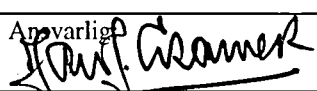


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Assessment of metal contamination in the north-  
western part of the Norskerenna

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<p>The abundances of metal pollutants such as As, Ba, Cd, Co, Cr, Cu, Hg, Ni, Pb, V and Zn have been documented in 128 short (&lt; 0.6m) sediment cores, collected from the north-eastern part of the Norskerenna, off-shore south-western Norway. The primary objective of this investigation was to assess the recent metal contamination of the seabed.</p> <p>Most of reported metals were analysed by ICP-AES except for Hg, Cd, Pb and As which were determined by atomic absorption. A Leco SC analyser was used for the TOC determinations.</p> <p>A reliable assessment of the metal contamination in modern, anthropogenically disturbed sediments requires control upon the natural background. This background has been estimated using metal abundances in sub-surface, pre-industrial sediment intervals.</p> <p>The background corrected metal abundances in the surface sediments indicate that the modern seabed is significantly contaminated with Pb, Ba and Hg. Contamination of the sediments by Cu, V and Zn appears to be relatively minor whereas contamination by As, Cd, Co, Cr and Ni is not apparent in the Norskerenna. The highest contamination levels of Cu, Hg, Pb, V and Zn were observed in fine-grained, TOC-rich sediments at the bottom of the basin suggesting that clay and/or organic particles are the major carriers of these metals. The source of Cu, Hg, Pb, V and Zn contamination remains to be identified. Strong Ba contamination at the south-western slope of the Norskerenna reflects supply of fine-silt-size barite from the off-shore hydrocarbon exploration sites where barite is used as a component of drilling mud.</p>			
Emneord: Marine geology	Geochemistry	Sedimentology	
Seabed sediments	Trace element	Contamination	

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## 1. INTRODUCTION

The trace element abundances in 128 short sediment cores have been used in an environmental assessment of the seabed in the north-western part of the Norskerenna, off-shore south-western Norway. A reliable estimation of contaminant levels in stratigraphical and, particularly, geographical contexts depends heavily on the correct understanding of natural variability of the sediment matrix. Increased levels of metals in one sample compared to another do not necessarily imply higher contamination levels, but may rather reflect differences in the matrix mineralogy. The abundances of metals in uncontaminated matrix sediments (background) have therefore been determined and the environmental significance of metal contaminants such as As, Ba, Cd, Co, Cr, Cu, Hg, Ni, Pb, V and Zn in the surface samples has been evaluated in the context of matrix variability.

The tabulated geochemical data, and stratigraphical and geographical distributions of metals in these sediment cores from the Norskerenna have been presented in an earlier NGU report by Bjerkli and Grimstvedt (1998). The textural and geotechnical characteristics of this sample set have been treated in reports by Bøe et al. (1997) and Bøe and Rise (1997; 1999).

## 2. MATERIALS

The sediment cores discussed here were collected from 128 locations in the north-western part of the Norskerenna (Fig. 1; Table 1). The sampling cruises with M/S Michael Sars in July 1995 and with M/S Håkon Mosby in September 1996 were organised by the Institute of Marine Research and the Geological Survey of Norway (Bjerkli, 1997; Bjerkli and Moen, 1997).

A multicorer (Barnett et al., 1984) was used as a sampling device, providing means for simultaneous recovery of up to 6 short cores with an undisturbed sediment-water interface. Two types of plastic tubes with inside diameters of 59mm and 96mm were used. The length of recovered sediment column ranged from 4 to 58 cm, being typically between 20 and 40 cm (Bjerkli, 1997; Bjerkli and Moen, 1997). The on-board subsampling for geochemical analyses was done from 96 mm tubes. Subsampling of cores from stations 135-180 was done at 2 cm

intervals from the sediment surface down to 20 cm and then, depending on the core length at 25-27, 35-37, 45-47 and 55-57 cm. Subsamples from stations 181-286 were taken at 1 cm intervals from the sediment surface down to 10 cm and then at 15-16, 20-21, 25-26, 30-31, 35-36, 40-41, 45-46, 50-51 and 55-56 cm. All geochemical samples were immediately frozen.

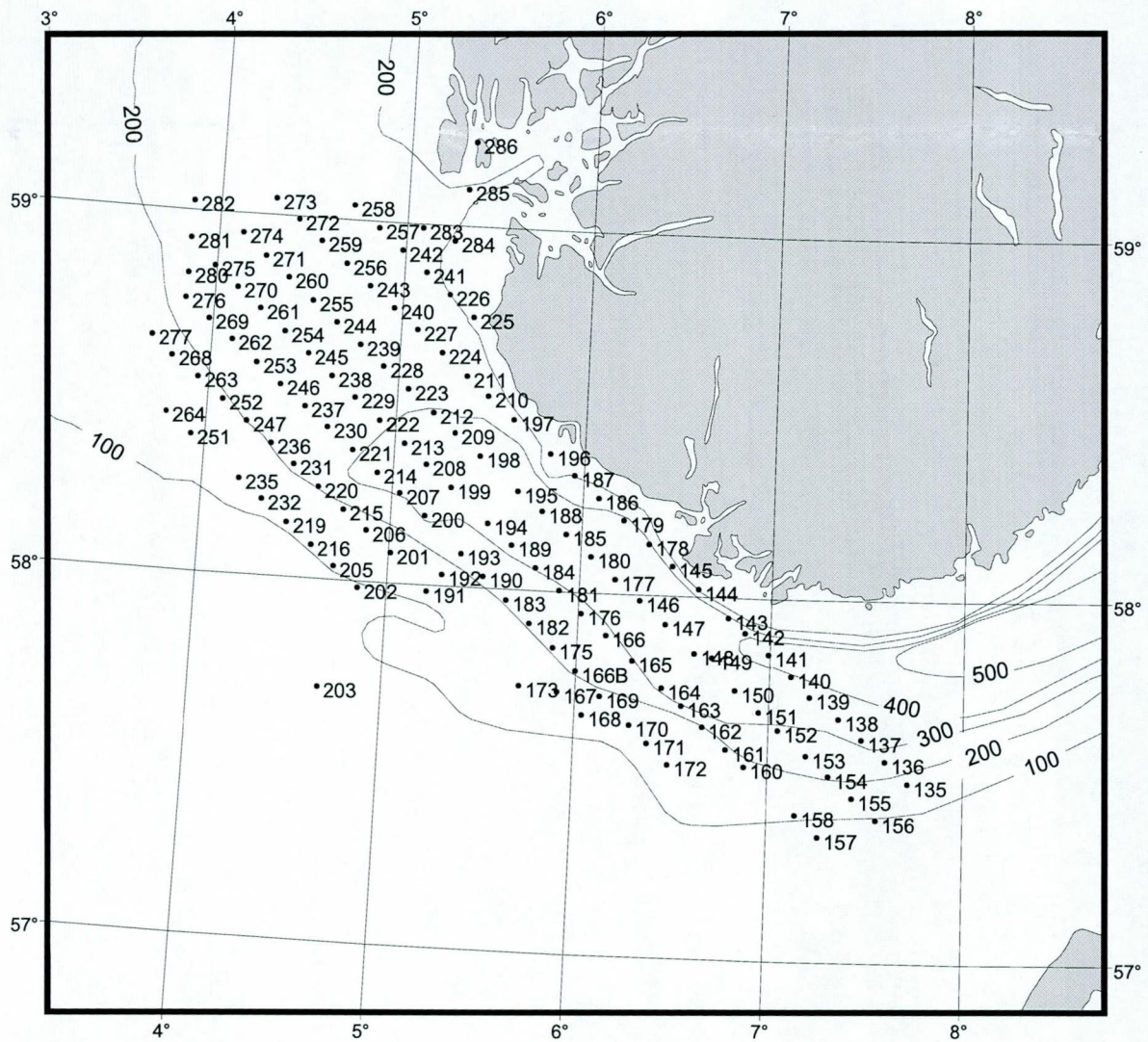


Fig. 1. Sample stations in the north-eastern part of the Norskerenna.

**TABLE 1. Geographical coordinates and water depths of sampling stations. Coarse sediment texture hindered the recovery of core samples at 16 stations (marked with "-" in sediment core column). The geographical positions of these 16 stations are not indicated on Fig. 1. Note that stratigraphical profiles of elemental abundances given in Bjerkli & Grimstvedt (1998) have been obtained from selected 63 stations.**

Station No.	Latitude	Longitude	Water depth	Sediment core	Stratigraphical profile
135	57,49593	7,7145	185	+	-
136	57,55717	7,59717	249	+	+
137	57,61617	7,47533	314	+	-
138	57,6725	7,35633	320	+	+
139	57,73183	7,2075	363	+	-
140	57,78758	7,10967	402	+	+
141	57,84567	6,99	419	+	-
142	57,90383	6,86483	400	+	+
143	57,94433	6,77617	396	+	+
144	58,02143	6,61667	384	+	-
145	58,08333	6,4769	368	+	+
146	57,985	6,31333	333	+	+
147	57,92167	6,45017	336	+	+
148	57,84333	6,60583	341	+	+
149	57,7981	6,70428	340	+	-
150	57,74467	6,82083	333	+	+
151	57,68613	6,9455	314	+	-
152	57,638	7,04733	291	+	+
153	57,56883	7,195	268	+	-
154	57,51333	7,31017	223	+	+
155	57,4545	7,43267	140	+	-
156	57,39473	7,5555	102	+	+
157	57,3452	7,26262	89	+	-
158	57,40467	7,14523	121	+	+
159	57,46265	7,02913	134	-	-
160	57,5339	6,877	190	+	-
161	57,58083	6,78267	201	+	+
162	57,64092	6,65788	283	+	-
163	57,69745	6,54648	309	+	+
164	57,74505	6,4415	293	+	-
165	57,81752	6,28738	289	+	+
166	57,88457	6,1455	285	+	+
166B	57,7827	5,99568	242	+	-
167	57,7226	5,90643	148	+	+
168	57,6617	6,03717	149	+	-
169	57,71562	6,12462	223	+	+
170	57,64005	6,28225		+	+
171	57,59063	6,37587	153	-	-
172	57,53368	6,48628	144	+	+
173	57,73505	5,70955	136	+	+
174	57,78312	5,78392	155	-	-
175	57,84415	5,87502	224	+	+



176	57,9425	6,013	290	+	-
177	58,04125	6,18205	340	+	-
178	58,14327	6,35095	330	+	+
179	58,20558	6,21508	315	+	+
180	58,10193	6,04985	341	+	-
181	58,00378	5,89517	296	+	+
182	57,90878	5,74802	248	+	+
183	57,9709	5,62203	238	+	-
184	58,0639	5,76587	299	+	-
185	58,16125	5,9178	339	+	-
186	58,26395	6,07977	244	+	-
187	58,32407	5,94952	189	+	-
188	58,22088	5,78778	336	+	+
189	58,12412	5,63672	302	+	-
190	58,03367	5,49703	262	+	+
191	57,98325	5,20655	146	+	+
192	58,03233	5,28112	207	+	-
193	58,09313	5,37492	288	+	-
194	58,18097	5,50818	308	+	+
195	58,27318	5,65588	336	+	-
196	58,38157	5,81857	218	+	-
197	58,47183	5,61822	306	+	-
198	58,3663	5,45052	335	+	+
199	58,2751	5,30633	322	+	-
200	58,19262	5,17715	309	+	+
201	58,08497	5,00855	197	+	-
202	57,98195	4,84857	109	+	-
203	57,86777	4,67133	102	+	+
204	57,92427	4,54512	101	-	-
205	58,03897	4,71732	117	+	-
206	58,1432	4,87523	239	+	+
207	58,2515	5,04048	309	+	-
208	58,33557	5,17067	321	+	+
209	58,42722	5,31207	322	+	-
210	58,53437	5,47852	274	+	-
211	58,58625	5,36017	259	+	-
212	58,48033	5,19303	302	+	+
213	58,38947	5,04925	308	+	-
214	58,30478	4,91648	302	+	+
215	58,19683	4,75102	268	+	-
216	58,09363	4,5924	126	+	+
217	57,98008	4,41922	98	-	-
218	58,03822	4,28572	93	-	-
219	58,15183	4,45827	144	+	-
220	58,25557	4,61423	290	+	-
221	58,36383	4,78027	292	+	-
222	58,45	4,91252	290	+	-
223	58,54135	5,05418	278	+	-
224	58,64817	5,22062	241	+	-
225	58,75005	5,3788	155	+	-
226	58,81027	5,24598	198	+	-
227	58,70733	5,08393	228	+	-
228	58,6007	4,91725	259	+	-
229	58,51023	4,77543	279	+	-

