Geology of the southern Bothnian Sea. Part I.

PER THORSLUND and STEFAN AXBERG

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Results are given from studies of two cores obtained from drillings in the lighthouses Västra Banken and Finngrundet (=Östra Banken), respectively, on the Finngrunden shoals. Results are also given from continuous seismic reflection profiling performed in the SW Bothnian Sea. The studies up to now permit a general account of the geology of the southwestern part of the Bothnian Sea with regard to the distribution of the sedimentary rocks and the stratigraphy and lithology of the Paleozoic sequence of strata. Cambrian and Tremadocian beds are treated in some detail, and data from the boreholes have been used in the interpretation of the seismic profiling.

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To the memory of Carl Wiman

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Preliminary report on the stratigraphy and lithology of Cambrian and Tremadocian beds of the Finngrunden banks

By Per Thorslund

With notes on the pre-Cambrian rocks

By P. H. Lundegårdh

Preface

Ever since the investigations by C. Wiman on erratics distributed to the south and southwest of the Bothnian Sea, many students have displayed keen interest in the morphology and geology of this area, particularly its sequence of Cambro-Ordovician beds. On various occasions, projects were discussed at the Palaeontological Institute of the University of Uppsala for obtaining a core through this sequence. The first attempt at realizing this goal was the drilling of a borehole on the Finngrunden shoals. The winter of 1966 was very cold, and an attempt was made to bore from the ice on the Västra Banken (Western Bank). This was made possible by a collaboration with the Geological Survey of Sweden. Men and material were brought to a suitable place on the bank by helicopter, but shortly afterwards, a change occurred in the weather, temporary as it turned out, followed by movement in the ice sheet around the shoal. Thus, for the sake of security, the operation was called off.

In 1969, Sjöfartsverket (the Swedish Board of Navigation) placed a modern lighthouse on Finngrundet (Eastern Bank; Fig. 1) which meant that the borehole project on the Finngrunden shoals could be taken up again. In the interval between June 24 and July 6, 1970, a core, 152,88 m deep, was obtained from the bedrock beneath the lighthouse. During the following year, a similar lighthouse was placed on Västra Banken, and in 1972, a core to a depth of 149 m was taken. Thanks to the courtesy of the Swedish Board of Navigation, the borings could be carried out within the lighthouses and with the full use of their space and facilities. With this and additional help, readily given from the authorities of the Board during the operations, also the core from Västra Banken could be obtained with the amount of money granted from the State Council for Scientific Research and from the Hierta-Retzius' Fond of the Royal Academy of Science.

Fig. 1. The lighthouse at Finngrundet (Eastern Bank). Photo P. Å. Thorslund.

The lighthouse at Finngrundet stands on Ordovician limestone, while that of Västra Banken is located on loose Quaternary sediments, the thickness of which had to be assessed before the boring. A continuous seismic reflection profile was taken on that bank in collaboration with the Department of Marine Geology at the Geological Institute of the University of Stockholm under the leadership of Dr. Tom Flodén. The results of this work were useful not only for the borehole operation, but also for the geological mapping of Västra Banken and the neightbouring area to the south.

The evaluation of the seismic profile has been treated separately by Mr. Stefan Axberg, whose map and description of the bedrock form the second part of this paper. The problems concerning the Quaternary deposits were treated earlier by Hoppe (1961), and will be discussed by Axberg elsewhere.

The bulk of the Ordovician sequence of the Finngrundet core has been worked out in detail

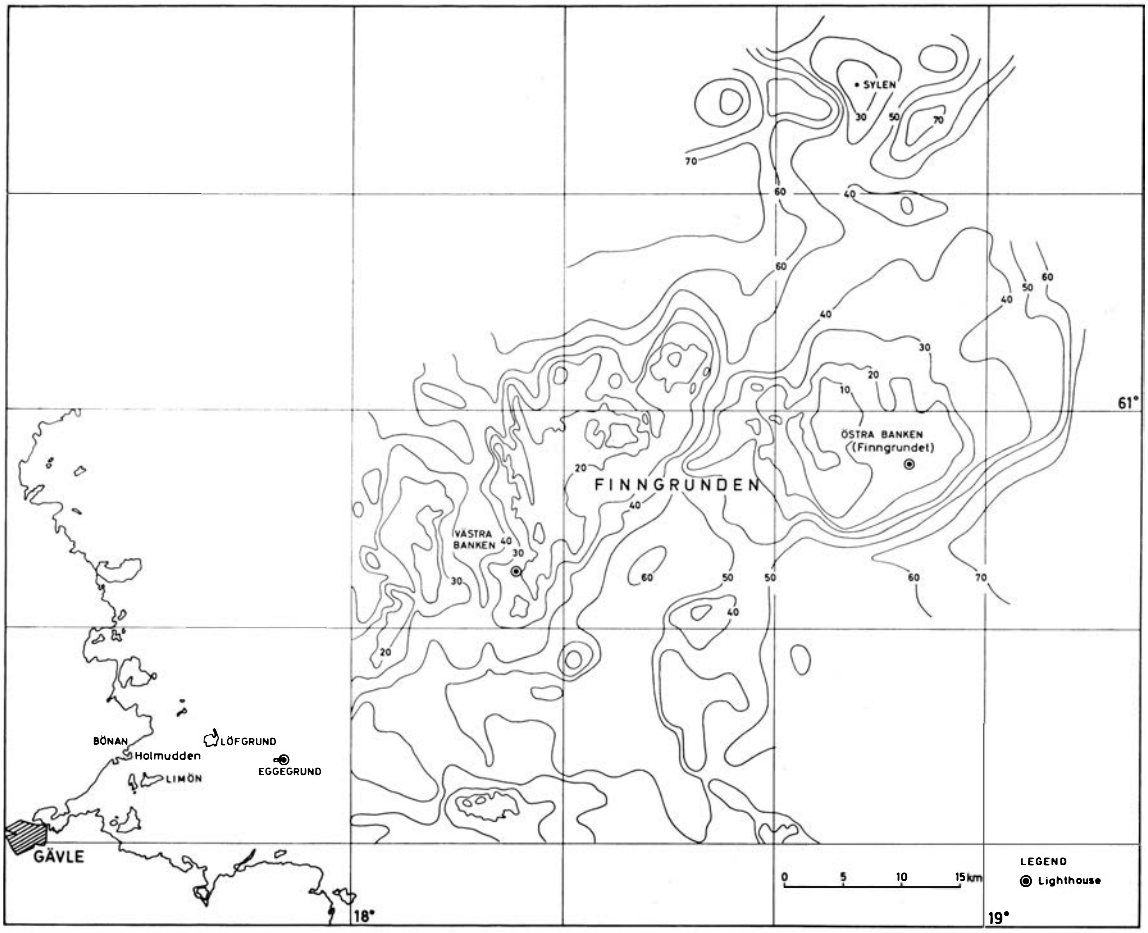


Fig. 2. Map showing the location of the lighthouses on the Finngrunden shoals. (Östra Banken = Finngrundet in this paper.)

by Dr. Torsten Tjernvik and Mr. Jan Johansson, while the Lower Cambrian and the Tremadocian beds of both cores have been treated by the present writer. The pre-Cambrian part of the Finngrundet core was investigated by Dr. P. H. Lundegårdh.

Stratigraphy and lithology of the cores from the Finngrunden banks

Introduction

Data obtained from borings on the Finngrunden shoals to the east of Gävle Bay have provided a valuable addition to our knowledge of the stratigraphy and tectonics of the southern part of the Bothnian Sea. The importance of these borings is attested to by the fact that they penetrated the Cambro-Ordovician sequence of the district; in addition, they have yielded details of importance for the evaluation of seismic profiles.

As already mentioned, the cores were taken within the lighthouses on the shoals, in 1970 on Finngrundet, in 1972 on Västra Banken. The location of the lighthouses is shown in Fig. 2.

No cores through the bedrock of the offshore area had been taken previously. In connection with fieldwork underlying the production of the geological sheet "Gävle", two borings were made on land in the coastal district, to the east of Gävle. They penetrated the pre-Cambrian rocks, and provided a substantial amount of information, important for the interpretation of the geology of the Bothnian Sea.

A short review of the previous work on the bedrock of this area is now presented in order to provide a background to the results obtained from the new borings.

Historical review

Thanks to comprehensive collecting and studies of erratics from the so called North Baltic District, Carl Wiman could present the fundamentals to our present knowledge of the pre-Quaternary sequence of the sedimentary rocks in the Bothnian Sea. In his paper of 1903, Wiman reported on the results of his investigations on material from the Cambrian and the Tremadocian beds after a historical résumé of previous observations. The remainder of the Ordovician sequence was treated in the paper of 1906, in which his interpretation of the tectonics of Gävle Bay was put forward and founded on observations published in the former paper. He assumed at that time, that the Ordovician beds exposed on the small peninsula Holmudden, south of Bönan, and on the islands to the south and east, belonged to the country rock, and, in addition, he described, in some detail, the sequence seen on the island of Limön. Regarding the extent of the sequence within the Bothnian Sea, Wiman thought that the Cambro-Ordovician beds occur in a few, comparatively small areas, isolated from each other, not far to the north and east of the coast of Uppland. He implied that the location of such an area could be deduced, with due regard to the direction of the movement of the inland ice, from a rich occurrence of erratics in a limited area. An isolated area of such a kind was supposed to be situated in the Gävle Bay, extending to the east, in the proximity of Eggegrund.

