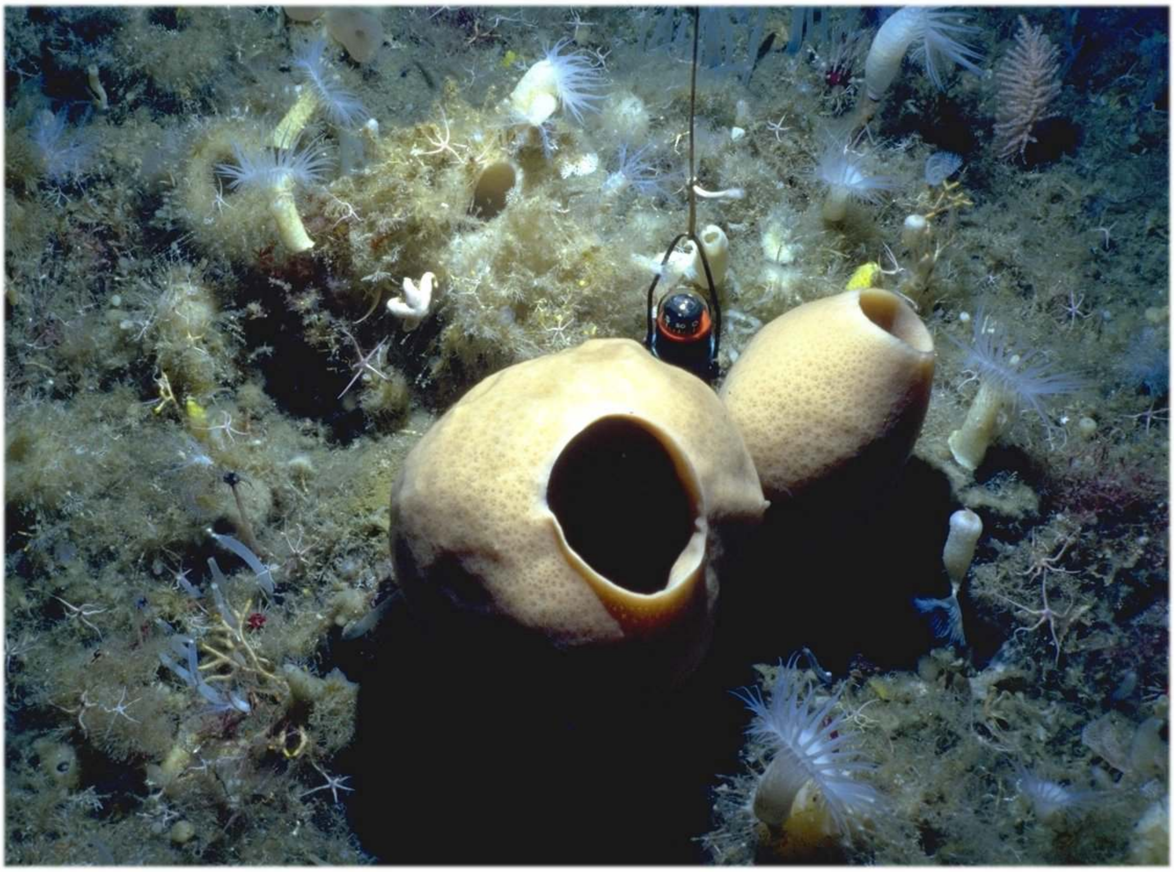
MARINE GEOLOGY OF THE CONTINENTAL SHELF OFF THE RIISER-LARSEN ICE SHELF, EASTERN WEDDELL SEA, ANTARCTICA

BY

Boris Winterhalter, Aarno Kotilainen, Ingemar Cato, Bernt Kjellin, Martin Jakobsson and Yngve Kristoffersen[1]



[1] The affiliation of the authors is given in the appendix 3

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BACKGROUND AND GOALS

The tasks set forth by the marine geological team (see appendix 3) on board the r/v Aranda, were to include detailed acoustic and seismic profiling, sediment surface sampling and diamond core drilling. The work was to be conducted in a limited shelf locality as a continuation of work conducted during the previous Finnarp expedition in 1989/90 and during some of the earlier Norwegian NARE expeditions off the Riiser Larsen Ice Shelf, eastern Weddell Sea.

The scientific goals were two-fold: firstly, a detailed morphological and surface geological map of the shelf utilizing the Datasonics, SIS 1000 chirp side scan sonar, EG&G, X-star chirp sub-bottom profiler, and secondly, a stratigraphic study making use of single channel seismic reflection profiling (sleeve gun array) and sediment sampling by shallow diamond drilling into the topmost 50 metres. The latter task was to be accomplished with a land prospecting wireline drilling rig mounted on the stern of r/v Aranda for drilling into expected over-consolidated diamicton for establishing a geological record of the glacial history of the region.

CONDITIONS

As anticipated during the planning of the cruise, actual success of the endeavour in the planned working area would be governed by ice-conditions. Unfortunately the entire length of the southeastern continental shelf of the Weddell Sea was blocked by a wide zone of fractured sea ice. Aranda was, with some difficulty, able to find its way through this ice barrier and reach the rather ice free polynya of the planned study area. The Rampen Bay, on the west side of Kvitkuven Ice Rise, was also partly free of winter ice, but the active ice-edge and the icebergs drifting in the area ice were considered as a continuous threat to the safety of the ship. Both profiling and drilling had to be aborted during many occasions, leading to a considerable loss in active working time.

PRELIMINARY RESULTS

In addition to data collection, some of the data handling and interpretation was conducted during the cruise itself. Upon return from the cruise and the arrival of the ship to home port, the collected material was subjected to laboratory analysis and interpretation. Much of this work is still going on.

Echo-sounding

The shipboard Deso 25 echo-sounder (15 kHz) was run continuously during transit from Cape Town to the Weddell Sea and back. Echo-sounding was also conducted during all the phases of seismic and acoustic profiling integrated with continuous positioning. In addition recordings were also made while lying tied up to the land fast ice for drilling in lee of the Kvitkuven Ice Rise.

These recordings gave a good indication of the magnitude of the tide (2.2 m) during 15-16 February, 1996. The shipboard acoustic doppler current profiler (ADCP) was used to monitor current direction and velocity. The detailed results will be published later.

During echo-sounding, positioning was logged either once every minute or once every 5 minutes, as deemed appropriate, using the integrated navigation system on board (multi-channel and multi-receiver GPS-system, Doppler Log, etc. Positioning information for the sonar and seismic reflection profiling was provided by a separate Magnavox MX200 6 channel GPS receiver. The WGS-84 datum was employed in all positioning.

