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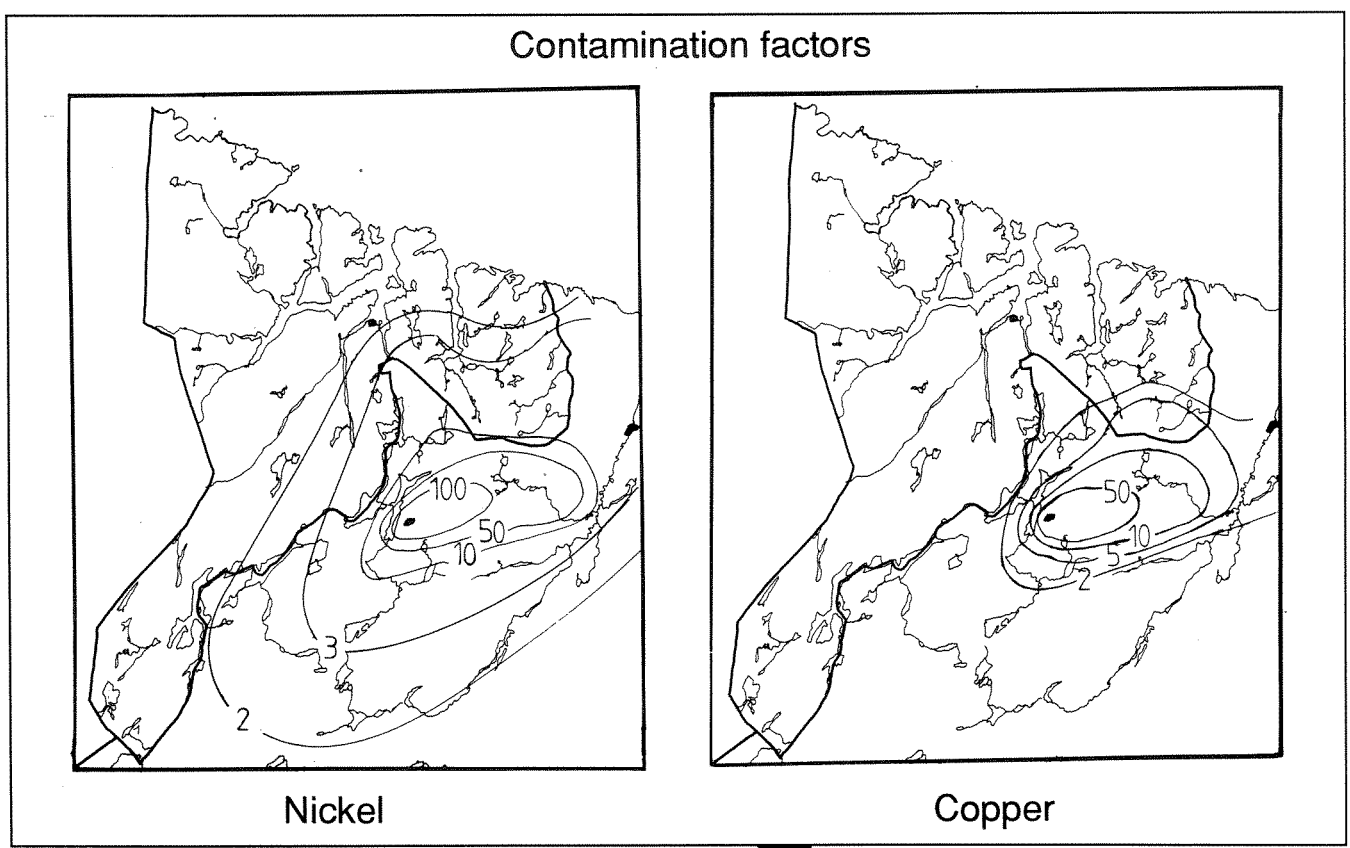
Heavy metal pollution in lake sediments in the border areas between Russia and Norway



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HEAVY METAL POLLUTION IN LAKE SEDIMENTS IN THE BORDER AREAS BETWEEN RUSSIA AND NORWAY.

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Abstract

The atmospheric emissions of Ni and Cu from the smelters in Nickel and Zapoljarny are the main sources for the increased concentrations observed for these elements in young lake sediments within a distance of 30 km from the smelters. The prevailing southwestern winds are distributing the pollution plume mainly in a northeastern direction leaving the sediments in lakes more remote than 15 km southwest of Nickel almost unaffected. Cot, Cu, Ni, Pb and Hg have elevated concentrations in sediment dating from the last hundred years and the onset of increased accumulation rates predates the smelting activity at Nickel and Zapoljarny. This reflects the long range transport of metals, but the maxima in accumulation rates for Co, Cu and Ni are consistent with the history of regional smelting activities. No elevated concentrations or accumulation rates was observed for Cd and Zn except in lakes receiving runoff from slag piles located close to Nickel. Runoff from the Nickel area is also an important source of contamination for Lake Kuetsjarvi and sediments in the Pasvik River system downstream this region. Expected ecological problems connected to heavy metal pollution of sediments on the Norwegian side of the border are mainly restricted to Ni and Cu in the Svanvik area, Pasvik River downstream the outlet from Lake Kuetsjarvi and the areas east of Pasvik River. The pollution problem is much more serious in the Russia where surface sediments in lakes between the smelters and the international border are seriously affected. Biological effects can be expected.

Contents

Introduction

The smelters in Nikel and Zapoljarny, run by the "Petchenganikel" company, are the main pollution sources in the border area of Norway and Russia emitting sulfur dioxide, dust and heavy metals to the atmosphere. The smelter in Nickel has been in operation since 1932; however, it was mainly built up after the Second World War. The smelter in Zapoljarny started up in 1955 (Wikan 1990). The annual emissions of sulphur dioxide are about 250.000 tons - three times the total annual emissions in Norway (Sivertsen et al 1991). The annual emissions of Ni in the 1970`s and 1980`s varied between 140 - 512 metric tons (Kryuchkov & Makarova 1989). The emissions of Ni, Cu and Co to the atmosphere in 1989, were estimated to be 504, 300 and 18 tons, respectively (Sivertsen et al 1991). The concentrations in air of these elements together with As and Cr differed most from typical background values in the region; however, surveys of metals in suspended particles in air revealed that V and Pb also followed a pattern similar to that of sulphur dioxide concentrations (Hagen et al.1991). The deposition of Ni and Cu exceeded background values by a factor of ten or more within the first 10 - 30 km from the smelters (Sivertsen et al. 1991). A rapid decline in the air concentrations was observed with increasing distances from the sources probably caused by a rapid fallout of the larger suspended air particles which are most enriched in Ni and Cu (Hagen & Sivertsen 1992).

Investigations of water and sediment quality started in 1986 on the Norwegian side and in 1989 on the Russian side. These data are published in project reports on heavy metals in sediments from : Vaggatemvatn and Bjørnevatn in the Pasvik River system (Rognerud 1990), 48 lakes from Sør-Varanger community (Rognerud & Fjeld 1990, Traaen et al. 1990), Dalvatn and Durvatn (Norton et al. 1992), and the Nickel area (Dauvalter 1992). They all report lakes with recent sediments that are enriched in metals caused by atmospheric emissions from the local smelters.

Sediments appear to reflect the integrated dose of metals to the lake, and sediment samples can reveal historical development and provide time-integrated informative data of high local representativity (Håkanson & Jansson 1983) and reliability (Håkanson et al. 1990). However, heavy metals may not be permanently fixed by the sediment, but can be recycled via biological and chemical agents, back into the water column. Sediment concentrations are often correlated to concentrations in aquatic animals (Krantzberg & Stokes 1989). Therefore sediment surveys can elucidate regional and historical trends in deposition of metals besides giving indications of possible biological effects.

An Expert Group on Water and Environmental Problems was established in 1988 under the Joint Norwegian-Russian Commission on Environmental Co-operation and a progress report dealing with acidification and concentrations of Ni and Cu in surface sediments and water has been prepeared (Traaen et al. 1991). The report presented here deals with the regional distribution of heavy metal contamination in surface sediments of all lakes surveyed before 1993 including an estimation of the historical trends in accumulation rates of heavy metals in two lakes (Dalvatn and Durvatn).