230	58,42312	4,64212	286	+	+
231	58,31452	4,47553	303	+	-
232	58,2119	4,31973	132	+	+
233	58,09838	4,14707	91	-	-
234	58,15526	4,02986	118	-	-
235	58,26458	4,19427	136	+	+
236	58,36835	4,34977	303	+	+
237	58,47703	4,51537	285	+	-
238	58,56588	4,64827	273	+	-
239	58,65682	4,78827	222	+	-
240	58,76383	4,95335	201	+	-
241	58,86787	5,1146	207	+	-
242	58,92457	4,9821	238	+	-
243	58,8215	4,8206	221	+	-
244	58,7149	4,65502	245	+	-
245	58,624	4,5152	268	+	-
246	58,53422	4,37842	286	+	+
247	58,4258	4,21408	292	+	+
248	58,32217	4,05897	144	-	-
249	58,2082	3,8893	116	-	-
250	58,264	3,7566	114	-	-
251	58,37883	3,92565	150	+	+
252	58,48167	4,08087	280	+	+
253	58,59027	4,24537	288	+	-
254	58,68077	4,38345	270	+	+
255	58,77183	4,52267	242	+	-
256	58,87873	4,68808	250	+	-
257	58,98232	4,84958	250	+	-
258	59,04153	4,71075	279	+	+
259	58,93813	4,54873	257	+	-
260	58,8312	4,38388	245	+	-
261	58,74048	4,2446	280	+	-
262	58,64872	4,106	286	+	+
263	58,53982	3,94167	256	+	-
264	58,43677	3,78718	153	+	+
265	58,32227	3,61645	124	-	-
266	58,37472	3,48877	114	-	-
267	58,49055	3,65792	121	-	-
268	58,5935	3,79655	235	+	+
269	58,7022	3,97662	278	+	-
270	58,79498	4,11698	288	+	+
271	58,8858	4,25582	283	+	-
272	58,99287	4,42035	258	+	+
273	59,04693	4,29147	275	+	-
274	58,93982	4,12653	292	+	+
275	58,84972	3,98827	282	+	-
276	58,75627	3,84505	272	+	+
277	58,64727	3,68183	207	+	-
278	58,54435	3,528	117	-	-
279	58,42897	3,35742	114	-	-
280	58,82515	3,84943	273	+	-
281	58,92218	3,85118	277	+	+
282	59,02553	3,85475	277	+	+
283	58,98915	5,08323	248	+	+

284	58,9585	5,25685	270	+	+
285	59,1033	5,31763	322	+	+
286	59,23278	5,3465	286	+	+

### 3. METHODS

The concentrations of reported elements were determined using the analytical methods and detection limits shown in Table 2. Most of the reported major and trace elements were analysed using Thermo Jarrell Ash ICP-AES 61. Hg concentrations were measured using the CETAC M-6000A atomic absorption cold vapor Hg Analyser. Perkin Elmer graphite furnace atomic adsorption (GFAA) system SIMAA 6000 was used for Cd, Pb and As determinations. For all these analyses acidified aqueous sample solutions were obtained by leaching 1 g of freeze-dried sediment in 7N HNO<sub>3</sub> in an autoclave at 120 °C for 1 hour (Norsk Standard NS 4770).

**TABLE 2. Applied analytical methods and detection limits of individual elements.**

Element	Method	Detection limit
Al	ICP-AES	20 ppm
Cu	ICP-AES	1 ppm
Zn	ICP-AES	2 ppm
Ni	ICP-AES	2 ppm
Co	ICP-AES	1 ppm
V	ICP-AES	1 ppm
Cr	ICP-AES	1 ppm
Ba	ICP-AES	1 ppm
Hg	AA/HMS-1	0.01 ppm
Cd	AA	0.02 ppm
Pb	AA	0.4 ppm
As	AA	3 ppm
Total organic C	Leco	0.1%

The elemental abundances in surface samples have also been determined using sample solutions obtained by digesting 100 mg sample in mixed acid including 1 ml aqua regia and 3 ml HF in a microwave oven (Bjerkli and Grimstvedt, 1998). However, these data are not included in the environmental assessment presented in this report.

The contents of total organic carbon ( $C_{tot}$ ) in samples were determined on the Leco SC-444 analyser using 100-350 mg of sample. Carbonate was removed by 10% HCl prior organic carbon measurements.

## **4. RESULTS**

Data for the environmentally significant metals (As, Ba, Cd, Co, Cr, Cu, Hg, Ni, Pb, V and Zn) presented in this report have been extracted from the larger geochemical dataset that includes numerous additional major and trace elements (Bjerkli and Grimstedt, 1998). Considering that the sediment trace element geochemistry is closely related to textural and mineralogical changes and to sedimentological regime (Buckley & Granston, 1991), parameters characterising the sediment matrix, such as Al and TOC abundances, are also evaluated. Geographical variations in the abundances of reported elements are graphically illustrated in Figs. 4a-14a where concentration ranges of individual elements are divided into five classes using the ArcView<sup>®</sup> "natural breaks" classification method. This method identifies breakpoints between classes using a statistical formula (Jenks' optimisation), and finds groupings and patterns inherent in the data.

### **4.1. Surface sediments**

#### **4.1.1. Aluminium, TOC**

The geographical distribution of Al (Figs. 2) is primarily dependent on the clay content of the sediments and reflects depositional conditions and current velocities at the seabed. Low Al values in coarse-grained, sandy sediments in relatively shallow stations along SW margin of the Norskerenna and high Al concentrations in the deepest stations in SE part of the study area (Fig. 2) indicate strong bathymetric control upon distribution of Al-rich, fine-grained sediments.

The geographical pattern of TOC (Fig. 3) correlates generally well with Al. This indicates winnowing of organic matter from relatively shallow, high-energy environments with coarse-grained sediments, and transport towards the calmest basins in the area.

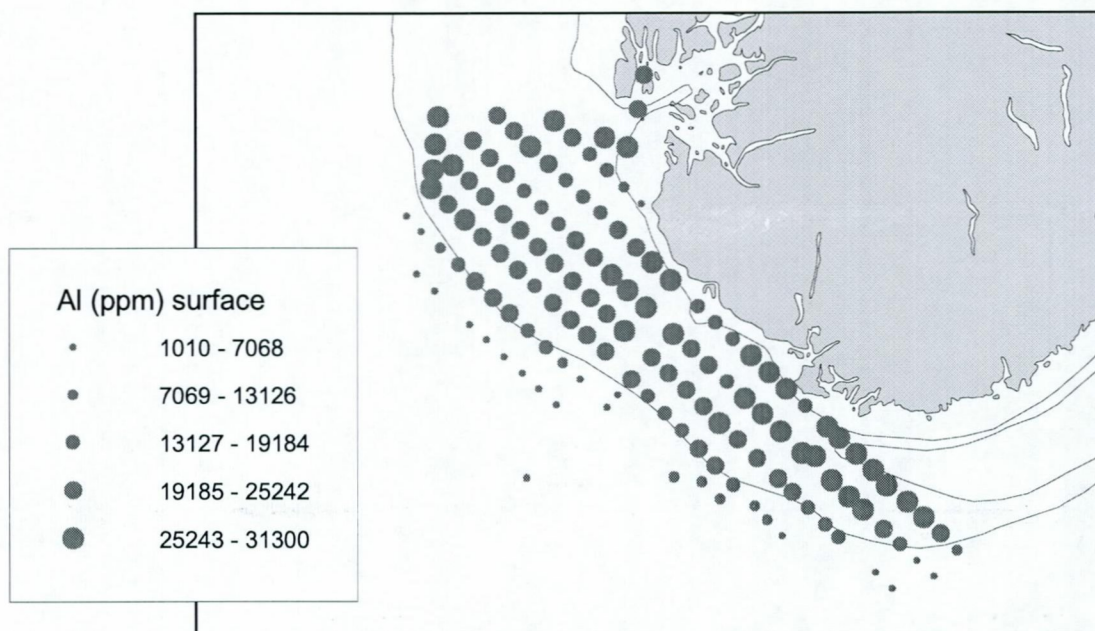


Fig. 2. Aluminum contents (ppm) in the surface sediments.

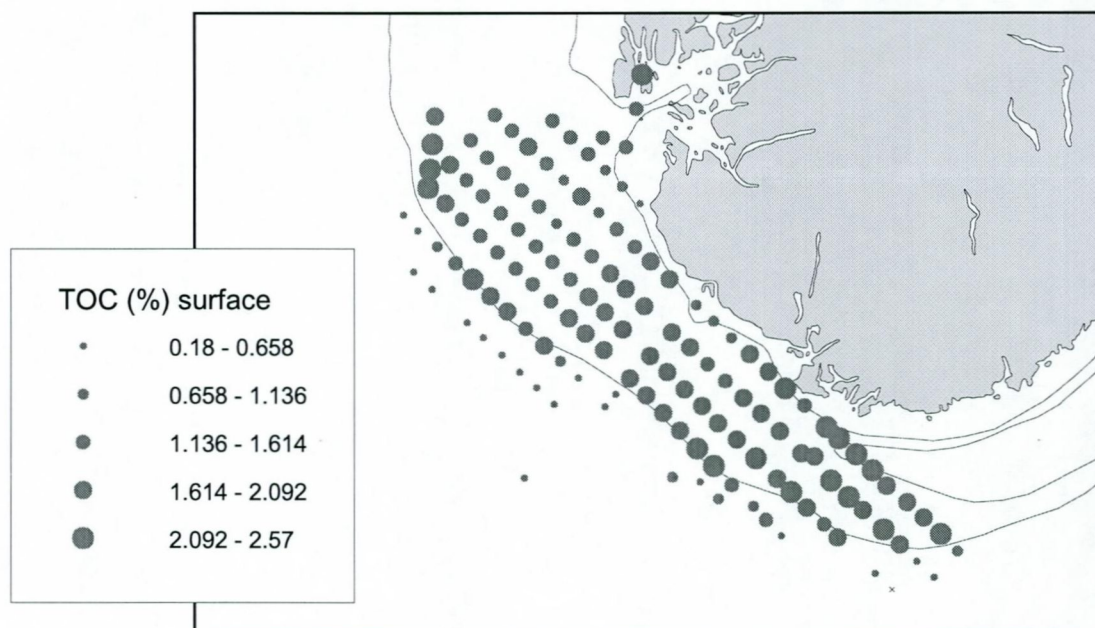


Fig. 3. TOC contents (%) in the surface sediments.

#### 4.1.2. Arsenic, Cobalt, Chromium, Copper, Lead, Nickel, Vanadium, Zinc

The distributions of these metals in the surface sediments (Figs. 4a-11a) are generally in phase with those of Al and TOC (Figs. 2; 3). Fine-grained sediments in the bottom of the Norskerenna, particularly at the eastern limit of the study area, have highest abundances of these metals while strongest depletions were found in sandy sediments at the south-western and southern margins of the study area.

#### 4.1.3. Cadmium, Mercury

Cd concentrations in surface sediments are generally higher in the north-western part of the study area (Fig. 12a). However, the distribution pattern of Cd is rather unsystematic and adjacent stations have occasionally contrasting Cd concentrations.

Surface sediments in stations along the southern coast of Norway, i.e. eastern part of the study area, have the highest Hg concentrations (Fig. 13a) while these concentrations show a decreasing trend towards north-west and south-east.

#### 4.1.4. Barium

The strongest Ba enrichments are found in sediments at the south-western slope of the Norskerenna, at about 200 m water depth (Fig. 14a). From this band of high Ba values, the concentrations generally decrease towards the Norwegian mainland in east and north-east.