However, Stina Gripenberg (1934), who had studied samples of sediments taken from the seabottom, showed that the extent was much larger than that assumed by Wiman, and in summarizing her results, she emphasized the discovery of a wide area of (Ordovician) limestone to the north of, and at the Finngrunden banks. In support of this, she referred to a short paper by Schön (1911) who reported the occurrence of erratics of Ordovician limestones and conglomerates on the island of Brämön close to the town of Sundsvall.

From boreholes in the Gävle Bay district, Westergård (1939) could show that the Ordovician rocks, outcropping on Limön, in reality are float and rafts within the till, resting on the gneissgranite bedrock. According to Westergård the same explanation is valid for the adjacent islands with small outcrops of Ordovician limestone. The core from Holmudden, which was taken near the fault slopes of Bönan, pierced Quaternary deposits, 21,9 m thick, with an accumulation of Ordovician limestone boulders at the top, and Lower Cambrian very hard "blue-green clay", 11,6 m thick, resting on Jotnian sandstone covered by an unfossiliferous, probably post-Jotnian, sandstone (cf. Axberg p. 53).

Veltheim's (1962) and Winterhalter's (1972) papers contain results of investigations which were a continuation, successively enlarged, of those made by Stina Gripenberg. Veltheim's studies of large samples of material from the sea-bottom confirmed Gripenberg's interpretation of the bedrock of the Finngrunden shoals, and enlarged our knowledge of the extent of the Ordovician beds in the Bothnian Sea, the bottom morphology of which was outlined with the aid of echo-sounding. As to the extent of various components in the sedimentary bedrock of the sea area, Veltheim summarized his results on a map (op. cit., Fig. 30, p. 156) in which the Palaeozoic beds are restricted to a few areas, which, according to Veltheim, are isolated from each other owing to erosion. The northern-most area with Palaeozoic beds mapped is ESE of Sundsvall in spite of the fact that he had noticed Hörnsten's report (1959) on the occurrence of Ordovician limestone boulders on the island of Härnön about 50 km NE of Sundsvall. According to Veltheim, it is very likely that dislocations took place in pre-Cambrian time after the deposition of the Jotnian sandstone as well as in post-Caledonian time, and maybe connected with Tertiary uplift of the Scandinavian shield. The latter dislocations were supposed to have occurred mainly in the western part of the sea area presumably along faults sub-parallel to the Swedish coast. Consequently, owing to subsequent erosion, downfaulting or downwarping would account for the present remnants of sedimentary bedrock preserved in the sea area. Evidently, Veltheim followed Wiman in assuming that accumulations of boulders on the sea bottom could be deduced from erosional remnants of sedimentary bedrock.

Veltheim did not take note of Westergård's results from the borings in the Gävle bay district, nor did Winterhalter, whose results and interpretations were founded on investigations performed by improved versions of Veltheim's methods; in addition, he made use of other methods, of which continuous seismic reflection profiling was vital for the enlargement of our knowledge of the bedrock. With the possibility of using new marine charts and echo-sounding data, Winterhalter drew a detailed bathymetric map. Evaluating the seismic profiling material, he had use of the data obtained from the boring on Finngrundet in the

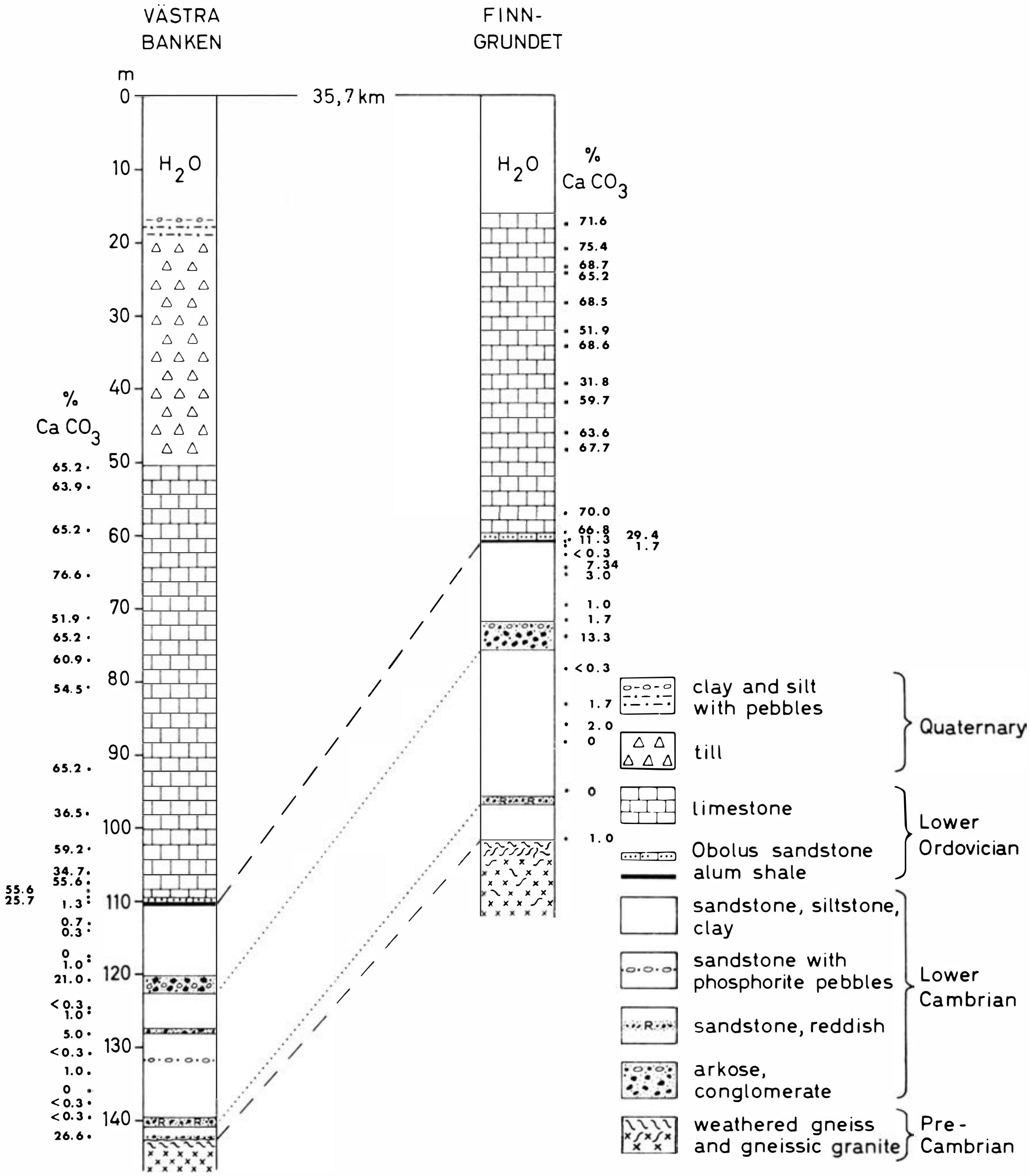


Fig. 3. Correlations between the core sections of the Finngrunden shoals.

summer of 1970 (op. cit. pp. 25, 31, 58); evidently these data were useful for mapping the limits between different lithological units. As seen in Fig. 4 (op. cit. p. 12), one of the profile lines went across Finngrundet not far from the lighthouse, the position of which is Lat. 60°59′N, Long. 18°37′E. Winterhalter's results are illustrated in a number of maps one of which (op. cit. Pl. 2 D) sketches the tectonics of the area, showing that the sedimentary formations are preserved in a syncline with the sequence gently dipping from the east, and, very likely, with a steep western

Table 1. Finngrundet. — Results of the analyses with the optical spectograph "Jumbo". The contents of Ti to Mg are given in per cent, those of Mo to As in ppm.