Methods

The sediment corer used for most lakes was an open barrel gravity type, made of plexiglas, with an automatic closing diaphragm. The sediment cores were sectioned, put in acid-washed polyethylene cups, deep-frozen and sent to the laboratory for analysis. Samples were freeze-dried and analyzed for loss on ignition (LOI) and metals. Statistical tests have revealed that organic carbon together with water associated with ferric hydroxide are included in the LOI-values. Organic carbon in sediments may therefore be estimated from LOI and iron in sediments (FeSE): $OC=(LOI-0.48FeSE)^{-1.9}$ ($r^2=0.81$, n=241) (D.Hongve, National Institute of Human Health, Oslo, pers.comm.).
Metal analysis were performed at Norwegian Institute of Water Research, Oslo. Freeze-dried sediment (1g) was digested in nitric acid under pressure (120^0C). Pb, Cd and Ni were determined on a Perkin Elmer 560 graphite furnace atomic absorption spectrophotomer (AAS). Fe was determined on a flame AAS. Hg was determined utilizing cold vapor atomic absorption. Detection limits were as follows: Pb, 1 $\mu g \cdot g^{-1}$; Cd, 0.5$\mu g \cdot g^{-1}$; Ni, 2.5$\mu g \cdot g^{-1}$; Hg, 0.05$\mu g \cdot g^{-1}$; Fe, 20$\mu g \cdot g^{-1}$.
Standard reference sediments (NBS 1645) were submitted randomly among the samples. The analytical results were systematically lower than the certified total values. However, the deviation was less than 20% (Hg,-13%; Cd,-15%; Pb,-2%; Ni,-11%). This is because the nitric acid digestion metod does not dissolve refractory silicates. The precision varied for the different elements. The coefficient of variation was: Hg, 5%; Pb, 6%; Ni,23%; Cd,30%. Detection limits and precision were generally adequate for this study.

Cores from Dalvatn and Durvatn were retrieved from the deeper parts using a stationary pistion corer (Davis & Doyle 1969) The cores were vertically extruded and sectioned at the lake in 0,5 cm sections from 0 to 10 cm, and in 1,0 cm sections thereafter. Sediment was placed in Whirl-packTM bags and returned to the University of Maine (USA). Sediment was homogenized in the Whirl-PackTM bags, and air dried at 95 ^{0}C. Weight loss was calculated as water content. Alternate dried intervals were sent to P. G. Appleby at Liverpool, UK, for gamma analysis for radiometric dating. Gamma ray spectroscopy for ^{210}Pb, ^{226}Ra, ^{137}Cs, ^{134}Cs, ^{235}U, ^{238}U, ^{40}K, and ^{241}Am was performed using a well-type, coaxial, low background, intrinsic germanium detector fitted with a NaI(TI) escape suppression shield (Appleby et al.1986). The remaining sediment samples were heated in porcelain crucuibles at 550 C for 3 hours. Weight loss was calculated as organic content. Approximately 0,1 g of "ignited" sediment was placed in a solution using the methods of Buckley & Cranston (1971). This process places the entire sample into solution. Thus, "bulk" chemistry is determined. Chemical analyses for various elements were performed by AAS with a graphite furnace or flame. Analyses for Cd, Co, Cu, Ni, Pb, and Zn were performed on alternate intervals of sediment not analyzed for ^{210}Pb. Detection limits were: Cd, 0,06 µg/g; Co, 1,0 µg/g ; Cu, 0,7 µg/g ; Ni, 0,7 µg/g ; Pb, 1 µg/g; Zn, 11 µg/g, on an ignited weight basis.

Geology and geochemistry

The geology and geochemistry in the the Sør-Varanger/Pechenga region are rather complex (Fig 1). In the central area rocks from the Petsamo group have a folded pattern around the smelters and mines in Nickel and Zapolyarny (Lieung 1990). This group consist of volcanic and sedimentary rocks with more "calcic" mineralogy than the gneiss and granite rocks found south and north of this area.

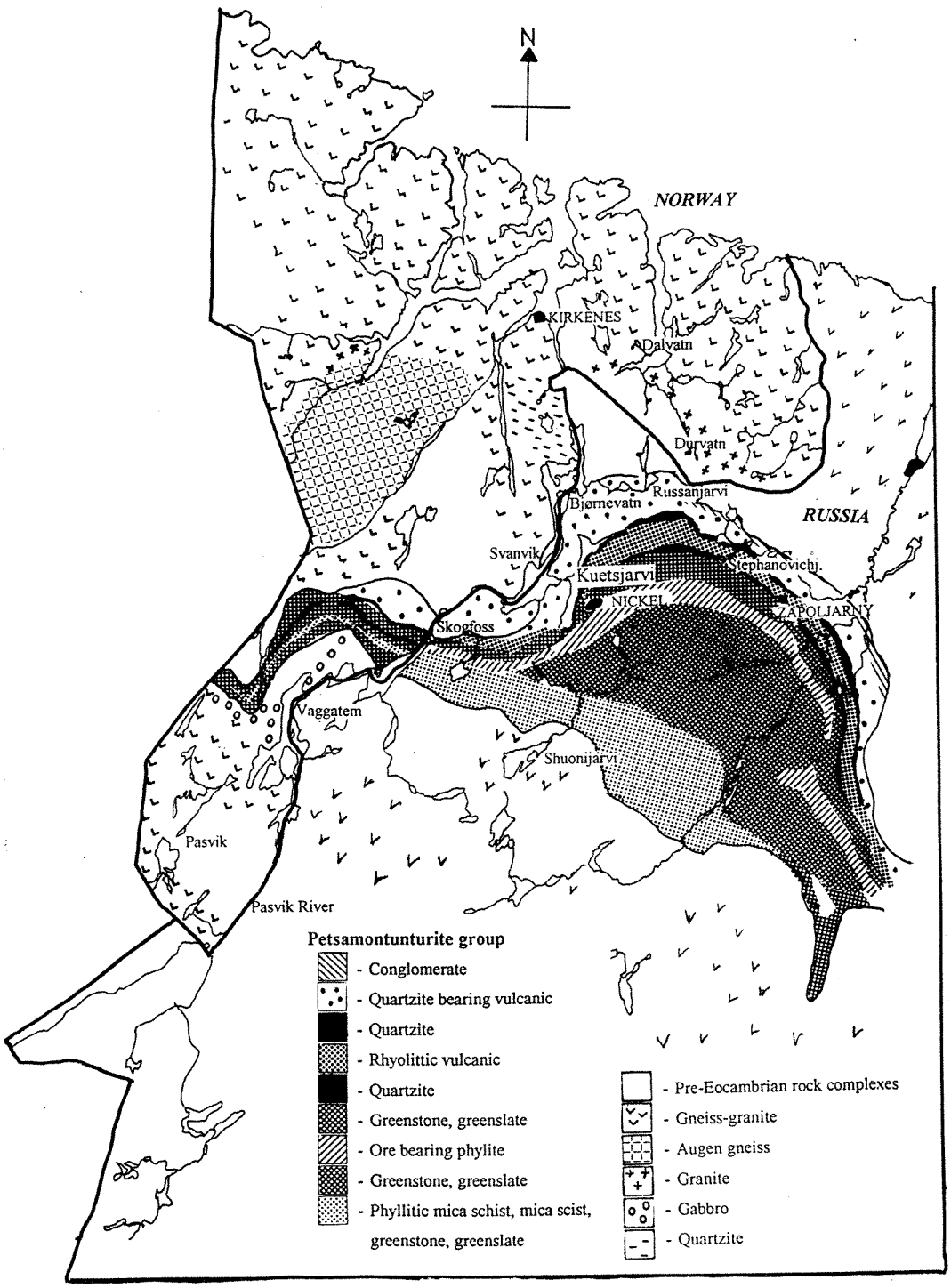


Fig.1. Geology in the border areas between Norway and Russia.

It consists of, among others, calcium rich rocks and a phyllite enriched in Ni and Cu. This region therefore include areas with naturally elevated concentrations of Ni, Cu, Co and Cr. The Petsamo group of rocks are easily weathered and have most likely affected the geochemistry of morains both locally and north/northeast of the area which was the direction of the glacier movements.
The regions north of the Petsamo group are dominated by gneiss and granite which are low in calcium content and high in aluminium minerals. The regions south of the group consist mainly of gneissic rocks, but rocks enriched in Ni and Cu commonly appear on the Russian side (Lieung 1990).
The Petsamo group also appear on the Norwegian side south of Skogfoss(Pasvik), but the rest of the geology in Sør-Varanger community is dominated by gneiss and granite.

Sediments in the Pasvik River system.