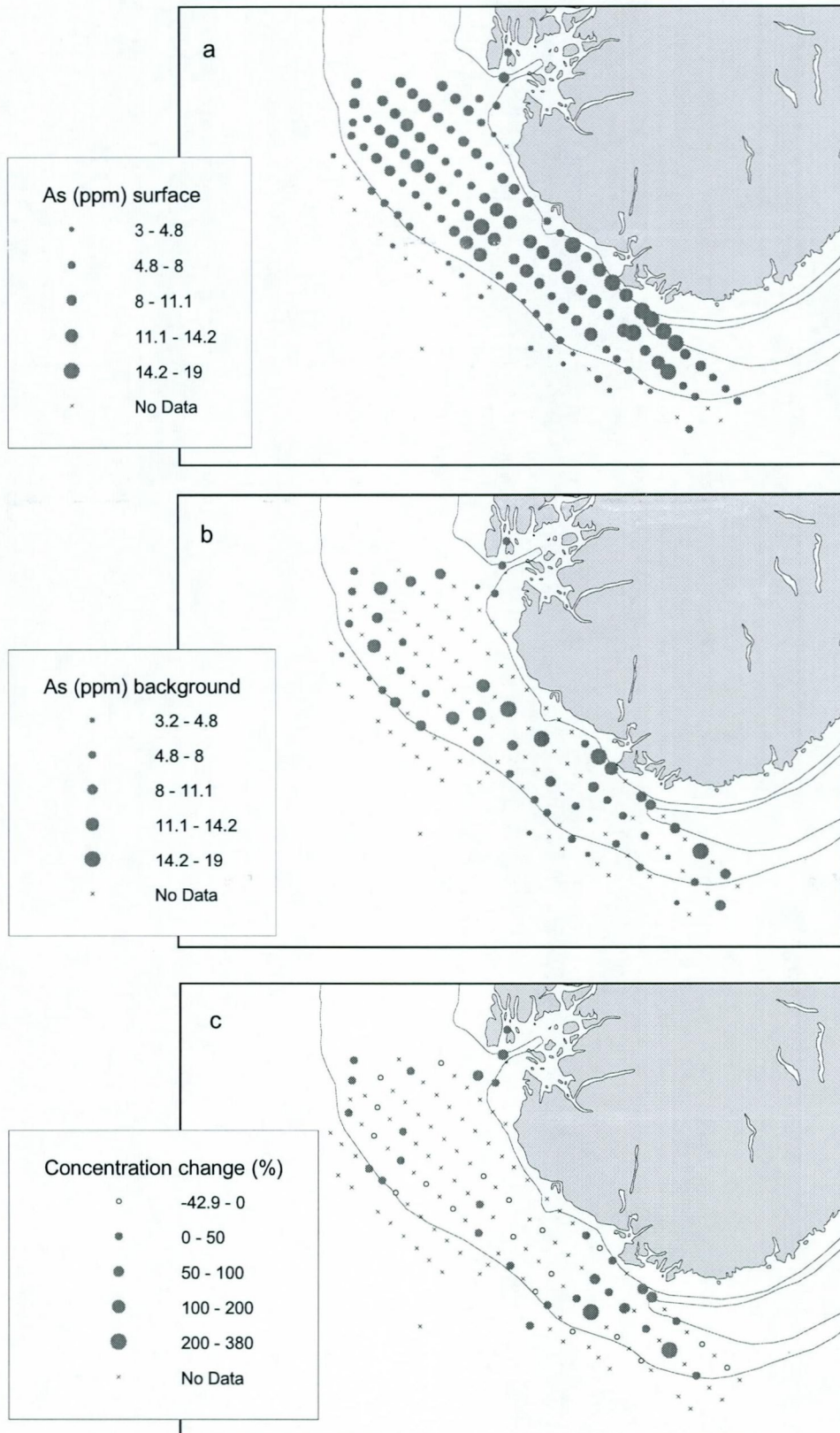


Fig. 4. Arsenic contents in the surface sediments (a) and in the background (b), and concentration change (%) from background to surface (c). Background (b) and concentration change (c) are given only for stations with stratigraphical data.

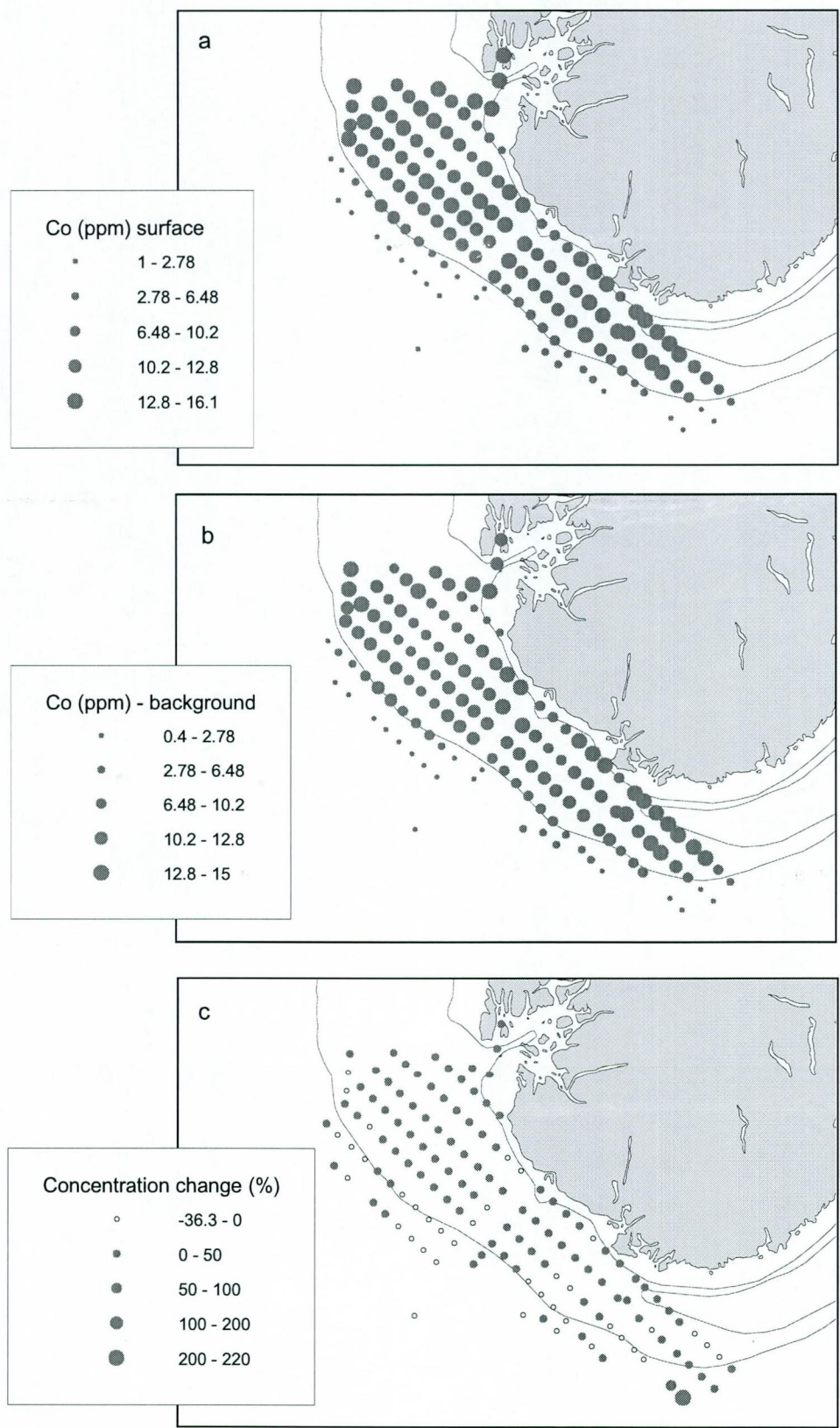


Fig. 5. Cobalt contents in the surface sediments (a), in the background (b), and concentration change (%) from background to surface (c). Background has been calculated using Al as a reference element.



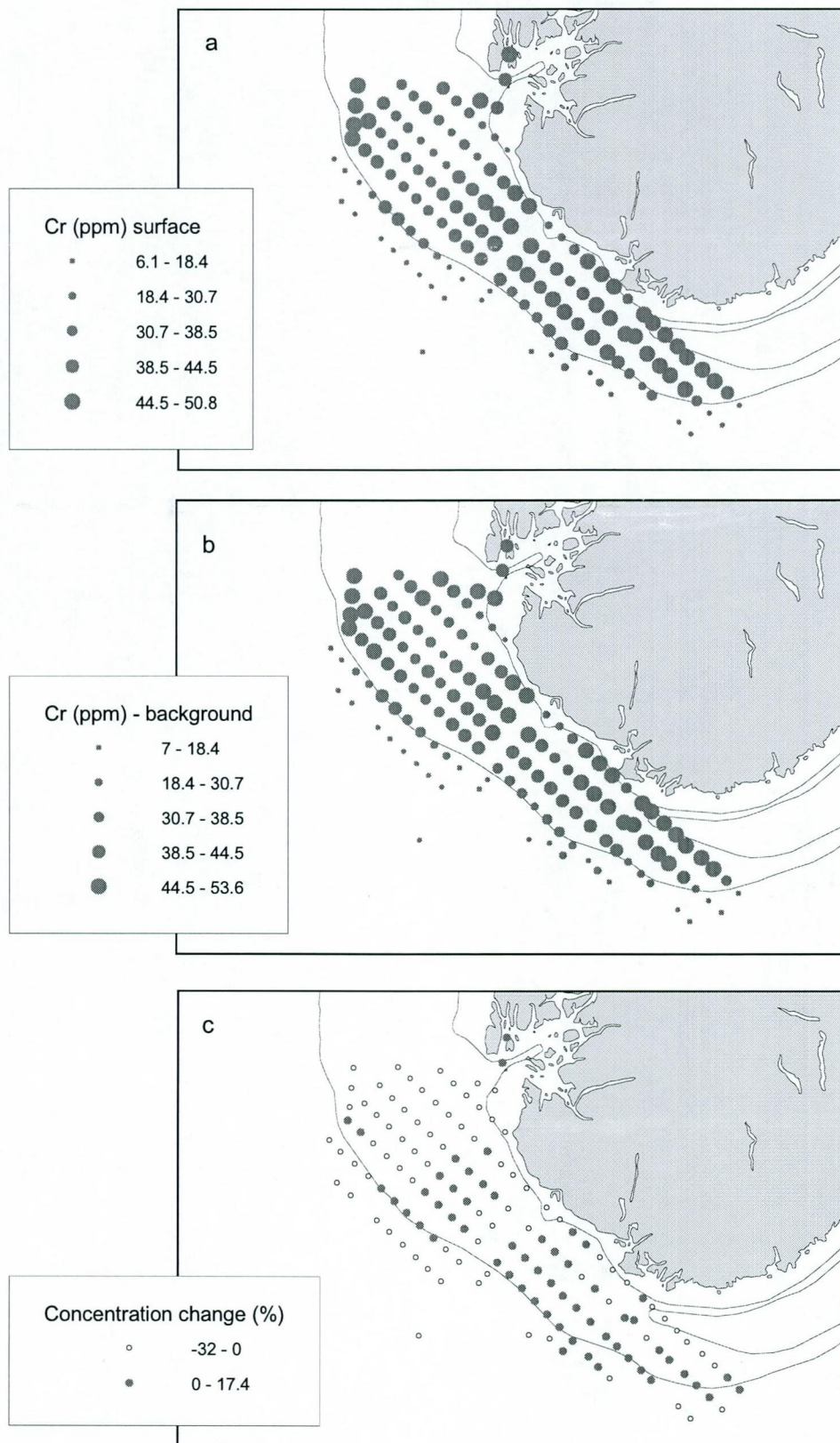


Fig. 6. Chromium contents in the surface sediments (a), in the background (b), and concentration change (%) from background to surface (c). Background has been calculated using Al as a reference element.

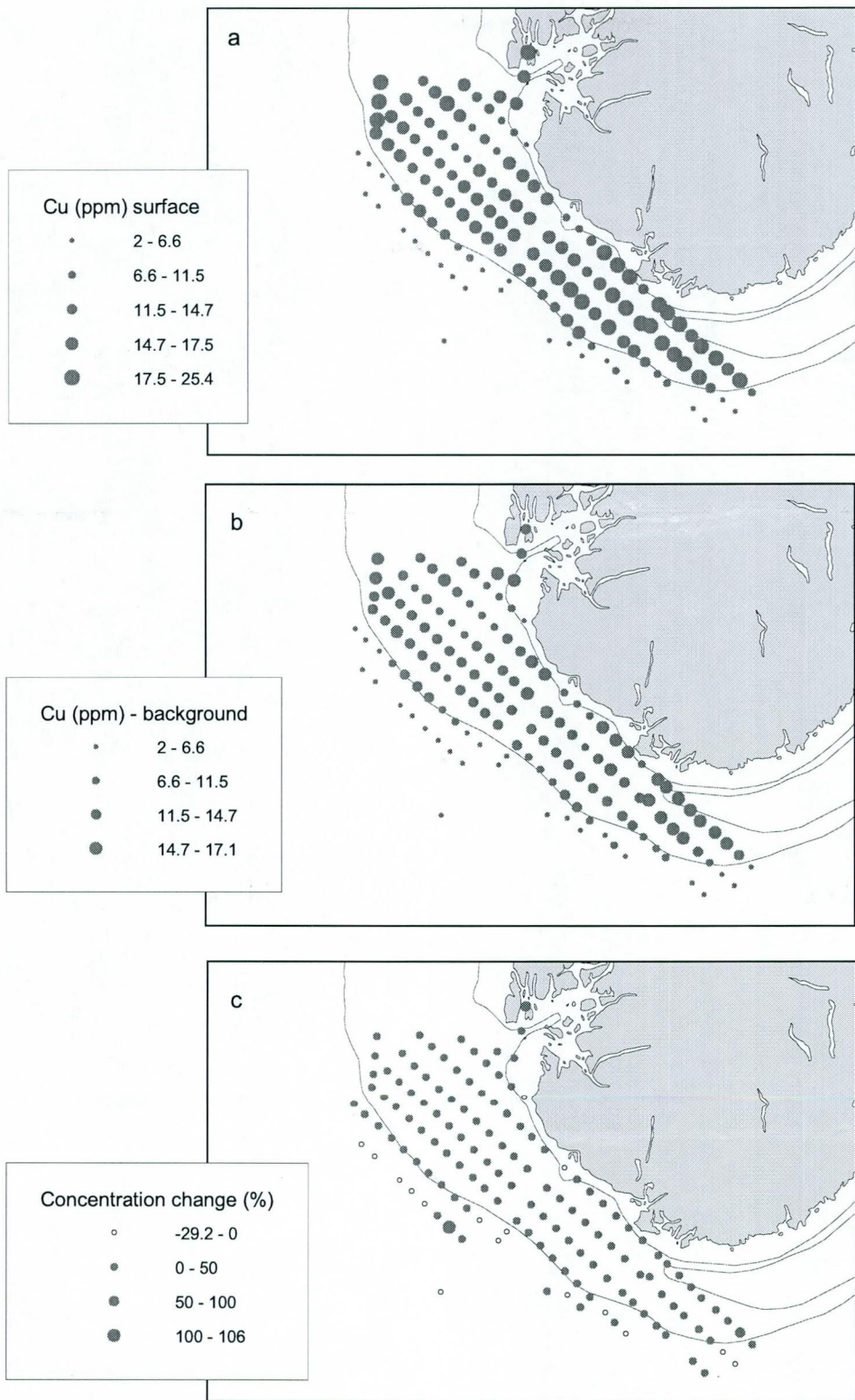


Fig. 7. Copper contents in the surface sediments (a), in the background (b), and concentration change (%) from background to surface (c). Background has been calculated using Al as a reference element.

