Recent bottom sediments in Agfardlikavsâ and Qaumarujuk fiords near Mârmorilik, West Greenland

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As part of an environmental background sampling program, carried out prior to the disposal of tailings from the lead-zinc concentration plant at Mârmorilik into Agfardlikavsâ, the recent bottom sediments of the fiord system around the township have been subjected to detailed analysis as to grain size distribution, mineral content and the distribution of certain trace elements.
Meltwater streams from the nearby Inland Ice margin and from local glaciers carry finegrained primary mineral detritus into the adjacent fiords, in three different depositional environments. The bottom sediments can be correlated to the surrounding bedrock.
The distribution pattern of a number of trace elements in the bottom sediments is partly related to their mineral content, partly to selective sorption processes which take place in the marine environment.

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Exploitation of the lead-zinc deposit "Sorte Engel" near Mârmorilik in West Greenland, was preceded by environmental studies before final permission was granted to deposit the tailings of the concentration plant in Agfardlikavsâ fiord. As part of these studies, samples of recent bottom sediments in the fiord region around the site were subjected to detailed analysis, fig. 1 and 2, and table 1.

The ore deposit occurs in the Mârmorilik Formation of the Rinkian mobile belt of Archean age, as described by Henderson and Pulvertaft (1967) and by Escher and Pulvertaft (1976). However, recently the Mârmorilik Formation has been recognized as, most likely, being of possible early Proterozoic age, according to Garde and Pulvertaft (1976), with a minimum age of 1.7 b.y.

The Mârmorilik Formation is a major carbonate rock sequence in the Precambrian of West Greenland, otherwise dominated by gneiss, regionally called Umanak gneisses, fig. 1. Dolomite and calcite marble form the upper section of the formation, while other metasediments such as graphite schists, quartzites and semipelites are found in the lower parts, bordering the regional gneisses. The ore bodies occur about midway up the sedimentary column, concordant with the marbles. The formation has been subjected to intense internal folding and recrystallisation.

The fiord system in the area is branched, as can be seen in figure 1, which also shows schematically some of the geological features mentioned above. Of interest for this study is to note that the area around Mârmorilik is intersected by two fiords: Agfardlikavsâ, discharging into Qaumarujuk, which in turn is the extension of a branch of Perdlerfiup Kangerdlua. Extensive bottom sampling has been restricted to Agfardlikavsâ and Qaumarujuk, while a single sample has been taken on the northeastern steep slope of Perdlerfiup Kangerdlua.

The environmental study was particularly concerned with the distribution of certain heavy metal trace elements in the aquatic environment. In consequence the distribution of trace elements in the bottom sediments has been determined for Zn, Pb, Ni, Cu, As, Ag and Cd only.

Results of the environmental studies and follow-up inspection, with particular reference to the possible effects of tailings disposal in Agfardlikavsâ, have been briefly summarized by Bondam and Asmund (1974), Asmund (1975), Bollingberg (1975) and by Asmund, Bollingberg and Bondam (1976). Additionally comprehensive annual reports on the environmental impact of mining are published in Danish. These also contain analytical data on the water regime and biological samples, and data on the dissemination of waste products