Five sediment cores were taken from the deepest area (20m) in Vaggatemvatn (up stream from Nickel) and Bjørnevatn (downstream from Nickel) in the Pasvik River system (Fig.1). Mean concentrations of heavy metals and calculated contamination factors (Håkanson & Jansson 1983) are given in Fig. 2 and 3. Primary data are given in the appendix (Tab. I).

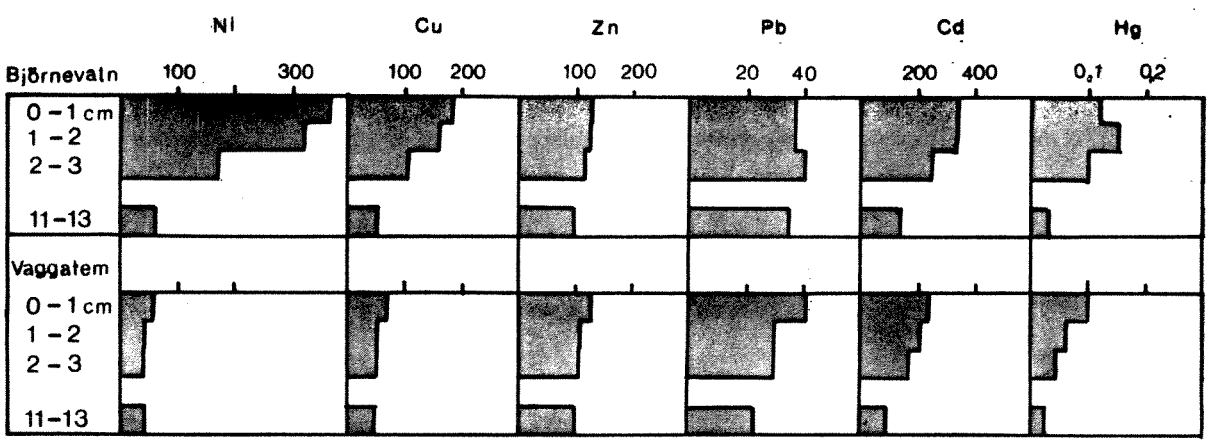


Fig.2. Concentrations of heavy metals in sediments ($\mu g\ g^{-1}$ d.w.$^{-1}$) from Vaggatemvatn and Bjørnevatn in the Pasvik River system (1989).

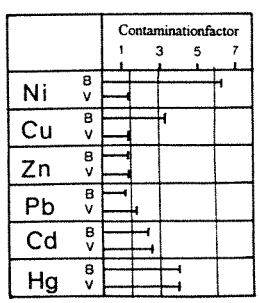


Fig.3. Contamination factors for surface sediments (0-1cm) in Bjørnevatn(B) and Vaggatem(V).

The atmospheric emissions of Ni and Cu from the smelters have heavily impacted elements in the surface sediments of Bjørnevatn, while only a slight degree of impact was found in Vaggatemvatn. Bjørnevatn also receives runoff from the Nickel area. Large areas with huge slag piles cause elevated concentrations of heavy metals, especially Ni and Cu, in the streams and rivers entering lake Kuetsjarvi and the Pasvik River upstream from Bjørnevatn (Fig.1). This indicates that runoff can be an important source for metal contamination in Kuetsjarvi and downstream in the Pasvik River. The concentration of Zn and Pb were close to background values in both lakes indicating low air emission and runoff of these elements from the industrial area. There was a moderate degree of impact for Cd and Hg in both lakes. However the background concentrations for these elements were extremely low and the increase towards the sediment surface may reflect the general deposition of atmospheric long-range pollutants. The deposition of these elements are generally low in northern Norway and low background concentrations are the reasons why it is possible to detect any impact at all. The Cd concentrations in the surface sediments were lower than most of the background values found in lakes from the rest of Norway, but the Hg concentrations were slightly higher (Rognerud & Fjeld 1990).

Historical trends in accumulation rates of heavy metals.

The total accumulation rates of Cu, Cd, Co, Ni, Pb, and Zn were calculated for sediments from Dalvatn and Durvatn (Fig. 4). Detailed informations are given in Norton et al.(1992). The accumulation rates for the sediment in Dalvatn was constant at 1900 $\mu g\ cm^{-2}\ yr^{-1}$ since an "in-wash" event (ca. 1916), and 1300 $\mu g\ cm^{-2}\ yr^{-1}$ prior to that. The sediment involved in the "in-wash event" is clearly old and contains no unsupported 210Pb. The strong enrichment in 226Ra along with several other radiogenic and chemical anomalies is most peculiar. This event may be anthropogenic linked. Durvatn had a constant rate of sedimentation (2400$\mu g\ cm^{-2}\ yr^{-1}$) throughout the whole period represented in the core. Thus, for both lakes, changes in the accumulation rates of trace elements in the last 50-60 years may be attributed largely to changes in atmospheric deposition.

For Dalvatn the accumulation rate for Cd was less than 0.0001 $\mu g\ cm^{-2}yr^{-1}$ throughout the core. Background accumulation rates for Co was about 0.12 to 0.18 $\mu g\ cm^{-2}yr^{-1}$ prior to 1800, but was approximately double this value since 1800, except during the in-wash event. The pattern for Cu was similiar to that of Co; the accumulation rate increased from 0.2 to nearly 0.5 $\mu g\ cm^{-2}yr^{-1}$ from the end of the in-wash event to the 1986 sediment interval. The accumulation rates for Ni followed that of Cu with an increase from 0.1 to 0.3 $\mu g\ cm^{-2}\ yr^{-1}$ since the in-wash event, and Pb also showed an increase in this period. There was no long term trend in accumulation rates of Zn except for the in-wash event.

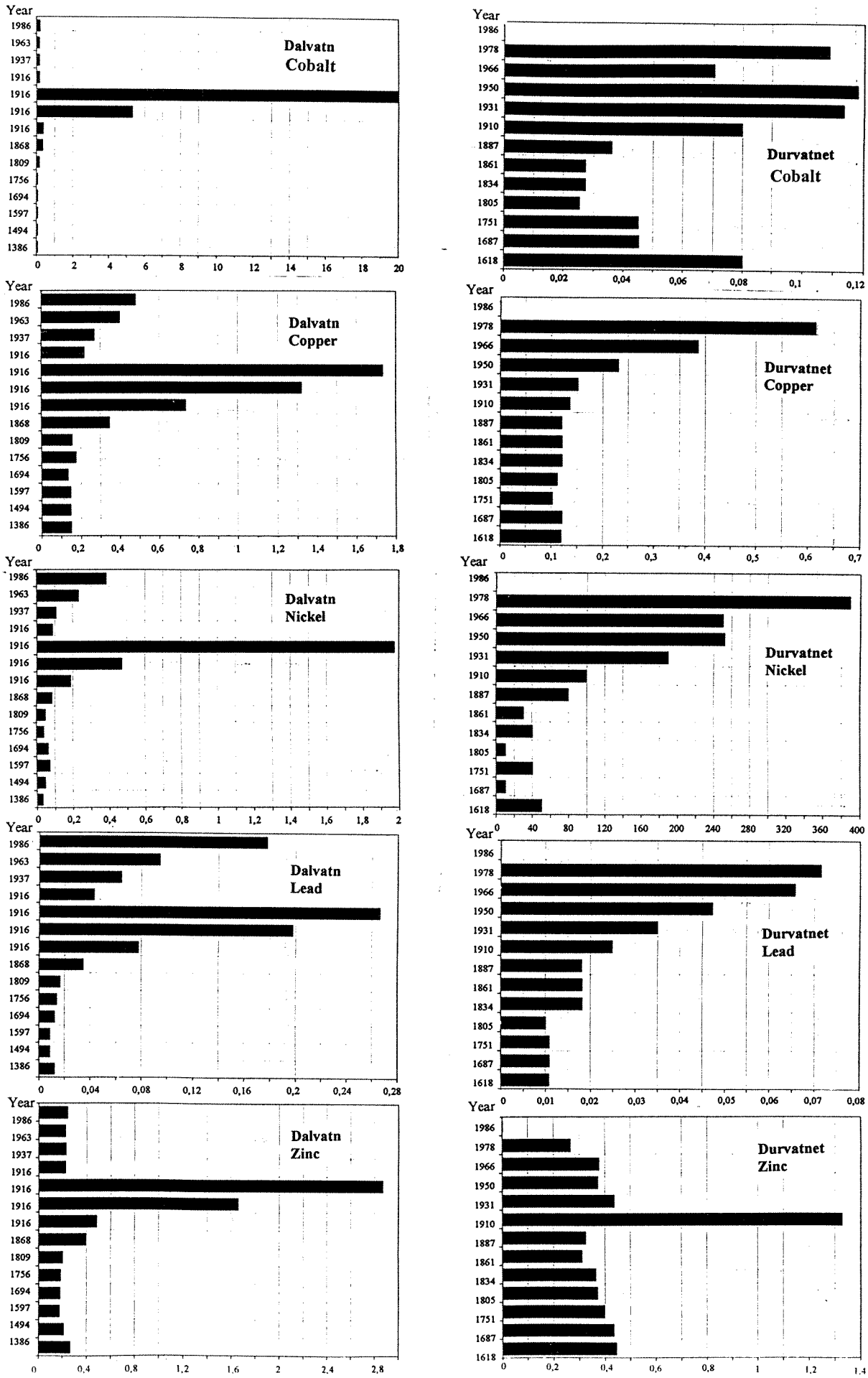


Fig.4. Accumulation rates(μg $cm^{-2}yr^{-1}$) of heavy metals in sediments from Dalvatn and Durvatn at different ages.