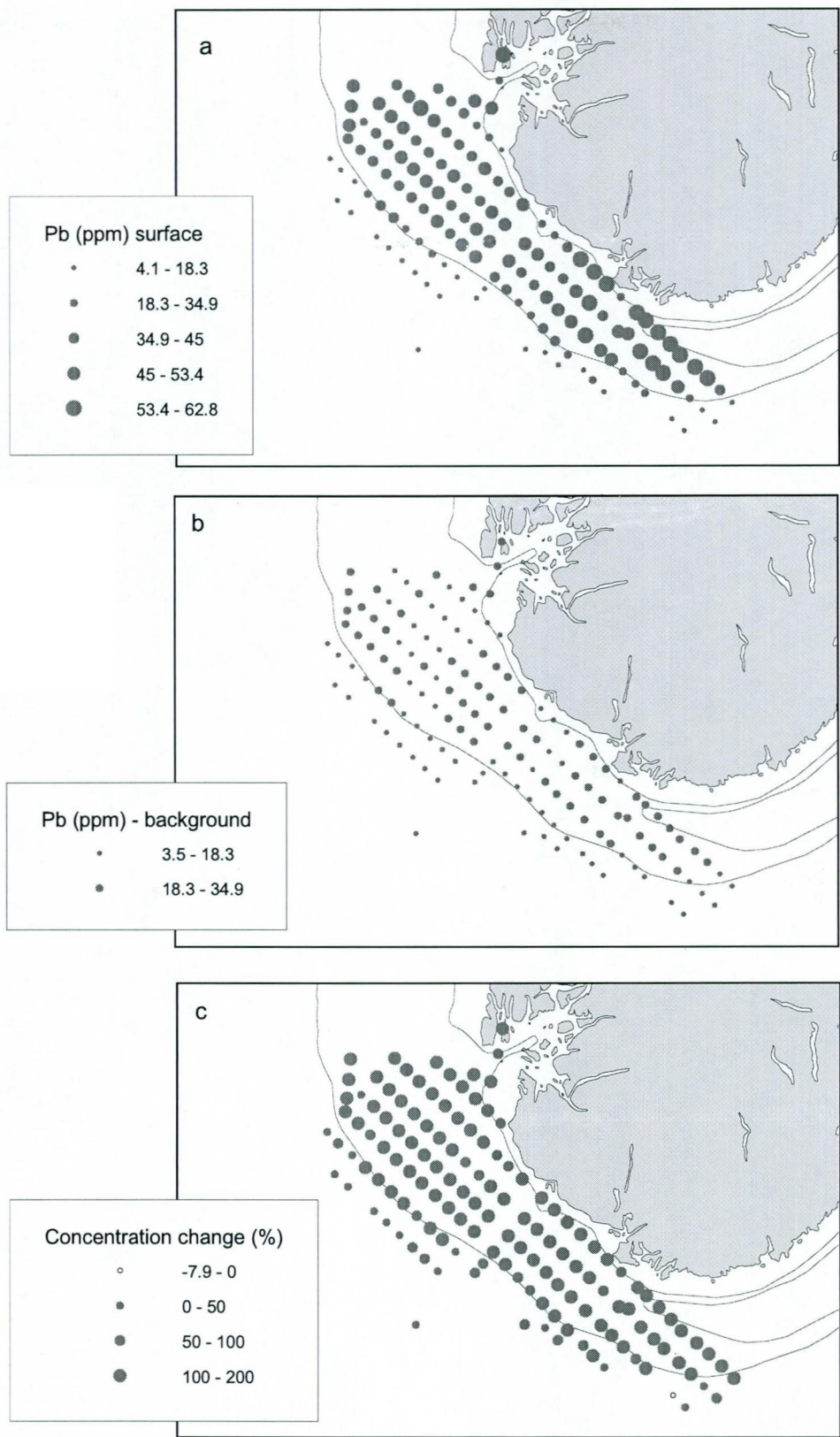


Fig. 8. Lead contents in the surface sediments (a), in the background (b), and concentration change (%) from background to surface (c). Background has been calculated using Al as a reference element.

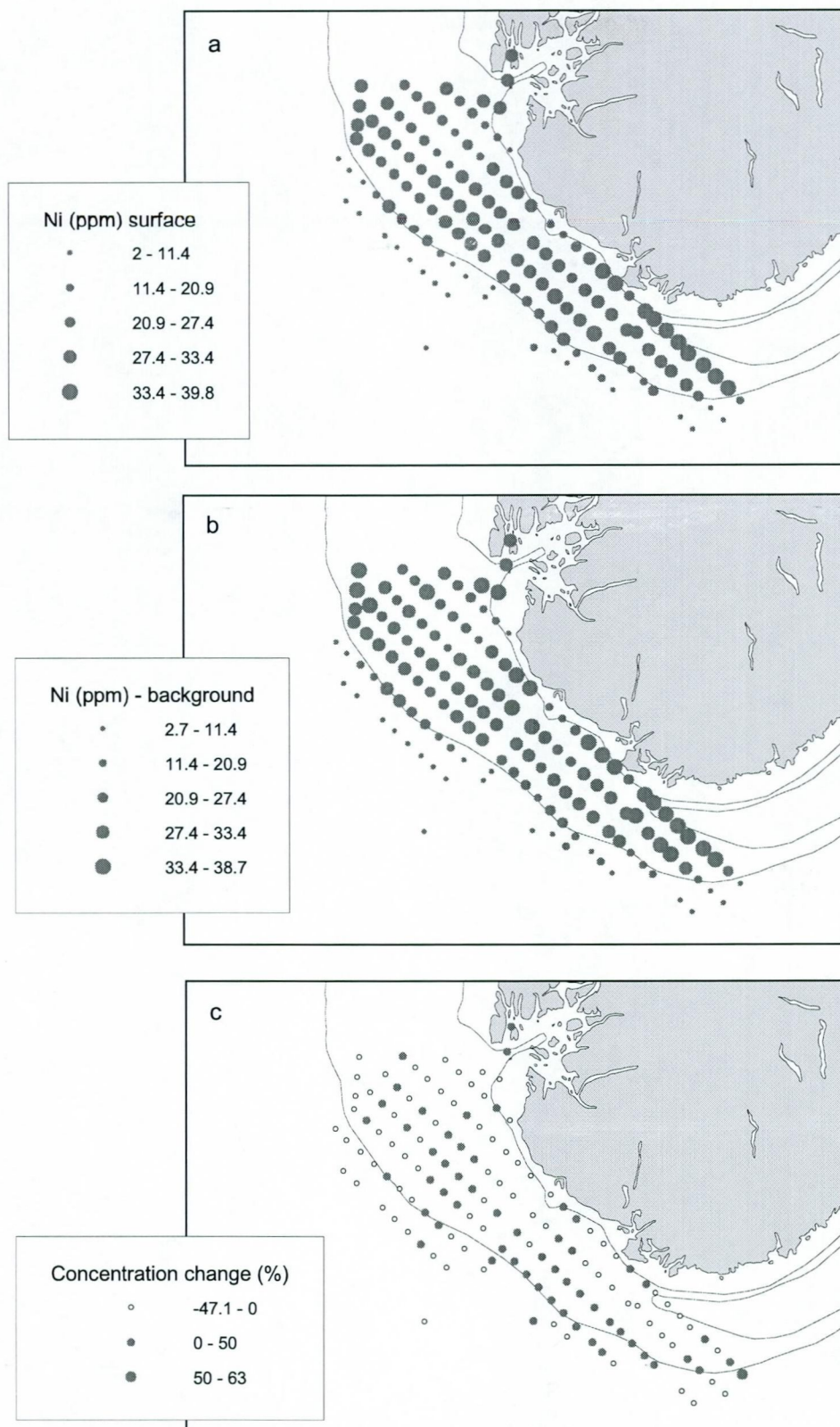


Fig. 9. Nickel contents in the surface sediments (a), in the background (b), and concentration change (%) from background to surface (c). Background has been calculated using Al as a reference element.

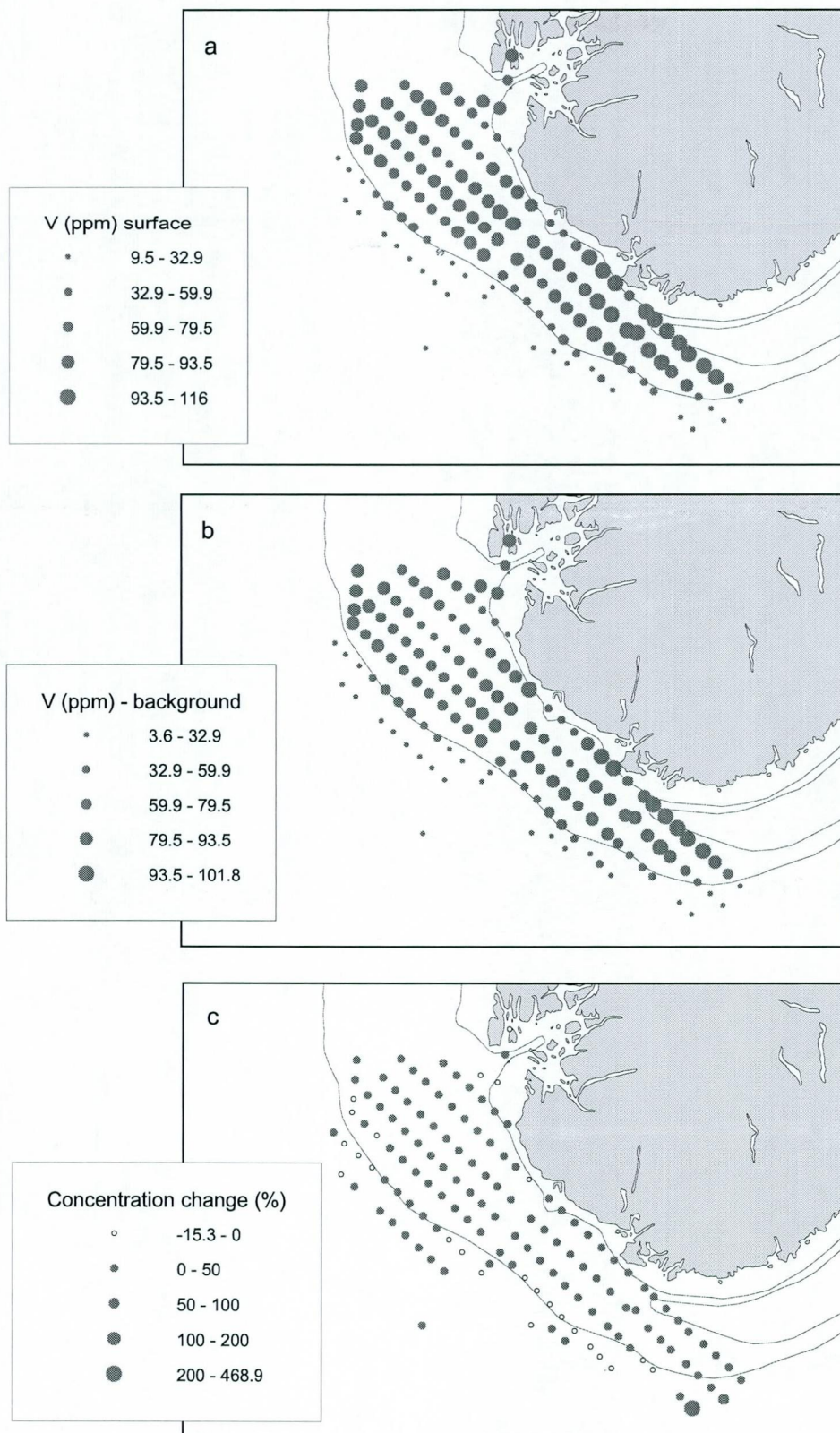


Fig. 10. Vanadium contents in the surface sediments (a), in the background (b), and concentration change (%) from background to surface (c). Background has been calculated using Al as a reference element.