Metres below sea-level	Ti	Fe	Mn	Ca	Ba	Mg	Mo	Cu	Pb	Zn	Ag	Bi	Cr	Ni	Co	Sn	Be	V	W	Sr	As
17,76	0,71	3,0	0,11	47,3	0,02	1,3	6,3	7	14,3	86,4	1,9	3,3	46,9	16,3	13,4	5,7	2,0	132	52	652	—
20,75	0,64	3,0	0,11	>48	0,02	1,3	8,2	9	18,3	96,7	2,3	3,5	48,0	13,8	12,9	6,6	2,2	109	56	703	—
23,88	0,66	3,0	0,11	>48	0,02	1,3	7,9	6	12,4	43,0	1,9	3,3	47,7	14,8	13,0	5,3	2,0	112	49	698	—
28,23	0,67	2,9	0,10	>48	0,02	1,3	6,1	6	9,9	41,1	1,0	2,9	47,2	16,5	12,9	5,0	1,9	123	51	600	—
32,37	0,69	2,6	0,06	37,5	0,02	1,3	3,1	4	6,5	37,9	0,6	2,3	46,4	20,3	14,0	2,6	1,4	164	32	533	—
41,97	0,66	2,6	0,06	39,0	0,02	1,4	4,2	4	6,9	42,1	0,9	2,6	44,8	18,7	12,0	2,2	1,3	158	39	560	—
46,50	0,66	2,7	0,06	41,4	0,02	1,4	4,4	5	7,5	52,2	1,0	2,9	43,8	17,1	12,8	2,9	1,6	141	43	590	—
48,10	0,65	2,8	0,09	47,2	0,03	1,5	4,9	6	9,9	61,2	1,3	3,1	44,1	16,4	12,3	4,3	1,9	133	46	587	—
57,00	0,68	3,2	0,10	46,6	0,03	1,4	29,0	8	29,4	77,4	1,7	3,8	44,0	14,9	11,4	5,4	2,0	145	50	706	—
58,13	0,63	3,9	0,09	47,4	0,02	1,4	7,8	10	16,2	100,7	2,3	4,3	45,9	15,0	12,6	6,7	2,0	118	52	765	—
58,88	0,68	2,9	0,11	>48	0,02	1,4	6,8	14	13,9	91,3	2,1	3,4	48,3	13,6	16,5	6,1	2,1	135	53	715	—
61,22	0,74	2,9	0,20	43,1	0,02	0,5	>194	26	1706,2	87,0	5,0	6,8	74,0	137,3	37,4	13,8	0,7	1874	55	684	198
62,78	0,90	2,2	0,02	1,7	0,02	0,9	1,1	4	11,2	8,4	—	1,4	76,1	26,6	14,0	0,6	1,5	329	16	124	37
64,47	1,43	2,1	0,10	26,7	0,03	0,8	3,1	5	16,1	30,3	0,2	1,9	104,6	17,0	12,2	1,3	2,4	264	50	274	1
65,65	1,02	2,5	0,03	4,5	0,02	1,0	1,2	5	8,3	15,9	—	1,5	75,6	25,3	14,6	0,7	1,8	313	21	166	24
67,57	1,00	3,0	0,02	1,6	0,02	1,1	0,9	5	9,9	13,9	—	1,8	78,5	28,7	16,7	0,8	1,7	334	19	157	37
69,85	1,02	3,5	0,02	2,9	0,02	1,1	1,0	5	12,6	14,7	—	2,1	73,9	30,1	21,5	0,7	1,8	291	19	167	58
73,65	0,76	2,5	0,21	45,0	0,03	0,8	4,4	7	12,7	46,2	1,1	2,6	77,4	11,1	14,8	3,6	2,6	188	45	375	94
78,10	0,92	3,1	0,01	0,5	0,02	0,9	1,1	6	12,0	14,2	—	1,5	74,7	27,3	16,0	0,8	1,6	340	16	136	39
83,20	1,04	3,4	0,02	2,8	0,02	0,9	2,0	10	21,6	12,1	—	1,6	70,0	25,9	13,8	0,8	2,0	340	20	221	64
86,50	0,86	3,0	0,01	0,5	0,02	0,9	1,1	5	17,6	13,1	—	1,6	72,5	25,9	11,8	0,7	1,9	368	14	132	13
88,12	0,95	3,8	0,01	3,5	0,02	1,0	7,3	10	51,5	12,4	—	1,7	76,2	36,9	15,6	1,1	1,8	326	20	204	57
95,00	1,03	3.2	0,01	0,5	0,02	1,1	0,9	4	6,9	18,8	—	1,5	82,5	34,7	13,9	1,0	1,6	427	20	143	5
101,80	1,28	2,2	0,01	3,0	0,02	0,9	1,0	8	9,0	13,8	—	1,6	72,8	23,4	14,0	0,9	3,3	317	22	110	24

limb cut off by faults near the Swedish coast. The seismic profiling enabled the mapping of the thickness of the Palaezoic sequence (op. cit., Fig. 19, p. 35) and of the limit between the two lithological units that are conspicuous in the reflection profiles; this limit, on the whole, corresponds to the boundary between the Cambrian and Ordovician systems. Several fault lines were recorded and others are inferred by Winterhalter, supporting his interpretation that the bedrock of the Bothnian Sea is block-faulted.

This brief review serves to show that studies of erratics have presented valuable information of the composition of the bedrock in the Bothnian Sea, but do not give a sufficient basis for detailed mapping, and that drilling and modern geophysical methods give the best data.

General comments on the core sections. — The sequences from the cores are represented diagrammatically in Fig. 3, in which a hint of the tectonics of the Finngrunden banks between the lighthouses is demonstrated by using the sea level as a reference level. At Finngrundet, the strata are evidently horizontal, while at Västra Banken they have a gentle dip (cf. p. 47, Fig. 7) — probably to the northwest, towards the continuation of the Bönan fault line (cf. Axberg, this paper p. 56).

In the sequence, important correlation surfaces are those at the Cambro-Ordovician boundary and at the top of the pre-Cambrian crystalline rocks, each pair of these surfaces being approximately synchronous. In this respect, some significance must also be attributed to the sudden appearance of coarse clastic beds in the dominantly clayey and silty sediments of the Lower Cambrian series of strata. Also the upper boundary of the Tremadocian sequence seems suitable for correlation.

Middle and Upper Cambrian beds are missing, and the Lower Cambrian may be incomplete. As there are no basal Cambrian conglomerates, the sub-Cambrian surface is smooth without depressions. The same can also be said of the sub-Ordovician surface as there are no coarse clastic sediments at the base of the Ordovician sequence, which in both cores comprises beds of the Öland Series only.

Analyses. — The obvious difference in the composition of the Cambrian and the Ordovician beds is reflected in the results of the analyses of the $CaCo_3$ content (see Fig. 3). In the Cambrian sequence only the coarse clastic layers are comparatively calcareous, since their matrix mainly consists of calcite. In addition, in the upper part of this sequence, there is a tendency towards an increase in the content of calcareous matter; this

Table 2. Västra Banken. — Results of the analyses with the optical spectrograph "Jumbo". The contents of Ti to Mg are given in per cent, those of Mo to Ge in ppm.

Metres below sea-level	Ti	Fe	Mn	Ca	Ba	Mg	Mo	Cu	Pb	Zn	Ag	Bi	Ni	Co	Sn	Be	V	W	Sr	As	Ge
54,55	0,68	2,7	0,10	51,5	0,04	1,5	5,3	3	9,3	75,1	1,5	2,7	17,7	13,6	5,1	1,9	126	46	660	0	0
60,50	0,71	3,2	0,15	>52	0,19	1,5	7,7	9	15,1	112,4	2,4	3,5	16,8	15,3	6,9	2,3	105	61	779	0	0,264
66,50	0,71	3,3	0,18	>52	0,02	1,3	10,2	11	21,5	146,0	3,4	3,8	13,2	14,0	9,9	2,6	93	77	844	0	0.500
72,50	0,70	3,0	0,09	44,7	0,03	1,6	4,0	4	7,0	57,9	1,1	2,7	16,4	14,3	4,0	1,9	146	41	629	0	0
78,50	0,78	3,0	0,11	43,2	0,03	1,3	5,4	6	11,0	81,1	1,6	3,1	16,8	14,7	4,3	2,0	146	53	709	0	0,181
81,95	0,74	3,2	0,12	49,8	0,12	1,4	6,6	7	13,7	98,6	2,2	3,2	16,7	14,9	5,9	2,3	122	58	753	0	0,261
87,35	0,74	2,9	0,12	47,3	0,03	1,5	5,3	7	10,0	80,7	1,6	3,1	18,9	19,1	4,3	2,0	158	49	728	0	0,153
93,23	0,75	3,3	0,12	52	0,04	1,3	8,0	9	17,2	113,8	2,5	3,5	18,0	16,1	7,3	2,2	149	65	787	0	0,415
99,15	0,72	3,1	0,07	33,2	0,03	1,2	2,2	2	4,6	36,6	0,4	2,2	24,6	14,5	2,2	1,5	179	29	529	0	0
104,25	0,81	3,7	0,08	43,8	0,03	1,4	4,6	4	8,7	67,0	1,2	3,1	20,4	13,8	4,3	1,8	175	46	640	0	0,073
107,52	0,73	3,5	0,06	34,4	0,03	1,3	2,6	2	4,8	36,3	0,5	2,2	20,3	11,4	2,1	1,4	181	32	560	0	0
108,25	0,78	2,2	0,02	4,8	0,15	1,1	0,7	4	12,9	16,1	0	1,4	33,6	60,0	0,7	1,0	365	15	220	19	0,002
108,85	0,68	3,5	0,13	>	0,11	1,4	8,8	27	18,4	125,1	2,9	3,8	12,6	13,0	8,2	2,5	114	64	864	0	0,515
109,45	0,70	4,3	0,11	46,4	0,03	1,4	5,1	12	11,0	79,6	1,5	3,3	15,2	10,7	5,0	1,6	134	48	721	0	0,200
110,06	0,89	2,5	0,04	35,3	0,06	1,4	5,1	3	4,9	32,1	0,3	1,8	19,4	10,6	2,0	1,6	205	34	400	0	0
110,29	0,91	2,6	0,03	15,4	0,05	1,7	1,5	5	4,3	15,5	0	1,4	21,5	8,7	0,8	1,3	232	25	326	12	0
110,38	0,78	2,6	0,03	6,6	0,35	1,0	0,7	3	4,1	16,6	0	1,5	26,6	12,1	0,6	1,3	384	14	517	0	0,029
110,49	0,59	3,1	0,05	23,6	0,36	1,0	1,4	6	5,6	20,9	0,1	1,9	13,4	7,9	1,6	2,2	722	20	772	0	0,165
110,59	0,84	2,6	0,09	34,4	0,27	0,7	14,1	27	94,5	49,4	4,1	3,0	132,9	210,0	3,8	0	2613	63	997	700	0,064
110,61	0,81	2,4	0,10	36,4	0,22	0,8	8,8	19	440,2	49,8	3,4	2,8	141,6	206,3	3,6	0	2509	63	980	628	0,321
110,78	0,83	2,9	0,13	41,3	0,07	0,8	>187	42	150,4	87,5	4,3	4,2	59,2	97,6	7,7	1,8	911	80	1150	222	0,972
111,30	1,24	2,4	0,03	5,0	0,03	0,9	0,7	5	20,3	149,5	0	1,4	22,5	16,6	0,7	1,5	270	27	186	41	0,027
115,30	0,88	2,3	0,02	1,1	0,02	1,0	2,0	4	8,4	12,4	0	1,2	26,0	15,0	0,5	1,4	321	12	118	0	0,050
119,45	0,94	2,6	0,03	1,6	0,03	1,0	0,9	4	10,4	14,7	0	1,2	29,0	17,4	1,0	1,2	418	18	166	6	0,064
122,87	0,79	2,0	0,21	39,6	0,03	0,8	5,7	7	9,3	34,0	0,5	2,2	11,8	10,1	2,7	1,2	341	35	327	0	0
126,35	1,01	3,0	0,01	1,7	0,02	1,0	6,9	5	21,2	16,5	0	1,1	27,3	14,6	0,9	1,5	343	24	197	59	0,089
126,60	1,09	3,0	0,03	4,5	0.03	1,1	0,6	6	25,5	15,4	0	1,0	22,6	12,9	0,8	1,7	339	25	223	24	0,044
129,30	1,12	2,9	0,04	12,6	0,02	0,9	0,7	10	64,8	24,8	0	1,8	20,4	15,9	1,6	2,4	586	27	189	14	0
135,30	1,45	2,5	0,04	13,6	0,03	0,9	1,0	41	16,6	35,1	0,1	1,3	26,5	22,2	7,3	3,0	269	35	179	16	0
137,90	1,03	3,1	0,02	0,8	0,02	1,4	0,4	1	9,6	14,6	0	1,4	38,4	23,5	0,8	2,0	444	18	140	28	0,087
139,31	1,04	2,7	0,03	1,6	0,02	1,3	1,0	2	5,4	15,5	0	1,4	32,6	15,0	0,8	2,3	423	23	161	13	0,062
141,10	0,99	2,9	0,02	0,5	0,03	1,2	0,5	3	4,4	16,6	0	1,2	34,6	16,8	0,7	1,8	435	20	125	15	0,085
143,95	0,65	3,2	0,50	52	0,04	0,6	9,6	23	19,9	92,0	2,4	3,0	16,9	20,8	6,5	5,4	400	96	>1364	0	0,061