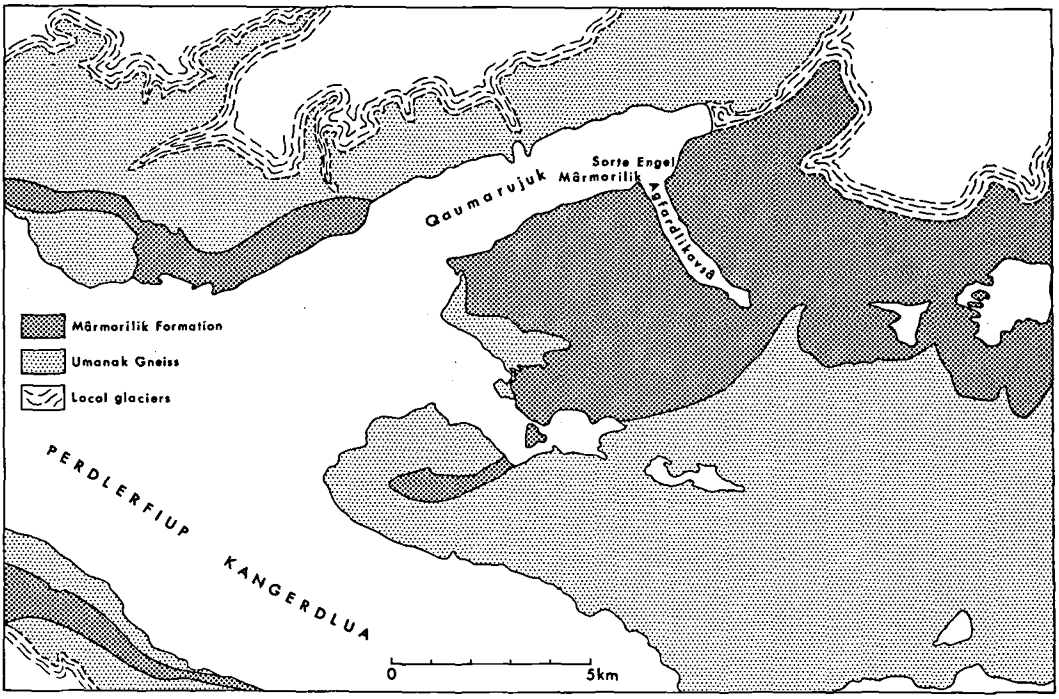

Fig. 1. Sketch-map of the fiord system around Mârmorilik, with the main geological units indicated.

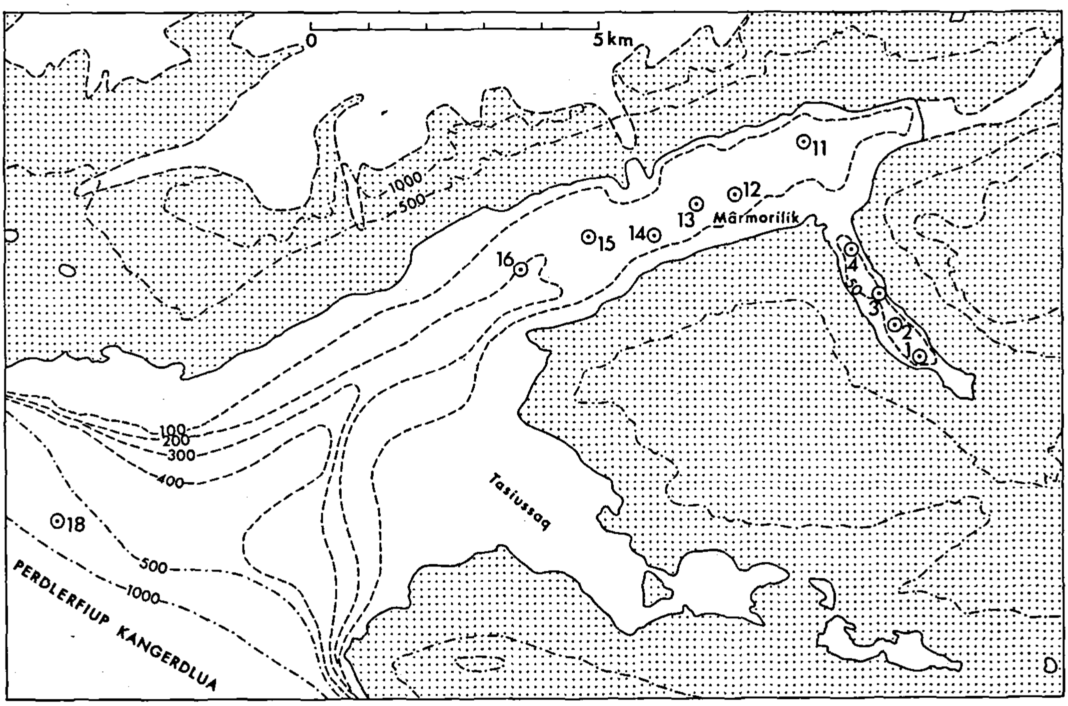

Fig. 2. Bathymetric sketch-map of the fiord system around Mârmorilik. Depth contours in metres. The numbered sampling stations are indicated.