Sounding data submitted to NGDC

Echo-sounding data acquired with the Krupp-Atlas Deso 25 echo-sounder on board the r/v Aranda en route from Capetown to the eastern Weddell Sea and back to Capetown has been submitted to the National Geophysical Data Centre in Boulder, Colorado, USA. The contribution was duly acknowledged by Tom Niichel, LCDR/NOAA, Manager of the Bathymetric Data Acquisition Program.

Due to poor S/N ratio in the received deep water echoes, the automatically digitized data gave unreliable readings. Therefore the bathymetric datafile delivered to NGDC was compiled manually. The depth was read off the echograms for each 1 minute of recording time. The actual distance between consecutive readings varied with ship speed. However, average ship speed of 10 knots was maintained throughout most of the survey, except during night time in growler infested waters or during extremely bad weather. The reading accuracy was dependent on water depth and the scale of the echogram while the echo-sounder accuracy itself was stated by the manufacturer to be within 1 m/s. The recorder range and scale (phasing) were set to suit the water depth. All readings in the submitted data file were corrected to the standard velocity of 1500 m/s.

The sounding data is stored at NGDC as two way travel time to 1/10,000 of a second, based on the 1500 m/s sound velocity. In this way, the end users of the bathymetric data are able to apply what ever correction table they choose.

Bathymetry and sea-floor morphology of the study area

Echo-sounding and acoustic data was initially analysed on board and a preliminary bathymetric map was constructed. The echo-sounding recordings in the study area were digitized with continuous position fixes. The digitized depth values corrected for the average speed of sound (1450 m/s) on the shelf during the survey as established by CTD-soundings, were plotted and contours drawn both by hand and by computer. Bathymetric data collected during previous cruises in the area could be utilized only with considerable difficulty due to unreliable positioning (prior to continuous GPS coverage).

The target area exhibits a variable topography, with the seaward extension of the shoal forming the Kvitkuven Ice Rise on one hand and the shelf break, leading into deeper water, on the other. In the intervening shelf area glacial deposition, iceberg scouring, and marine erosion have led to a rather irregular topography. One of the most marked features is a valley-like depression running mid shelf parallel with an assumed older extent of the ice-shelf. It is most probably an erosional channel formed by tidal currents near the grounding line of a more seaward position of the ice margin. The possible role of slumping of the prograded sediments can not be excluded.

The final bathymetric and morphological maps are being prepared as a joint task between SGU and GSF. The automatically digitized echo-sounding data is currently being verified with the actual echograms to minimize possible inclusion of spurious depth values in the final bathymetric map. The morphological map of the study area will be based on the combined information gathered from the echograms, sonograms (side scan sonar recordings), sea bed photographs and sediment samples.

Underwater observations

For detailed video observations of small scale sea floor features at the Rampen Bay site, a Benthos Mini-Rover II, remotely operated vehicle (ROV) was employed. An automatic sea floor camera (Photosea) utilizing standard 35 mm film, both in colour and black and white, was used at 12 stations. A set of these slides and black and white photographs have been scanned and stored on CD-ROM as JPEG-format images.

Figure 1. Abundance of various sponges, sea anemones, sea urchins, holothurians, and brittle stars completely cover the diamicton underneath. The camera trigger weight in the upper centre of the photo has a diameter of 50 mm. The site was located on the submarine extension of the bedrock elevation under the Kvitkuven Ice Rise. The water depth at the site was 156 m.

The seabed photo stations were primarily chosen to help in the interpretation of the side scan sonar imagery. In addition to information on the texture of the seabed, the photos also revealed a great diversity in benthic macro fauna. In the photos taken from the rather shallow (150-160 m) submarine extension of the elevated bedrock formation under the Kvitkuven Ice Rise, the abundance of sessile bottom animals was astonishing, in fact they completely covered the sea bed itself from view.

Sites that were considered to be riddled with iceberg scours (deduced from the side scan images) showed exposed diamicton with varying amounts of organic debris. It is probable that the re-colonisation of a sea floor tract obliterated by a ploughing iceberg is a rather rapid phenomenon. This assumption is based on the fact that sessile animals were seen in almost all pictures. However, on-site testing should be conducted to establish the rate of re-colonisation.

