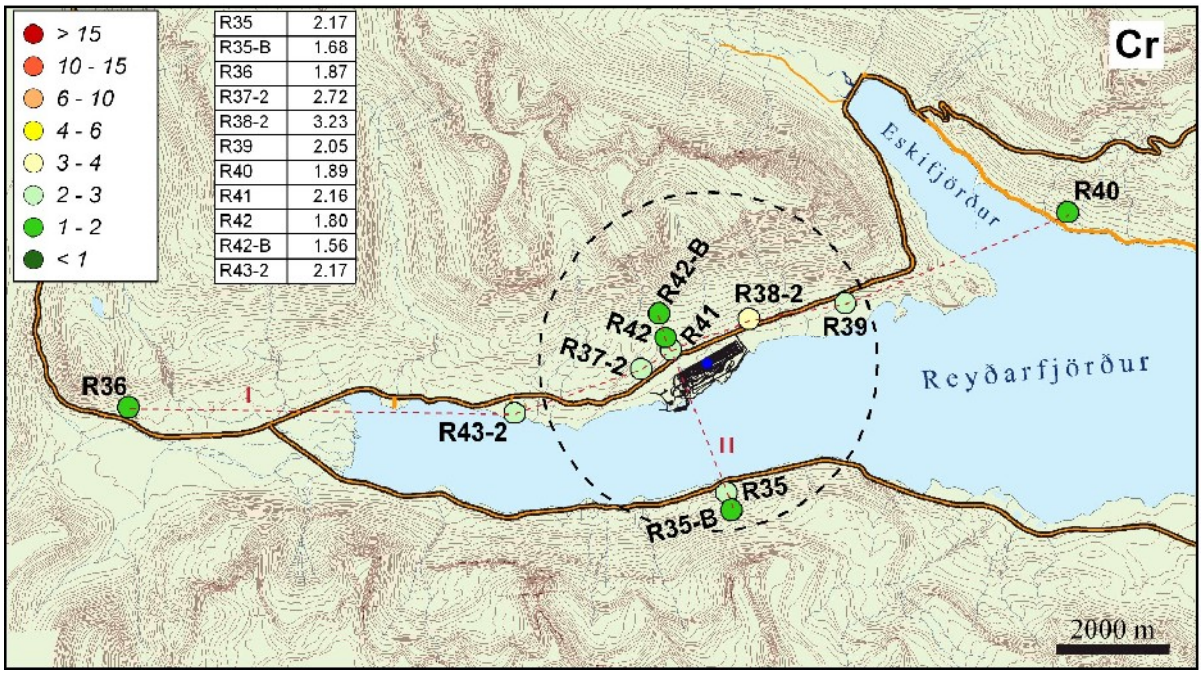


Figure 4. **(A)** Average chromium (Cr) concentration at different distances (<3 km, 3–100 km, >100 km) from the aluminium smelter site in Reyðarfjörður for the 2000 and 2005 survey and at the industrial sites at Grundartangi and Straumsvík. - *Styrkur* chromium *í mosa í mismunandi fjarlægð frá álveri í Reyðarfirði (<3 km, 3–100 km, >100 km) árin 2000 og 2005. Til samanburðar er einnig sýndur styrkur króms við iðjuverin á Grundartanga og í Straumsvík.*

(B) Spatial distribution of chromium concentration in mosses along the sampling transects close to the aluminium smelter site in Reyðarfjörður in 2005. For details see also Figure 2. - *Styrkur króms í mosa í Reyðarfirði og nágrenni. Nánari skýringar á 2. mynd.*

4.4 Copper (Cu)

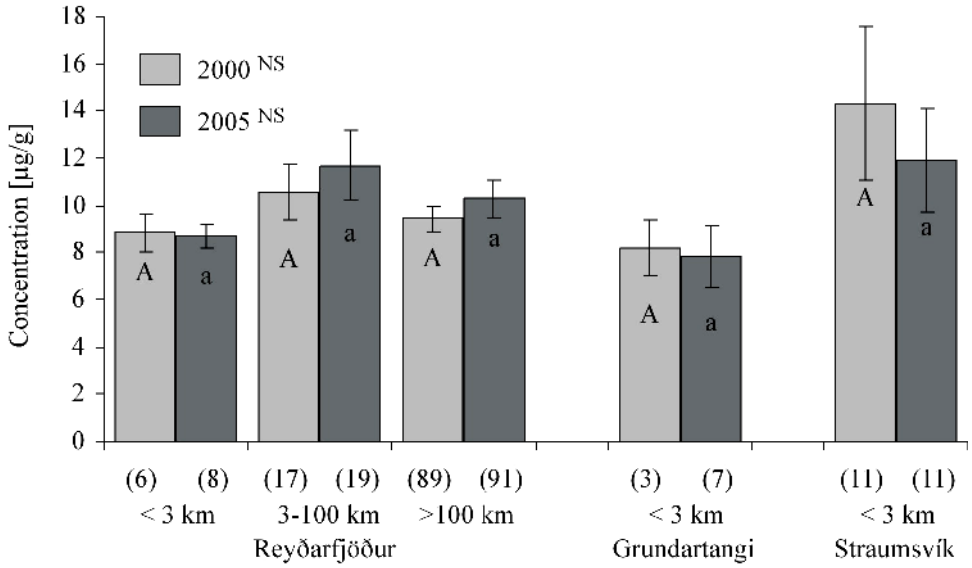
In the 2005 survey the copper concentration within Reyðarfjörður ranged between 6.94 and 10.73 µg/g which is in the medium range for samples from Iceland (Figure 5, Appendix 2). The highest values were found along the shoreline of the fjord close to the smelter site.

Comparison of copper concentration between distance classes or sites did not reveal any significant difference for either the 2005 or the 2000 survey. Also, changes with time were low. However, a significant change was found for the Straumsvík site between 2000 and 2005 (14.3 to 11.9 µg/g; $P<0.05$, $n=11$).

The values from Reyðarfjörður are low compared to most European values. However, the samples at the shoreline of the fjord show somewhat higher concentrations than samples in rural areas of Scandinavia (Buse et al. 2003). In Iceland, soil dust and volcanic ash are probably the main reasons for copper content in mosses (Rühling et al. 1992, Rühling and Steinnes 1998). Therefore, the relatively high concentration in the fjord might be related to soil dust.

Copper (Cu)

A.



B.

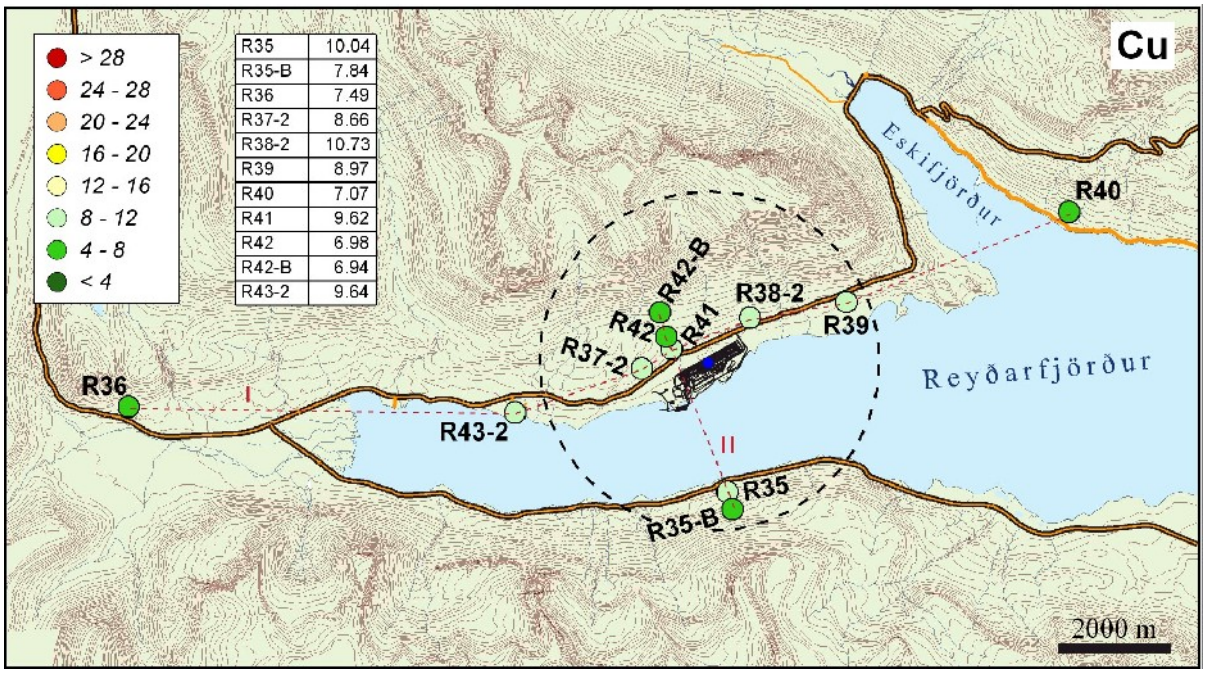


Figure 5. **(A)** Average copper (Cu) concentration at different distances (<3 km, 3–100 km, >100 km) from the aluminium smelter site in Reyðarfjörður for the 2000 and 2005 survey and at the industrial sites at Grundartangi and Straumsvík. - *Styrkur* kopars *í mosa í mismunandi fjarlægð frá álveri í Reyðarfirði (<3 km, 3–100 km, >100 km) árin 2000 og 2005. Til samanburðar er einnig sýndur styrkur* kopars *við iðjuverin á Grundartanga og í Straumsvík.*

(B) Spatial distribution of copper concentration in mosses along the sampling transects close to the aluminium smelter site in Reyðarfjörður in 2005. For details see also Figure 2. - *Styrkur kopars í mosa í Reyðarfirði og nágrenni. Nánari skýringar á 2. mynd.*

4.5 Iron (Fe)

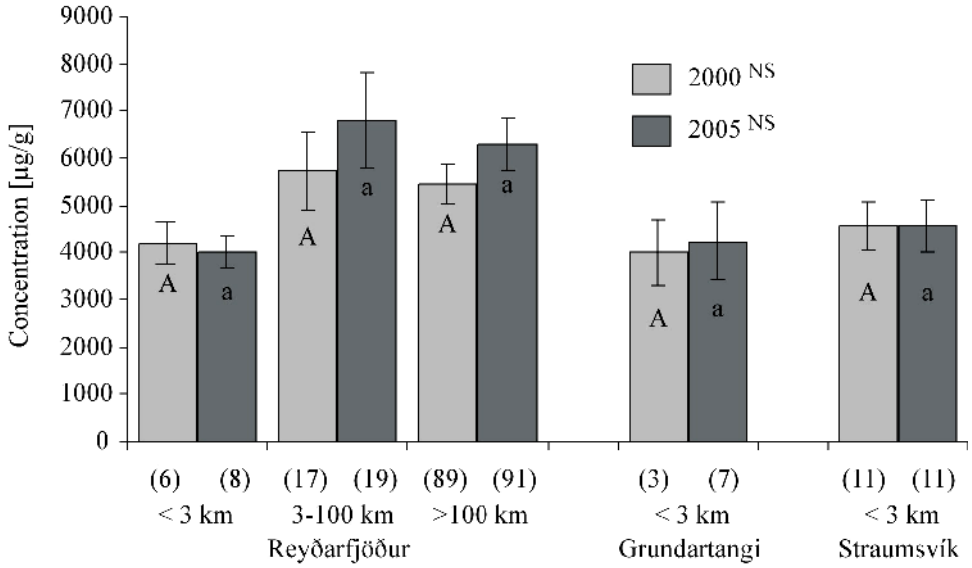
In 2005, the concentration of iron in Reyðarfjörður varied between 2640 and 5242 µg/g (Figure 6). The distribution pattern within the fjord shows that concentrations are, in general, high along the shoreline, especially close to the smelter site. The lowest concentrations were found at the sites farthest from the sea.

Comparison of iron concentration between distance classes or sites did not reveal any significant difference for either the 2005 or the 2000 survey (Figure 6). Between the two surveys in 2000 and 2005 samples within >100 km have increased significantly from 5456 to 6306 µg/g ($P<0.05$, $n=82$).

Compared to Scandinavia and Central Europe, the concentration of iron in moss in Iceland is extremely high and is evidently affected by soil dust (Rühling et al. 1992, Rühling and Steinnes 1998). However, the Reyðarfjörður samples are medium to low in iron content compared to other samples from Iceland (Appendix 2). This was expected as the site is outside the zone of high soil erosion and volcanic activity (Arnalds 1990 and Arnalds et al. 1997). The relatively high concentration of iron along the shoreline and close to the smelter site in Reyðarfjörður is probably caused by soil dust.

Iron (Fe)

A.



B.