In Durvatn, the accumulation rate for Cd was less than 0.001 $\mu g\ cm^{-2}\ yr^{-1}$, suggesting that little or no atmospheric input of Cd has been present. Since 1900, the accumulation rate of Co has been elevated over values typical of the previous 200 years. The values in the 19th century were also relatively high and thus the cause of the modern elevated values can not be assigned with confidence to atmospheric emissions. However, the timing is coincident and it is known that significant amounts of Co are emitted annually from the smelters. Cu showed a clear and strong increase in accumulation starting around 1910 and increasing at least to 1978. The increasing accumulation rate for Pb started in the late 19th century, well before the industrial activity in this region. The accumulation for Ni increased by the end of the 19th century to a maximum at least as resent as 1978. The accumulation rate for Zn declined through the period with an exception of one interval (1910) which is probably an analytical artifact.

The ratio between the accumulation rates in the most recent settled sediment and a "reference sediment" from the 1920's, before the smelters were established, is given in Tab.1.

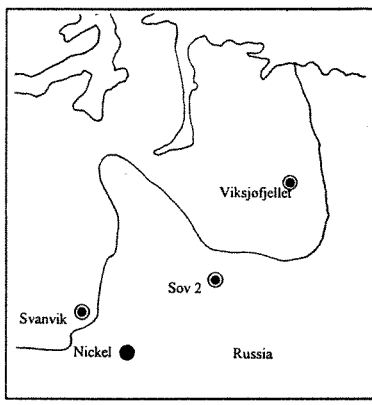
Tab. 1. The ratio between the accumulation rates in the most recent settled sediment and in sediments from the 1920's.

	Ni	Cu	Pb	Co	Cd	Zn
Dalvatn	3.8	2.1	4.1	2.0	1	1
Durvatn	3.9	4.4	2.4	<1	1	<1

During the active period of the smelters the accumulation rates of Ni, Cu and Pb have increased by factors of 2-4. The lakes are located downwind from the smelters and the increase of Ni and Cu is caused by atmospheric deposition from these sources. The atmospheric depositions of these elements elsewhere in Finnmark are low (Steinnes et al.1990, Rognerud & Fjeld 1990, Sivertsen et al. 1992). The increase in Pb accumulation rates are most probably caused by the general increase in contamination of Pb in the atmosphere of the northern hemisphere (Norton et al.1990), but the smelters are also emitting Pb, although in relatively small amounts (Hagen et al.1991). The results for Co are rather obscure. There seems to be no significant effect of atmospheric deposition of Cd and Zn from the smelters.

Concentrations of heavy metals in the upper 10 cms of sediments in five "deep" lakes at different distances from the smelters.

Shuonijarvi is located 20 km southeast of the Nickel smelter, while Russanjarvi, Stephanovicjarvi, Durvatn and Dalvatn are located 16,17,22 and 32 km north-northeast respectively (Fig.1). The lakes were selected based on the dominating south-southwestern winds in the region, carrying the pollution plume in mainly a north-northeastern direction (Hagen et al.1991). Concentrations of many heavy metals in suspended particles in air decrease with distance from the smelters (Fig.5). However, the values for elements like Cd and Co are low indicating a low deposition. Hg has not been measured. Water quality and some lake characteristics are given in Tab.2.



Element	Concentration (ng m^{-3})		
	Sov 2	Viksjøfj.	Svanvik
Nickel	18	6	2
Copper	17	5	2
Zinc	10	5	7
Lead	5.5	2.2	1.4
Cadmium	1.0	0.16	0.12
Cobalt	0.7	0.20	0.10

Fig.5. Calculated mean concentrations of heavy metals in suspended particles in air Oct.91-March 92 (Hagen & Sivertsen 1992).

Tab 2. Water quality, loss of ignition (LOI)in sediment and water depth of sediment sampling.

	pH	Alk. µmol l^{-1}	TOC mgC l^{-1}	SO_4 mg l^{-1}	Ni µg l^{-1}	Cu µg l^{-1}	LOI(%) 0-10 cm	Depth m
Shuonij.	6,7	106	3,1	4,6	4.9	3.8	16-21	32
Steph.j.	7,4	330	1,9	13,0	19.5	13.4	23-34	12
Russanj.	7,0	153	2,7	7.9	19.5	6.5	25-27	33
Durvatn	6.8	110	1.8	4,7	-	-	24-37	16
Dalvatn	5,7	10	1.7	5.5	5.9	3.0	34-44	21

The lakes (except Dalvatn) had a near neutral pH and were moderately buffered. They were rather low in humic acids, received excess sulfate and had elevated concentrations of Ni and Cu in the water. The organic content in the sediments was high enough to allow regional comparisons of metal concentrations between lakes (Parslow 1977). In acidic lakes a decline in concentration towards the sediment surface is often observed for "mobile" elements like Cd, Zn and Ni, caused by dissolution to lake water (Norton et al. 1981), reduced sedimentation (Evans et al. 1983) or diagenetic processes (Carignan &Tessier 1985).The geochemistry on the Russian side of the boarder and the emissions of alkaline dust from the smelters are both factors causing a near neutral pH in the lakes. The absence of low values and large variations in pH among the lakes is therefore favourable when doing comparisons. However, on the Norwegian side, east of Pasvik river, large areas with granitic bedrock combined with atmospheric depositions of sulfate leads to a lot of acidic lakes with a reduced chance of accumulating "mobile" elements in the sediments.

The sediments in the five lakes, located from south of Nickel to the Barents Sea, were analyzed for five heavy metals (Fig 6). The accumulation rates of sediments were found to be constant for the whole profile in Durvatn and at least for the latest 60 years, in Dalvatn. Therefore it seems reasonable to assume that the concentrations in the upper 10 cms reflect the changes in the atmospheric flux term. In Shuonijarvi, south of Nickel there was barely any impact of the smelters at all. The increase in Pb concentrations towards the surface is mainly caused by the general pollution of the atmosphere on the northern hemisphere during the latest 100 years (Norton et al. 1990). However the annual deposition is low and is detectable in the sediments mainly because the background value are very low.

Russanjarvi and Stephanovicjarvi, located close to the smelters on the downwind side, have Ni and Cu concentrations significantly higher than background values in the upper 10 cm for Russanjarvi and in the upper 4 cm for Stephanovicjarvi. The concentrations in younger sediments declined further north at Durvatn and Dalvatn. The sedimentation rate was probably much higher in Russanjarvi than the other lakes. The maxima observed in the 5-7 cm layer are difficult to explain without dating of the core. Concentrations of Pb and Co increased towards the surface due to atmospheric deposition where the smelters are one of the sources. There were no increases in concentration of Zn and Cd (not shown, values below detection limit, Tab.II appendix) in any of the lakes.