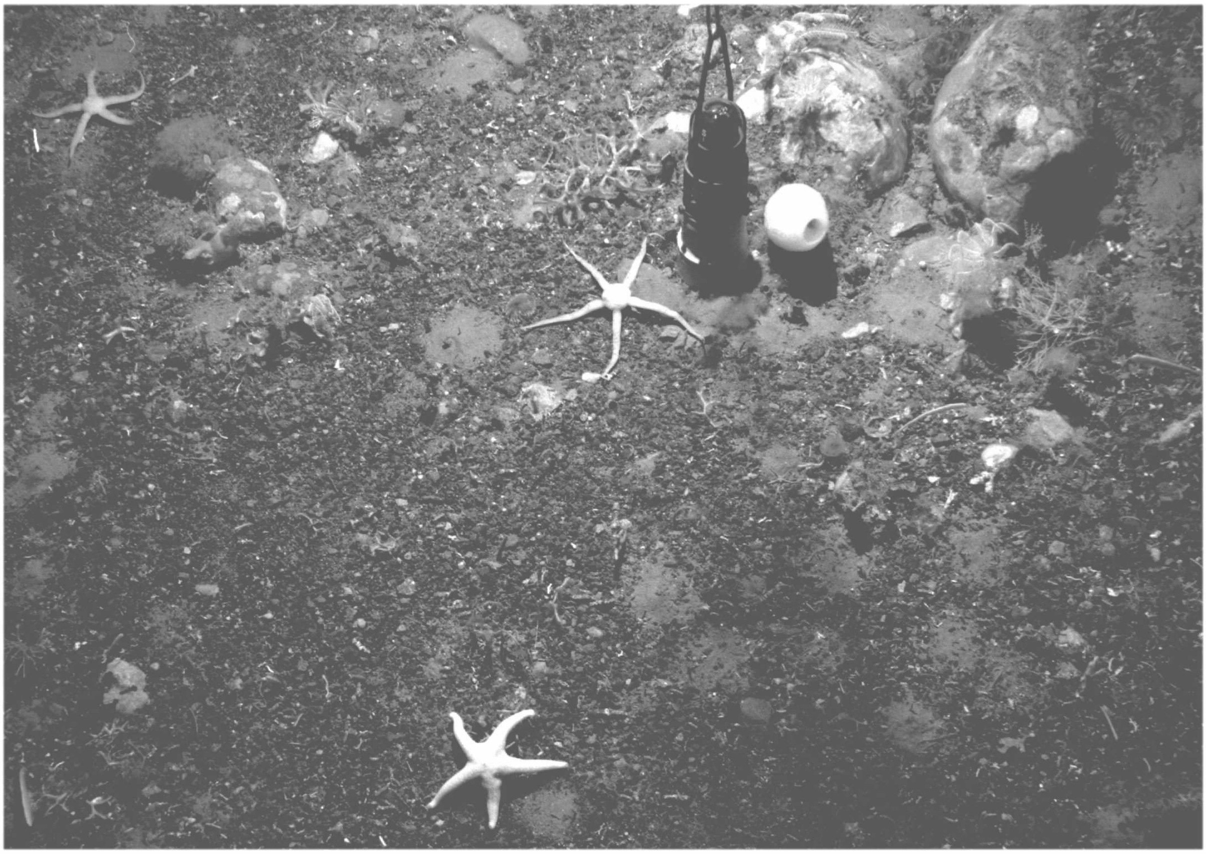

Figure 2. A photograph of the seabed in 234 m of water, a depth often frequented by icebergs. The area has been recently ploughed by an iceberg, leaving an abundance of organic debris partly covering the glacial marine sediments and ice-rafted boulders. Sessile animals, except for a sponge next to the camera trigger weight, have not yet colonized the area. Fast moving starfish are moving in.

Sediment sampling

Sea floor sediments were sampled at 21 stations using a small size (20 x 20 cm) box corer (modified Jonasson-Olausson type) and the Gemini, twin barrel, gravity corer (type Niemistö). The sediment material was photographed, described and sub-sampled for future laboratory analysis. The sediment samples have been analysed at the Geological Survey of Finland.

Of the sediment samples (incl. sub-samples) 18 were subjected to grain size determinations using a combination of sieving and Sedigraph measurements. The grainsize distribution (see Appendix 1) is typical of glacial marine sediments. The actual grainsize composition of the samples is obviously governed by secondary processes. Thus, in areas of significant current activity the fines are washed away and a residual sand or gravelly sand remains.

Table 1. Sea floor sediment samples taken from the Kvitkuven Shelf area. Table prepared by M.Jakobsson and A.Kotilainen.

Sample	Latitude, Longitude	Depth (m)	Bio Index	Sediment type - notes	
S2	72 14.95 S, 15 36.17 W	349	2	S-f.S	
S3	72 14.72 S, 15 35.31 W	363	2	S-f.S	
S4	72 15.44 S, 15 28.03 W	452	3	S-f.S	
S5	72 23.14 S, 16 46.87 W	330	4	Bio	
S6	72 23.11 S, 16 47.87 W	345	4	Bio	
S7	72 23.21 S, 16 48.92 W	358	4	Bio	90% biog. cover
S8	72 30.94 S, 16 32.00 W	213	3	S-f.S	
S9	72 28.84 S, 16 35.71 W	275	1-2	S	possibly ripple
S12	72 25.37 S, 16 38.70 W	287	3	f.S	
S13a	72 26.80 S, 16 27.49 W	150	4	Bio	
S13b	72 26.82 S, 16 27.60 W	150	4	Bio	Gemini core
S14a	72 23.50 S, 16 30.38 W	300	1	s.G	surface disturbed
S14b	72 23.50 S, 16 30.38 W	300	2	si.f.S	surface disturbed
S15	72 23.14 S, 16 31.77 W	322	4	Bio	
S16	72 21.87 S, 16 34.86 W	322	2	f.s.Si	
S17	72 21.20 S, 16 34.41 W	304	2	c.S/f.s.Si	
S18	72 21.59 S, 16 33.19 W	340	2	f.S	
S19	72 22.68 S, 16 26.49 W	318	1 ?	g.s.Si	surface disturbed
S20	72 23.307 S, 16 23.017 W	314	2-3	Di ?	
S21	72 25.41 S, 16 24.31 W	233	2-3 ?	s.G ?	
S22a	72 26.603 S, 16 25.194 W	157	4	Bio	
S22b	72 26.565 S, 16 25.677 W	157	4	Bio	Gemini core

Biogenic material (Bio-index): 1 = free from the biogenic material, 2 = a few biogenic fragments, 3 = partly covered by biogenic material, 4 = fully covered by biogenic material
Sediment description: Cl = clay, cl = clayey, Si = silt, si = silty, S = sand, s = sandy, G = gravel, g = gravely, S = stones, st = stony Di = diamicton, f = fine, c = coarse, m = medium, bio = biogenic, example: fine sandy silt ***.f.s.Si***, coarse sand ***c.S***

The sediment samples were sub-sampled for chemical analysis. Most of the 29 sub-samples were subjected to three different analytical procedures. Three different leaching methods were applied: 503 (nitric acid and microwave heating), 508 (hydrofluoric acid and perchloric acid digestion), 201 (a weak leach using ammonium acetate) to establish the solubility of the different elements, a means to establish “bio-availability”. The following elements were analysed using the analytical methods (ICP, ICP-MS, and ICP-AES) established at the GSF: Ag, Al, As, B, Ba, Be, Bi, Ca, Cd, Co, Cr, Cu, Fe, K, Li, Mg, Mn, Mo, Na, Ni, P, Pb, Rb, S, Sb, Sr, Th, Ti, Tl, U, V, and Zn. Some of the results are presented in Appendix 2.

Drilling

A drill site was chosen off Kvitkuven Ice Rise, in Rampen Bay, while the ship lay tied up to land fast sea ice. The drilling was based on the utilization of a 56 mm outer diameter riser, (B-wire line) and a 45 mm OD drill string to give a 35 mm dia. core sample. The riser was kept in place by a 1.3 ton bottom frame and tensioned at top with wire strung counter weights, together forming a passive heave compensator.

Sediment coring by diamond drilling was limited to one drilling station and a total recovery of abt. 3 metres of sandy sediments including 0.3 m of core through three basalt boulders. The two attempts at drilling were both terminated due to ice conditions endangering safety of the ship. The first one was aborted just before the riser reached the bottom and due to the hasty retrieval caused by the proximity of an iceberg led to the loss of a greater part of the riser. The second attempt was terminated due to the breaking up of the land fast sea ice to which Aranda was tied up.