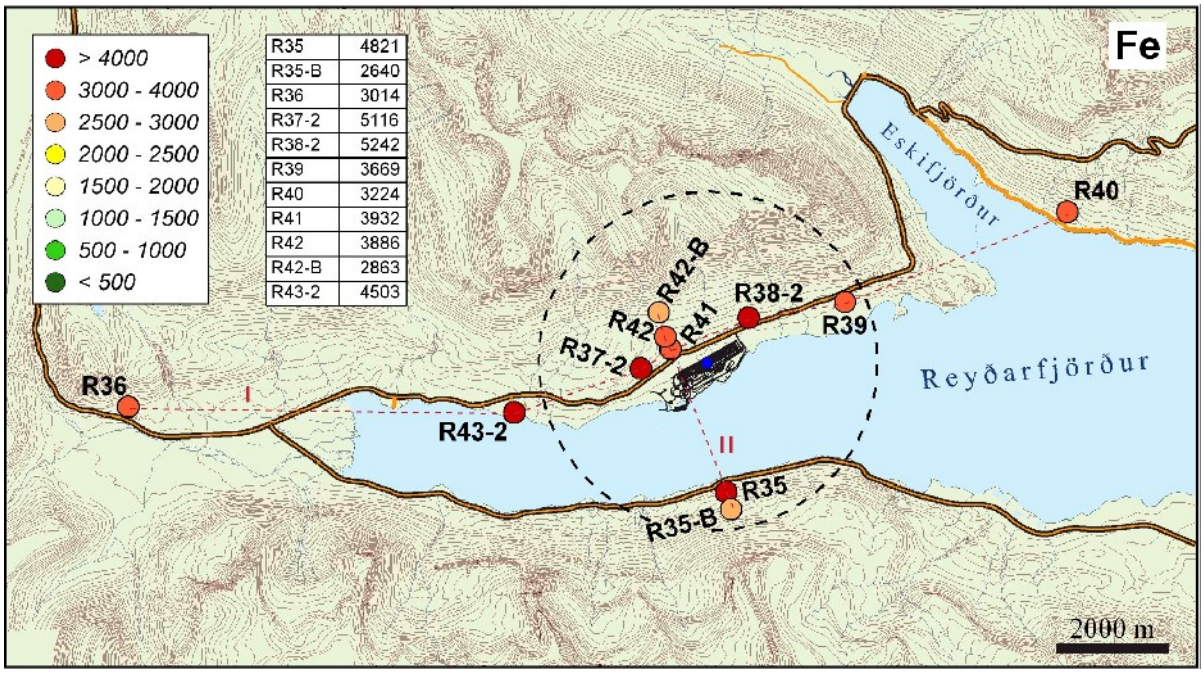


Figure 6. **(A)** Average iron (Fe) concentration at different distances (<3 km, 3–100 km, >100 km) from the aluminium smelter site in Reyðarfjörður for the 2000 and 2005 survey and at the industrial sites at Grundartangi and Straumsvík. - *Styrkur járns í mosa í mismunandi fjarlægð frá álveri í Reyðarfirði (<3 km, 3–100 km, >100 km) árin 2000 og 2005. Til samanburðar er einnig sýndur styrkur járns við iðjuverin á Grundartanga og í Straumsvík.*

(B) Spatial distribution of iron concentration in mosses along the sampling transects close to the aluminium smelter site in Reyðarfjörður in 2005. For details see also Figure 2. - *Styrkur járns í mosa í Reyðarfirði og nágrenni. Nánari skýringar á 2. mynd.*

4.6 Mercury (Hg)

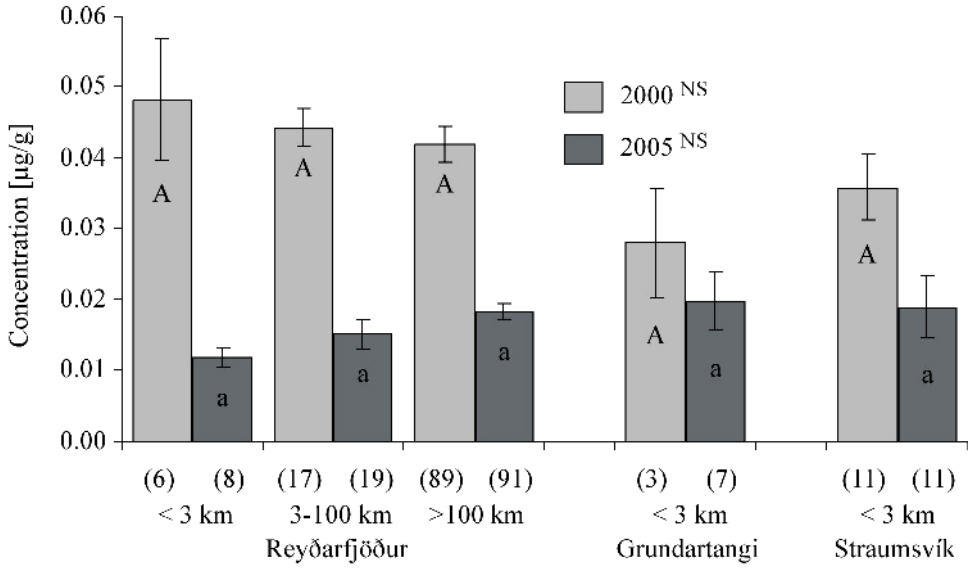
In the 2005 survey, concentration of mercury in Reyðarfjörður ranged from 0.003 to 0.019 µg/g. These values do not indicate any distinct pattern of distribution within the fjord (Figure 7). Compared to the whole Icelandic data, the samples close to the smelter site in Reyðarfjörður (>3 km) are medium to low (Appendix 2).

The concentration of mercury close to the smelter site (<3 km) was not significantly different from any other distance classes or areas compared for either 2000 or 2005 (Figure 7). However, the comparison of paired values indicates a significant decrease between 2000 and 2005 throughout all distance classes compared. The mercury concentration decreased as follows: Reyðarfjörður (< 3 km) from 0.048 to 0.012 µg/g ($P<0.01$, n=4), 3–100 km from 0.044 to 0.018 µg/g ($P<0.001$, n=16), > 100 km from 0.042 to 0.018 µg/g ($P<0.001$, n=82) and at Straumsvík from 0.036 to 0.019 µg/g ($P<0.001$, n=11).

Earlier studies in Iceland show that mercury concentrations in mosses are generally low and similar to Scandinavia and central Europe (Rühling and Steinnes 1998, Buse et al. 2003). Mercury is one of the metals which is readily transported over long distances (Poikolainen et al. 2004). In Iceland no strong local emission sources for mercury are known. Therefore, the decrease in concentration between 2000 and 2005 is likely to be a result of decrease in the long-range transport of mercury to the country (Working Group on Effects 2004).

Mercury (Hg)

A.



B.

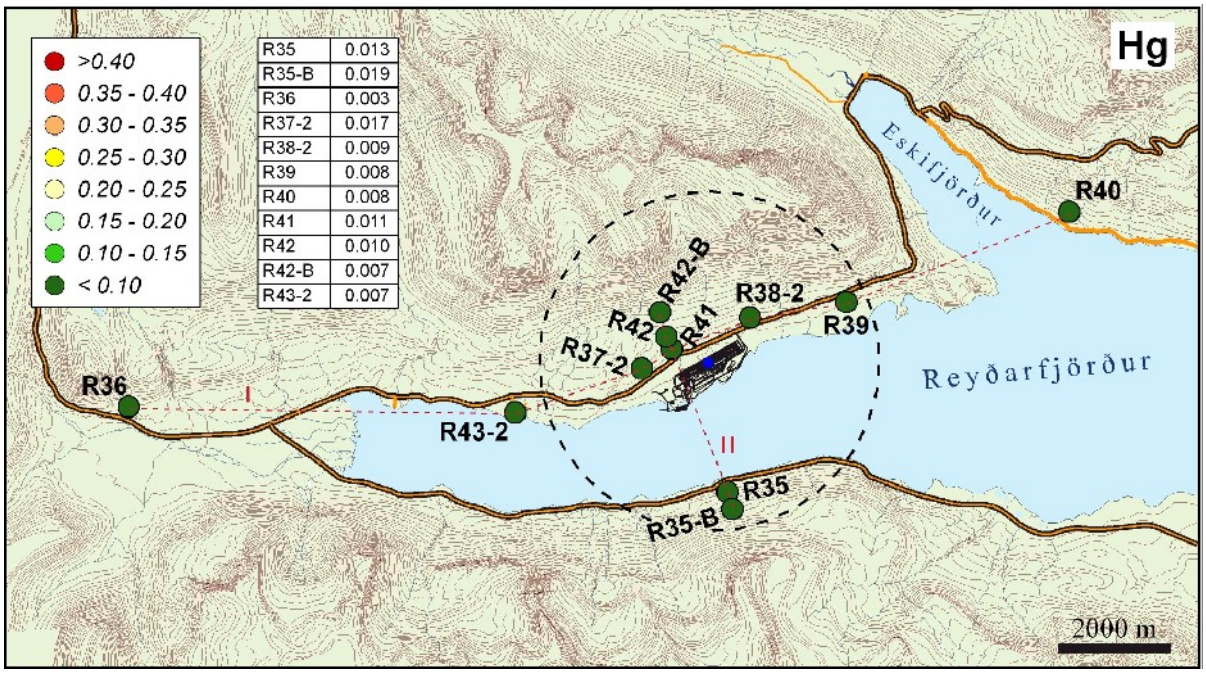


Figure 7. **(A)** Average mercury (Hg) concentration at different distances (<3 km, 3–100 km, >100 km) from the aluminium smelter site in Reyðarfjörður for the 2000 and 2005 survey and at the industrial sites at Grundartangi and Straumsvík. - *Styrkur kvikasilfurs í mosa í mismunandi fjarlægð frá álveri í Reyðarfirði (<3 km, 3–100 km, >100 km) árin 2000 og 2005. Til samanburðar er einnig sýndur styrkur kvikasilfurs við iðjuverin á Grundartanga og í Straumsvík.*

(B) Spatial distribution of mercury concentration in mosses along the sampling transects close to the aluminium smelter site in Reyðarfjörður in 2005. For details see also Figure 2. - *Styrkur kvikasilfurs í mosa í Reyðarfirði og nágrenni. Nánari skýringar á 2. mynd.*

4.7 Nickel (Ni)

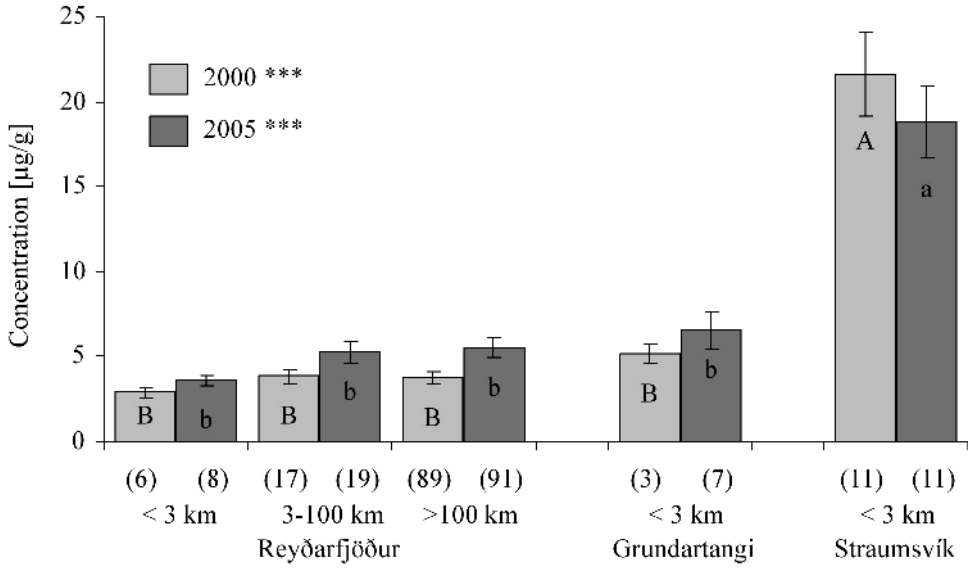
In 2005, the nickel concentration in Reyðarfjörður ranged between 2.62 and 4.43 µg/g and showed a pattern of relatively high concentration along the shoreline and close to the smelter site (Figure 8).

Both in 2000 and 2005, the samples close to the smelter site (<3 km) did not differ significantly from any other site or distance class compared, except for Straumsvík which had much higher values than all other sites and classes (Figure 8). However, test of paired samples showed that the nickel concentration had changed considerably between the two surveys, increased from 3.8 to 5.2 µg/g ($P<0.01$, n=16) for distance class 3–100 km and from 3.7 to 5.5 µg/g ($P<0.001$, n=82) for >100 km but decreased at Straumsvík from 21.6 to 18.8 µg/g ($P<0.05$, n=11).