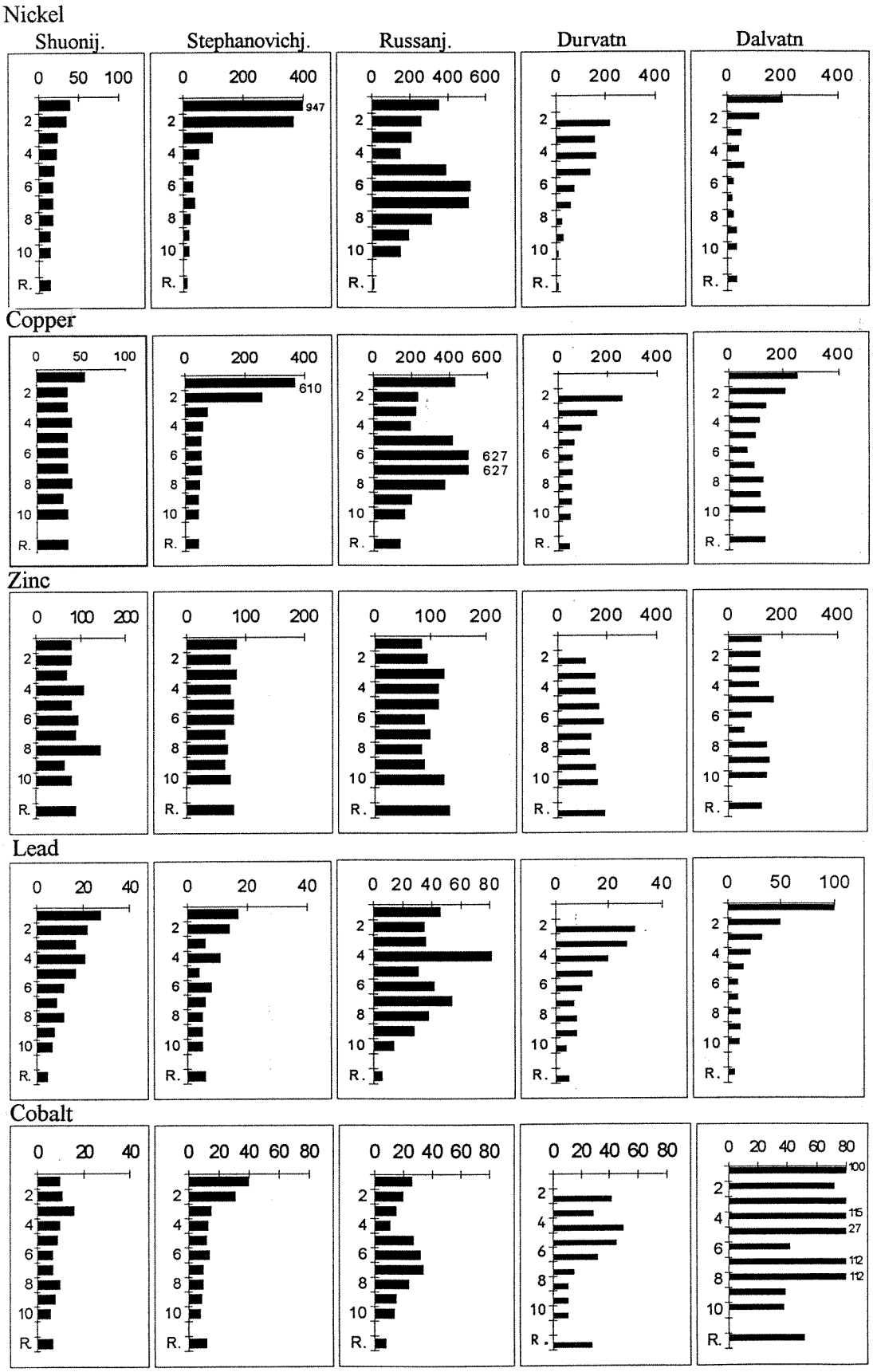


Fig.6. Concentrations of heavy metals(μg g^{-1} $d.w^{-1}$) in the upper 10cms and reference sediment (R) in five lakes located from south of Nickel to the Barents Sea.

Regional variation in concentrations of heavy metals in surface sediments (0-1 cm), and contamination factors.

The regional sediment survey consist of data from 50 lakes (Fig.7) all sampled from the deepest part. Based on information about Ni deposition (Sivertsen et al. 1992), Ni concentrations in lake water (Traaen et al. 1991) and geochemistry (Lieung 1990), the area was divided into four subregions (Fig.7).

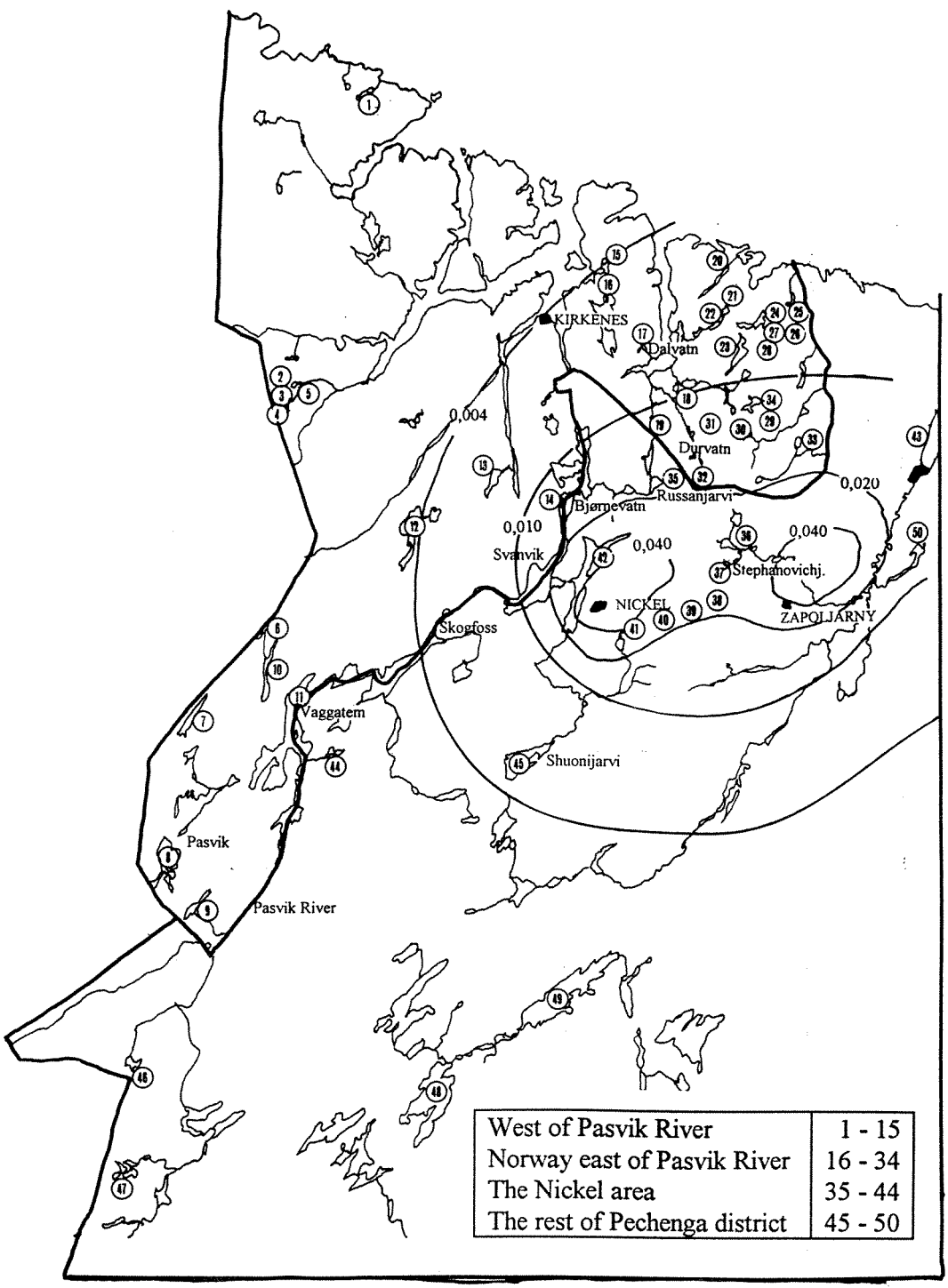


Fig.7. Locations of the lakes in four subregions (inset). The calculated dry deposition of nickel (g m^{-2} yr^{-1}) for the period April 1990-March 1991 are also shown as isolines (Sivertsen et al. 1992). The dry deposition is close to total deposition in this region.

"The Nickel area" lying closest to the smelters, " the rest of the Pechenga district", "Norway east of Pasvik River" and the part of Sør Varanger community located"west of Pasvik River". The sedimentation rate of metals is dependent on many factors in addition to the "dose", among which are lake depth, pH of the water, flushing rate, and organic content in sediment. The deepest lakes were found in subregion"Norway east of Pasvik River"(8-64 m), while the lakes in the other areas were between 5 and 33 m deep(Fig 8). The lakes on the Norwegian side were generally low in alkalinity with pH between 5 and 7, while the Russian lakes were well buffered and had a near neutral pH (Fig 8). The organic content in the sediments (LOI) did not show any large differences in the subregions. Deeper lakes (Norway east of Pasvik River) and more alkaline lakes (Russia) are factors favouring metal accumulation in sediments (Håkanson & Jansson 1983).