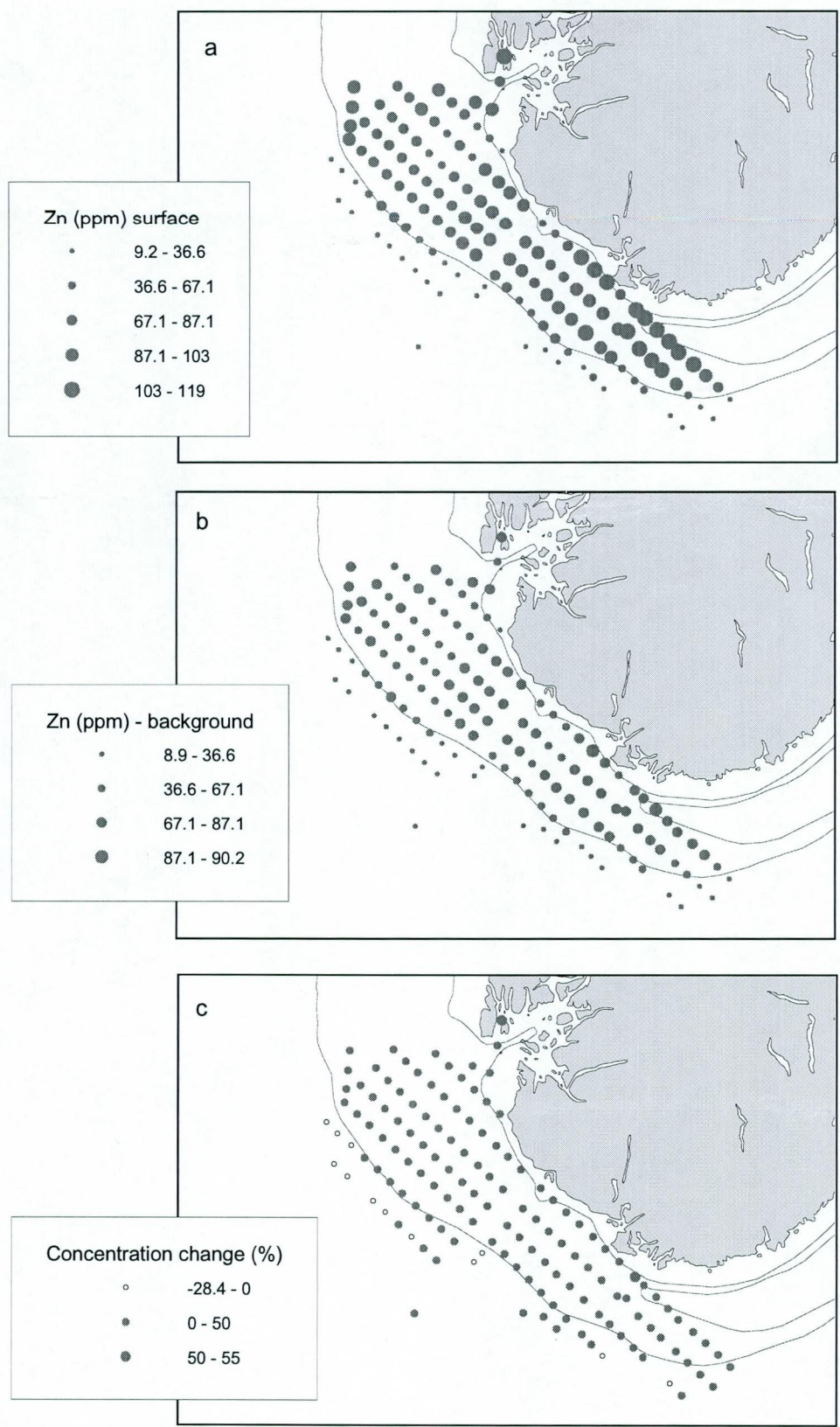


Fig. 11. Zinc contents in the surface sediments (a), in the background (b), and concentration change (%) from background to surface (c). Background has been calculated using Al as a reference element.

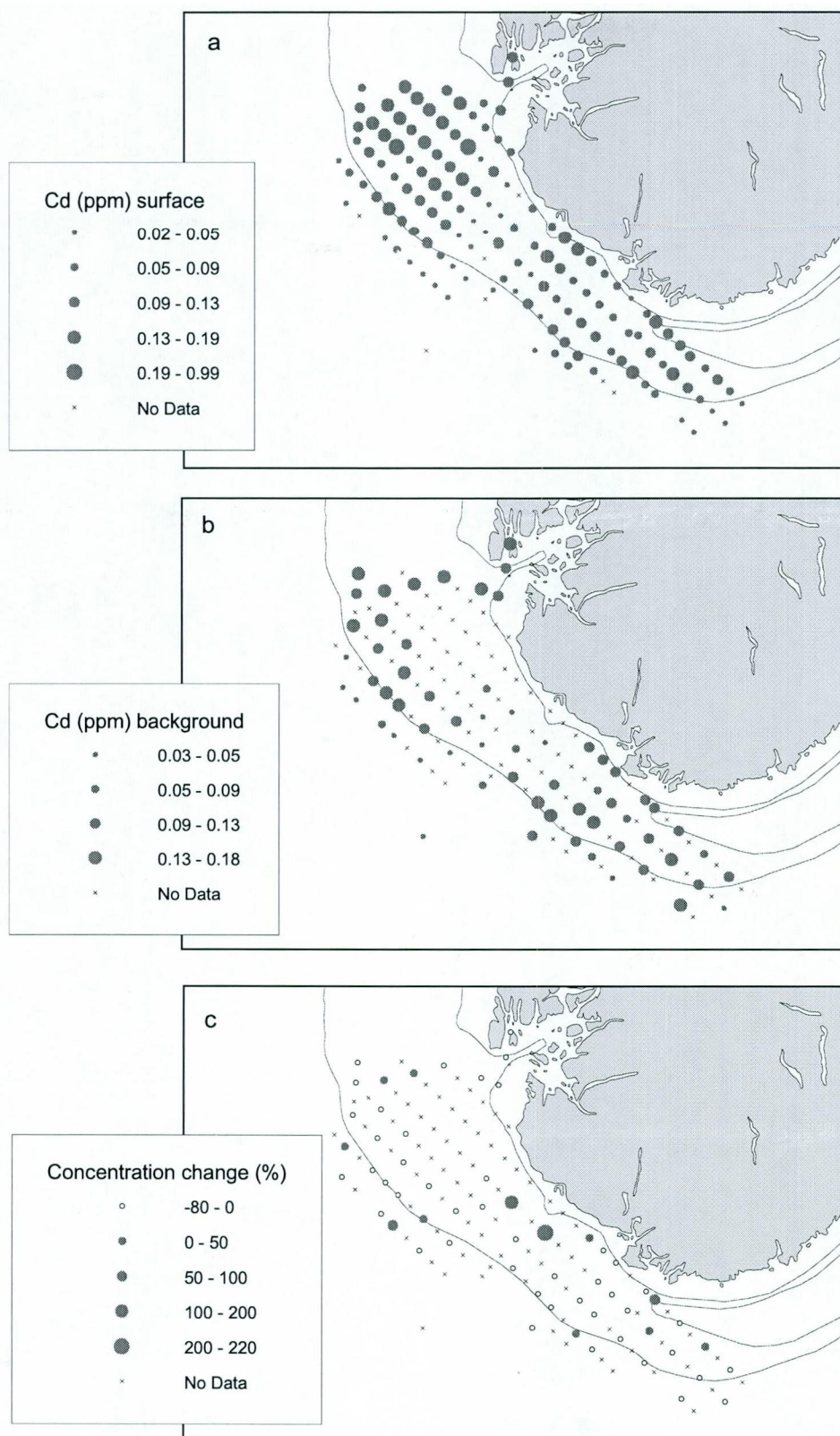


Fig. 12. Cadmium contents in the surface sediments (a) and in the background (b), and concentration change (%) from background to surface (c). Background (b) and concentration change (c) are given only for stations with stratigraphical data.

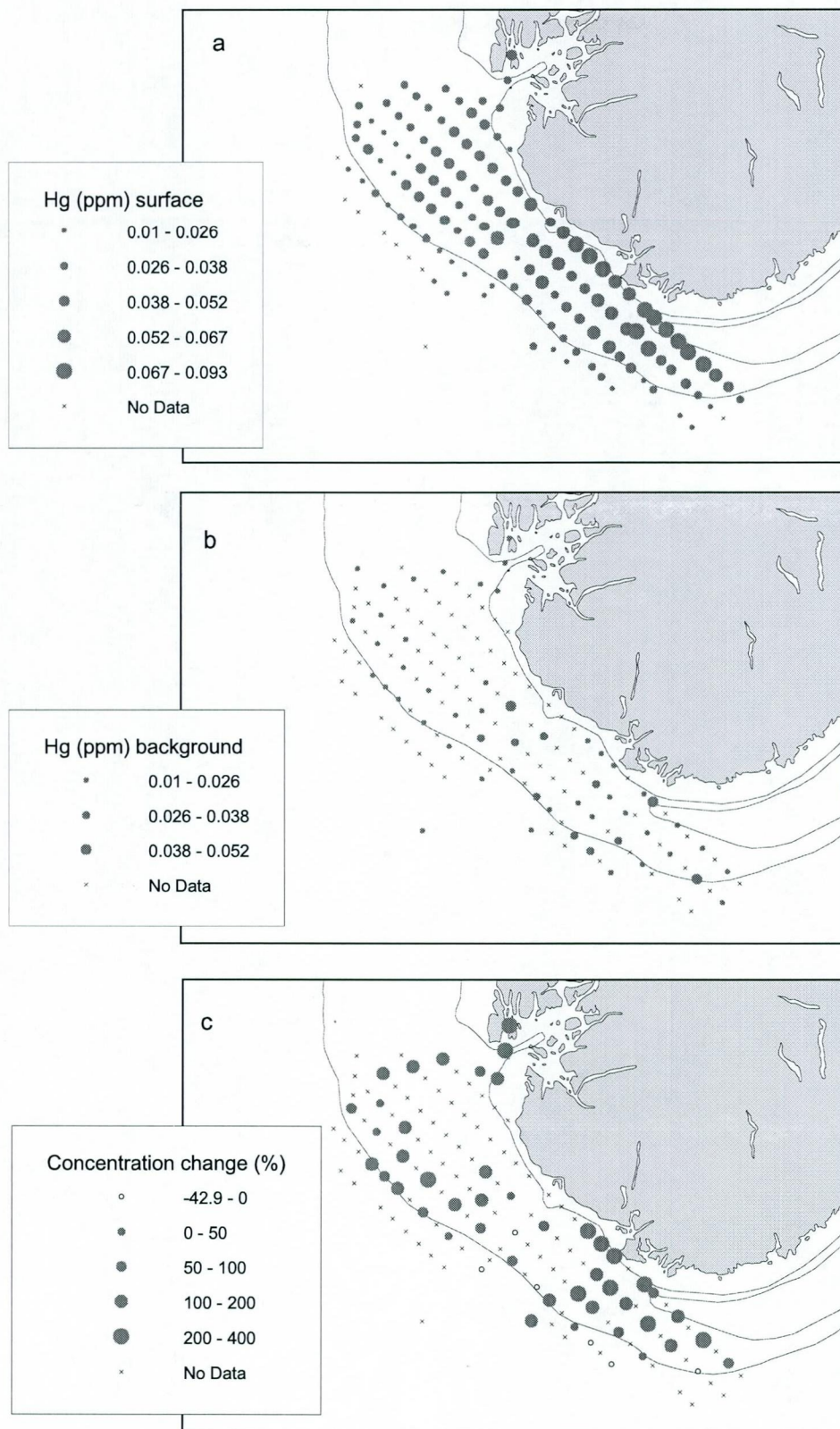


Fig. 13. Mercury contents in the surface sediments (a) and in the background (b), and concentration change (%) from background to surface (c). Background (b) and concentration change (c) are given only for stations with stratigraphical data.