The medium to low values in moss samples from Reyðarfjörður are within the normal nickel range for the country (Appendix 2) which is relatively high compared to other European countries (Rühling and Steinnes 1998, Buse et al. 2003). The relatively high values found along the shoreline of the fjord showed a similar pattern as found in 2000 survey. Why these sites show higher values is not clear but it is probably related to soil dust.

Nickel (Ni)

A.



B.

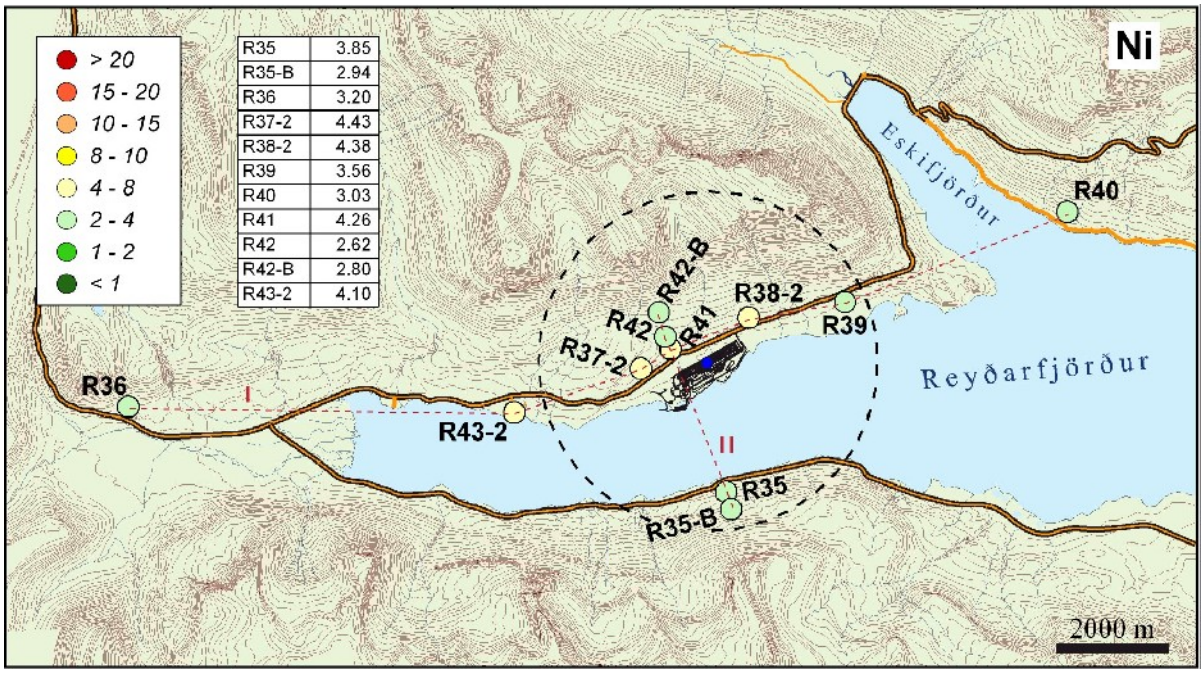


Figure 8. **(A)** Average nickel (Ni) concentration at different distances (<3 km, 3–100 km, >100 km) from the aluminium smelter site in Reyðarfjörður for the 2000 and 2005 survey and at the industrial sites at Grundartangi and Straumsvík. - *Styrkur nikkels í mosa í mismunandi fjarlægð frá álveri í Reyðarfirði (<3 km, 3–100 km, >100 km) árin 2000 og 2005. Til samanburðar er einnig sýndur styrkur nikkels við iðjuverin á Grundartanga og í Straumsvík.*

(B) *Spatial distribution of nickel concentration in mosses along the sampling transects close to the aluminium smelter site in Reyðarfjörður in 2005. For details see also Figure 2. - Styrkur nikkels í mosa í Reyðarfirði og nágrenni. Nánari skýringar á 2. mynd.*

4.8 Lead (Pb)

In the Reyðarfjörður area, lead concentration ranged from 2.42 to 4.83 µg/g in the 2005 survey and did not show a clear distribution pattern (Figure 9). However, the sites on the southern shoreline of the fjord had the highest concentration values.

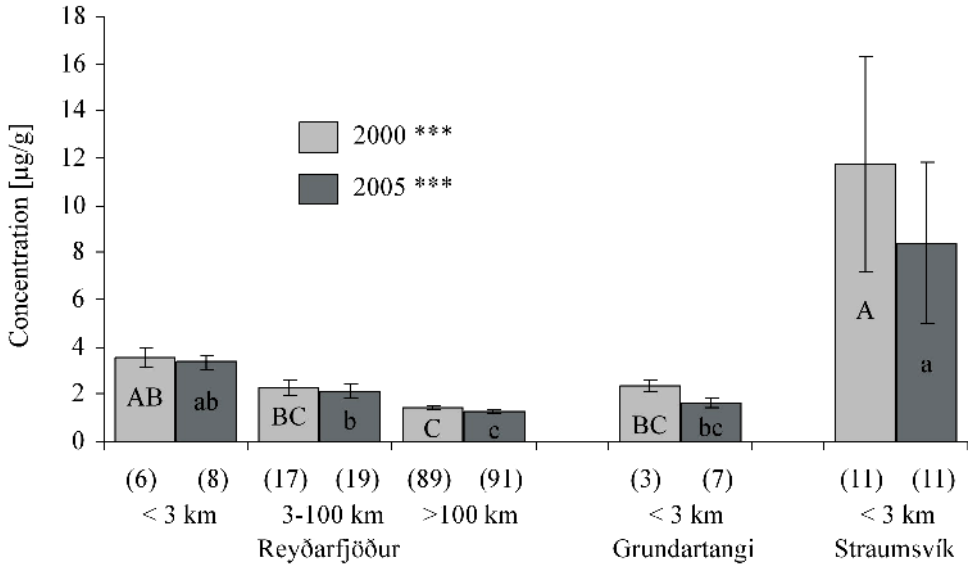
Statistical analysis revealed that, in 2000 and 2005, the samples close to the proposed smelter in Reyðarfjörður (<3 km) were not significantly different from other distance classes or sites, except for the >100 km class which had significantly lower values than were found in Reyðarfjörður (Figure 9).

Comparison of paired values showed a decrease in lead concentration between 2000 and 2005, although only significant for the distance class > 100 km (from 1.44 to 1.25 µg/g; $P<0.001$, n=82) and Straumsvík (from 11.74 to 8.39 µg/g; $P<0.001$, n=11).

Compared to the Icelandic data the lead concentration in Reyðarfjörður is relatively high (Appendix 2) and similar to other values on the southeast coast. This distribution pattern has been found in earlier surveys and has been explained by long-range transport from abroad (Rühling et al. 1992, Rühling and Steinnes 1998). However, the Icelandic values are low compared to other countries in Europe. (Rühling and Steinnes 1998, Buse et al. 2003).

Lead (Pb)

A.



B.

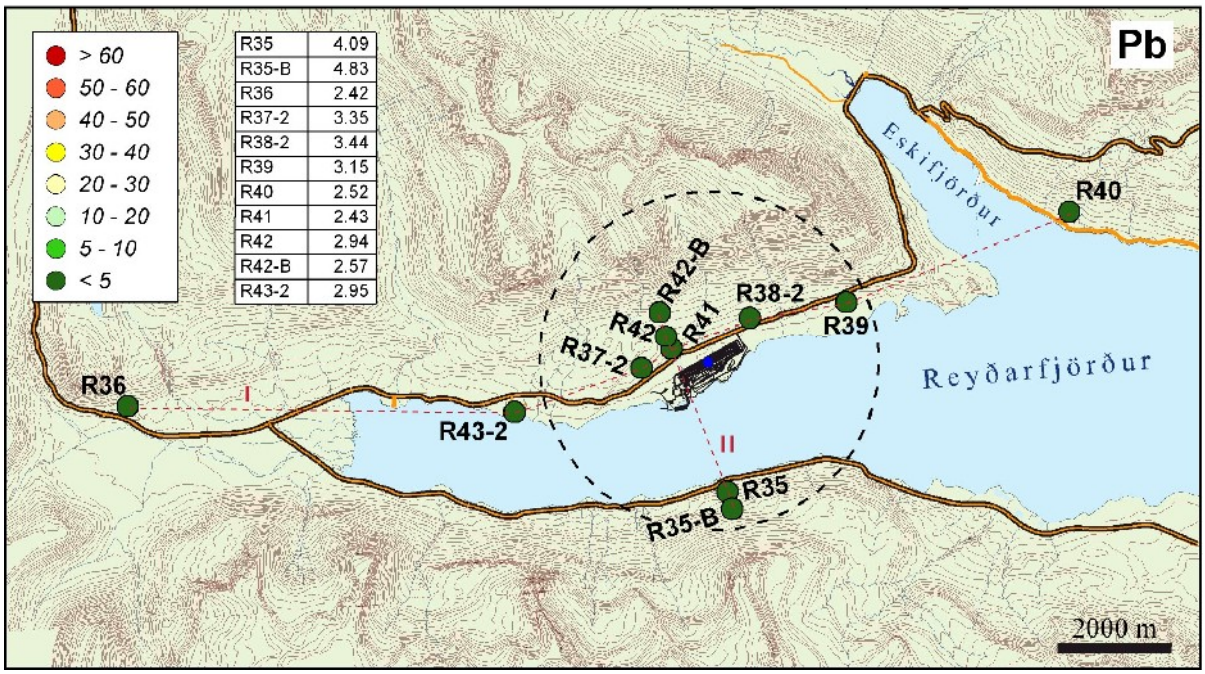


Figure 9. **(A)** Average lead (Pb) concentration at different distances (<3 km, 3–100 km, >100 km) from the aluminium smelter site in Reyðarfjörður for the 2000 and 2005 survey and at the industrial sites at Grundartangi and Straumsvík. - *Styrkur blýs í mosa í mismunandi fjarlægð frá álveri í Reyðarfirði (<3 km, 3–100 km, >100 km) árin 2000 og 2005. Til samanburðar er einnig sýndur styrkur blýs við iðjuverin á Grundartanga og í Straumsvík.*

(B) Spatial distribution of lead concentration in mosses along the sampling transects close to the aluminium smelter site in Reyðarfjörður in 2005. For details see also Figure 2. - *Styrkur blýs í mosa í Reyðarfirði og nágrenni. Nánari skýringar á 2. mynd.*

4.9 Vanadium (V)

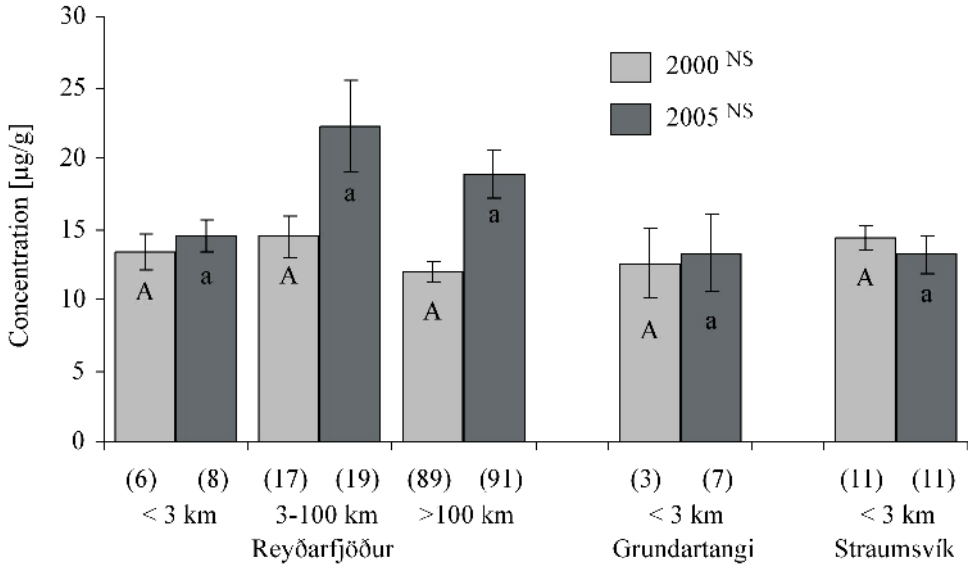
In the 2005 survey, vanadium in the Reyðarfjörður area ranged from 10.0 to 19.9 µg/g. The highest values were found at the shoreline close to the smelter site (Figure 10).