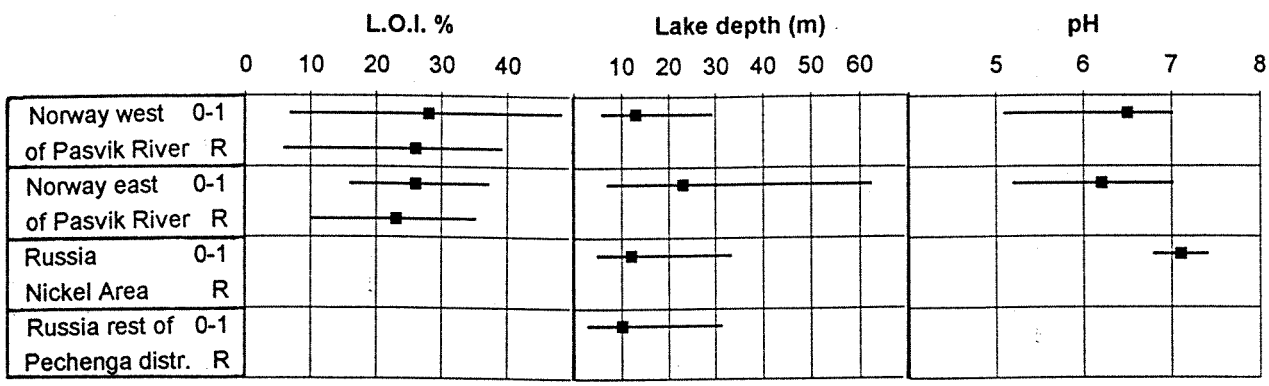


Fig.8. Mean values and range of values for loss on ignition(LOI) in sediments, lake depth and pH from lakes in the four subregions.

Mean values and span in concentrations of heavy metals in surface sediments and background values for the different regions did show the impact of the smelters (Fig.9). The concentrations of Ni in the surface sediments were much higher than background values (up to 100x) in the Nickel area. An increase was also found in the rest of the Pechenga district and in Norway east of Pasvik River (2-3x), while there was a slight or barely any increase west of Pasvik River. The same pattern was also found for Cu although the increase was more moderate. The concentrations of Pb and Hg were significantly higher in the surface sediments than in background sediments in all regions. The increase was also about the same order of magnitude for Pb in all regions, but it was significantly higher for Hg in the Nickel area. There was no detectable differences between Cd concentrations in surface and background sediment in any regions (values below detection limit < 0.5 ppm) except 3 lakes close to mining and smelting activity in Nickel probably exposed to runoff from these activities.
The background concentrations for the metals in the different regions were fairly constant throughout the area in spite of a large variation in bedrock geochemistry.

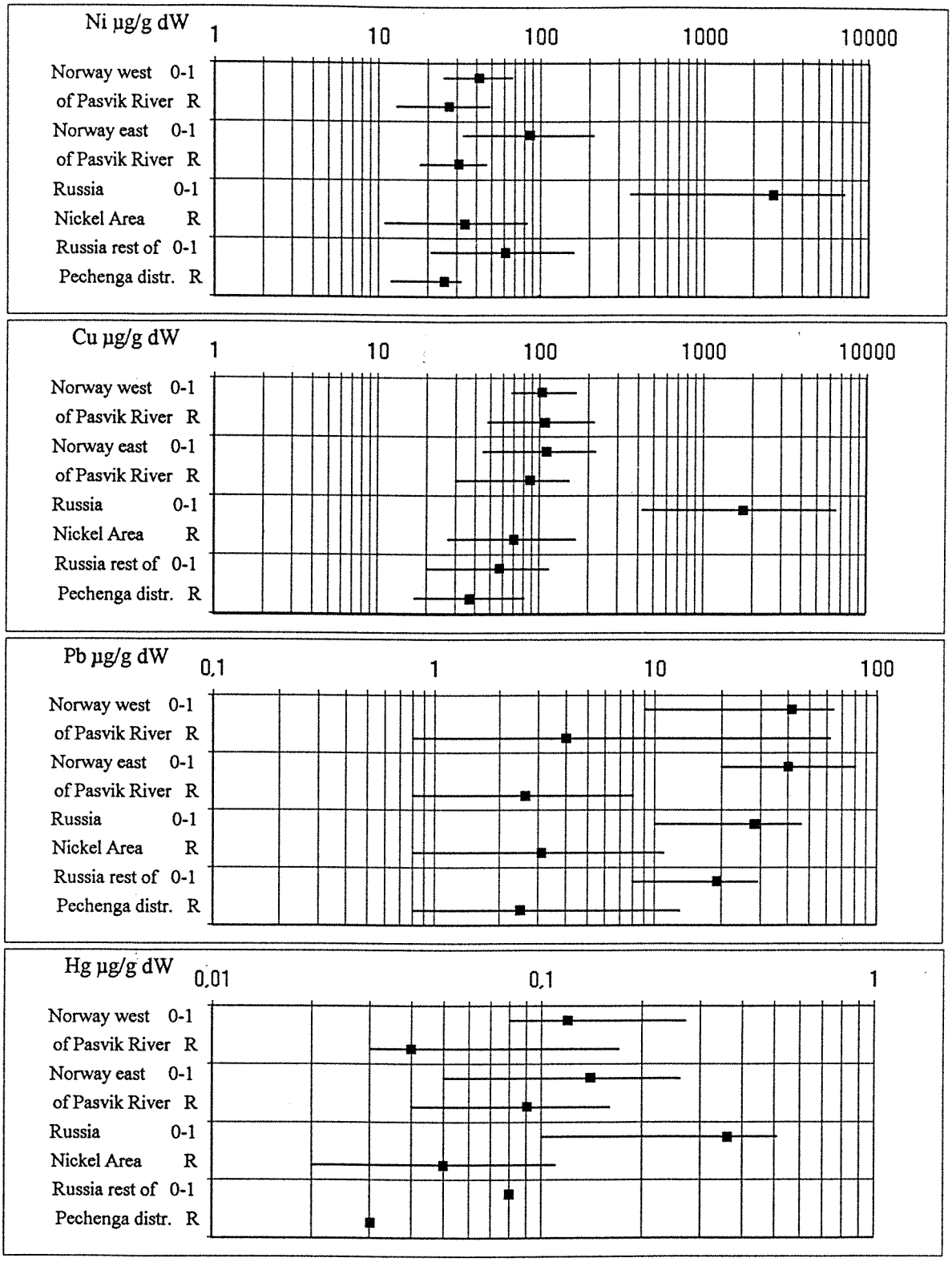


Fig.9. Mean values and span in concentrations of heavy metals in surface sediments (0-1 cm) and reference sediments (R) from the four subregions.

Contamination factor, or degree of impact, measured as the ratio between the concentration in surface and background sediment will therefore show the same variation picture as the concentration results. Contamination factors for the same elements are shown as "isoline maps" in Fig.10 and 11. These maps for Ni and Cu showed almost the same pattern as was calculated for dry depositions of Ni (Fig.7), and observed concentrations in lake water (Traaen et al.1990). The impacts decline very rapidly to the south and west. North of the smelters (downwind) a rapid decline is also present. The contamination factor for Hg in sediment could not be calculated because many reference sediments had concentrations below the detection limit. However, the pattern for concentrations (Fig.12) is the same as for Ni and Cu.

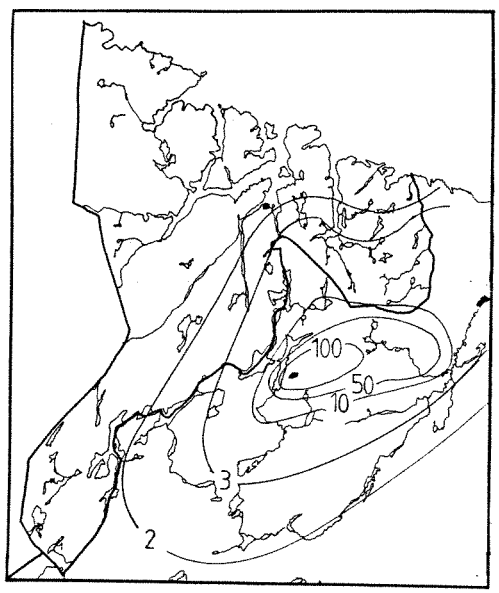


Fig.10. Contamination factors for nickel in surface sediments.