is pronounced in the Finngrundet core sequence in which a comparatively thick bed of argillaceous limestone occurs near the top.

Some samples, most of them taken from the core above the Cambro-Ordovician boundary to 1 1/2 m from this boundary, were analysed for their phosphorus content, with the following result:

Finngrundet Metres	P_2O_5 %		Västra Banken Metres
59,86	0,84	0,19	109,82
60,24	4,70	1,48	110,06
60,47 +	6,98	2,22	110,29
60,64 +	4,02	3,60	110,46
61,22 +	1,84	6,64	110,57 +
61,41	1,38	7,86	110,69 +
61,88	0,19	5,88	110,71 +

\+ Samples taken from the Tremadocian *Dictyonema-Obolus* beds.

The above analyses were performed, using photospectrometry, by Dr. Ulf Sturesson at the Paleontological Institute in Uppsala.

The analyses of selected elements were carried out with the optical spectograph "Jumbo" at the Geological Survey of Sweden, and the results are seen in Tables 1 (Finngrundet) and 2 (Västra Banken). Comments on the analyses are given on p. 48.

Dr. Astrid Andersson at the Ranstadverket Laboratory of the Atomic Energy Authority, kindly carried out analyses on two samples of *Dictyonema* shale from the Finngrundet core with the following result:

	V %	U %
Finngrundet 60,78 m	0,172	0,0241
Finngrundet 61,15 m	0,209	0,0191

The pre-Cambrian rocks. — Gneissic rocks form

Table 3. The pre-Cambrian part of the Finngrundet core.

Metres below sea-level	
102,01—117,55	Reddish grey, originally coarse augen-granite which is strongly schistose (augen-gneiss-granite) and shows considerable weathering (kaolinization?). The schistosity planes have an angle of about 45° with the axis of the core. There are a few dikes or dikelets of red pegmatite; between 109,9 and 111,2 some intercalations of weathered fine-grained amphibolite.
117,55—118,0	Breccia of augen-gneiss-granite, weathered.
118,0 —118,60	Augen-gneiss-granite as between 102,01 and 117,55.
118,60—119,10	Brecciated, and in part disintegrated, augen-gneiss-granite; weathered.
119,10—119,40	Augen-gneiss-granite as between 102,11 and 117,55.
119,40—121,26	Red, acid, coarse to medium-grained gneiss-granite; weathered.
121,26—126,28	Augen-gneiss-granite as between 102,01 and 117,55.
126,28—126,90	Amphibolite, fine—to finely medium-grained; weathered.
126,90—132,35	Augen-gneiss-granite as between 102,01 and 117,55.
132,35—133,42	Augen-gneiss-granite interstratified with amphibolite; both weathered.
133,42—134,35	Brecciated and partly disintegrated augen-gneiss-granite; weathered, and cut by a vertical crack filled with calcite.
134,35—167,60	Augen-gneiss-granite as between 102,01 and 117,55, although not so strongly weathered. The rock contains scattered zones of brecciation and thin zones of mylonite. Pegmatite is lacking, but the gneiss-granite has been locally transformed (regenerated) to coarse, secondary granite without any visible signs of schistosity. Weathering is weaker in the secondary granite than in the gneiss-granite.

the substratum of the Cambro-Ordovician sequence in both cores.

At Västra Banken, the borehole penetrated 4,13 m of reddish grey augen-gneiss-granite with strong schistosity. Two pegmatite dikes occur, one of which is beneath the Cambrian beds (cf. Pl. I, Fig. A) being 31 cm thick and resting on a comparatively fine-grained gneiss with a dip of about 50° in relation to the axis of the core. The weathering is strong and the feldspars of the pegmatites have been partly altered to kaolin(?).

The pre-Cambrian part of the Finngrundet core was investigated by Dr. P. H. Lundegårdh of the Geological Survey of Sweden (Table 3 p. 42). From his investigation Lundegårdh concludes: "It is evident that the pre-Cambrian crystalline basement has been cut by a tectonic zone in the vicinity of the borehole. The large vertical extent of the weathering indicates a down-fault of the pre-Cambrian crystalline basement."

The Quaternary beds at Västra Banken

According to the borehole log, the sediments immediately beneath the lighthouse are clayey and silty with boulders and pebbles, of which only fragments of grey Ordovician limestone and predominant pre-Cambrian rocks were recovered from the boring.

Between 25,30 m and 34,20 m below sea-level core portions were taken from the sediments (together 6,20 m) comprising sandy, grey and brownish till with fragments of pre-Cambrian crystalline rocks and of red and grey Ordovician limestones. Below a depth of 34,20 m, and above the bedrock surface, there are a few remaining fragments of pre-Cambrian rocks and abundant pieces of grey limestone, some of which represent the Upper Ordovician "Östersjökalksten" (Baltic limestone).

The Cambrian sequence

Only the Early Cambrian beds are present in the Cambrian sediments of the cores. These are almost 7,5 m thicker at Finngrundet than at Västra Banken, being 40,95 m and 33,29 m, respectively. So far, the Cambrian sequence of the cores has mainly been studied macroscopically. The results of this investigation are given in Tables 4 and 5 (pp. 44 and 45, resp.), and diagrammatically illustrated in Fig. 4. Parts of the Cambrian section of the core from Västra Banken are shown in Plate 1, Figs. B—E. However, a closer sedimentological study is necessary and will be done later. For a general view of the development of the Early Cambrian sedimentation in the Bothnian Gulf area, more material is required, which means taking cores from the central and northern part of the area. The investigation so far has resulted in many problems, the interpretation of which will be made possible and easier only by the acquisition of new material.