Comparison among distance classes and sites did not reveal any statistically significant differences in 2005 or in 2005 (Figure 10). However, between the two surveys in 2000 and 2005, there was a significant increase in vanadium concentration both at the distance class 3–100 km (from 14.5 to 22.2 µg/g ($P<0.01$, $n=16$) and class >100 km (from 12.0 to 18.8 µg/g; $P<0.001$, $n=82$). Although not significant, a similar trend was also found in the area close to the Reyðarfjörður smelter site.

For Iceland, the values close to the smelter site in Reyðarfjörður are in the medium range (Appendix 2). However, compared to Europe all Icelandic vanadium concentration values are high (Rühling and Steinnes 1998, Buse et al. 2003). Earlier studies in Iceland have shown that high vanadium concentrations are strongly associated with areas of high soil erosion. This is probably the main reason for the high levels detected in the 2005 survey. Soil dust patterns also seem to be responsible for the higher values close to the smelter construction area at the shoreline.

Vanadium (V)

A.



B.

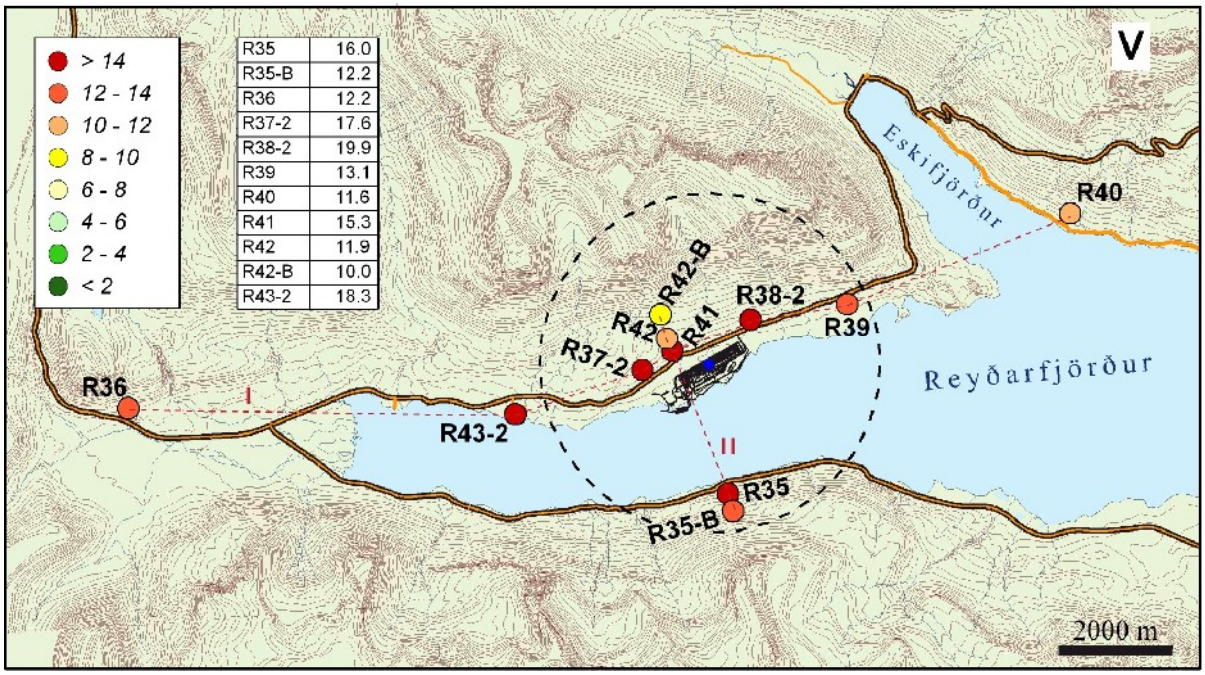


Figure 10. **(A)** Average vanadium (V) concentration at different distances (<3 km, 3–100 km, >100 km) from the aluminium smelter site in Reyðarfjörður for the 2000 and 2005 survey and at the industrial sites at Grundartangi and Straumsvík. - *Styrkur vanadíums í mosa í mismunandi fjarlægð frá álveri í Reyðarfirði (<3 km, 3–100 km, >100 km) árin 2000 og 2005. Til samanburðar er einnig sýndur styrkur vanadíums við iðjuverin á Grundartanga og í Straumsvík.*

(B) Spatial distribution of vanadium concentration in mosses along the sampling transects close to the aluminium smelter site in Reyðarfjörður in 2005. For details see also Figure 2. - *Styrkur vanadíums í mosa í Reyðarfirði og nágrenni. Nánari skýringar á 2. mynd.*

4.10 Zinc (Zn)

In 2005, zinc concentration in mosses in Reyðarfjörður ranged from 16.3 to 34.2 µg/g and did not show a clear distribution pattern within the fjord (Figure 11).

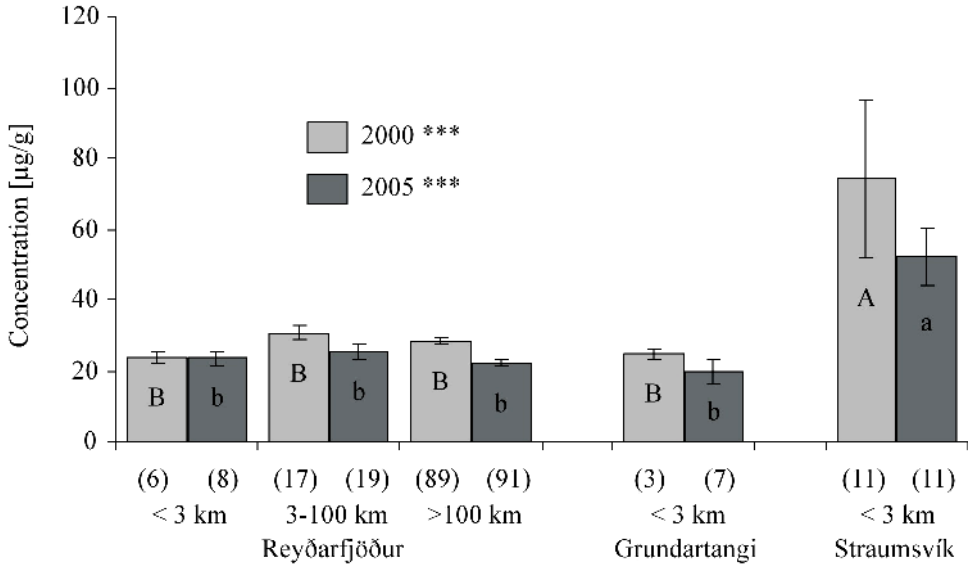
In 2000 and 2005, zinc concentration in moss close to the smelter site (<3 km) were similar to other areas and sites, but significantly lower than values around the Straumsvík smelter (Figure 11).

Comparison of paired values showed a significant decrease in zinc concentration between 2000 and 2005 for the distance classes 3–100 km (from 30.7 to 25.4 µg/g; $P<0.01$, n= 16) and > 100 km (from 28.4 to 22.2 µg/g; $P<0.001$, n=82). Although not significant, a similar trend was found for Straumsvík and Reyðarfjörður.

The values close to the Reyðarfjörður smelter site have a wide range compared to other samples in Iceland (Appendix 2). They were, however, low compared to most areas in Europe (Rühling and Steinnes 1998 and Buse et al. 2003). The decrease seems to be related to changes in the long range transport to Iceland.

Zinc (Zn)

A.



B.

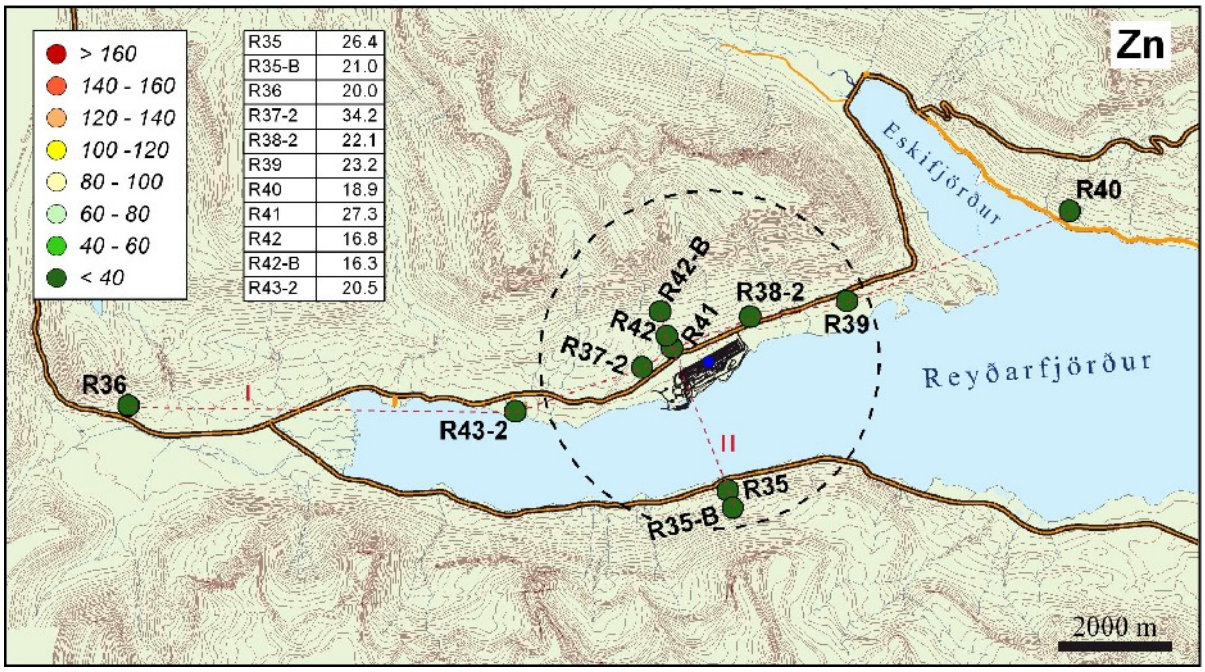


Figure 11. **(A)** Average zinc (Zn) concentration at different distances (<3 km, 3–100 km, >100 km) from the aluminium smelter site in Reyðarfjörður for the 2000 and 2005 survey and at the industrial sites at Grundartangi and Straumsvík. - *Styrkur sinks í mosa í mismunandi fjarlægð frá álveri í Reyðarfirði (<3 km, 3–100 km, >100 km) árin 2000 og 2005. Til samanburðar er einnig sýndur styrkur sinks við iðjuverin á Grundartanga og í Straumsvík.*

(B) Spatial distribution of zinc concentration in mosses along the sampling transects close to the aluminium smelter site in Reyðarfjörður in 2005. For details see also Figure 2. - *Styrkur sinks í mosa í Reyðarfirði og nágrenni. Nánari skýringar á 2. mynd.*

4.11 Sulphur (S)

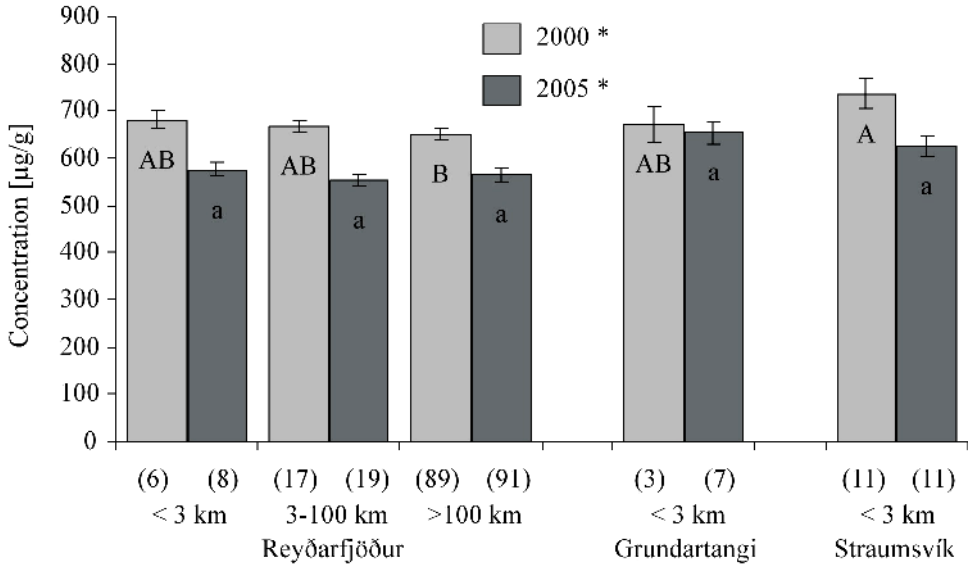
In the 2005 survey, sulphur concentrations ranged from 484 µg/g to 616 µg/g in the Reyðarfjörður area and no clear concentration pattern was observed within the fjord (Figure 12).