in the bottom sediments. So far five annual reports have been published under the common heading "Recipientundersøgelse, Agfardlikavsâ, Qaumarujuk", for the years 1972, 73, 74, 75–76, 76–77.

Bohn (1975) studied the arsenic content in marine organisms from the area.

Sampling and methods

A bathymetric sketch-map of the fiords adjacent to Mârmorilik, with the sample localities indicated, is given in figure 2. The geographical positions of the stations and their water depths are listed in table 1.

Table 1. Geopraphical positions of the sampling stations in the fiord region around Mârmorilik.

Station number	Position	Depth in metres
1	71°06.'4 N/51°14.'0 W	55
2	71°0..'7 N/51°14.'8 W	54
3	71°07.'0 N/51°15.'0 W	72
4	71°07.'4 N/51°16.'0 W	70
11	71°08.'4 N/51°17.'4 W	202
12	71°07.'9 N/51°19.'3 W	180
13	71°07.'8 N/51°20.'4 W	202
14	71°07.'5 N/51°21.'6 W	204
15	71°07.'5 N/51°23.'4 W	222
16	71°07.'2 N/51°25.'3 W	205
18	71°04.'9 N/51°38.'5 W	860

The bottom samples were collected with a tube corer, internal diameter 35 mm, from the Greenland Fisheries Research vessel "Adolf Jensen". The core length was about 50 cm, in most cases. Sampling for environmental inspection was carried out with a triangular bottom sampler for obtaining three parallel samples at each locality. The internal tube diameter is also 35 mm, but core length is only about 10 cm. After splitting the core, which was kept frozen during the subsequent handling, encased in the acrylic plastic core barrel, samples were taken out by transverse slicing at predetermined interval over varying core lengths in order to avoid possible seasonal variations in the composition of the bottom muds.

The content of lead and zinc was determined by means of atomic absorption spectrometry, analyst J. Kystol, while the other trace elements were determined with the optical spectrograph, analyst H. Bollingberg. Particle size distribution was measured by gravity sinking in a water column at 18°C. The carbonate content of the bottom samples was determined by cold extration with 20 per cent hydrocloric acid in a sealed vessel, according to the method described by Müller and Gastner (1971).

The bottom sediments

The bottom sediments of the fiord system around Mârmorilik are greygreen silty muds, characterized by the lack of clay minerals, which is a feature commonly observed in recent sediments in Greenland (Heling, 1976) or other sub-arctic environments, like Glacier Bay, Alaska (O'Brien and Burrell, 1970).

The fiord system itself features three different geological settings: Agfardlikavsâ with moderate water depth from 55 to 74 m, is wholly surrounded by carbonate rock cliffs, separated by a treshold at 21 m below sea level from Qaumarujuk, which constitutes the second sedimentary environment. The bottom of this fiord is generally rather flat with an average waterdepth of 186 m, having a number of minor depressions at between 209 and 249 m depth and a few mounds at about 90 m below sea level. To the south Qaumarujuk is bordered by carbonate rock, to the north by gneisses. Finally, the outer, western part of the fiord system is a separate environment, having a narrow, sloping bottom. Where merging with Perdlerfiup Kangerdlua, the waterdepth is around 1100 m. The adjacent rocks are mainly gneiss, with a subordinate layer of marble limestone along its northern margin.

The clastic material accumulated on the bottom of the fiords clearly reflects these different physical environments, as wil be discussed in the following sections dealing with the particle size distributions, the mineral assemblages and the distribution of certain trace elements.