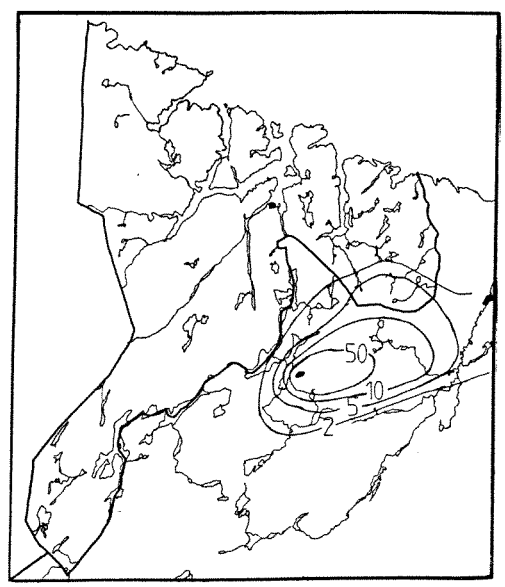


Fig.11. Contamination factors for copper in surface sediments.

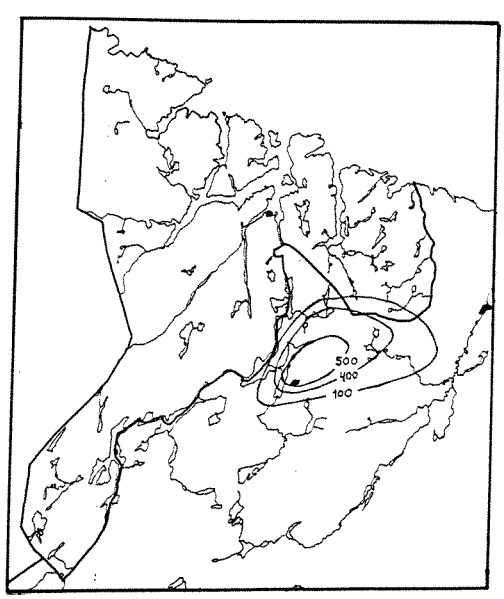


Fig.12. Concentrations of mercury in surface sediments($\mu g\ g^{-1}d.w^{-1}$). The reference values are close to or below detection limit making it erroneous to do calculations of contamination factors.

Conclusion

The atmospheric emission of Ni and Cu from the smelters in Nickel and Zapoljarny are the main sources for the increased concentrations observed for these elements in young sediments within a distance of 30 km from the smelters. The prevailing southwestern winds are distributing the pollution plume mainly in a northeastern direction from the smelters leaving the sediments in lakes more distant than 15 km southwest of Nickel almost unaffected. The atmospheric depositions of these elements are low elsewhere in northern Scandinavia (Ruhling et al 1987, Steinnes et al 1988) and only a slight or no degree of impact in recent sediments have been detected (Rekolainen et al 1986, Johansson 1989, Verta et al. 1989, Rognerud & Fjeld 1990)

The atmospheric emissions from the smelters are also the reasons for the higher concentrations of Hg observed in young sediments from the Nickel area. The emissions of sulphur and chemical oxidants from the smelters are factors which can increase the general deposition of Hg from the atmosphere (Lindberg et al 1987, Norton et al. 1990), but direct emissions of Hg caused by the smelting of the sulphur-rich ore delivered from Norilsk may also be a part of the explanation. There is a slight increase in concentration from background to surface sediments also in the other regions reflecting the general increase in anthropogenic emissions to the atmosphere in our century (Lindberg et al 1987) There is a clear south/north decrease in the concentration of Hg in the atmosphere over Scandinavia and the degree of anthropogene impact as far north as Finnmark is generally slight (Iverfeldt & Rhode 1988, Rognerud & Fjeld 1990)

There were no indications in the sediments of significant increased depositions of Pb, Zn and Cd caused by atmospheric emissions from the smelters. However surface sediments in lakes receiving runoff from slag piles or mines close to Nickel had elevated Cd concentrations.

The concentration of Pb was about 10 times higher in the surface sediment than background values in the whole region. The deposition of Pb from the atmosphere has increased significantly in our century (Norton et al.1990), although the deposition in northern Scandinavia is rather low (Ruhling et al.1987, Steinnes et al.1988). However, it is possible to detect these low depositions because the background values are extremly low. In fact they are among the lowest found in an extensive survey of lake sediments in Norway, and the surface values are close to most background concentrations found in Southern Norway (Rognerud & Fjeld 1990). The atmospheric pollution of heavy metals from the smelters in Nickel and Zapoljarny is mainly restricted to Ni, Cu and Hg. Lakes in the area between Nickel-Zapoljarny and the border with Norway are most affected. Lakes on the Russian side are generally well buffered which favours accumulation of "mobile" elements like Ni in the sediments. Outside these regions the impact was slight to moderate for all the elements surveyed.

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Appendix

Tab.I Surface sediments (0-1 cm). 5 parallel cores at 2 lakes in Pasvik River (1989). Mean value = $\bar{X}$, dw = dry weight, L.O.I. = loss of ignition

Parameter \ Unit		Bjørnevatn					
		1	2	3	4	5	$\bar{X}$
L.O.I.	%	13,0	12,9	14,4	13,6	13,8	13,5
OC	mgC/g d.w.	6,3	5,9	6,5	6,6	6,7	6,4
Ni	µg/g d.w.	281	334	169	3,5	372	292
Cu	"	151	170	110	172	185	158
Zn	"	129	120	107	127	126	122
Pb	"	34	22	29	31	37	31
Cd	ng/g d.w.	300	320	200	330	340	298
Hg	"	130	120	80	130	120	116

Parameter \ Unit		Vaggatem					
		1	2	3	4	5	$\bar{X}$
L.O.I.	%	15,2	16,4	15,3	13,0	13,3	14,6
OC	mgC/g d.w.	7,2	7,5	7,4	6,5	6,3	6,9
Ni	µg/g d.w.	53	52	21	52	55	47
Cu	"	68	67	38	66	68	61
Zn	"	108	109	67	126	127	107
Pb	"	44	40	22	36	41	37
Cd	ng/g d.w.	240	220	80	220	240	200
Hg	"	90	90	20	90	100	78

Tab.II Primary data of lakes (location see Fig.7) in the regional survey. Max. lake depth, loss of ignition (LOI) and atmospheric dry deposition of Ni are given. All concentrations as $\mu g \cdot g^{-1} \cdot dw^{-1}$ except Hg ($ng \cdot g^{-1} \cdot dw^{-1}$).