Comparison of the Reyðarfjörður site (<3 km) with the other sites and distance classes did not reveal a significant difference for either the 2000 or 2005 surveys (Figure 12). However, between the two surveys the concentration of sulphur decreased significantly at all the distance classes and sites compared. The results were as follows: In Reyðarfjörður < 3 km from 682 to 575 µg/g ($P<0.05$, n=4), class 3–100 km from 669 to 553 µg/g ($P<0.001$, n=16), class < 100 km from 651 to 565 µg/g ($P<0.001$, n=82) and Straumsvík from 737 to 625 µg/g ($P<0.01$, n=11).

For Iceland, the samples from Reyðarfjörður show upper medium concentrations (Appendix 2). A comparison to European values is not possible as sulphur is not measured outside Iceland.

Sulphur (S)

A.



B.

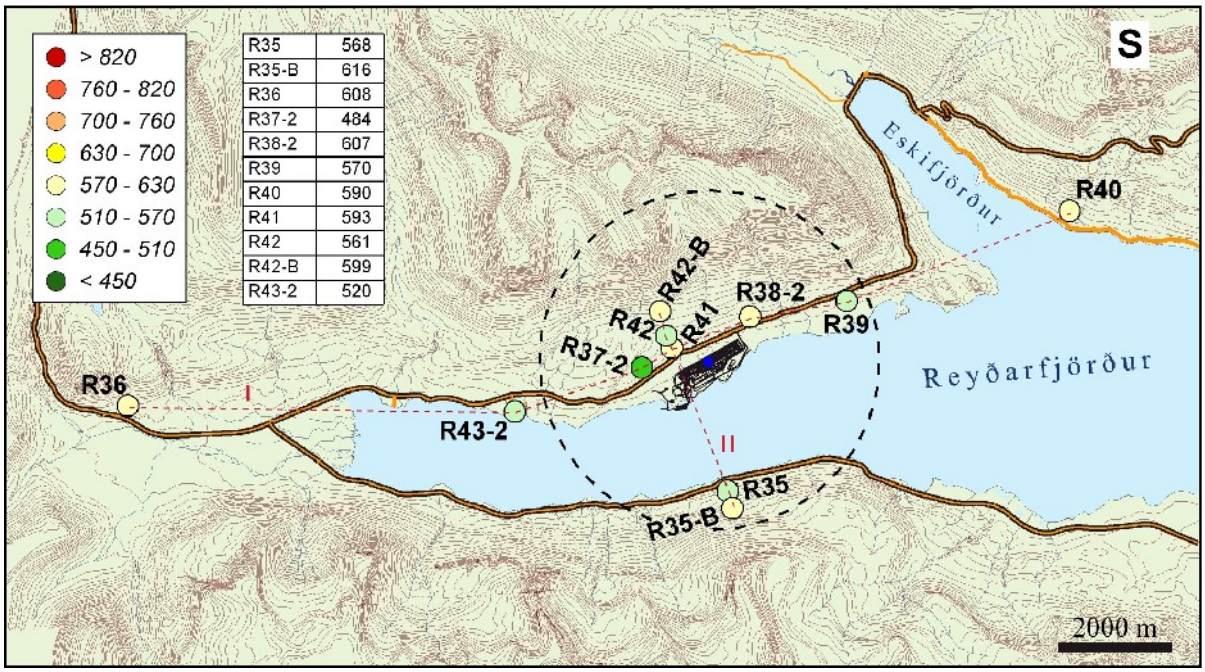


Figure 12. **(A)** Average sulphur (S) concentration at different distances (<3 km, 3–100 km, >100 km) from the aluminium smelter site in Reyðarfjörður for the 2000 and 2005 survey and at the industrial sites at Grundartangi and Straumsvík. - *Styrkur brennisteins í mosa í mismunandi fjarlægð frá álveri í Reyðarfirði (<3 km, 3–100 km, >100 km) árin 2000 og 2005. Til samanburðar er einnig sýndur styrkur brennisteins við iðjuverin á Grundartanga og í Straumsvík.*

(B) Spatial distribution of sulphur concentration in mosses along the sampling transects close to the aluminium smelter site in Reyðarfjörður in 2005. For details see also Figure 2. - *Styrkur brennisteins í mosa í Reyðarfirði og nágrenni. Nánari skýringar á 2. mynd.*

5 CONCLUSION

The results of the moss surveys in 2000 and 2005 provide a good base for future monitoring of heavy metals and sulphur in the Reyðarfjörður area.

Within Reyðarfjörður the highest concentrations of most of the heavy metals were found near the aluminium smelter site, especially along the sea shore.

Although the distribution pattern within the fjord was similar for most elements they could be divided into four types:

1. Arsenic (As) and zinc (Zn) – had the highest concentration close to the proposed smelter, particularly along the shore on both sides of the fjord (samples R37-2, R41, R38-2, R39 and R35).
2. Chromium (Cr), iron (Fe), copper (Cu), nickel (Ni) and vanadium (V) – had the highest concentration within an elongated area close to the proposed smelter and along the shore (samples R43-2, R41, R38-2, R39 and R35).
3. Cadmium (Cd), mercury (Hg) and lead (Pb) – had the highest values on both sides of the fjord close to the smelter site and were found in comparatively high concentrations on the mountain slopes on the south site of the fjord (samples R37-2, R41, R39, R35 and 35-B).
4. Sulphur (S) – no distinct distribution pattern was observed.

The results presented demonstrate that the concentration of nickel (Ni) and cadmium (Cd) has increased within Reyðarfjörður between 2000 and 2005. Similar tendency was also found for copper (Cu), iron (Fe) and vanadium (V). In Iceland the concentrations of all these elements are related to aeolian dust due to high soil erosion, reflecting the composition of bedrock and volcanic tephra. The increased concentration of the above mentioned elements in Reyðarfjörður could be related to increased soil dust, as their concentration also rose in the country as a whole during this period. Soil disturbance during construction of the smelter may also have enhanced these effects locally.

The concentration of lead (Pb) and sulphur (S) decreased in Reyðarfjörður during 2000 to 2005 as for the country as a whole. In Iceland lead is naturally in low background concentration and no local emission sources are known. Therefore, the decreased concentrations of the elements indicate a decline in long-distance transport. The reason for decreasing amounts of sulphur is also likely to be related to decline in long-distance transport.

6 ACKNOWLEDGEMENTS

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APENDICES

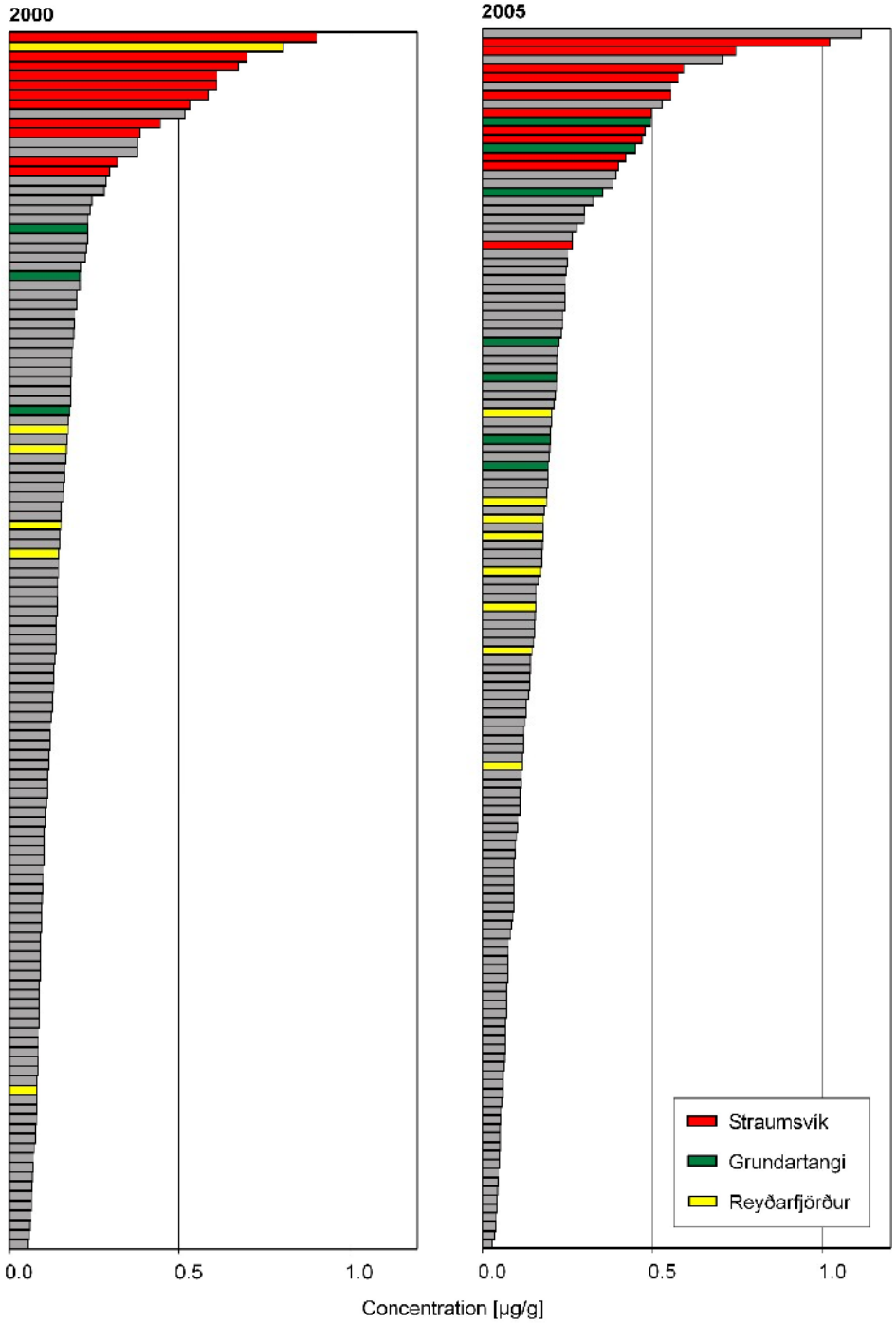
APPENDIX 1: Quantification Limits
Magngreiningarmörk

Substance *Efni*	Quantification Limit µg/g *Magngreiningarmörk*
As	0.00810
Cd	0.00075
Cr	0.00945
Cu	0.00075
Fe	0.03150
Hg	0.00315
Ni	0.03150
Pb	0.00060
S	5.10000
V	0.44550
Zn	0.05850

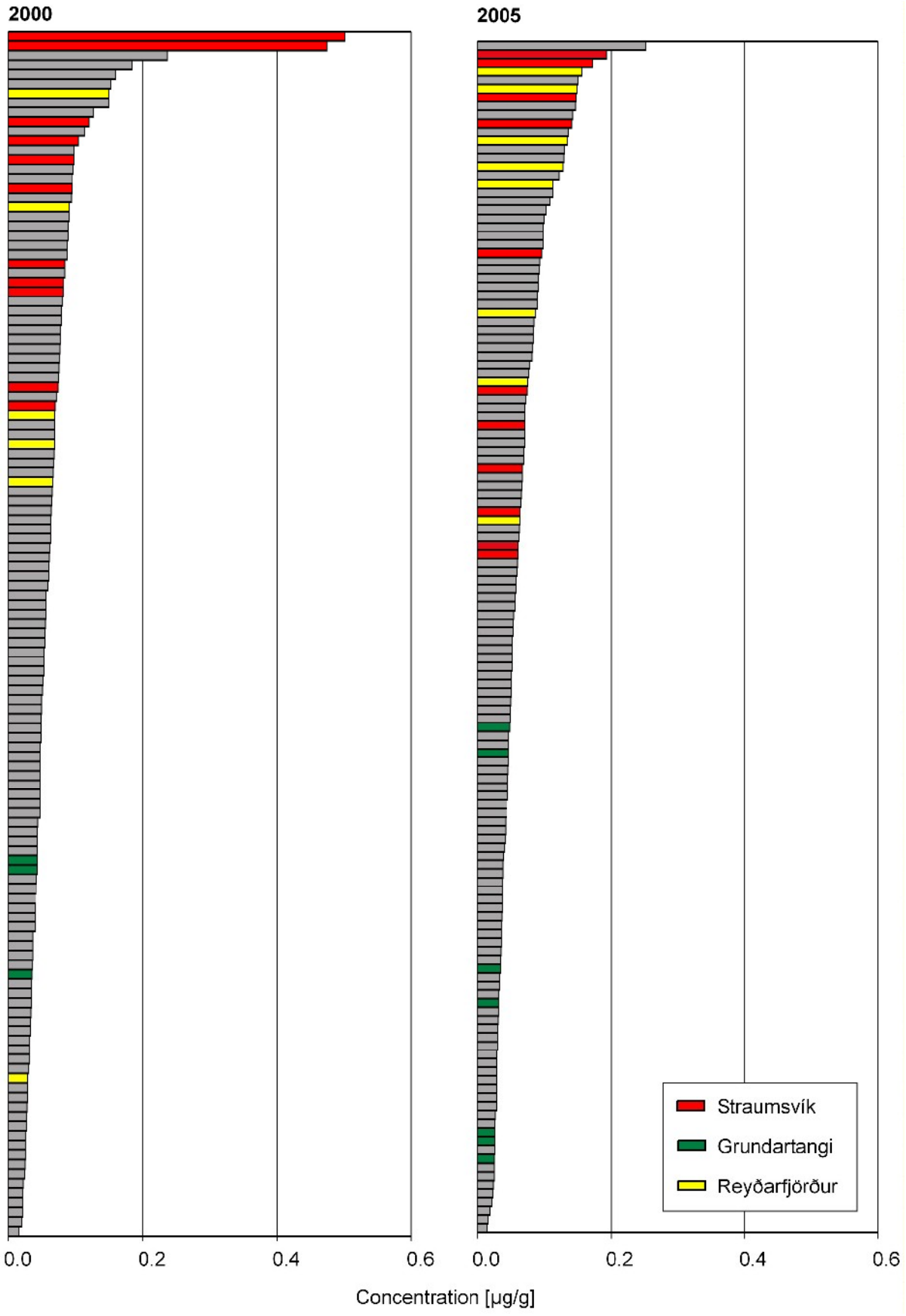
APPENDIX 2: Concentration in samples of the 2000 and 2005 Icelandic moss survey
Styrkur efna í mosasýnum frá 2000 og 2005