During the second attempt 18 metres of sea bottom strata had been penetrated in 31 hours with the recovery of 3 metres of sediment. Unconsolidated sandy sediments had a tendency to flow into the drill string preventing the inner sampling tube to land and lock in place. This was the reason for the low recovery rate. The general concept of rotary wireline drilling of the type tested is considered feasible from a stationary vessel like Aranda (either in land fast ice or employing dynamic positioning) and may potentially bridge the gap between conventional gravity- or piston coring and a full blown drill ship operation. The core material has been studied by Dr. Kari Strand (cf. K. Strand & Y. Kristoffersen, in this progress report)

Sides scan sonar profiling

The Datasonics SIS 1000 chirp side scan sonar (SSS), operated by the Geological Survey of Sweden (SGU), was used to run a survey across the target area and a few additional profiles run east of the main study area. A sounding interval of 1 second was used, corresponding to a maximum swath width of 1450 metres (at a sound velocity of 1450 m/s). Raw data was stored in SEG-Y format on Exabyte tape during a total of 36 hours of survey time. The distance between parallel track lines was chosen to provide some degree of overlap. The total sonar coverage was approximately 300 sq.km. The sub-bottom profiler (2-10 kHz) was employed in parallel with the SSS to provide a vertical profile of the sea-bottom, although the penetration into the glacial marine sediments was very poor.

The side scan sonar images were preliminarily speed and slant range corrected on board and cut and pasted to form a mosaic covering most of the study area. The most pronounced sea floor features were the various iceberg scours crisscrossing the shelf generally at depths ranging between 250 and 350 metres. Scours deeper down along the shelf slope were probably of older origin denoting the former extent of the ice shelf at a lower sea level stand. Various iceberg grounding traces are also observed.

A side scan sonar profile was run close to the ice edge west of Rampen Bay. The ice shelf could be verified to be floating in 250 metres of water, and having a submerged thickness not exceeding 200 m. Sediment (sand) ripples with wave length in the 5 to 10 metre range could also be observed in areas of lesser water depth close to the ice front. A closer scrutiny of the SSS-mosaic superimposed on bathymetric data will give further details on the processes to be observed on a glaciated Antarctic shelf.

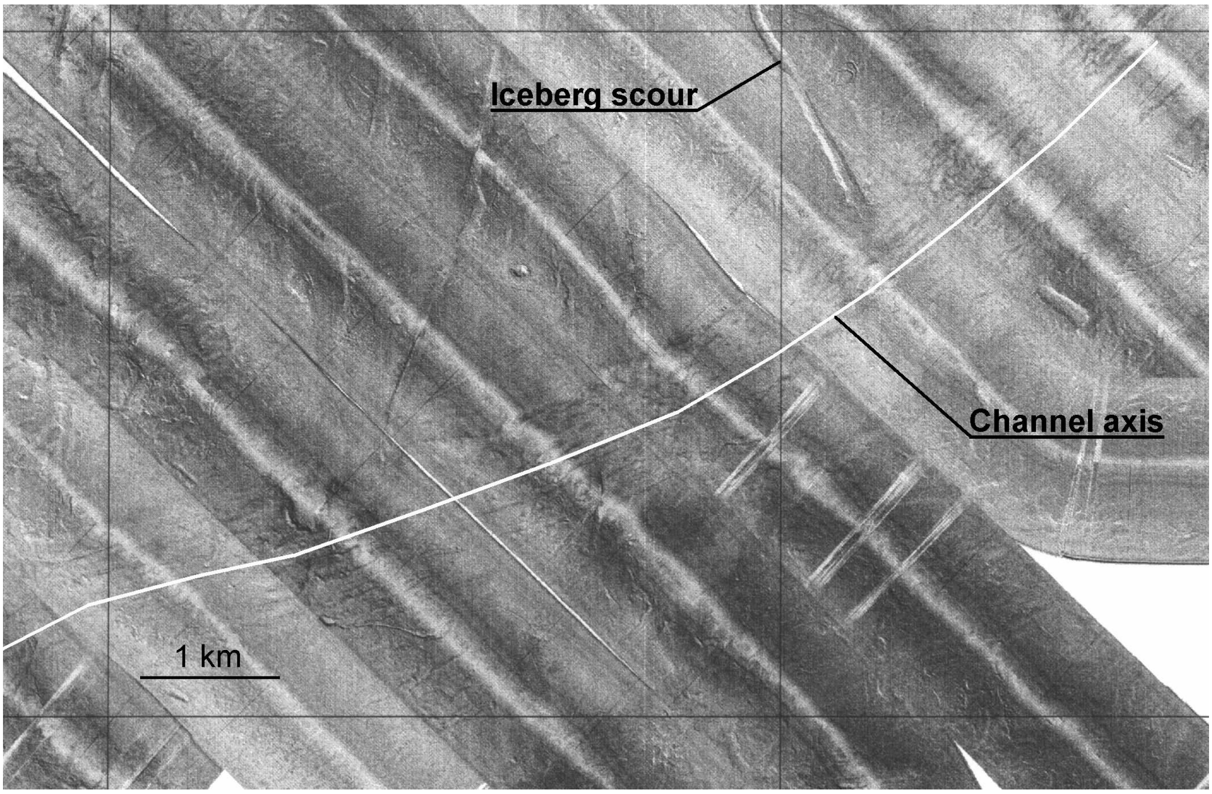

Figure 3. A portion of the side scan sonar mosaic of the Kvitkuven shelf prepared by Bernt Kjellin of the Swedish Geological Survey. Iceberg scours abound in the area. The large scour from the top of the picture ends when the iceberg lost contact with the bottom due to deeper water along the erosional channel (axis marked by white line) crossing the area. The sonogram seems to indicate that sedimentary strata are exposed on the bottom of the channel and that the axis parallels the strike of the beds.

A new rectified and geo-referenced mosaic has been newly prepared at the Geological Survey of Sweden (cf. Fig. 3). The mosaic is currently being compared with bathymetric data, grain size data on sediment samples, and the information extracted from the seabed photographs. A geological interpretation of the study area is under preparation.

Sub-bottom profiling

Seismic reflection profiling. The 2 x 40 cu.in sleeve gun array with appropriate acquisition and processing hardware, provided by the Norwegian Polar Research Institute, was used to cover a substantial part of the planned study area. The rather dense grid chosen, provides data for a very detailed 3-D-construction of the geology down to the first multiple. The raw seismic data was stored digitally on disk, analog data on DAT tape and recorded on a EPC-graphic recorder. In addition, the signal from a separate hydrophone streamer was processed and stored on magneto-optical disk with the new UASP-acoustic acquisition and processing system operated by GSF.

X-Star chirp profiler. The new X-star chirp sub-bottom profiler (0.5-12 kHz) acquired by the University of Stockholm, just prior to ship departure from Helsinki, posed serious difficulties to the operators due to both software and hardware problems. These were only partly solved during the cruise. Due to the high reflectivity of the glaciated shelf and the low output energy provided by the malfunctioning topside unit, the data recorded remained poor in quality. In addition to sporadic registration of sub-bottom data, sea floor reflectivity was also measured. *(The problem was after the cruise identified to have been caused by faulty potting of the connector between the tow-cable and the underwater unit.)*

Neither the Datasonics sub-bottom profiler nor the X-star profiler could give any substantial information on the quality or the stratigraphy of the topmost sediments. This was most obviously due to the high reflectivity of the glacial marine sediments in conjunction with distribution of sessile benthic fauna on one hand and detritus on the other. The X-star did provide some useful information on the actual reflectivity during a few transects.