From the results of Wiman's research, it may be thought that the Cambrian sequence in the area

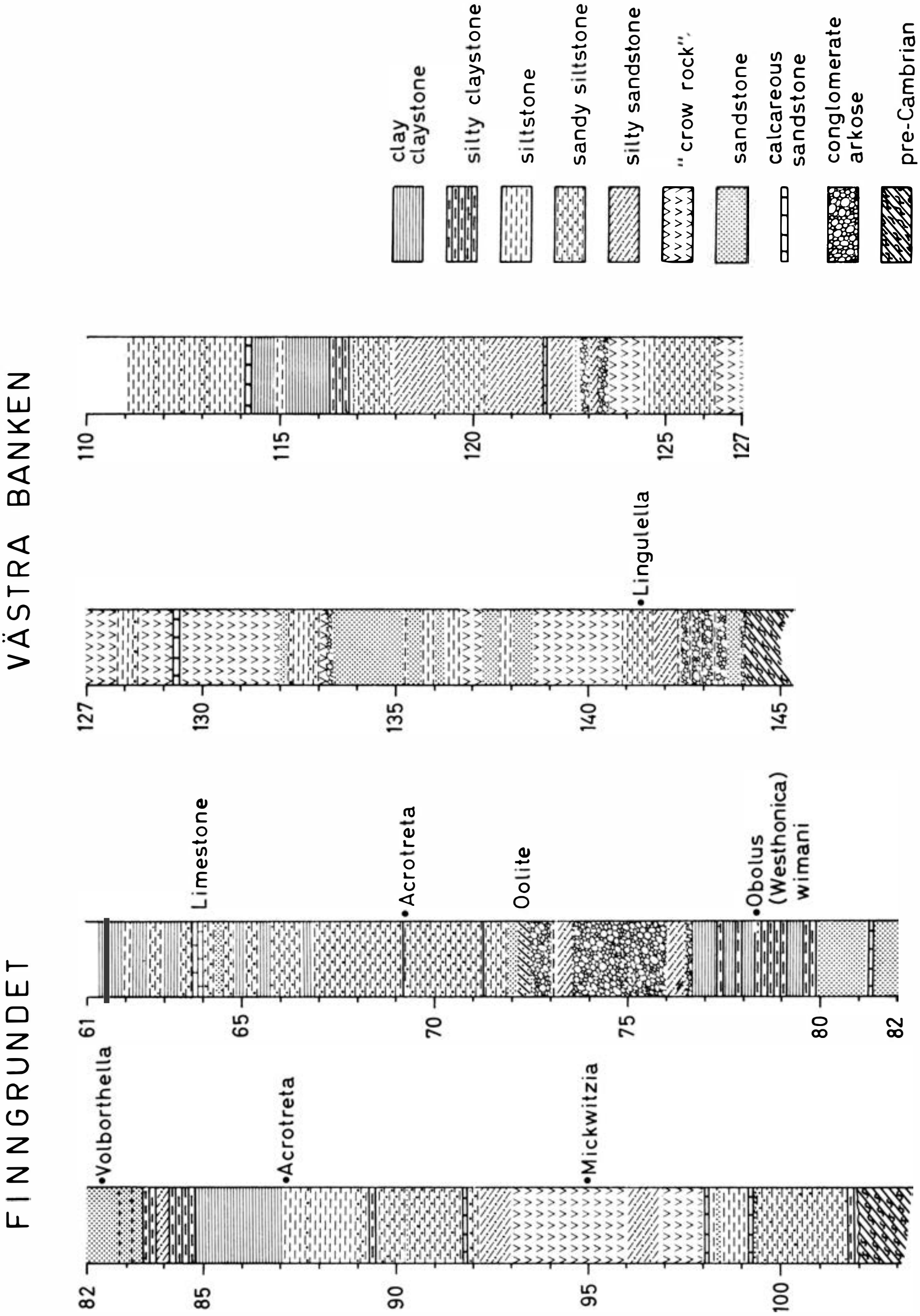


Fig. 4. Diagrammatic sections of the Lower Cambrian strata of the Finngrunden shoals.

Table 4. The Lower Cambrian sequence at Finngrundet.

Metres below sea-level	
102,01—117,55	Basement: Reddish grey, coarse augen-granite, strongly schistoce (augen-geniss-granite) and rather strongly weathered (kaolinized?).
101,94—102,01	Greenish grey clay with thin seams of clayey arkose. A layer of clayey gravel at the indistinct boundary toward the sub-stratum, the uppermost part of which has thin fissures filled with clay.
101,77—101,94	Greenish grey clay and siltstone with a few thin intercalations of whitish grey fine-grained sandstone. At 101,91 m crystals and aggregates of pyrite.
98,39—101,77	Grey siltstone alternating with comparatively thin layers of clay, and with lenses, lumps, seams, layers, and tubes of various form of light grey fine-grained sandstone, the content of clay decreasing upwards in the sequence. Beds of hard calcareous sandstone, 5 cm and 10 cm thick, at 100,12 m and 99,13 m respectively.
98,27— 98,34	Greenish to yellowish grey, mottled (white-spotted) sandstone with sparse glauconite. Scattered small pellets rich in Ti (cf. Fig. 5).
98,05— 98,27	Crushed into pieces during the drilling: greenish grey siltstone with glauconite, concretions of pyrite, grey argillaceous sandstone, a bed of calcareous sandstone intersected with branching fissures filled with calcite.
96,92— 98,05	Grey, partly silty sandstone, almost without stratification throughout. "Crow rock" (Hessland 1953).
95,92— 96,92	Greenish grey and light grey argillaceous sandstone, some parts mottled brown-reddish, with irregular stratification, occasional cross-bedding, and with a few almost vertical tubes. Glauconite very rare.
92,13— 95,92	Argillaceous, fine-grained sandstone, grey with scattered small parts reddish brown, and with irregular stratification. Content of glauconite scarse. A hard bed, 4 cm thick, at 93,82 m. — *Mickwitzia* sp. at 94,97 m. "Crow rock".
89,12— 92,13	Grey to dark grey siltstone with irregular intercalations and lumps of light grey sandstone up to 90,62 m; subsequently siltstone and silty clay with thin layers of fine-grained sandstone with glauconite. Dark brown "spots", branches, and filaments of "algae". A 4 cm thick bed of calcareous sandstone at 91,94 m, intersected with branching fissures filled with calcite.
87,27— 89,12	Dark, upwards darkish grey shaly siltstone with lenses, lumps, and thin, in some parts, very thin, seams of light grey sandstone with glauconite.
84,13— 87,27	Darkish grey and grey claystone with thin layers or lenses of light grey sandstone, upwards grading into silty claystone with scattered lenses and layers of sandstone to which the content of glauconite is concentrated. — *Actrotreta* sp. at 89,50 m.
83,52— 84,13	Sequence with graded bedding, each unit consisting of grey argillaceous sandstone with glauconite, irregularly stratified, upwards grading into dark siltstone.
79,97— 83,52	Greenish grey argillaceous sandstone with glauconite but without stratification. Below 81,22 m a bed, 10 m thick, of light grey calcareous sandstone intersected with branching fissures filled with calcite. ?*Kutorgina* sp. at 82,02 m, *Volborthella* sp. at 82,22 m.
76,62— 79,97	Claystone and silty claystone with a few intercalations of light grey sandstone with glauconite. "Algae" common. The uppermost 0,7 m consist of grey, soft, montmorillonitic clay. *Obolus* (*Westonica*) *wimani* Walcott and *Acrotreta* sp. at 78,22 m.
76,56— 76,62	Grey silty clay with lenses and lumps of coarse arkosic sandstone.
74,46— 76,56	Dark siltstone with irregular intercalations of light grey sandstone with glauconite.
75,87— 76,46	Light grey, fine-grained sandstone, comparatively hard, with glauconite and grains of feldspar, and with a few thin silty layers.
72,50— 75,87	Arkosic sandstone and arkose, partly coarse, with a few intercalations of siltstone, of which the thickest, 11 cm, occurs above 72,97 m. The arkosic beds with calcite matrix. Accumulations of pyrite in the uppermost part.
72,20— 72,50	Brown to greenish oolite with nodules of phosphorite. The ooids are mixed with arkosic sand.
71,96— 72,20	Dark grey, medium-grained sandstone with pyrite.
67,0 — 71,96	Grey and dark-grey siltstone with some intercalations of claystone, and with thin layers, seems, lenses, and lumps of light grey sandstone with glauconite. *Acrotreta* sp. at 69,27 m.
61,94— 67,0	Dark grey siltstone and claystone with laminately stratified layers and flat lenses of light grey, fine-grained sandstone, the content of sandy intercalations decreasing upwards in the sequence. Above 64,55 a bed, 21 cm thick, of grey hard sandstone. A bed of argillaceous limestone, 30 cm thick, above 64,00 m has cone-in-cone structures in the basal part and branching fissures filled with calcite in the middle part. Aggregates of pyrite occur as concretions and thin layers(?), the thickest one, 8 mm, at 62,98 m.
61,27— 61,94	Grey claystone and clay with a layer (or a lens), 1 cm thick, of pyrite about 5 cm below the Cambro-Ordovician boundary. The topmost part, 1,5 cm thick, of the clay sequence is whitish grey and has small aggregates of pyrite.

Table 5. The Lower Cambrian sequence at Västra Banken (Pl. I, Figs. A—F).