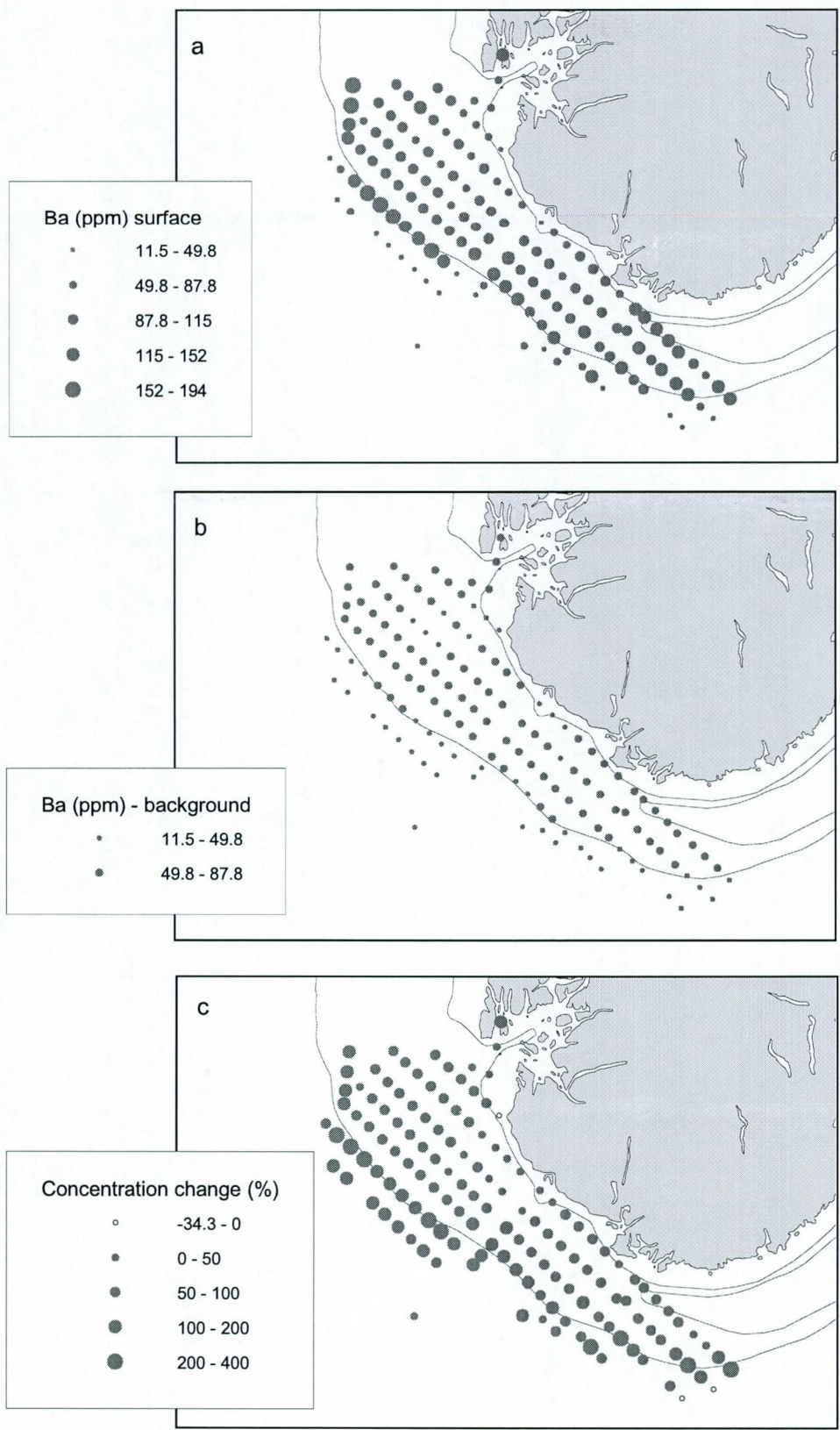


Fig. 14. Barium contents in the surface sediments (a), in the background (b), and concentration change (%) from background to surface (c). Background has been calculated using Al as a reference element.

## 4.2. Background concentrations

Marine sediments are contaminated if they contain sediment components, including environmentally hazardous metals, above natural background levels. A reliable assessment of the metal contamination of recent sediments can therefore only be made if the natural background is well defined. Under the condition of stratigraphically monotonous lithology and immobility of the target metals during diagenesis, the metal abundances in sub-surface, pre-industrial sediment intervals provide a good approximation of the background abundances at the particular locality. The background concentrations of metals in contaminated sediments can also be calculated using a reference element that (i) is not a contaminant, (ii) is abundant in the matrix, and (iii) has a defined ratio to the metal in the matrix. If such a relationship between the reference element and the metal pollutant can be established for the matrix sediments in a study area, the contamination levels in surface sediments can be estimated without studying subsurface intervals.

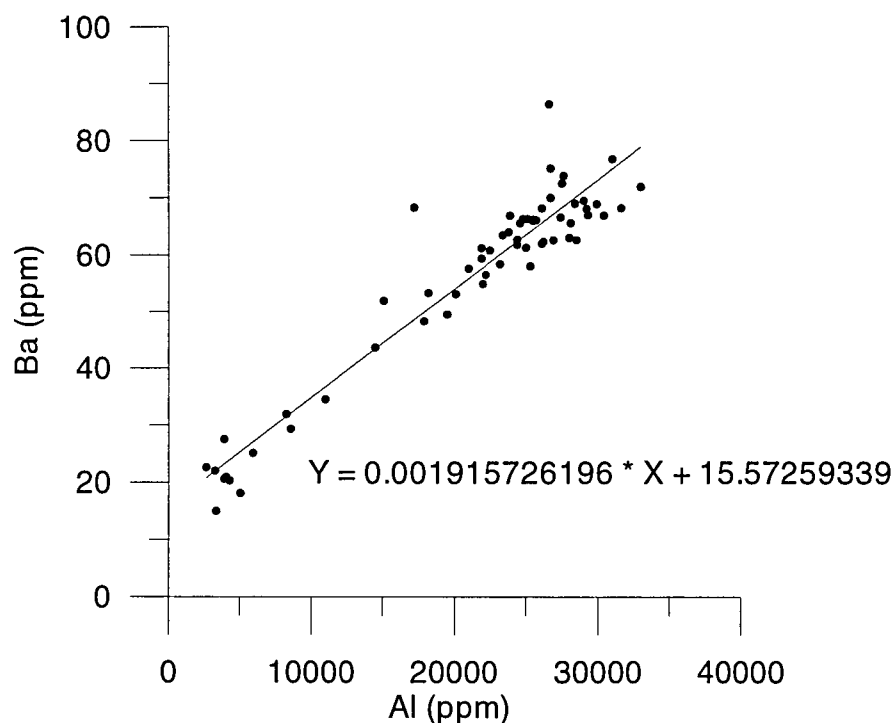
### 4.2.1. Background concentrations of metals using Al as reference element

The concentration vs. depth profiles of Ba, and commonly also of Pb, i.e. metals with relatively high concentrations in surface sediments due to contamination, stabilise at nearly constant level about 5-15 cm down core (Bjerkli and Grimstvedt, 1998). These sub-surface sediments with uniform metal profiles allow the estimation of background metal abundances. Uncontaminated, texturally different sub-surface sediments from 63 stations (i.e. stations with stratigraphical profiles) show a nearly linear correlation for Al with Ba, Co, Cr, Cu, Ni, Pb, V and Zn (Figs. 15-22). On these correlation diagrams (Figs. 15-22) there is one data point, representing the deepest analysed interval from each station with stratigraphical profile. The observed consistent relationships suggest that background (matrix) Ba, Co, Cr, Cu, Ni, Pb, V and Zn occur primarily in Al-bearing phases (most likely clay minerals), and indicate that Al concentration can be used as a proxy for the background metal abundance.

Excluding the post-depositional mobility of Al and its participation in contamination processes, it appears reasonable to assume that the correlations between Al and the above listed metals seen in sub-surface sediments also apply for the background (matrix) component in the contaminated surface sediments. Thus, the correlations of Ba, Co, Cr, Cu, Ni, Pb, V and Zn with Al in sub-surface intervals provide the basis for calculating the background

concentrations of these metals in the contaminated sediments from the known Al concentrations. The formulas in Figures 15-22 are used to calculate background values of metals from the respective Al concentrations. The background determination using Al as a reference element has made it possible to estimate the metal pollution at all 127 stations, including the 65 stations for which there are only geochemical data available for the surface sediments.

Geographical distribution of calculated background concentrations of Co, Cr, Cu, Pb, Ni, V, Zn and Ba are shown on Figs. 5b-11b; 14b, respectively. Note that the class boundaries on these background figures are generally the same as used in case of the surface sediments to facilitate comparison.



*Fig. 15. Correlation diagram for Al and Ba in un-contaminated sub-surface sediments.*

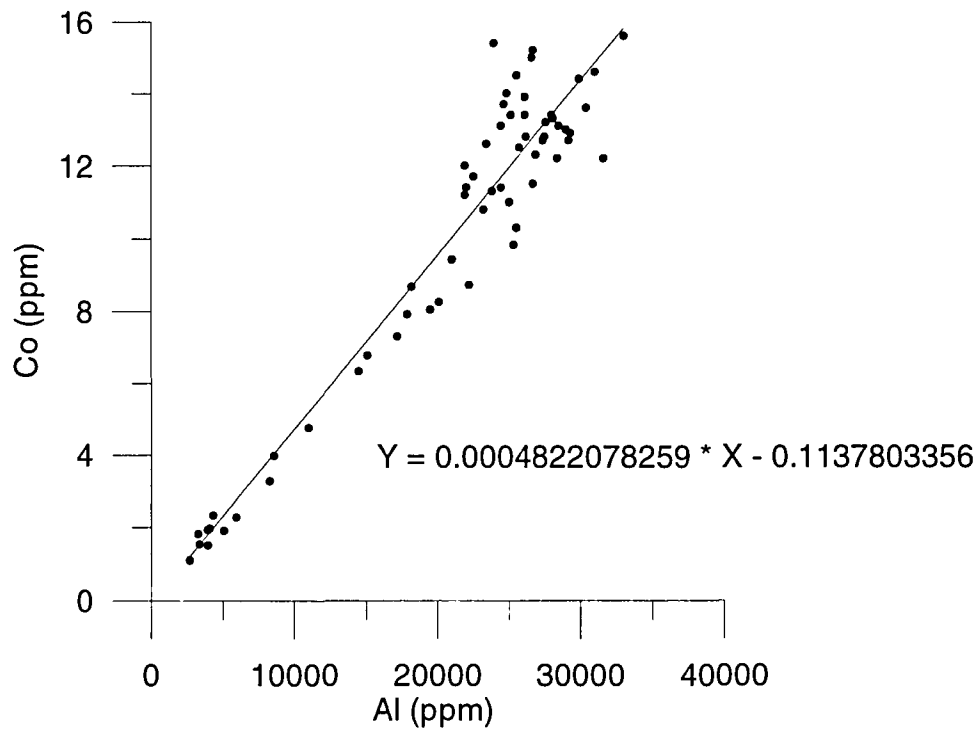


Fig. 16. Correlation diagram for Al and Co in un-contaminated sub-surface sediments.

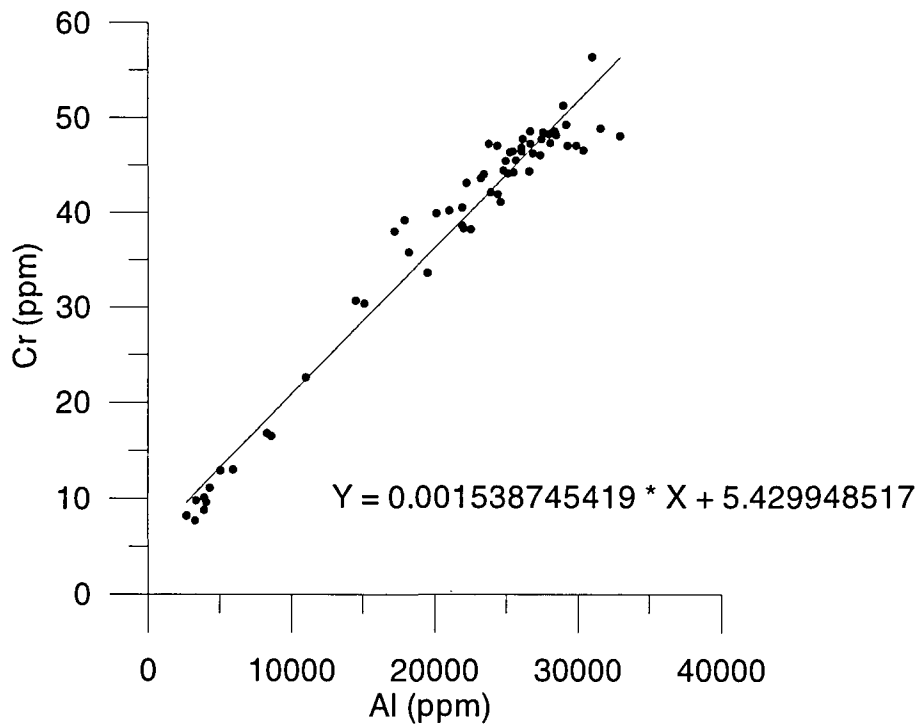


Fig. 17. Correlation diagram for Al and Cr in un-contaminated sub-surface sediments.