Geological interpretation

A first interpretation of the single channel seismic reflection profiles has been made at GSF. Various reflectors have been traced and digitized and the trace characteristics have been used to group them into seismo-stratigraphic units. Based on the seismic reflection profiles run across the target area, the geology of the shelf can be divided into two major phases: the older seaward dipping strata forming the substratum have been eroded and followed by a period of shelf progradation. Topset strata have later been eroded and replaced by patches of horizontal or semi-horizontal beds of till(?) and glaciomarine sediments(?). The channel mentioned above running parallel to the ice front half way across the present shelf may in part be due to subglacial channeling of tidal currents possibly exposing the sediments below the unconformity.

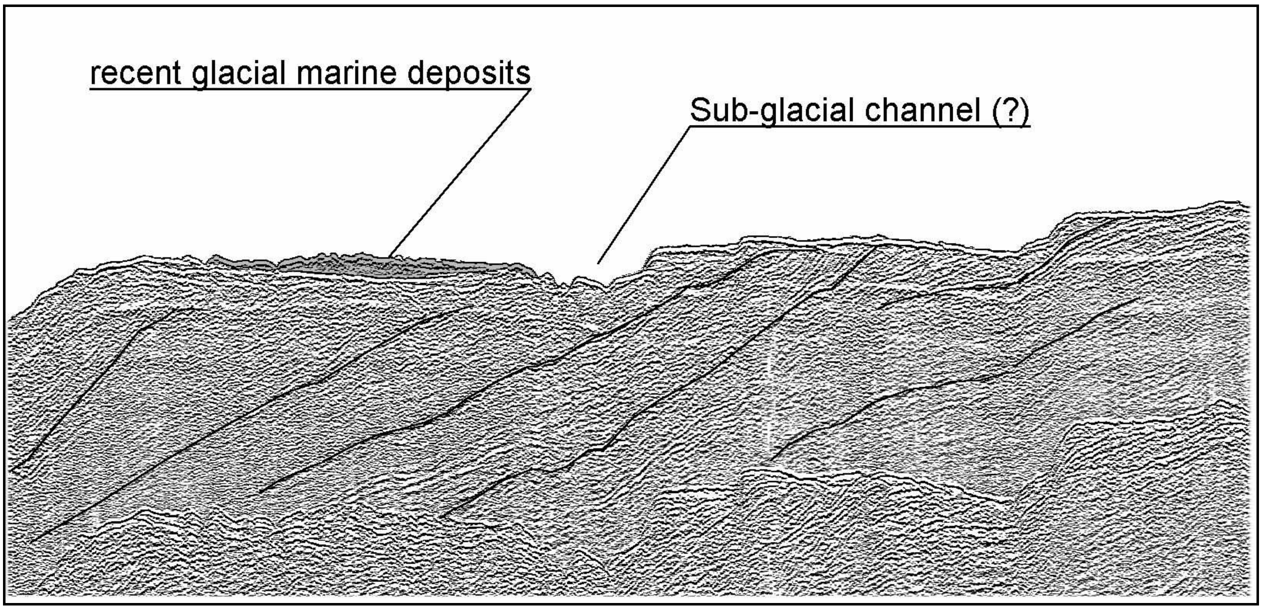

Figure 4. Seismic reflection profile (9607) across the shelf from the Kvitkuven Ice Rise to shelf break. Length of profile is 15 km and running in a NW to SE direction. During the Pleistocene the ice extended over the shelf edge. At a later stage the channel in the middle of the profile was obviously formed sub-glacially by tidal currents in the vicinity of the grounding line located on the slightly higher part of the shelf.

Due to lack of sediment cores from the area, the dating of the sediments below and above the unconformity, must be left to future expeditions. However, considering the distribution of surficial sediments, the erosional surface may have formed during the last major Pleistocene glacial advance, i.e. during the low-stand of the global oceans the ice-shelf extended beyond the present shelf break. The thick sediments (over 50-80 m) forming the visible part of the Kvitkuven shoal possibly constitute the tail of a drumlinoid formation underlying the Ice Rise. The ice obviously had several minor stand-stills, giving rise to a whole set of grounding line deposits, as inferred from the SSS-profiles.

The correlation of the identified seismic units with actual geological stratigraphy is pending additional information on the geology of the region. Unfortunately the misfortunes involved with the drilling on the shelf, badly needed ground- truthing is still lacking.

Ground-truthing of the acoustic seabed data had to rely on surface sediment samples taken at the 21 locations and bottom photographs at 12 sites. The visual and acoustic data showed that sediment distribution in this particular study area is mainly affected by four factors: 1. sediment input from the glaciers; 2. occasional trapping by bottom-dwelling fauna; 3. wave and tidal current activity; and 4. iceberg scouring (bulldozing).