Particle size distribution

The bottom sediments consist of locally derived, unweathered rock debris, transported to the fiords by meltwater streams from the nearby situated margin of the Inland Ice, and from the local glaciers at high altitudes, on land. The range of the particle size distribution in all the samples

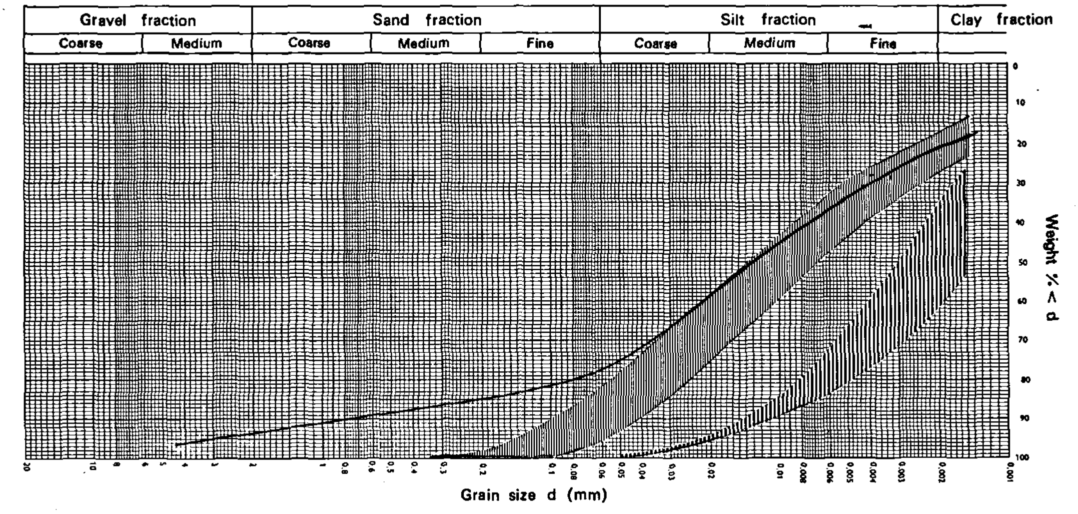

Fig. 3. The range of particle size distribution of the bottom sediments of Agfardlikavså, Qaumarujuk and station 18, as cumulative curves on a logarithmic scale.

collected in the three different environments is reflected in figure 3, which shows that the bottom sediment of Agfardlikavsâ is a rather well-sorted, finegrained, silty mud. The amount of coarser material is augmenting in the bottom sediment of Qaumarujuk, in which the contribution of the grain sizes above 0.06 mm is mainly derived from the non-calcareous surrounding rocks, which contain more abrasive silicates and quartz. The sorting is becoming less pronounced, a feature which is prominent for the bottom sediments of the outer part of the fiord system, where gravel-sized rock fragments make up about 5 weight per cent of the sample.

Table. 2. Carbonate content in weight %, determined as calcite by cold extraction with diluted hydrochloric acid in a sealed vessel.

	station	$\bar{x}$	range	s
Agfardlikavsâ	......	76.3	68.5–82.5	5.4
	1	82.0		
	2	80.8		
	3	77.0		
	4	69.2		
Qaumarujuk	......	23.9	15.0–44.5	8.8
	11	26.2		
	12	24.3		
	13	22.5		
	15	18.0		
	16	24.7		
	18	13.0		

$\bar{x}$ = arithmetic mean
s = standard deviation

The carbonate content

A main indicator for the source of the rock debris in the bottom sediments is the content of carbonates.

Table 2 shows the content of easily soluble carbonates only, as determined by cold extraction with diluted hydrocloric acid in a sealed vessel, and recalculated as calcite. Chemical analysis of a restricted number (8) of samples reveals that the carbonate phase is dolomitic in composition. Recalculation according to the chemical analyses gives the following mean composition of the carbonates:

Agfardlikavsâ	$Mg_{1.12}Ca_{0.88}(CO_3)_2$
Qaumarujuk	$Mg_{1.15}Ca_{0.85}(CO_3)_2$
Station 18	$Mg_{1.18}Ca_{0.82}(CO_3)_2$

The slight increasement of magnesium over calcium may be contributed to magnesium uptake from sea water. It is lowest where fresh water from meltwater streams enter the fiords system.