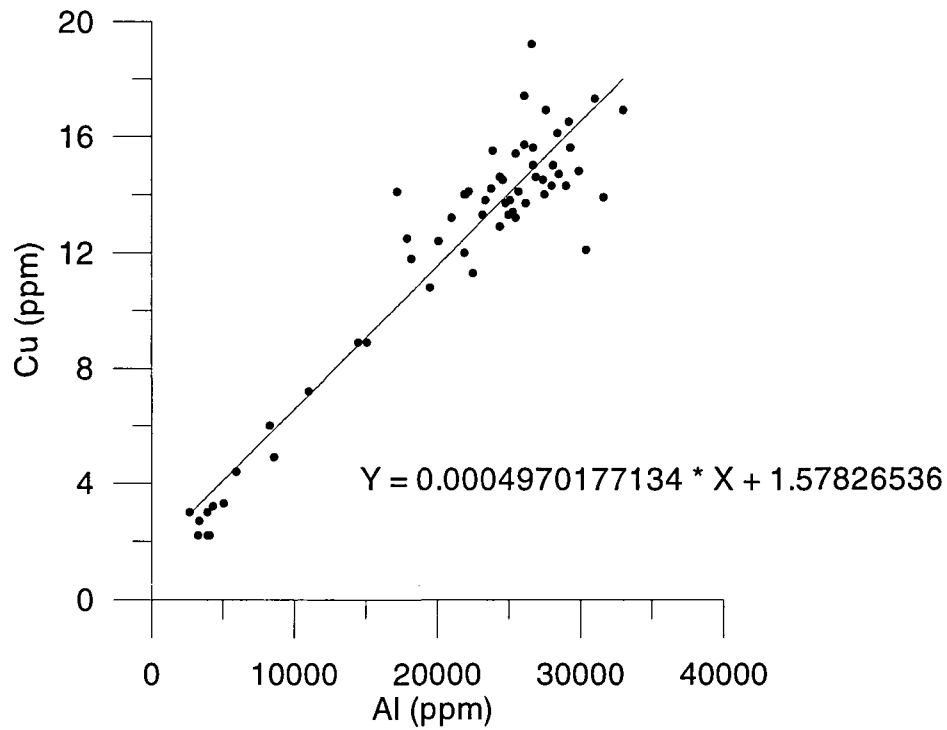


Fig. 18. Correlation diagram for Al and Cu in un-contaminated sub-surface sediments.

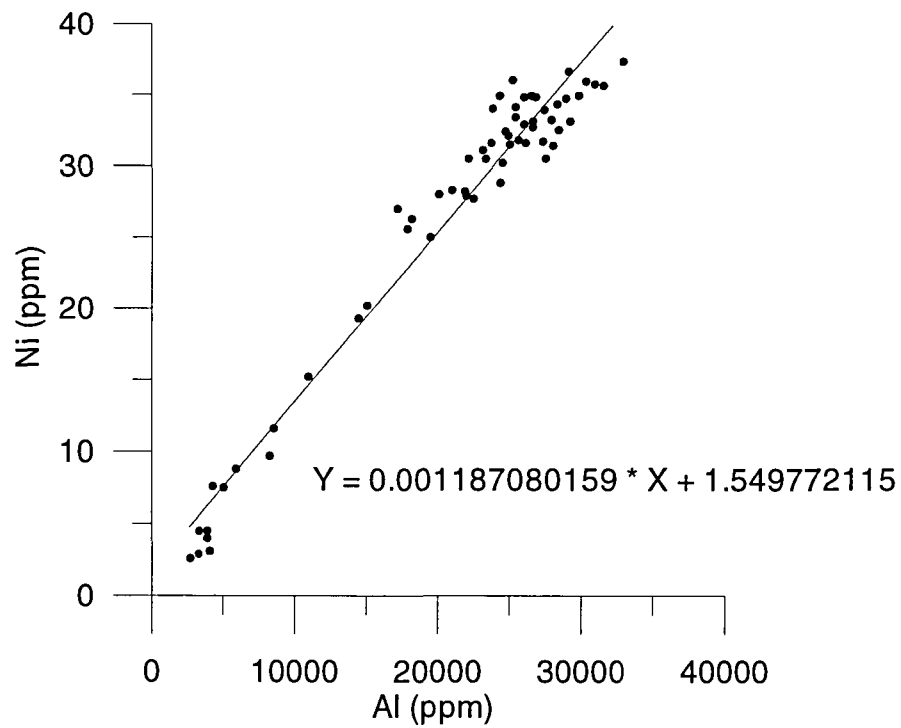


Fig. 19. Correlation diagram for Al and Ni in un-contaminated sub-surface sediments.

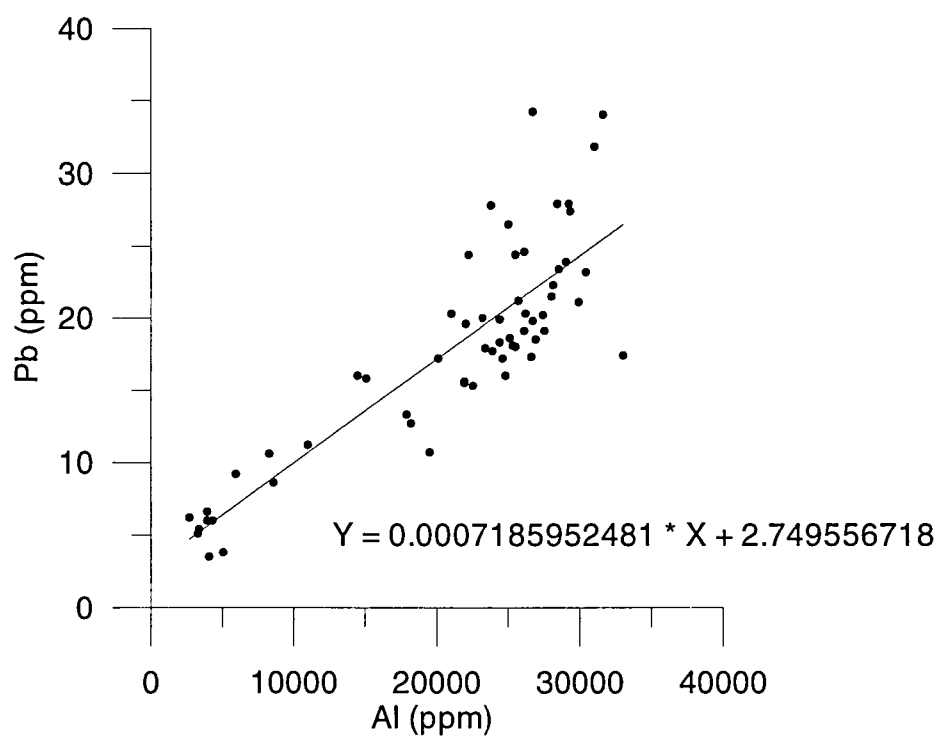


Fig. 20. Correlation diagram for Al and Pb in un-contaminated sub-surface sediments.

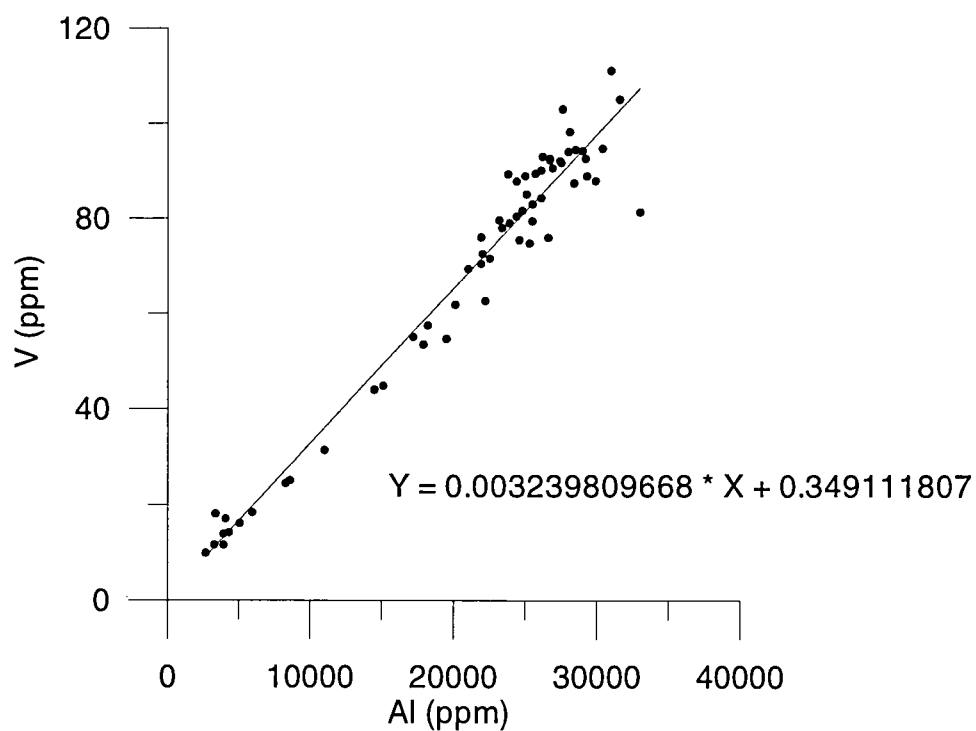
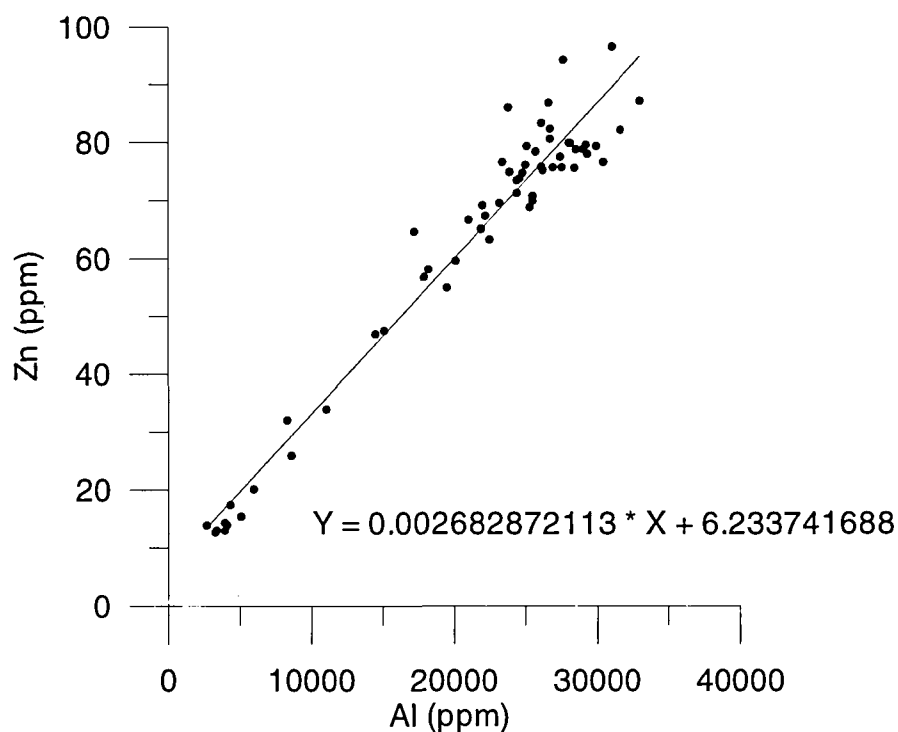


Fig. 21. Correlation diagram for Al and V in un-contaminated sub-surface sediments.



*Fig. 22. Correlation diagram for Al and Zn in un-contaminated sub-surface sediments.*

#### 4.2.2. Background concentrations of metals using subsurface sediments

The background concentrations of metal pollutants such as As, Cd and Hg cannot be estimated using reference element since their correlation with Al or with any of the other major elements is poorly defined in the subsurface sediments (Figs. 23-25). Still, the comparison of As, Cd and Hg contents in the surface sediments with sub-surface intervals allows the estimation of the recent environmental change at 63 stations for which there is stratigraphical data available. Concentrations of As, Cd and Hg in sub-surface intervals that reflect background abundances of these metals are shown in Figs. 4b, 12b, 13b. The data points in Figs. 4b, 12b, 13b show the metal abundances in the deepest analysed intervals.