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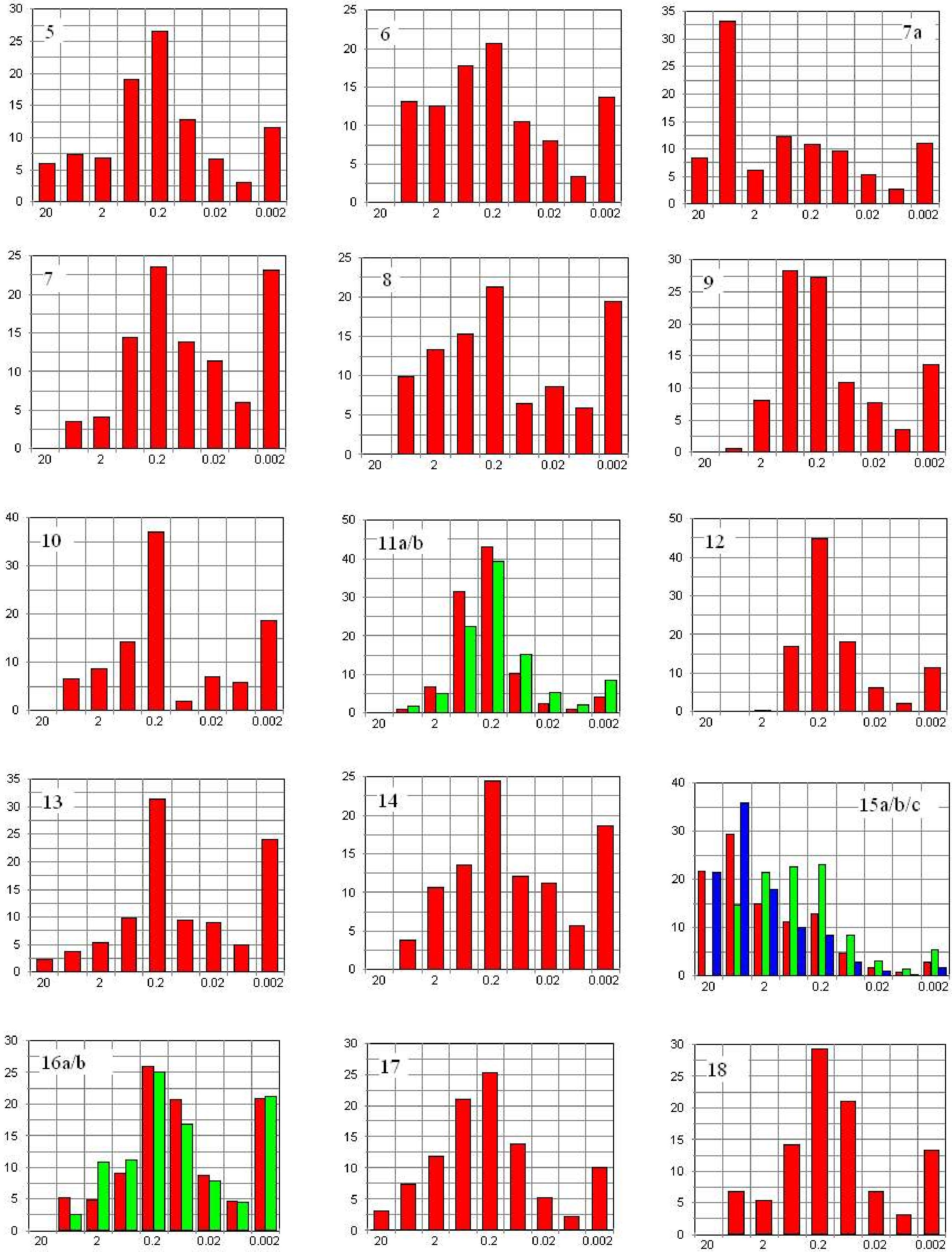
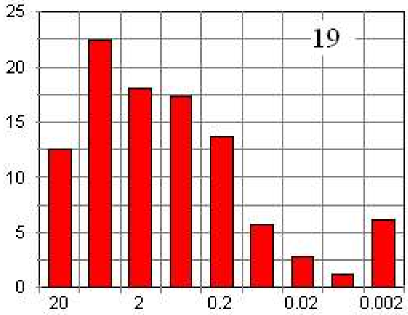
Appendix 1. Grain size distribution of seabed sediment samples from the Kvitkuven shelf

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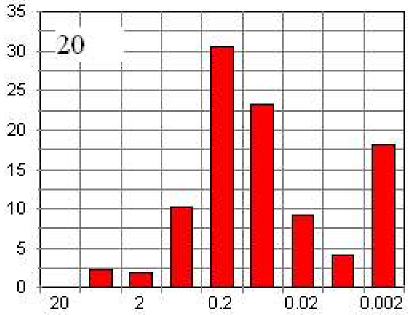
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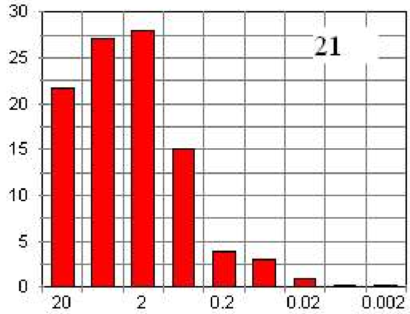
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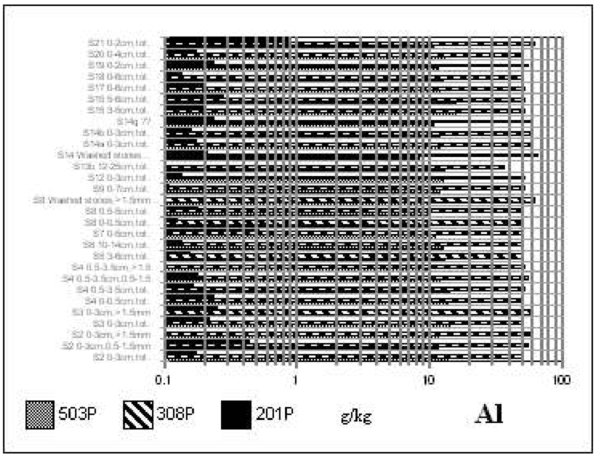
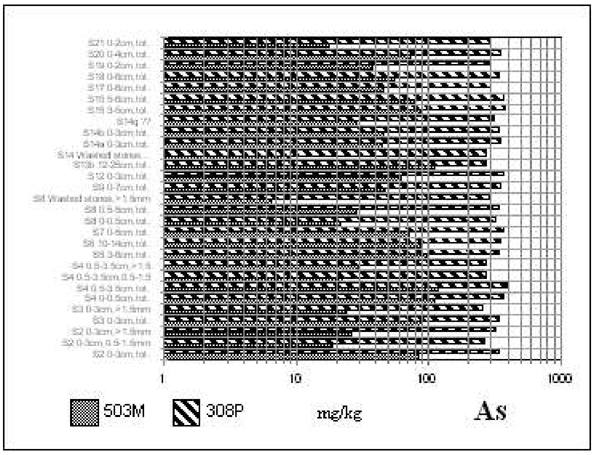
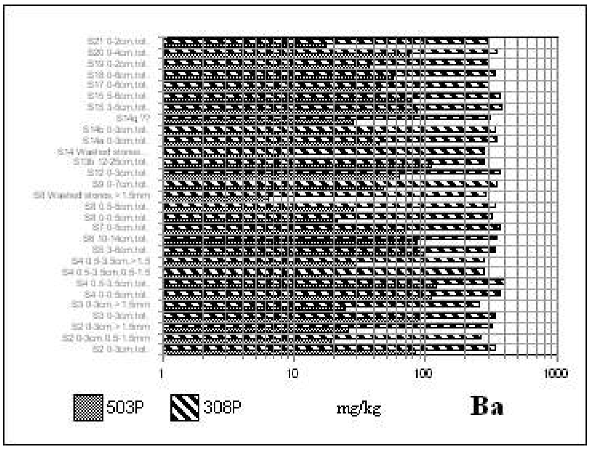
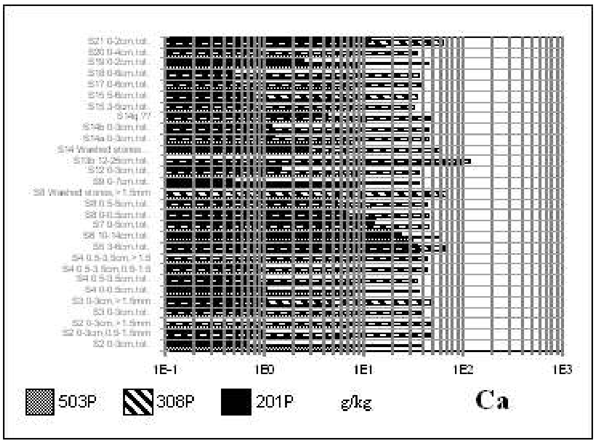
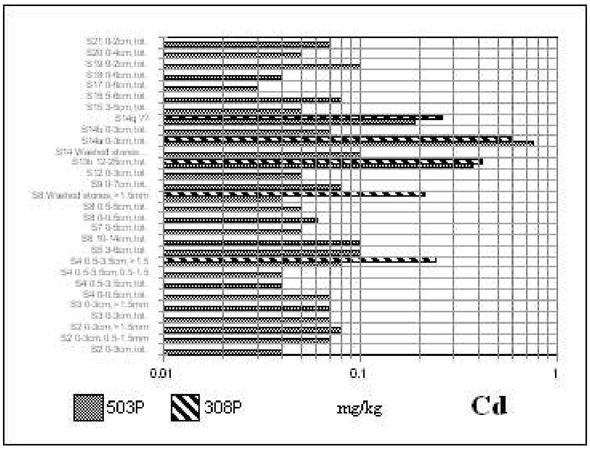
Appendix 2. Chemical composition of selected seabed sediment samples from the Kvitkuven shelf.