The mineral composition

As could be expected, the bottom sediment of Agfardlikavsâ consists nearly exclusively of dolomitic carbonates, even in the size fraction below 2 μm, as confirmed by X-ray diffraction. The amount of usually more coarsegrained silicates and quartz, derived from semipelitic rocks, quartzites, schists and gneiss, is rather subordinate.

The finegrained size fraction below 6 μm of the bottom sediment of Qaumarujuk is likewise composed of carbonate minerals mainly. Above the grain size of 10 μm, silicates and quartz become the dominant minerals, together with appreciable amounts of magnetite. The assemblage of silicate minerals in the bottom samples reflects the mineral composition of the surrounding bedrock, especially in the outer part of the fiord system, where common minerals like mica, hornblende, feldspars and quartz make up the bulk. The relative amount of micas is noteably less in the outer part of the fiord as compared to the inner part, while the content of rock fragments is augmenting in the outer part. Again, the carbonate minerals are largely present in the size fraction below 6 μm in the samples from station 18.

Trace elements

The distribution of certain trace elements has been determined in the bottom sediment samples in conjunction with the environmental studies. A number of these elements are supposed to be derived from the sulphidic ore minerals which are found in the dolomitic limestones.

The suphides of the Mârmorilik Formation are pyrite, sphalerite and galena, predominantly found in ore shoots and ore bodies, though frequently occurring dessiminated in the marbles. Chalcopyrite is virtually absent in the know ores. The cadmium to zinc ratio of the sphalerite is approximately 0.006. The ore, moreover, contains some tennantite, which is reflected by the arsenic and silver content of the ore, averaging 120 ppm As and 22 ppm Ag respectively.

The distribution of lead, zinc, copper, nickel, arsenic, silver and cadmium, together with the iron content of the bottom sediments, is summarized in table 3 for all the analyzed samples

Table 3. The content of some trace elements in the recent bottom sediments of the fiords around Mârmorilik, in ppm.

	Agfardlikavsâ				Qaumarujuk				St. 18	
ppm	range	$\bar{x}$	s	n	range	$\bar{x}$	s	n	$\bar{x}$	n
Zn	156–233	205	20	29	122–159	138	12	26	75	3
Pb	14–33	25	5	19	17–37	27	6	19	29	3
Ni	45–78	59	9	23	35–60	52	6	20	54	3
Cu	27–46	37	6.5	23	23–41	33	7.5	20	22	3
As						9.3		1		
Ag	0.8–2.3	1.2	0.4	19	0.9–2.0	1.2	0.4	20	1.0	3
Cd	1.4–1.5	1.4		6	0.9–1.0	0.9		4		
% Fe	2.25–3.90	3.15	0.50	19	1.40–3.20	2.55	0.35	22	2.15	3

$\bar{x}$ = arithmetic mean
s = standard deviation
n = number of samples

within 50 cm depth from the bottom surface. The analytical results have been grouped according to the previously, physically established environments. Figure 4 shows the vertical distribution of the zinc content only at each sampling site in the different parts of the fiord system. Figure 5 shows the vertical distribution of copper, nickel and zinc in the upper layers of the bottom sediment of Agfardlikavsâ, in order to demonstrate the rather close relationship between the distribution of copper and nickel as compared to zinc.

The same distribution pattern is found in the other two fiord regimes, although the level of the zinc content is gradually becoming lower towards the outer part of Qaumarujuk, while the content of copper and nickel remains about the same.