Concentration of heavy metals and sulphur in moss samples collected throughout Iceland in the 2000 and 2005 moss survey, shown in a descending order. The samples collected <3 km around the aluminium smelter in Straumsvík (red), ferro-silicon plant and aluminium smelter at Grundartangi (green) and at the smelter site in Reyðarfjörður (yellow) are marked. – *Styrkur þungmálma og brennisteins í mosa sem safnað var víðsvegar um land árin 2000 og 2005. Sýnum er raðað eftir magni viðkomandi efnis. Sýni sem safnað var í nágrenni (< 3 km) verksmiðjanna eru merkt með mismunandi litum: Straumsvík (rauð), verksmiðjur á Grundartanga (græn), álver í Reyðarfirði (gul).*

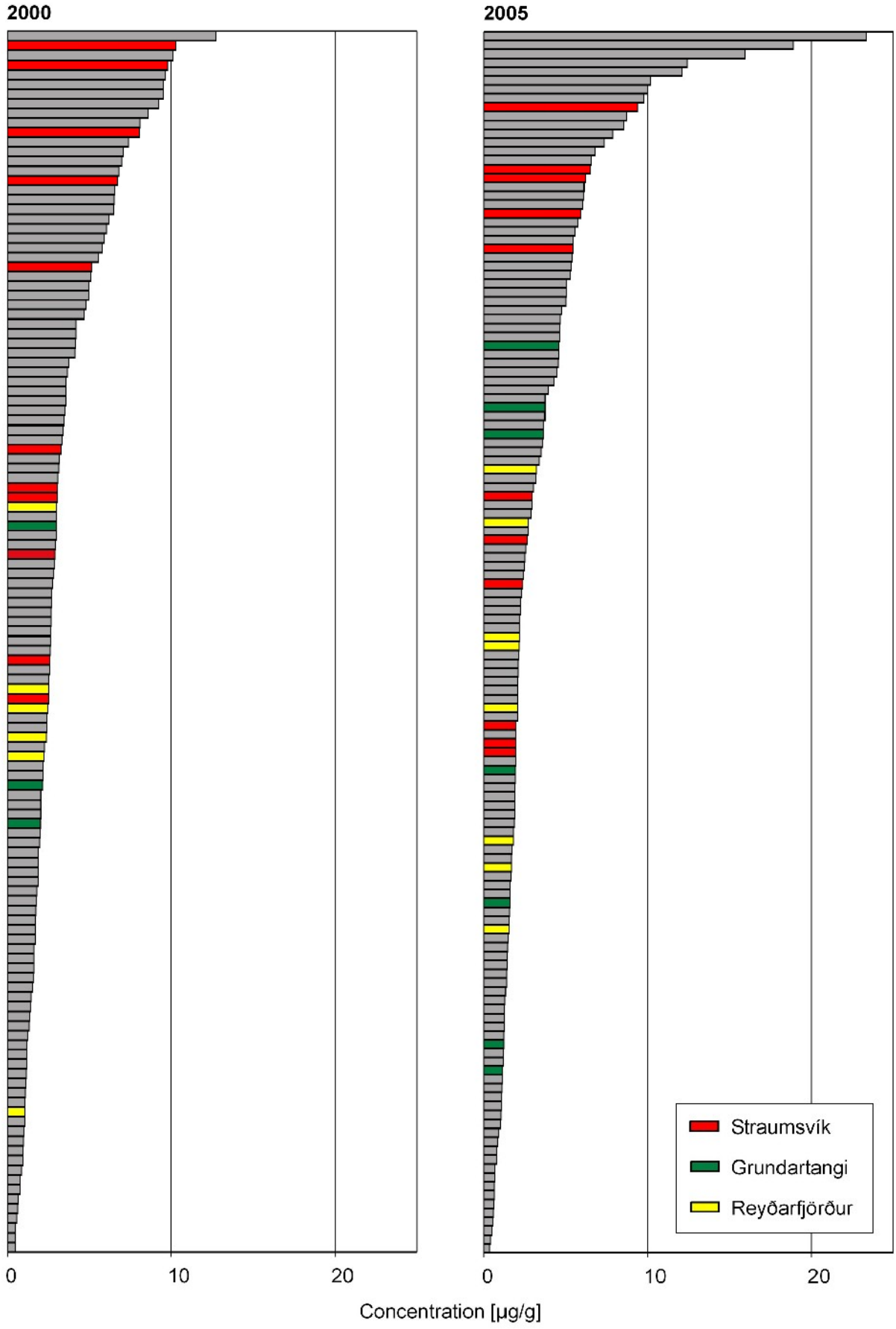
Arsenic (As)



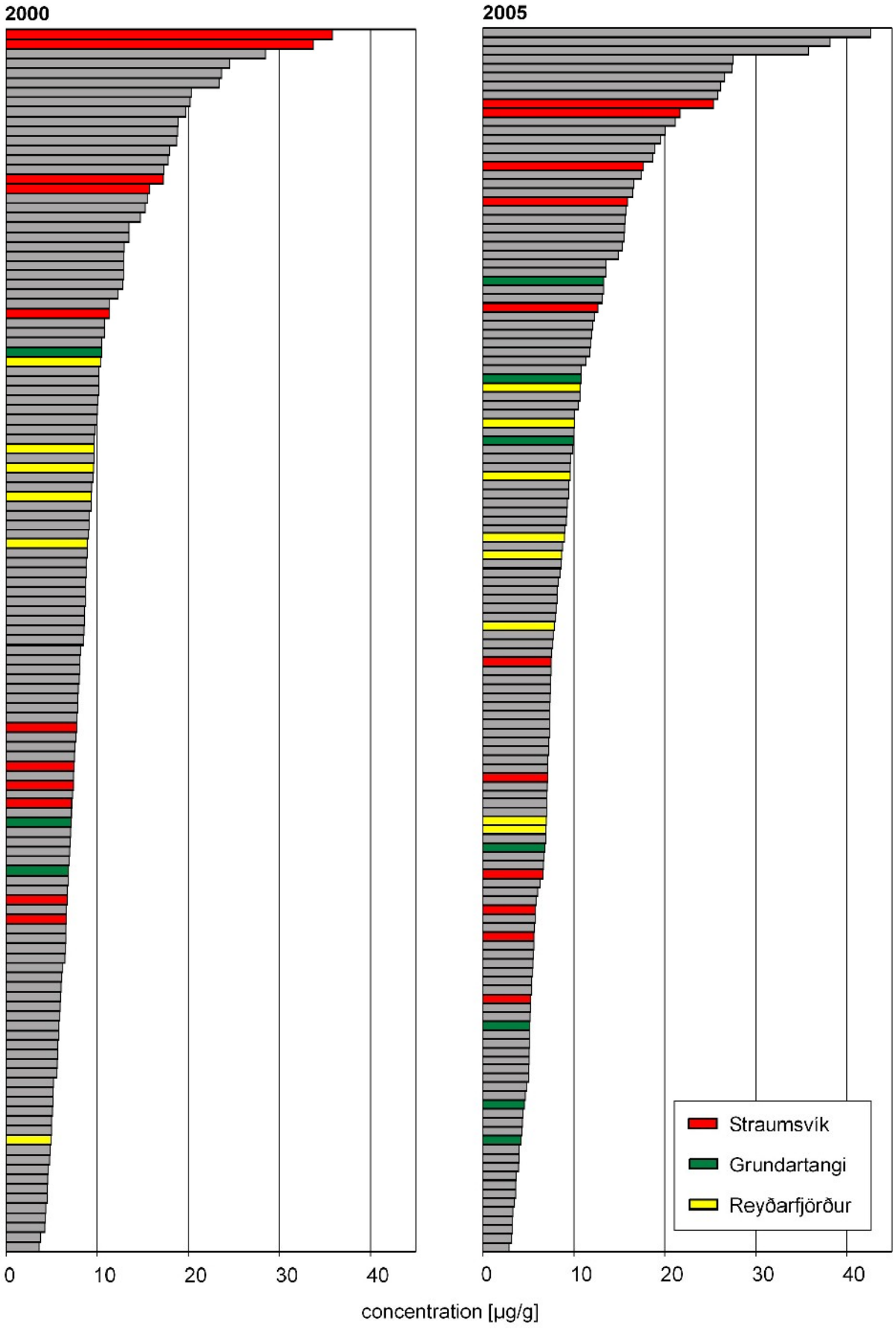
Cadmium (Cd)


2000
2005
Straumsvík
Grundartangi
Reyðarfjörður
0.0
0.2
0.4
0.6
Concentration [µg/g]

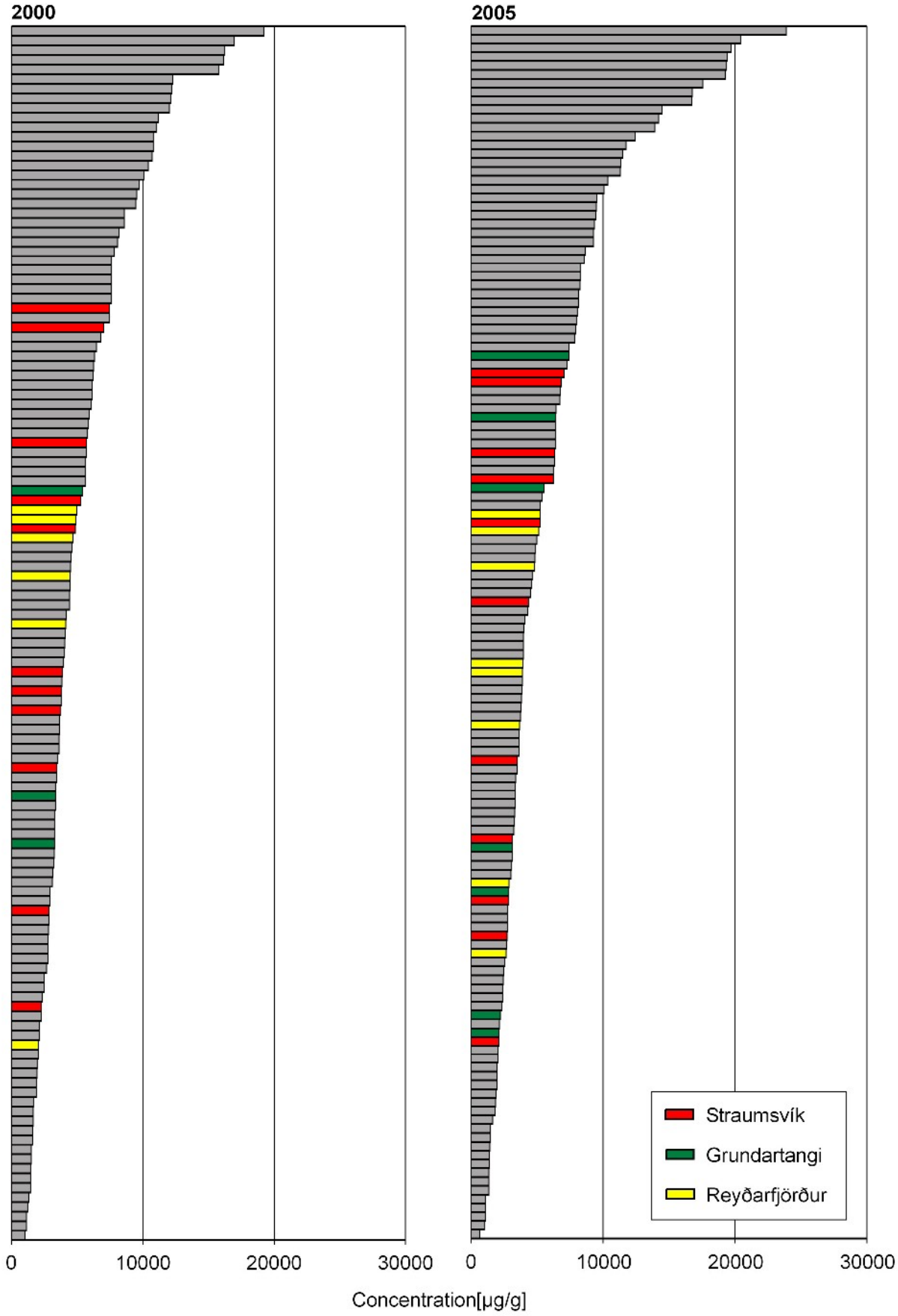
Chromium (Cr)