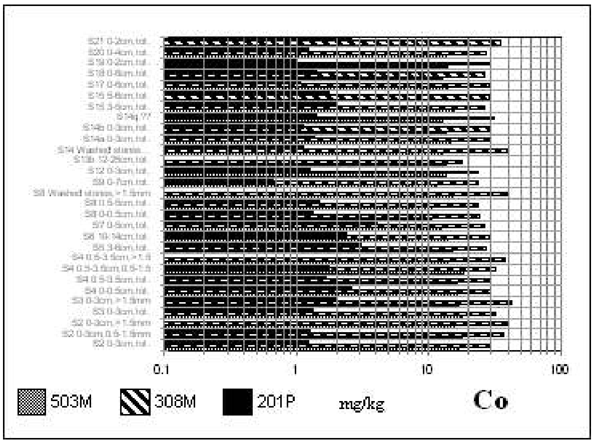


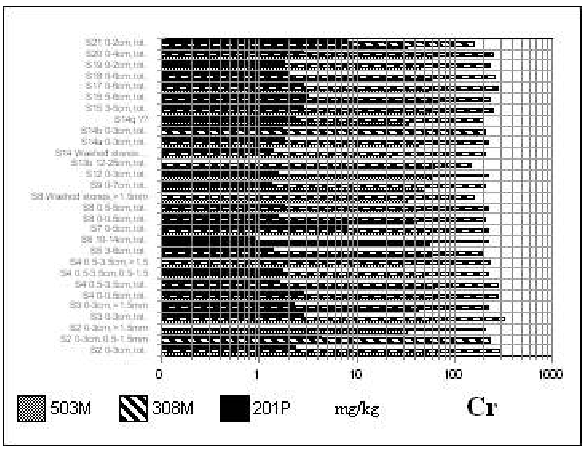


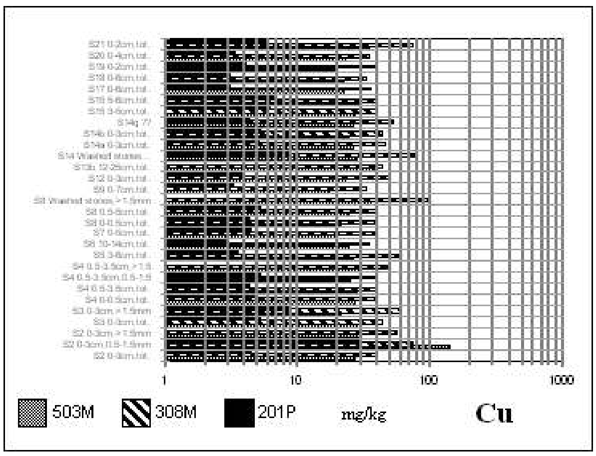


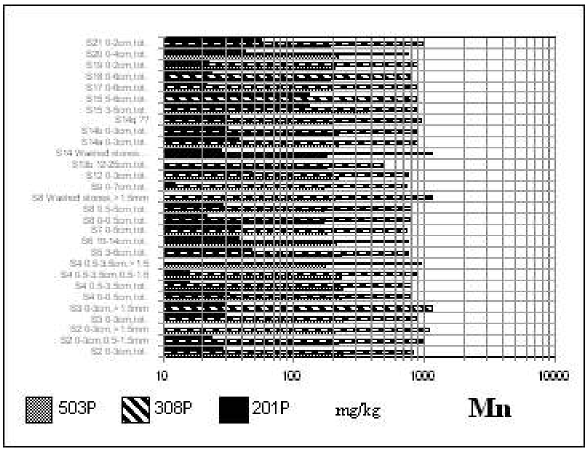








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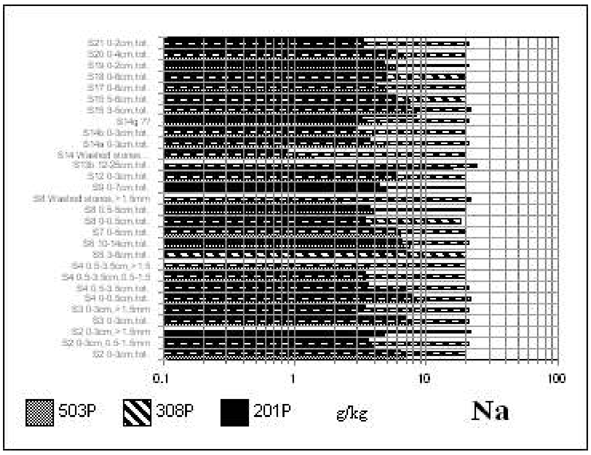
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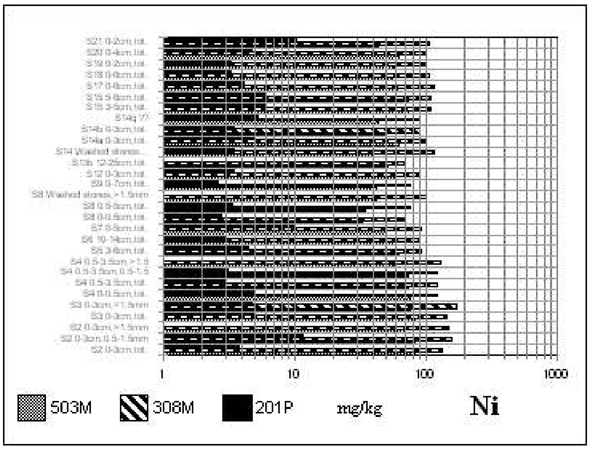
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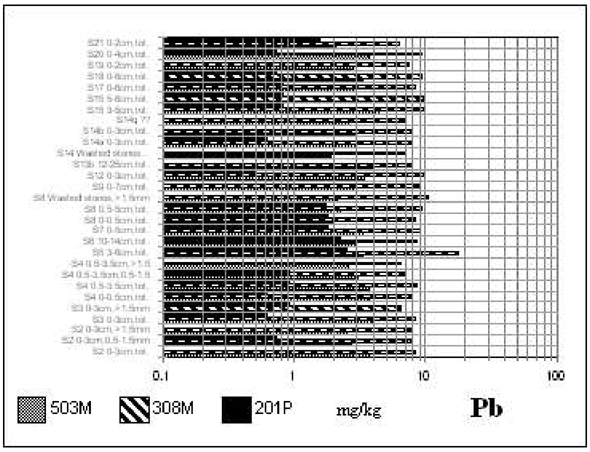
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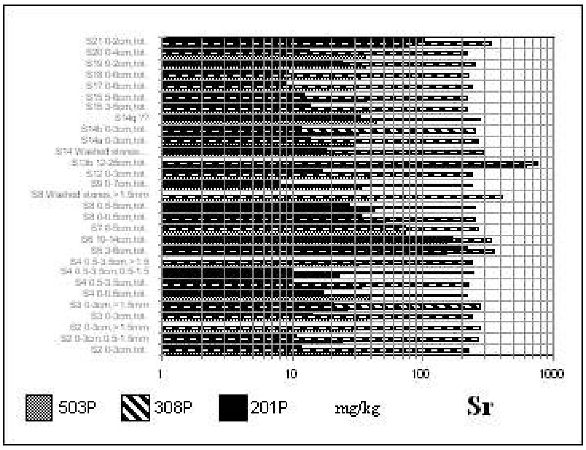
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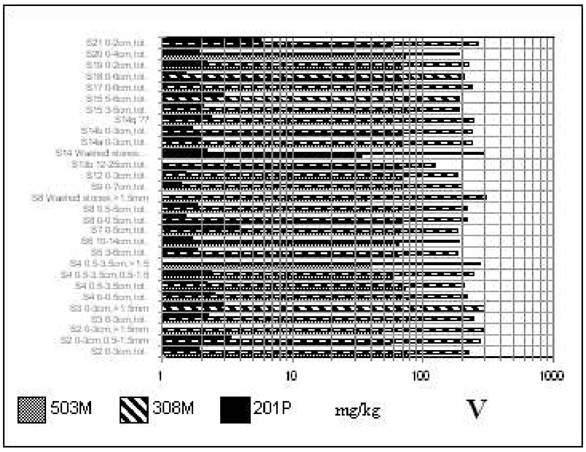
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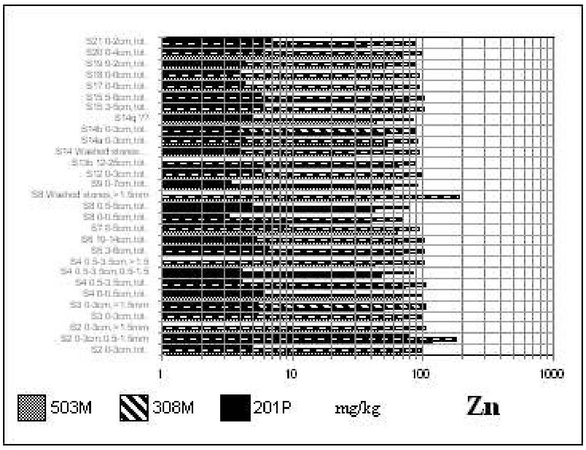
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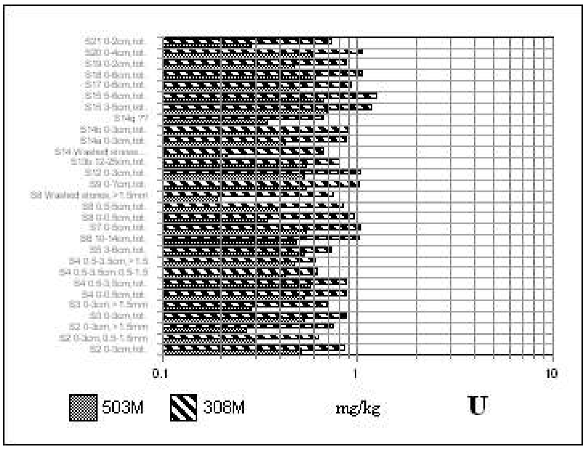
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mg/kg
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Appendix 3.

THE MARINE GEOLOGICAL TEAM MEMBERS AND DUTIES

Geological Survey of Finland:

Boris Winterhalter	Overall responsibility and coordination for the marine geological activities, echo-sounding, underwater video and photography.
Matti Tuhkanen	Data acquisition for TOPOS-based sidescan sonar mosaicing and for the UASP-system for processing of seismic reflection data. Assisting in drilling operations.
Aarno Kotilainen	TOPOS operator, sediment sampling and assisting in sundry geological chores. Assisting in drilling operations.

Geological Survey of Sweden:

Ingemar Cato	Group chief of Swedish team, sharing in sidescan sonar and sub-bottom profiler data acquisition and interpretation.
Bernt Kjellin	SIS 1000 sidescan sonar and sub-bottom data acquisition, mosaicing and interpretation. Assisting in drilling operations.

University of Stockholm:

Martin Jakobsson	X-star operator, data acquisition, processing and interpretation. Assisting in drilling operations.
Arne Lif	Technical backup for X-star and overall aid in solving electronic device problems.

University of Bergen:

Yngve Kristoffersen	Group chief of Norwegian team on drilling and seismic reflection operations, data acquisition and interpretation.
Hans Berge	Installation of the drilling rig, design of modifications and assisting in sleeve gun operations

Geo Drilling A/S:	Erik Hansen and Alf Larsen as drill rig operators.