Figures 4 and 5 illustrate the differences between some of the trace elements with respect to their proportional relationship as to the solid components of the sediments. A similar kind of selectivity as to the solid phase has been studied in recent freshwater sediments, as reviewed by Förstner (1977). It has been noticed by subsequent environmental site inspection, that the remaining sulphides from the tailings of the concentration plant at Mârmorilik are rather soluble in sea water. For instance, it has been demonstrated (Asmund in Recipient-undersøgelse 1974, Agfardlikavsâ, Qaumarujuk), that a maximum concentration of 1215 ppb of ionic Pb^{2+} can be reached by dissolving galena in sea water containing 884 ppm S, 0.535M Cl^- and 11.2 mg O_2/l, as in the actual case at Mârmorilik. The measured concentrations of dissolved lead in sea water above the disposed tailings are around 1100 ppb.

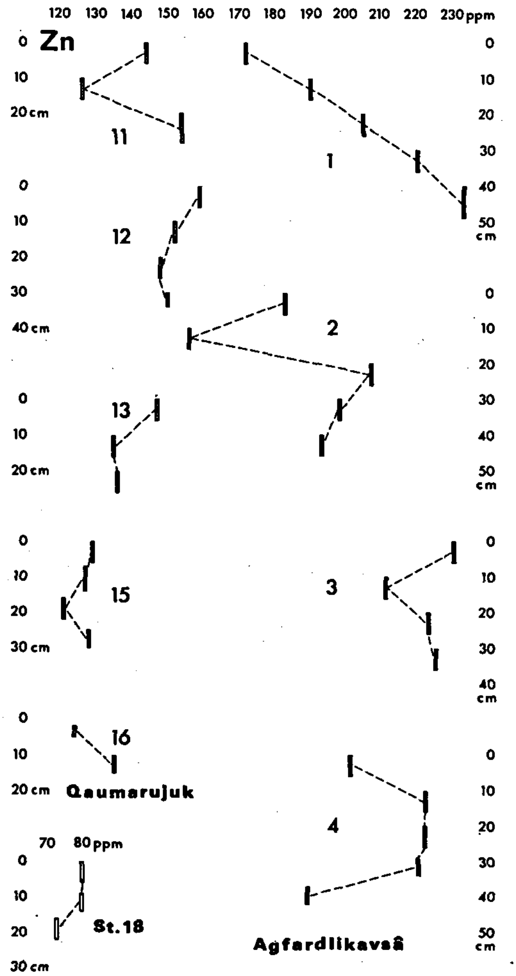

Fig. 4. *The vertical distribution of zinc in the bottom sediments of Agfardlikavsâ, Qaumarujuk and station 18, in ppm. The numbers refer to the sampling stations.*

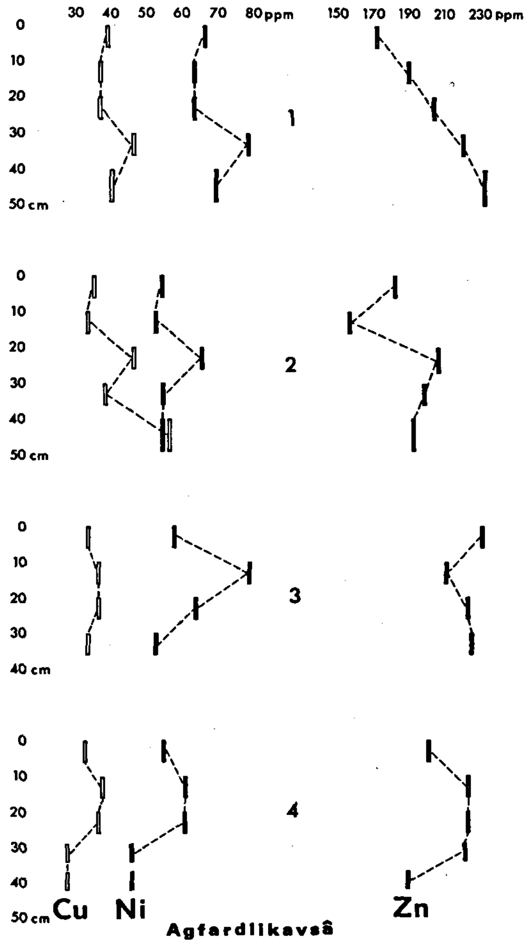

Fig. 5. *The vertical distribution of copper, nickel and zinc in the bottom sediments of Agfardlikavsâ, in ppm. The numbers refer to the sampling station.*