2000
2005
0
10
20
0
10
20
Concentration [µg/g]
Straumsvík
Grundartangi
Reyðarfjörður

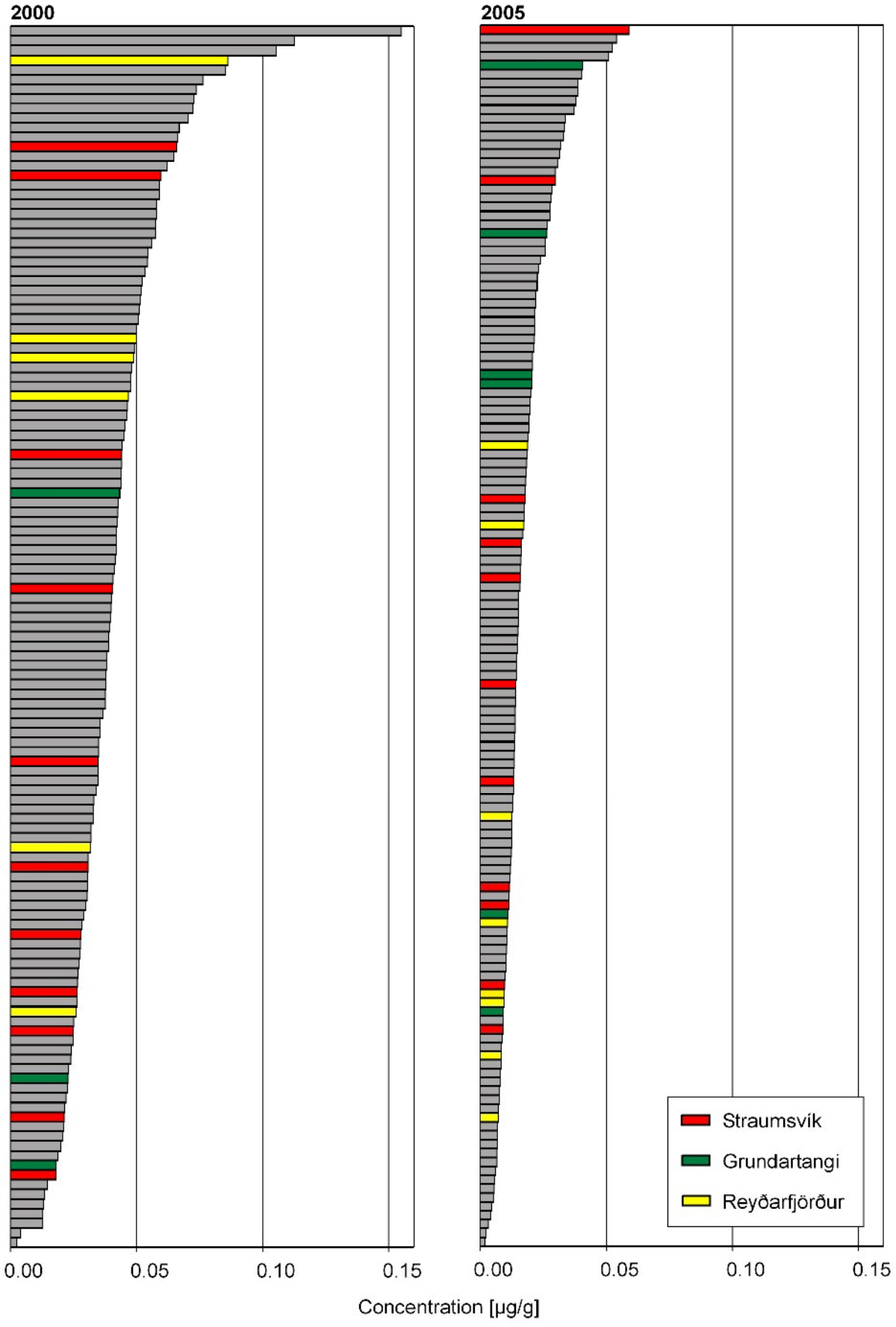
Copper (Cu)


2000
2005
0
10
20
30
40
concentration [µg/g]
Straumsvík
Grundartangi
Reyðarfjörður

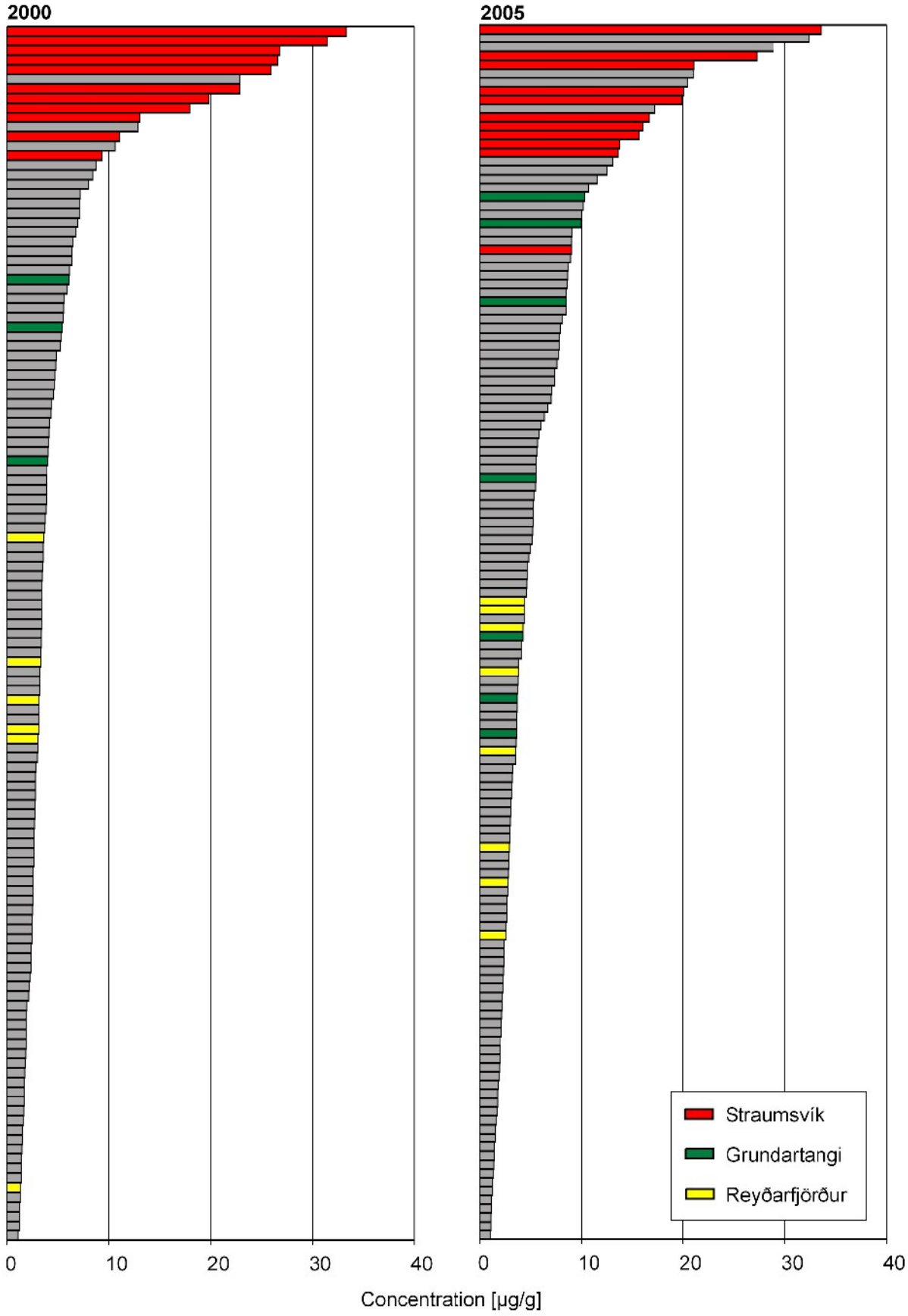
Iron (Fe)


2000
2005
0
10000
20000
30000
Concentration[µg/g]
Straumsvík
Grundartangi
Reyðarfjörður

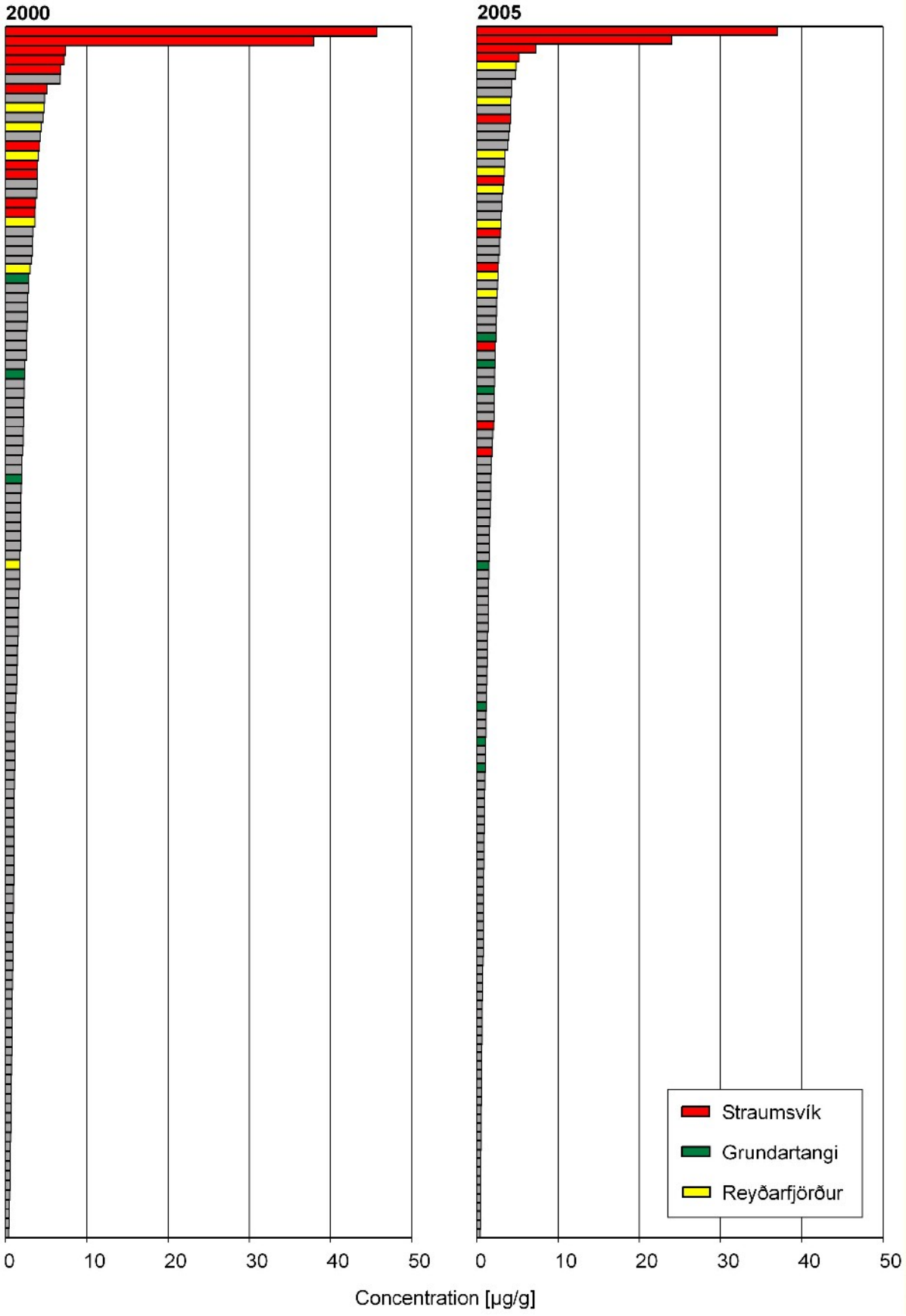
Mercury (Hg)