Metres below sea-level	
144,38—148,20	Basement: Red and reddish grey gneiss with pegmatite veins, weathered. — 144,07—144,38 Pegmatite, strongly weathered (kaolinized?).
143,96—144,07	Hard conglomeratic sandstone or arkose with calcareous matrix, and with well rounded fragments, those of quartz up to 6 mm, some feldspar grains slightly larger.
141,68—143,96	Argillaceous sandstone varying in coarseness and colour, below 143,20 m with intercalations of dark grey siltstone, between 142,40 m and 143,0 m, and 141,90 m and 142,0 m mostly brownish red with some yellowish brown parts, and with lumps of light grey sandstone. Arkosic beds with sharp boundaries toward their fine-grained substratum (tidal graded bedding; Pl. 1, Fig. B). Some small grains of glauconite in the uppermost silty part above 141,90 m.
140,90—141,68	Dark grey sandy siltstone with "spots" and filaments of "algae". Glauconite infrequent. *Lingulella* sp. at 141,38 m.
138,44—140,90	Mottled grey and darkish grey, silty sandstone with glauconite ("crow rock").
133,35—138,44	Beds, lenses, and lumps of light grey fine-grained sandstone with glauconite sparsely, intercalated with layers of dark grey siltstone and a few layers of clay, or claystone. "Crow rock" structure in some parts. The sandstone beds between 133,40 m and 135,26 m are impregnated with bituminous matter (Pl. 1, Fig. C).
123,52—133,35	Dark grey sandstone with "crow rock" structure alternating with beds of siltstone and sandy siltstone. 132,98—133,35 m "crow rock" with stmall aggregates of pyrite, and with phosphoitic nodules in the lower part; 129,34 m—129,50 m hard, somewhat calcareous sandstone, comparatively coarse, with glauconite and scattered coarse grains of quartz and feldspar (Pl. 1, Fig. D).
123,09—123,52	Coarse arkosic sandstone with phosphoritic nodules. Matrix with glauconite, calcareous and somewhat argillaceous. A fragment of feldspar at 123,50 m is 22 mm long (Pl. 1, Fig. E).
116,95—123,09	Dark grey siltstone and silty sandstone with glauconite; below 117,10 m with irregular stratification, containing seams, lenses, and sporadic lumps of sandstone, partly with calcareous matrix; coarse arkosic beds, 5 cm and 3 cm thick, below 122,84 m and 122,70 m respectively.
114,25—116,95	Mainly dark grey silty claystone and claystone.
110,78—114,25	Mainly dark grey siltstone with mostly thin intercalations of fine-grained sandstone with glauconite. 114,12 m—114,25 m slightly calcareous sandstone with aggregates of galena. Some layers of light grey clay in the uppermost part. Crystals and aggregates (thin layers, lenses) of pyrite occur with intervals throughout this part of the sequence.

is mainly built up of comparatively hard beds, sandstones and clastics. It is easy to imagine, however, that due to glacial erosion, only fragments of such beds could become erratics. The loose silty and clayey components of the sequence, eroded and carried by the ice, were disintegrated and redeposited within a southerly fan from the area, forming an important constitutent of the Quaternary clayey beds there.

As shown in Fig. 4, the content of sandstone and sandy sediments in the cores is relatively small, decreasing in an easterly direction within the Finngrunden banks. As the thickness of the sequence increases in that direction, so does the content of clayey matter. It is also evident, that the bulk of the erraticcs collected and described by Wiman were brought from a large area north of the Finngrunden banks.

A first glance at the core sections brings to light three notable observations. One of them concerns the absence of conglomerates, or coarser beds of any thickness, at the base of the sequence. This means that the sub-Cambrian surface under the lighthouse of the Finngrunden banks is smooth. This surface was formed by denudation over a long period, which seems evident from the fact that the basement rocks of pre-Cambrian gneisses are weathered, and in some places, deeply weathered.

A second observation of particular interest refers to the sudden appearance of fairly coarse arkosic beds situated in the sequence surprisingly high above its base. A definite interpretation of the environment of deposition of these beds will be

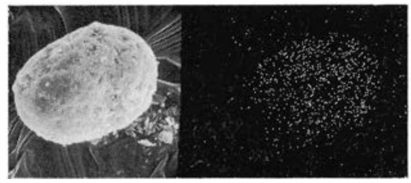


Fig. 5. a. Pellet from the core portion 98,27—98,34 m from Finngrundet (Table 4 p. 00). × 1000 in SEM. *b.* X-ray image of the same pellet showing the high concentration of Ti. Photo Henning Ivert.

possible in the future with more material available from other parts of the marine area. Evidently, the arkosic sediments emanated from pre-Cambrian rocks exposed between the Caledonian geosyncline and the Bothnian Gulf in an area (peninsula?) from where they were dispersed by streams, probably turbidity currents. It should be noted that the arkosic beds are thicker at Finngrundet than at Västra Banken which may indicate the direction of the streams. From Winterhalter's paper (1972, p. 35, Fig. 19), it is possible to conclude that the thickness of the Cambrian sequence increases considerably to the northeast and the north from the Finngrunden banks. It can also be postulated that an increase in thickness took place from these banks in a southerly direction towards Gotland, the thickness of the Lower Cambrian sequence of strata with fossils being 57,5 m at Gotska Sandön and approximately 80 m at File Haidar on Gotland.

Calcareous beds in the sequence, particularly at Finngrundet, are notable and also the rich occurrence of pyrite in the uppermost clayey part.

"Crow rock", mentioned in Tables 4 and 5, is a translation (Hessland 1953 p. 53) of the local Swedish word *kråksten*, by Westergård (1938 p. 16) described as "a peculiar greenish grey spotted rock, made up of rapidly alternating, very thin layers or small lenses of argillaceous or pure sandstone and shale in which the originally pronounced stratification has been veiled or destroyed by burrowing animals".

The Lower Tremadocian beds

The Ordovician Series begins in both cores with *Dictyonema-Obolus* beds. Their thickness at Finngrundet, 0,99 m, is nearly five times that at Västra Banken. They consist of three main lithological components: sandstone, alum shales, and limestone (stinkstone). The distribution of these components can be seen from Figs. 6 and 7.

The basal sandstone layer, about 1,5 cm thick in both cores, is slightly coarser than the other beds below the limestone. Like those, it consists of an impure quartz sandstone, spotted by flakes of mica (biotite and muscovite, the latter less common), with scattered grains of glauconite, small aggregates or single crystals of pyrite, and a calcareous matrix.

A lense- or crescent-shaped pyrite concretion of at least 3 cm thickness was pierced at Finn-

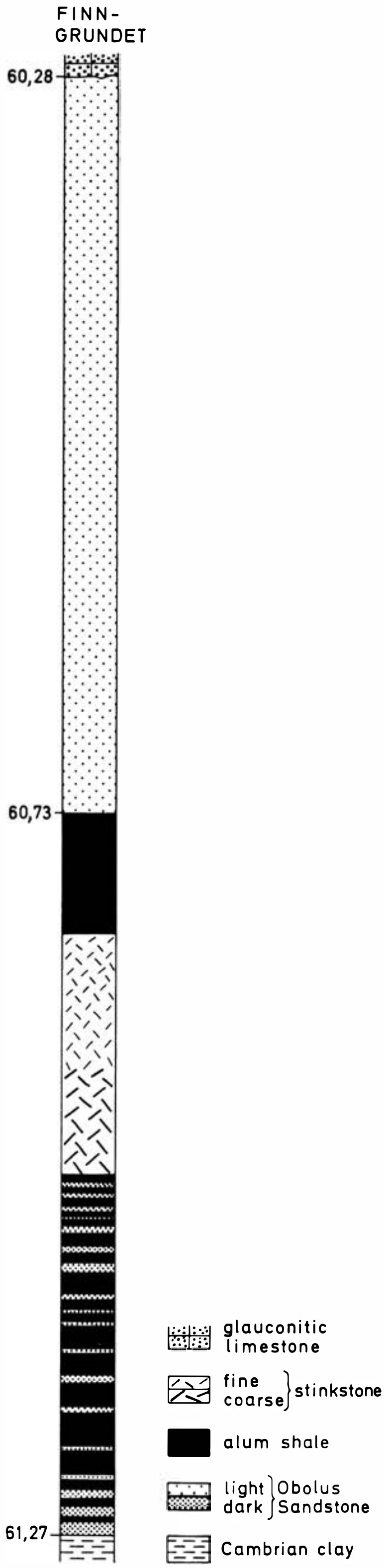


Fig. 6. Diagrammatic section of the lowermost Ordovician beds at Finngrundet.

grundet, and is located in the core portion below the limestone. Similar concretions of various size have been reported from deposits of moraine in East Sweden; they are supposed to derive from Tremadocian *Ceratopyge* shales in the Gulf area (Hessland 1949).

The sandstone is unsorted, with rounded or subrounded grains. As seen in the basal layer at Finngrundet, the largest grains of quartz are 0,4 × 0,34 mm; grains of feldspar are rare, the largest of those observed being 0,4 × 0,3 mm. Small fragments of inarticulate brachiopods are not uncommon, but are more frequent towards the top of the sequence, and this is reflected in the content of phosphate (cf. p. 41). Determinable fragments of *Obolus* occur in the upper light sandstone which is spotted green by glauconite. The darker sandstone has a varying content of bituminous matter.

Occasionally, the alum shales contain flakes of mica, small shell fragments, mostly weathered white or blue from vivianite, and pyrite or marcasite. These minute components, together with conodonts, are concentrated on some "bedding surfaces"; they also occur profusely in transition zones between sandstone beds and pure shales, or as intercalations in the shales.

Fragments of graptolites are found in the shaly parts. They are small and indeterminable in the Västra Banken core. A few bigger fragments of *Dictyonema* in the lower and upper shales of the Finngrundet core do not permit a specific determination due to the imperfect preservation. They may, however, belong to specimens of *Dictyonema sociale* (Salter) or *Dictyonema flabelliforme* (Eichwald), with those in the shales beneath the limestone possibly belonging to the former species, and those above it, to the latter. Apparently, shales with *D. sociale* are present in the sequence north of the Finngrunden banks. According to Tjernvik (personal communication), this species was found by him in an erratic piece of *Obolus* conglomerate with a shaly surface on the coast outside the town of Söderhamn. It has also been collected in a thin lense of alum shale intercalated in the basal Ordovician conglomerate at Skattungbyn in the Siljan district. The original description of *D. flabelliforme* was based on specimens occurring in Tremadocian shales of the Baltischport (= Paldiski) district of Estonia (cf. Bulman 1966).