Regarding the very fine grain size of the accumulated bottom sediments in Agfardlikavsâ, it seems likely that substantial dissolution of transported sulphides has taken place upon entering sea water, after which preferential chemical sorption of ionic species by mineral components has taken place, thereby influencing the distribution pattern of the trace elements in question. This is evidently the case for lead and zinc, which in the known occurences are found in a ratio of 1:3 respectively. In the bottom sediments of Agfardlikavsâ this ratio is approximately 1:9, in Qaumarujuk it is 1:5 and at station 18 again 1:3. Zinc is easily adsorbed on or co-precipitated with carbonate matter, as has been repeatedly demonstrated in fresh water environments, as reviewed by Förstner (1977), while lead is mainly adsorbed to the hydroxylated solid phase of the sediment, according to the same author.

Apparently it does not seem to be decisive whether the carbonates are detrital or not, and whether the conditions are saline or not, for zinc to be adsorbed. From table 3 it can be deduced that there is a linear correlation between the zinc and the calcite content of the bottom sediments in the three different environments of the fiord system, being calculated for 18 samples as $\varrho = 0.8133$.

Table 4. Correlation coefficent for copper, nickel, lead and zinc in Qaumarujuk (Q) and Agfardlikavså (A). Confidence limit 95%.

	Cu	Ni	Pb	Zn	
Q	-	0.47	-0.12	-0.07	Cu
A	-	0.73	-0.17	-0.13	
Q		-	-0.17	-0.24	Ni
A		-	-0.17	-0.22	
Q			-	0.18	Pb
A			-	0.09	

Correlation coefficients with a confidence limit of 95% for the trace elements copper, nickel, lead and zinc are listed in stable 4. The table shows that copper and nickel are associated in the bottom sediments of both Agfardlikavså and Qaumarujuk, presumably present in a state of chemical equilibrium with the oxidizing saline conditions, which seems also to be the case for lead and silver, as the level of content remains the same, irrespective of the amount of carbonates in the sediment. The silver content is persistently rather high.

Conclusions

Comparable coastal bottom sediments, consisting of locally derived detrital carbonates and silicates, together with quartz, which have been transported over a comparatively short distance from the source, are presumably restricted to the fiord regions of the northern hemisphere, where subarctic conditions prevail.

There are no detectable signs of chemical weathering, nor do the sediments contain a clay mineral component, or measurable amounts of organic matter. It is assumed that the trace elements contained in the finegrained detrital minerals, rather rapidly reach a state of chemical equilibrium upon deposition in the sea, in dependence on the saline conditions mainly, unless chemisorption is feasible, as is the case for zinc.

Dansk sammendrag

Som et led i en beskrivelse af den naturlige miljøbaggrund i fjordsystemet omkring Mårmorilik, forud for deponering af fast affald fra flotationsværket ved bly-zink minen »Sorte Engel«, i Agfardlikavså, blev prøver af bundaflejringerne i Agfardlikavså og Qaumarujuk underkastet en analyse af kornstørrelsesfordelingen, mineralsammensætningen og fordelingen af et antal sporelementer.

Smeltevandet fra Indlandsisens nærtbeliggende grænsezone, og fra lokale gletschere fører finkornet materiale, bestående af uomdannede mineraler, fra land ind i tre adskilte sedimentære omgivelser. Bundaflejringerne afspejler de omgivende bjergarters mineralsammensætning.

Fordelingsmønstret af et antal sporelementer i bundaflejringerne står i relation dels til mineralindholdet, dels til selektive chemosorptionsprocesser i det marine miljø.

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