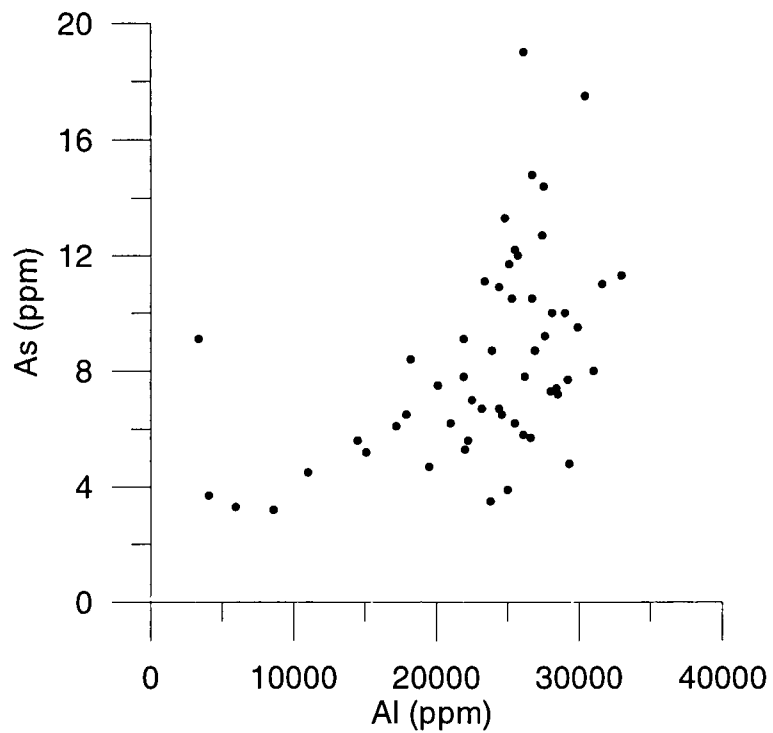


Fig. 23. Correlation diagram for Al and As in un-contaminated sub-surface sediments.

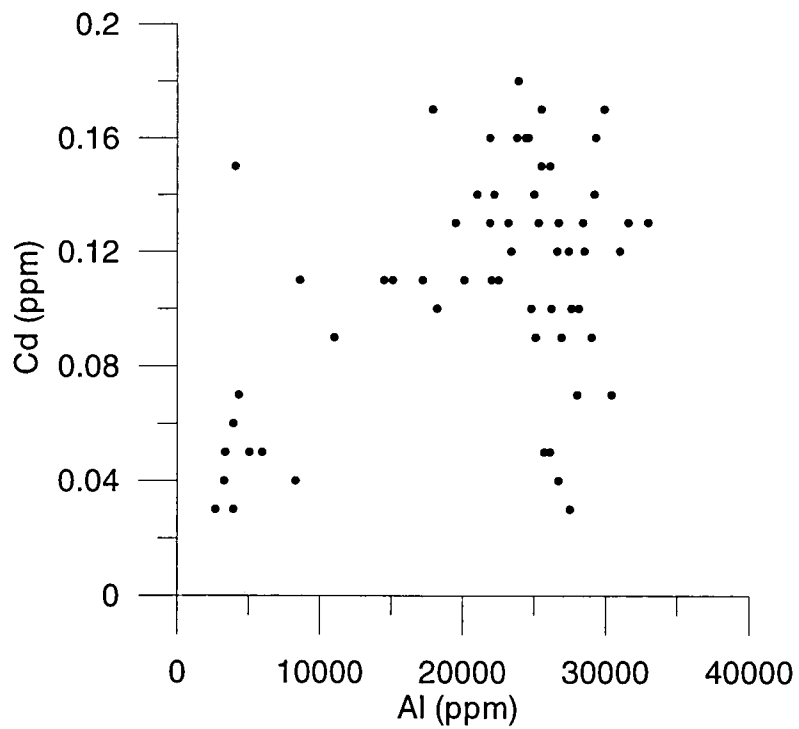


Fig. 24. Correlation diagram for Al and Cd in un-contaminated sub-surface sediments.



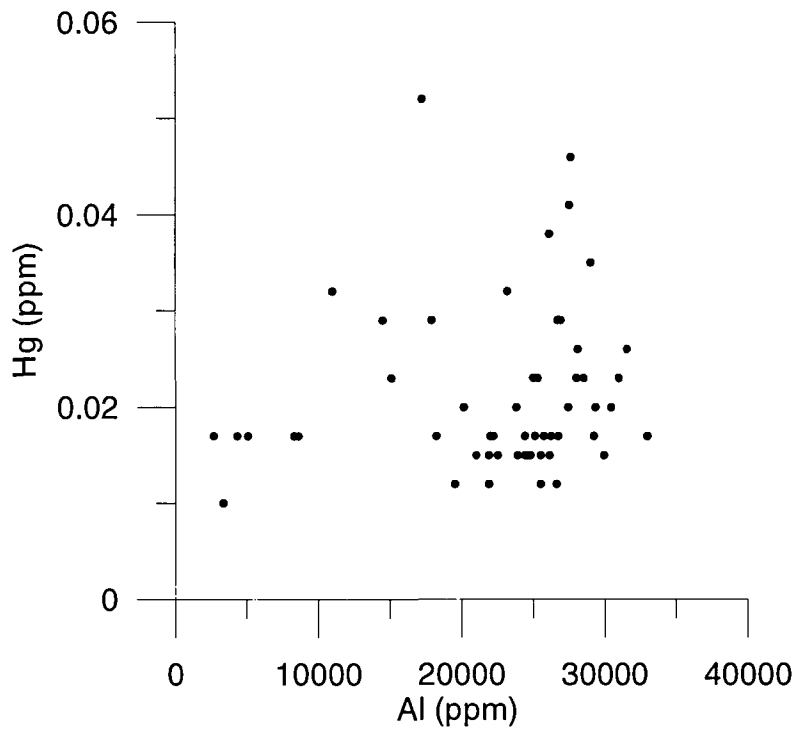


Fig. 25. Correlation diagram for Al and Hg in un-contaminated sub-surface sediments.

## 5. DISCUSSION – METAL CONTAMINATION IN THE SURFACE SEDIMENTS

The metal contamination of the surface sediments is illustrated with the aid of concentration-change maps (Figs. 4c-14c) that show the differences in % between the background and the measured metal concentrations at the surface. The concentration changes were calculated according to the following formula:

$$\text{Concentration change (\%)} = \frac{M_{surf}}{M_{back}} \times 100 - 100$$

where  $M_{surf}$  = metal concentration in the surface sediments, and  $M_{back}$  = metal concentration in the background. Note that  $M_{back}$  reflects concentrations in uncontaminated, sub-surface sediments in case of As, Cd and Hg while background values for Ba, Co, Cr, Cu, Ni, Pb, V and Zn were obtained using Al as reference element (see section 4.2.1.).

The concentration-change maps highlight the relative changes, and it is noteworthy that the areas with the highest relative change do not always overlap with the highest metal abundance

in the surface sediments (Fig. 8a vs. Fig. 8c). The open symbols in these diagrams represent a decrease in the metal abundance of the surface sample relative to background, whereas solid symbols reflect increase. The solid symbols are further divided into up to four, generally equal classes.

### **5.1. Arsenic, Cadmium, Cobalt, Chromium, Nickel**

Systematic geographical pattern and increasing values of As, Co, Cr, Ni and Cd in surface sediments towards the bottom of the Norskerenna (Figs. 4a; 5a; 6a; 9a; 12a) may give the wrong impression that contamination by these metals gradually increases with increasing water depth. Since the background values of As, Cr, Ni and Cd are largely within the same range as values for the surface sediments (Figs. 4c; 6c; 9c; 12c), there is no obvious reason to consider these metals as contaminants in the surface sediments. This generalisation applies also for Co in the southern part of the study area, but in the northern part the consistent increase in values (Fig. 5c) may hint at minor Co contamination from the Bokna fjord area. Strong geographic patterns of As, Cd, Co, Cr and Ni in surface sediments reflect textural and mineralogical variations in the study area and relatively high concentrations of these metals in the matrix (clay) minerals that are abundant in the bottom of the basin.

### **5.2. Copper, Vanadium, Zinc**

The results for Cu, V and Zn shown in Figures 7c 10c and 11c indicate < 50% increase for the content of these metals in the surface sediments throughout most of the study area. Although one has to be careful interpreting the environmental importance of these relatively small increases, the very consistent geographical patterns may suggest the possibility of minor Cu, V and Zn pollution in the Norskerenna. The cause of Cu, V and Zn pollution remains to be investigated – geographically uniform surface enrichments suggest effective dispersion of these pollutants and exclude specific point source within or in the immediate vicinity of the study area.

### 5.3. Mercury

Surface sediments in most of the stations show Hg concentrations above the background and more than half of the stations show increases of > 100% (Fig. 13c), indicating significant Hg contamination. However, the geographical pattern of Hg concentration change is rather irregular and does not allow tracking the source of Hg contamination. The disparity of the Hg surface abundance and the concentration change patterns (Fig. 13a vs. Fig. 13c) suggests that the systematic surface trends are most likely controlled by variations in the matrix mineralogy and do not reflect land-derived point contamination in southern Norway where the highest surface abundances occur.

### 5.4. Barium

Recent publications have shown that Ba enrichments in surface sediments of the eastern part of the Norskerenna reflect recent barite contamination (Thorsnes and Klungsøyr, 1997; Lepland et al., 2000). Since the onset of offshore hydrocarbon exploration in early 1970s, large quantities of barite have been released in the North Sea at drill sites where barite has been used as a principal component of the drilling mud. The dispersal of this "drilling barite" in the North Sea, and eastward transport of sediments by the oceanographic currents, are the likely explanation for the surface enrichment of Ba in the study area. The supply of Ba from easterly directions is also supported by the geographical patterns of surface sediment Ba abundances (Fig. 14a) and Ba concentration changes (Fig. 14b) that both show decreasing values from east to west.

Earlier studies (Sæther et al. 1996; Thorsnes and Klungsøyr, 1997; Lepland et al., 2000) have determined that the grain-size of the North Sea drilling barite is within the fine silt range. The strongest Ba enrichments occur in a band at about 200 m water depth on the western slope of the Norskerenna (Fig. 14c), and likely reflect hydrodynamic conditions, most suitable for accumulation of this fine silt size barite. Such barite has apparently been winnowed and bypassed in the shallower, high-energy sedimentary environments further up-slope where sandy sediments occur. Minor amounts of drilling barite have reached the bottom of the basin due to low current velocities, unable to transport fine silt size barite particles, in the deepest areas of the basin.

## 5.5. Lead

The strong enrichment of Pb contents in the surface sediments relative to the background values indicates significant recent contamination. Except for one, all stations in areas with water depth of >200 m exhibit concentration change of >100% (Fig. 8c). Highest contamination levels with concentration changes up to 150-200% were found in stations at the very bottom of the Norskerenna (Fig. 8c) where the finest sediments occur.

The Earth's atmosphere and surface have been contaminated by Pb due to ore processing since Greek and Roman times (Nriagu & Pacyna, 1988; Hong et al., 1994), and particularly during the middle decades of the last century when Pb was widely used as gasoline additive (Smith & Flegal, 1995). The re-distribution and deposition of atmospherically supplied Pb in the marine environment is largely dependent upon interaction of Pb with suspended particles. Scavenging of Pb onto surfaces of suspended organic matter and/or clay minerals is likely to aid removal of Pb from the water column. Significant Pb contamination levels can in such a case be found in areas where the preferred Pb substrates selectively accumulate.

The geographical pattern of Pb concentration change (increase) correlates generally well with Al and TOC variations (Figs. 2-3), suggesting that indeed dissolved Pb may have been scavenged and removed from the water column either by clay minerals or by organic matter. The relative importance of these two potential Pb substrates remains to be studied.

## 6. SUMMARY

The environmental state of the seabed in the north-western part of the Norskerenna has been assessed by studying the abundances of As, Ba, Cd, Co, Cr, Cu, Hg, Ni, Pb, V and Zn in 128 sediment cores. Concentrations of As, Cd, Cr and Ni in the surface sediments are generally within the same range as the natural background, indicating that these metals are not likely contaminants in the Norskerenna. Cu, V and Zn show slight enrichment (0-50%) in the surface sediments relative to the background, and are considered as minor contaminants (Table 3). This minor contamination by Cu, V and Zn is consistently seen in the deeper parts (> 200 m) of the Norskerenna. Co appears to be a minor contaminant in the northern part of

the study area, but not in the south. Ba, Hg and Pb are the most significant metal contaminants in the Norskeranna (Table 3); their concentrations in the surface sediments are typically 50-200 % above background values.

**TABLE 3. Estimates of relative metal contamination in surface sediments: - no contamination; +/- minor contamination in specific areas; + minor contamination; ++ significant contamination**

Metal	Contamination level
As	-
Ba	++
Cd	-
Co	+/-
Cr	-
Cu	+
Hg	++
Ni	-
Pb	++
V	+
Zn	+

The contamination levels of most metals are generally low in areas with sandy sediments along the south-western margin of the study area, and increase towards the bottom of the Norskerenna where Al- and TOC-rich fine-grained sediments accumulate. This indicates that fine-grained clay and/or organic particles are the principal scavengers and carriers of metal contaminants. Ba is the only metal whose contamination is not controlled by the distribution of the fine-grained sediments. The highest Ba contamination at the south-western slope of the Norskerenna, reflect recent supply of fine silt size barite from the off-shore oil exploration sites where barite is used as a component in drilling mud.

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