In some respects, the sequence at Finngrundet is similar to that in Estonia where the thickness, however, is much greater. The repetition of sandstone beds with layers of *Dictyonema* shale is a distinctive feature common to both (Fig. 8).

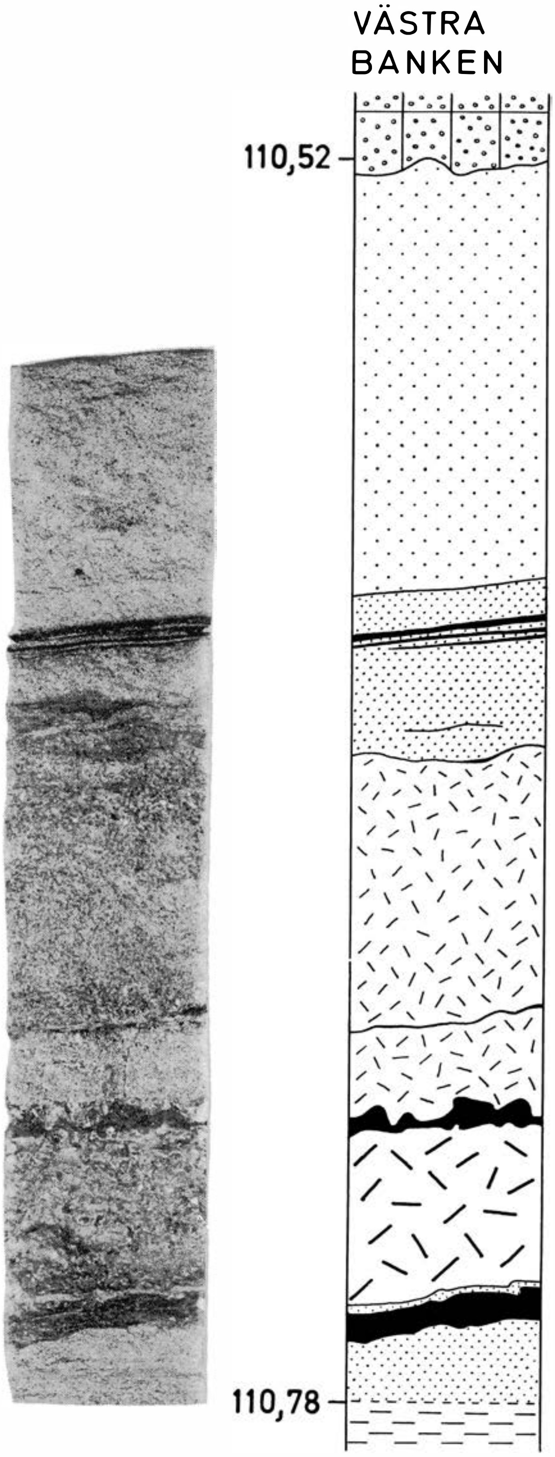


Fig. 7. Obolus-Dictyonema beds of the Västra Banken core with a diagrammatic section (legend, see Fig. 6).

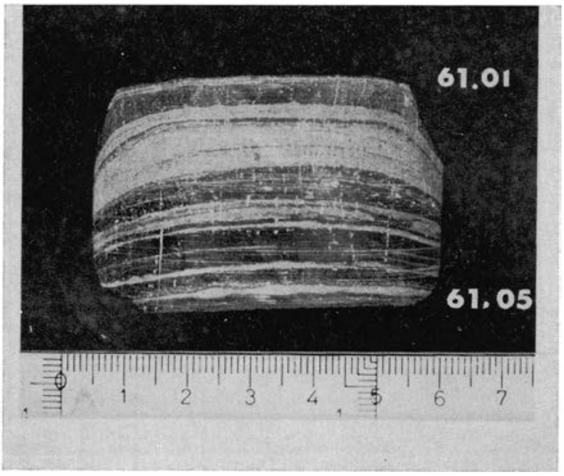


Fig. 8. Core portion with alum shale (black) and *Obolus* Sandstone indicating shifts in direction or strength of water currents during deposition. Finngrundet.

In Estonia, this repetition occurs in the upper part of the sequence and beneath a topmost, comparatively thick bed of *Dictyonema* shales. The Estonian sandstone, with or without shell beds and conglomerates, forms the lower part of the sequence (cf. Öpik 1929). Beds korresponding to these deposits, and also to the widespread thick beds of detritus and marcasite in Western Estonia, are not found in the Finngrunden core sections in which the *Dictyonema* shales are covered by *Obolus* Sandstone. The upper boundary of this sandstone is represented by a discontinuity surface (Pl. I, Fig. F). The richly glauconitiferous limestone above it contains scattered grains of quartz and a number of redeposited fragments of *Obolus*.

As in Estonia, the Ordovician Period in the Bothnian Gulf area commenced with a transgression after a considerable hiatus, and this is reflected by the sudden appearance of high contents of several trace elements in the Tremadocian beds. Such elements are, for instance, V, Mo, Ag, Pb, Cu, Sr, Sn, Ni, Bi, W, and Ge (Tables 1 and 2, p. 40 and 41, resp.; cf. Loog 1962 p. 290).

Acknowledgements. — The borehole project on the Finngrunden shoals was made possible through the support and assistence of the following authorities and gentlemen to whom I am greatly indebted: the authorities of the Swedish Board of Navigation, particularly Gunnar Kjellgren and Björn Tännström, respectively former Director and Assistent Director of the Building Section of this Board; Ansgar Falkenborn, former Director of the Pilot Service of Gävle; Mr. Gunnar Brundell, Gävle; K. A. Lindbergson, former Director-General of the Swedish Geological Survey; my colleagues, Professors I. Hessland, University of Stockholm, G. Regnéll, University of Lund, and R. A. Reyment, University of Uppsala; to the men who did the drilling, and to the boat crews for transporting equipment to and from the lighthouses.

My sincere thanks are also due to the technical staff of the Paleontological Institute in Uppsala for their valuable assistance during the preparation of this report, particularly to Mrs. Dagmar Engström for preparing the text figures, Mrs. Eva Eklind for typing the manuscript, Mr. Gustav Andersson for photographs, and Dr. Niall Mateer for the linguistic correction of my manuscript. Professor Reyment has kindly criticized and reviewed the entire manuscript. Thanks are due to Professor B. Collini for generous help with the manuscript.

Last, but not least, I want to thank my co-authors for their contribution to the results obtained up to now to the borehole project, and particularly I want to address myself to Torsten Tjernvik, whose eminent knowledge of the Lower Ordovician stratigraphy and paleontology of the Swedish mainland has been of utmost value for the investigation and interpretation of the comparatively scanty material obtained from the boreholes. He has fulfilled his painstaking task in spite of long periods of illness, thus manifesting his great interest in the work.

Generous grants from the Swedish Natural Science Research Council and from the Royal Swedish Academy of Sciences enabled the borehole project and the analyses of the cores to be realized.

Preliminary results from seismic investigations in the southwestern Bothnian Sea

By Stefan Axberg

Introduction

The present investigation is part of a project dealing with the distribution, stratigraphy, and tectonics of the sedimentary rocks in the western part of the Bothnian Sea. This report is restricted to the southern part of that area (Fig. 9).

The interpretation of the seismic profiles is based on results derived from drillings on the Finngrunden banks. The field work was carried out during the years 1973—1976 from the R/V Strombus, Department of Geology, Stockholm University. The Decca Navigator system, South Bothnian chain, was used to obtain position fixes. Approximately 2600 km of continuous seismic reflection profiles and 10 seismic refraction stations were