		DYP	GT	(%)	pH	TOC	Ni			Ann.dep.	Cu		
		(m)	0-1	R			0-1	R	Kf	ugNi/m2	0-1	R	Kf
1	f.Marejavr. (11A3)	15	23	25	6,4	1,4	56	24	2,3	1	166	215	<1
2	Navnløst (12A1)	6	35	36	5,7	2,4	32	30	1,0	1	68	78	<1
3	Navnløst (12A3)	7	30	31	6,2	3,5	67	26	2,6	1	111	114	<1
4	Bøttemyrv. (12A4)	18	48	39	6,3	2,9	57	23	2,4	1	148	118	1,2
5	Vegvatn (630)	8	23	26	6,6	2,0	15	13	1,1	1			
6	Juomisj. (13A2)	6	38	34	6,4	1,9	38	21	1,8	1	69	65	1,1
7	Følvatn (619)	8	24	24	6,5	1,8	20	13	1,5	1			
8	Ellevatn (616)	12	35	29	6,9	4,1	19	20	1,0	1			
9	Ødevatn (615)	12	7	1	7,0	5,3	17	20	1,0	1			
10	St.Spurv. (620)	12	21	19	6,7	1,9	50	48	1,1	1			
11	Vaggatem vatn	23	15	10	7,0		55	42	1,3	1	68	48	1,4
12	St.Samettj. (623)	22	20	17	6,6	2,3	40	35	1,1	4			
13	Sagvatn (14A3)	29	21	24	6,0	8,6	63	29	2,1	6	102	112	<1
14	Bjørnevatn	23	13	9	7,0		373	59	6,3	15	185	56	3,3
15	Strimpv. (8A3)	10	32	35	5,9	1,4	76	29	2,6	4	75	100	<1
16	L.Ropelvv. (627)	32	25	10	6,3	1,9	54	43	1,2	4			
17	Dalvatn (1A3)	21	37	29	5,7	1,7	156	37	4,2	6,5	220	134	1,6
18	Rabbv.	29	25		6,4	1,8	32	20	1,6	10			
19	Serdiv. (2A1)	23	31	28	5,5	1,1	79	24	3,3	11	208	143	<1
20	Coalbmej. (626)	17	32	25	6,4	1,1	53	42	1,2	5			
21	Gravsj. (610)	62	26		6,4	0,9	48	30	1,6	6			
22	Langv.	42	25		6,2	1,0	50	32	1,5	6			
23	L.Djupv. (6A2)	19	22	2	5,0	0,3	46	38	1,2	7	98	97	1
24	Holmev.	28	17		6,3	0,9	60	30	2,0	7			
25	f. Høgfjellv. (7A2)	32	25	26	5,1	0,5	63	34	1,8	7	97	151	<1
26	Gardsj. (608)	40	23	27	6,6	1,7	81	32	2,6	8			
27	Guoikaluob. (7B2)	12		28	6,3	0,8	57	35	1,6	8	55	122	<1
28	Navnløst (7B1)	9	26	28	5,6	1,5	118	32	3,7	8	74	73	1
29	s.Skardv. (5A2)	10	16	21	6,4	1,2	91	34	2,7	16	54	37	1,4
30	Durvatn	16			6,8	1,8	200	24	9,1	16	201	30	6,7
31	N.Ørretv. (3A3)	7	23	18	6,4	1,9	175	27	6,4	16	88	51	1,7
32	Hundv. (613)	8	24	23	7,0	2,1	158	45	3,5	18			
33	Korpv. (605)	15	27	25	6,9	2,5	63	20	3,1	16			
34	L.Skardv. (5A3)	19		33			60	18	3,3	16	45	30	1,5
35	Russanj.	33	27	26	7,0	2,7	355	11	32	20	429	140	3
36	Majarvi. 325/328	10	26		7,0	4,3	990	16	62	30	910	27	34
37	Stephanovicj.	12	33	30	7,4	1,9	947	14	67	30	610	44	14
38	Navnløst 293/296	5					1884	20	94	40	2089	28	75
39	Navnløst 305/308	5					6490	52	124	40	1823	166	11
40	Saraslaki 317/320	5	22				1130	24	47	40	1120	22	51
41	Navnløst 313/316	5					7206	55	131	40	6495	52	125
42	Kuetzjar. 213/216	20	15				2227	83	27	30	540	79	7
43	Triforojar. 176/538	9					98	21	1,4	10	98	64	1,5
44	Nillijarvi 156/546	3					83	17	4,9	3	94	81	1,2
45	Tsuonnjarvi	31	23	16	6,7	3,1	39	13	3,0	4	43	34	1,3
46	Toartesjar. 151/550	9					23	12	1,9	1	42	18	2,3
47	Kochejar. 201/204	5	41				21	16	1,3	1	22	17	1,3
48	Ulya 389/392	5					29	16	1,8	1	20	18	1,1
49	Alakajar. 393/396	7					38	24	1,6	1	23	23	1
50	Santojarvi 182/529	13					159	32	4,9	18	114	40	2,9

Tab.II Continue

		Pb			Cd			Zn			Hg			Co		
		0-1	R	Kf	0-1	R	Kf	0-1	R	Kf	0-1	R	Kf	0-1	R	Kf
1	f.Marejavr. (11A3)	64	62	1	0,2	<0,5	<1		112		130	150	<1		20	
2	Navnløst (12A1)	48	22	2		1,4			595		50	53	<1		7	
3	Navnløst (12A3)	44	7	6	0,7	<0,5	1,5		373		70	93	<1		39	
4	Bøttemyrv. (12A4)	39	8	13	0,4	<0,5	1,0		205		180	170	1,0		14	
5	Vegvatn (630)	32	11	3	0,1	0,1	1,0				140	60	2,0		5	
6	Juomisj. (13A2)	35	5	7	0,7	0,7	1,0		96		80	51	1,5		5	
7	Følvatn (619)	41	2	20	0,6	0,3	2,0				130	40	3,2			
8	Ellevatn (616)	62	2	31	0,1	0,1	1,0				270	60	4,5			
9	Ødevatn (615)	9	2	4	0,1	0,1	1,0				60	40	1,5			
10	St.Spurv. (620)	47	21	2	0,2	0,2	1,0				140	60	2,3			
11	Vaggatem vatn	41	23	2	0,2	0,1	2,0	127	98	1,3	100	20	5,0			
12	St.Samettj. (623)	40	2	20	1,4	0,6	2,1				180	40	4,5			
13	Sagvatn (14A3)	38	<1	38	0,3	<0,5	1,0		128		110	120	<1		23	
14	Bjørnevatn	37	35	1	0,3	0,1	3,0	126	94	1,3	120	30	4,0			
15	Strimpv. (8A3)	37	2	18	0,3	<0,5	1,0		122		190	190	1,0		42	
16	L.Ropelvv. (627)	29	5	6	0,4	0,2	2,0				180	80	2,2			
17	Dalvatn (1A3)	80	8	10	<0,5	<0,5	<1	126	384	<1	100	80	1,1	56	38	
18	Rabbv.	26	2	13	0,2	0,2					150	90	1,7			
19	Serdiv. (2A1)	43	3	14	0,5	<0,5	1,5		107		130	130	1,0		17	
20	Coalbmej. (626)	82	38	2	0,7	0,6	1,1				260	120	2,1			
21	Gravsj. (610)	30	1	30	0,6	0,5	1,1				120					
22	Langv.	46	1	46	0,6	0,5	1,1				110					
23	L.Djupv. (6A2)	43	1	43		<0,5			99		140	55	2,5		19	
24	Holmev.	61	2	30	0,2	0,2	1,0				150					
25	f. Høgfjellv. (7A2)	36	<1	36	0,2	<0,5			93		150	120	1,2		29	
26	Gardsj. (608)	25	5	5	0,3	0,3	1,0				190	80	2,4			
27	Guoikaluob. (7B2)	29	8	3	0,1	0,6	<1		148		80	160	<1		32	
28	Navnløst (7B1)	39	<1	39	0,4	<0,5	1,0		122		110	97	1,1		23	
29	s.Skardv. (5A2)	34	<1	34	0,3	<0,5	1,0		125		50	35	1,4		11	
30	Durvatn	27	2	13				126	96	1,3				34	10	
31	N.Ørretv. (3A3)	46	<1	46	0,7	0,8	<1		235		150	53	3,0		36	
32	Hundv. (613)	33	3	11	0,5	0,1	5,0				240	60	4,0			
33	Korpv. (605)	20	3	7	0,2	0,1	2,0				140	40	3,5			
34	L.Skardv. (5A3)	29	<1	29	0,4	0,3	1,1		55		90	57	1,6		9	
35	Russanj.	46	6	7	<0,5	<0,5		83	135	<1	410	110	3,7	26	8	
36	Majarvi. 325/328	24	<1	24	0,8	<0,5	2,0	108	104	1,0	430	50	8,6			
37	Stephanovicj.	17	5	3	0,8	<0,5	2,0	87	77		270	44	6,1	81	12	
38	Navnløst 293/296	44	<1	44	1,2	<0,5	3,0	91	55	1,7		16				
39	Navnløst 305/308	11	<1	11	<0,5	<0,5		439	185	2,4	510	25	20,4			
40	Saraslaki 317/320	30	<1	30	1,4	<0,5	3,5	104	50	2,1	105	30	3,5			
41	Navnløst 313/316	32	<1	32	2,5	<0,5	6,2	170	73	2,3	410	32	12,8			
42	Kuetzjar. 213/216	19	10	1,9	<0,5	<0,5		249	163	1,5						
43	Triforojar. 176/538	12	8	1	<0,5	<0,5		160	153	1,0						
44	Nillijarvi 156/546	18	<1	18	<0,5	<0,5		146	176	<1	52	31	1,7			
45	Tsuonnjarvi	29	5	6	<0,5	<0,5		75	90							
46	Toartesjar. 151/550	22	3	7	<0,5	<0,5		119	76	1,6						
47	Kochejar. 201/204	8	<1	8	<0,5	<0,5		83	56	1,5						
48	Ulya 389/392	19	<1	19	<0,5	<0,5		114	90	1,3						
49	Alakajar. 393/396	17	<1	17	<0,5	<0,5		112	77	1,5						
50	Santojarvi 182/529	25	<1	25	<0,5	<0,5		115	125	<1						

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