2000
2005
Straumsvík
Grundartangi
Reyðarfjörður
0.00
0.05
0.10
0.15
Concentration [µg/g]

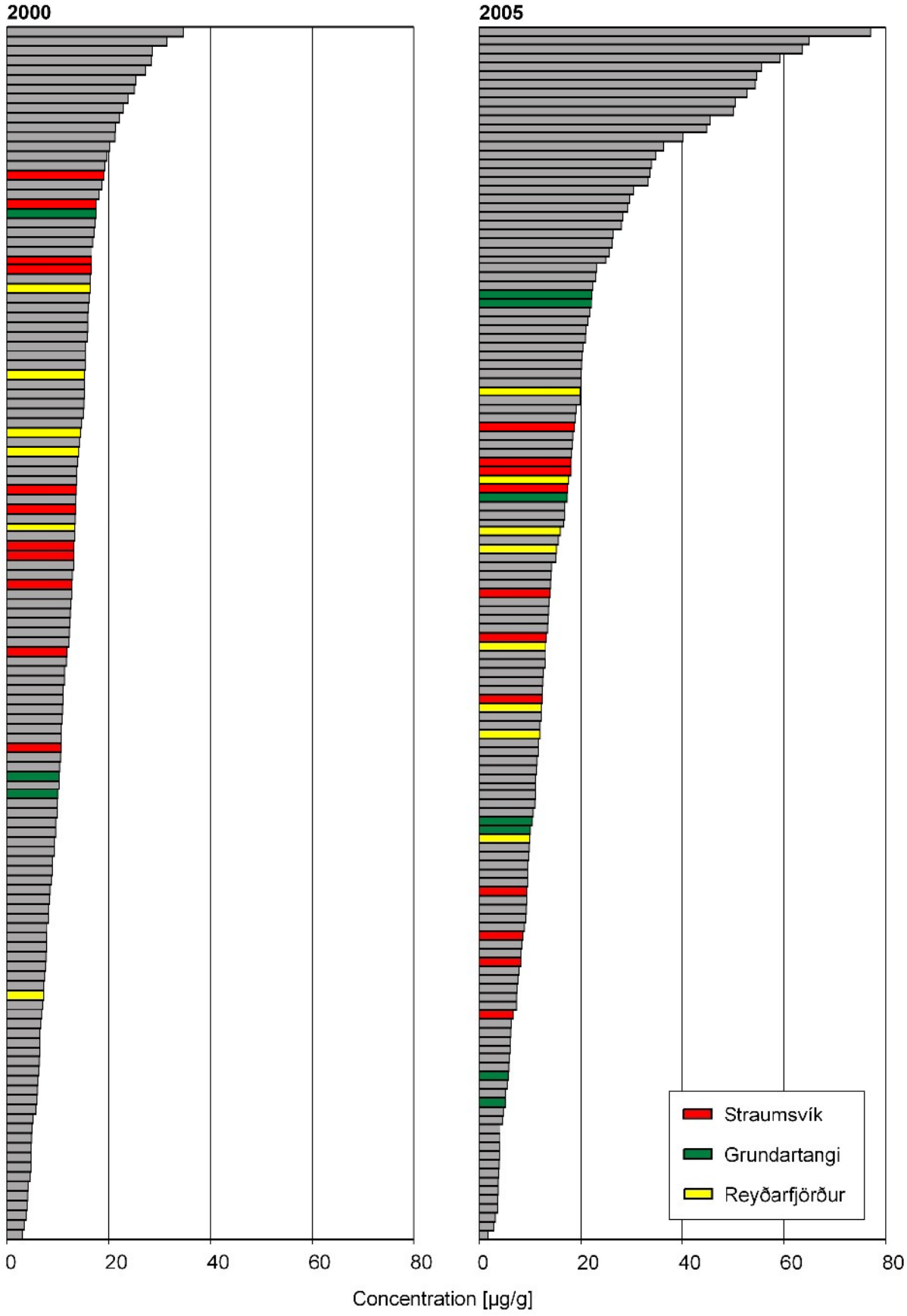
Nickel (Ni)


2000
2005
0
10
20
30
40
Straumsvík
Grundartangi
Reyðarfjörður
Concentration [µg/g]

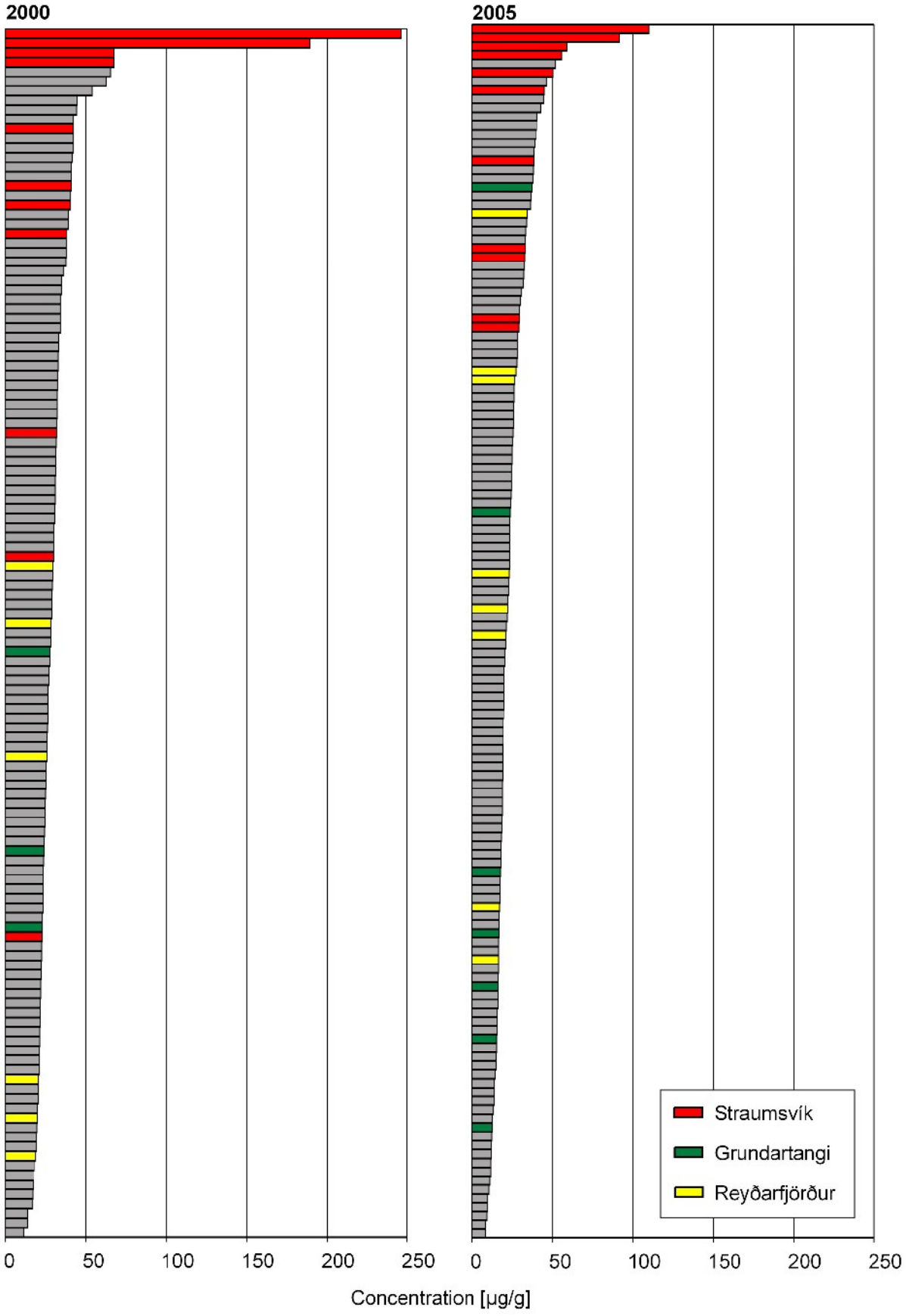
Lead (Pb)


2000
2005
Straumsvík
Grundartangi
Reyðarfjörður
0
10
20
30
40
50
Concentration [µg/g]

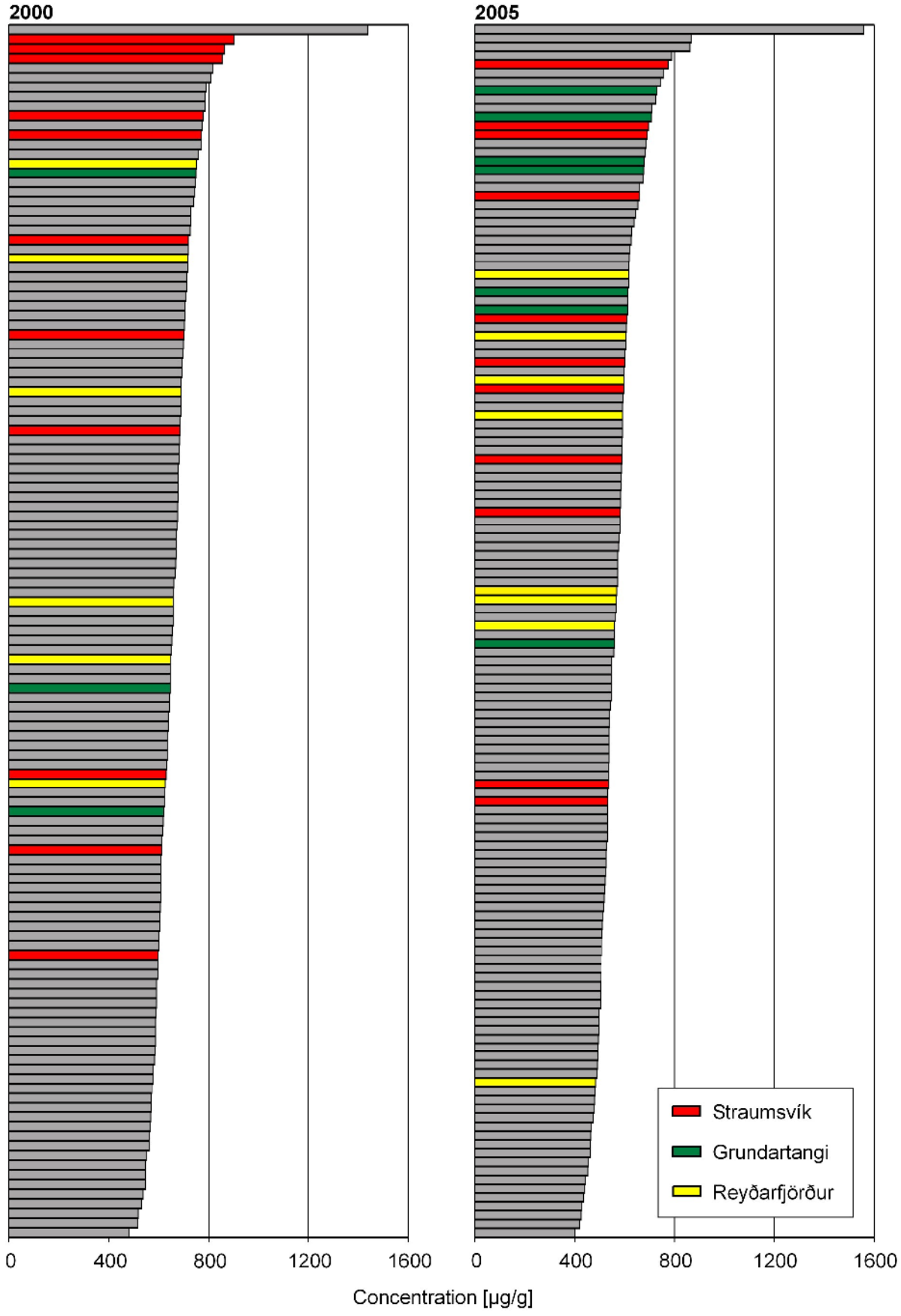
Vanadium (V)


2000
2005
0
20
40
60
80
Straumsvík
Grundartangi
Reyðarfjörður
Concentration [µg/g]

Zinc (Zn)


2000
2005
Straumsvík
Grundartangi
Reyðarfjörður
0
50
100
150
200
250
Concentration [µg/g]

Sulfur (S)


2000
2005
0
400
800
1200
1600
Straumsvík
Grundartangi
Reyðarfjörður
Concentration [µg/g]