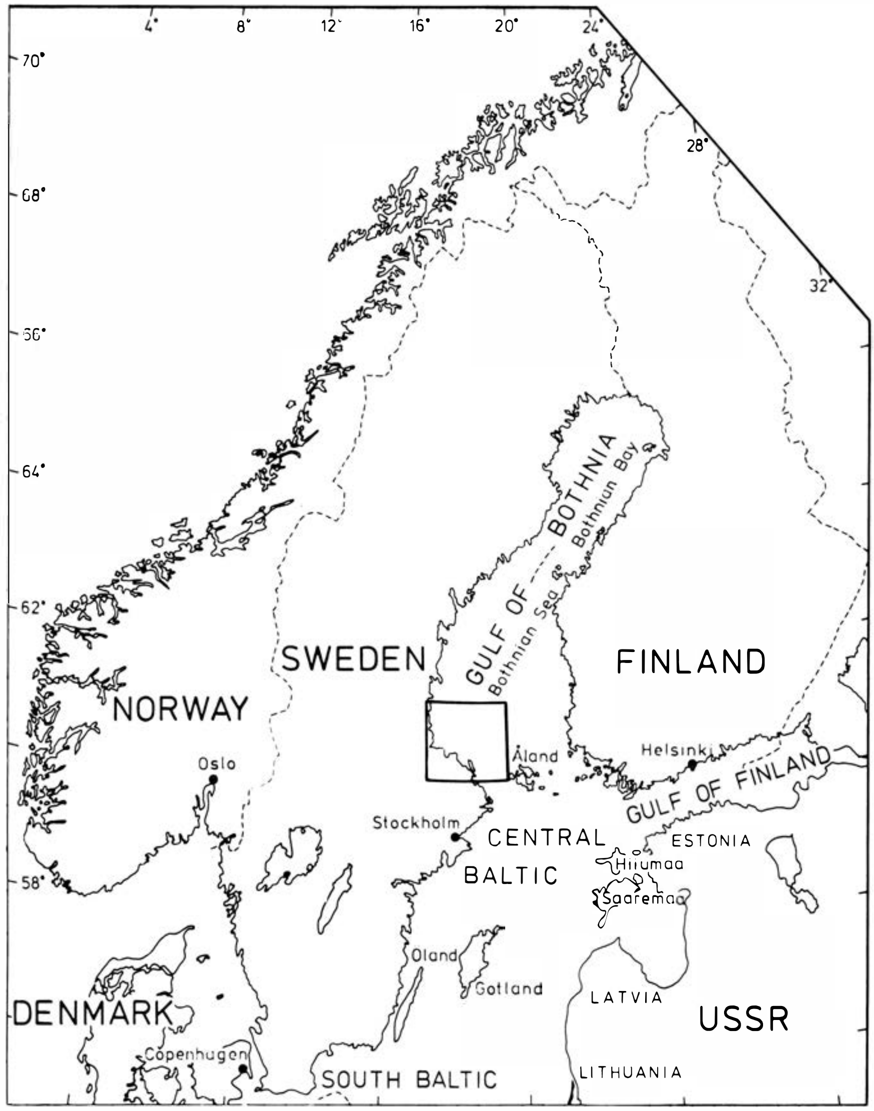


Fig. 9. Index map showing the location of the area investigated.

shot. The investigated area and the location of the seismic profiles is given in Fig. 10.

Penetration of the sedimentary rocks in the order of 200 m was occasionally obtained. However, the normal depth of penetration rarely exceeds 100—150 m in this area.

Acoustic stratigraphy

The term acoustic stratigraphy is introduced in this paper as it is believed that boundaries derived from acoustic investigations often are regarded falsely as chronostratigraphical boundaries (Fig. 11).

As the term acoustic stratigraphy stresses, an acoustic boundary is only an expression of a certain change of acoustic parameters in the sediments. These changes are mainly of a lithological character and generally denote either a discontinuance in the sequence or a change in the composition of the sediments.

Fig. 10. Area of investigation. The solid lines show the location of the continuous seismic reflection profiles made in 1973—1976 for this investigation. The thick lines denote portions of profiles reproduced in this paper. The adjacent numerals show the relevant figure number. The locations of the refraction seismic stations 1—10 are marked with asterisks.

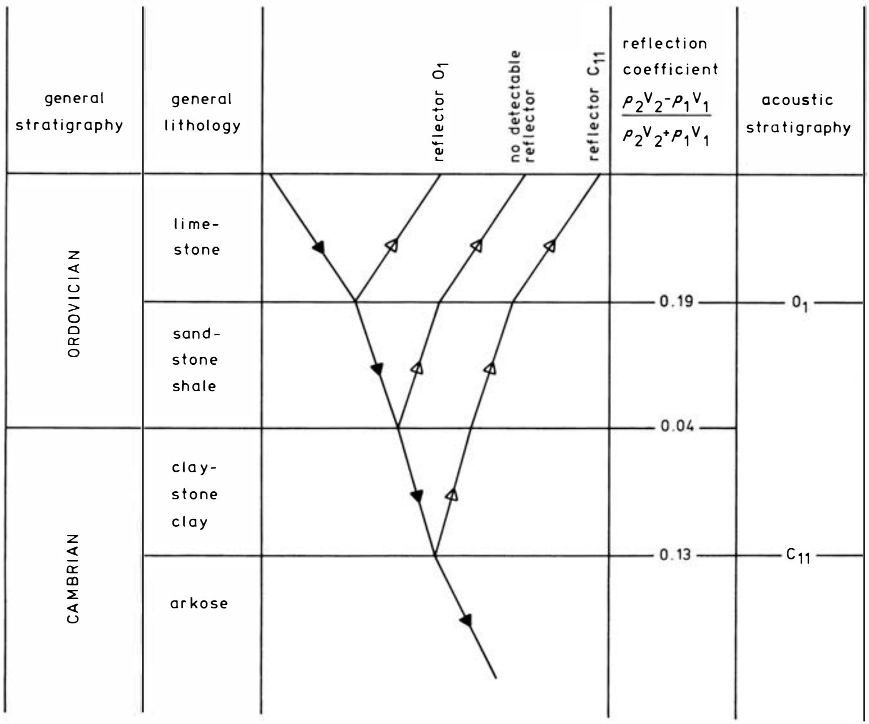


Fig. 11. Acoustic stratigraphy. The figure illustrates principally the relation between the general stratigraphy and the acoustic stratigraphy established in the area investigated. The reflection coefficients, calculated from assumed values of density and velocity, are not absolute figures; the numbers indicate only the relative magnitude of the reflection coefficient at selected surfaces.

List of acoustic boundaries

Q — boundary between Quaternary and pre-Quaternary sediments

O_{12} — hard surface in "*Raniceps*" Limestone

O_{11} — uppermost surface of *Limbata* Limestone

O_1 — transition zone between mainly shaly and mainly calcareous Ordovician strata (cf. B-surface in Winterhalter 1972)

C_{11} — thick arkosic bed with calcitic matrix in Lower Cambrian

C_1 — sub-Cambrian peneplain

The letters with indices denote acoustic boundaries found in the SW Bothnian Sea; they are not intended to correspond to markings of other areas.

Instrumentation

The continuous seismic reflection profiling (Hersey 1963) was performed with the following equipment.

A Bolt series 600 air gun fitted with a 30 cu ins chamber was used as transmitter. It was fired at 2000 PSI and at a rate of 40 shots per minute. The reflected signals were received by a 7 m hydrophone array consisting of 50 elements. The received signals were amplified and frequence filtered, band pass 100—200 Hz, and displayed on a Raytheon series 196A graphic recorder. The sweep time of the recorder was 0,5 seconds.

For the benefit of further signal processing, the received signals were recorded also before filtering on a magnetic tape recorder (Tandberg series 100). In order to improve the signal-to-noise ratio of the seismic signals, the unfiltered signals were processed by using simple summing methods on an Alpha LSI-2 mini-computer.

The processed profiles were transformed from the original time domain into the distance domain using the sound velocities derived from the seismic refraction profiles (Table 6). This process took place in a digital tracer and plotter system.

The instrumentation and field operation used for the continuous seismic refraction profiling (Hill 1963) was the same as described by Flodén (1975 pp. 10—12).

Determination of sound velocities

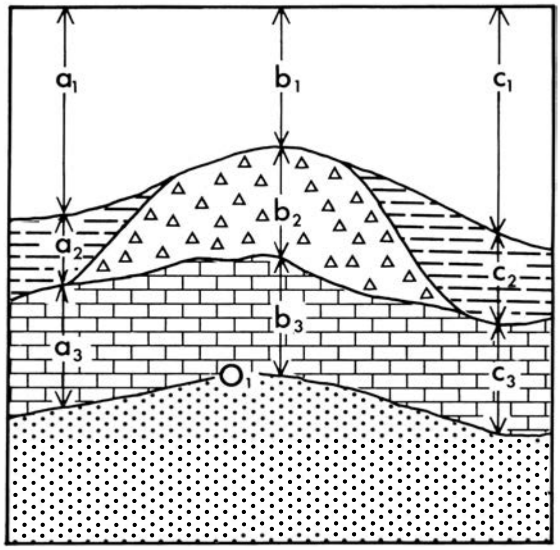
For a correct evaluation of continuous seismic reflection profiles, it is essential to determine the sound velacity of the investigated sediments. Without this information it is not possible to calculate a correct thickness between the acoustic boundaries.

Seismic refraction profiling was carried out for this purpose. The method of processing the refraction profiles was the same as that described by Flodén (1975 pp. 12—14). Within the investigated area, the sound propagation velocity in water was estimated to be 1,43 km/sec (cf. Winterhalter 1972 p. 10).

Calculation of the thickness of the Quaternary deposits, consisting mainly of clay and till, was carried out by adopting a velocity of 1,9 km/sec.

Table 6. Results from seismic refraction profiling. For location of stations, see Fig. 10.

station	velocity	assumed corresponding stratum
1	2,12 km/sec	Quaternary deposit (till)
	3,38	Ordovician limestone
	5,82	crystalline basement
2	3,44	Ordovician limestone
	5,84	crystalline basement
3	3,77	Ordovician limestone
	5,94	crystalline basement
4	3,34	Ordovician limestone
	4,80	Jotnian sandstone
	5,98	crystalline basement
5	3,64	Ordovician limestone
	4,77	Jotnian sandstone
	6,23	crystalline basement
6	3,56	Ordovician limestone
	4,76	Jotnian sandstone
	5,96	crystalline basement
7	3,29	Ordovician limestone
	4,08	Ordovician limestone
	5,49	crystalline basement
8	2,51	Cambrian clay/sandstone
	5,64	crystalline basement
9	4,68	Jotnian sandstone
	5,92	crystalline basement
10	3,41	Ordovician limestone
	4,14	Ordovician limestone
	4,79	Jotnian sandstone
	5,63	crystalline basement



	recorded TWT time	assumed layer	assumed velocity	calculated thickness	depth to reflector O_1
a_1	39 ms	water	1,43 km/s	27,9 m	
a_2	13 ms	clay	1,60 km/s	10,4 m	
a_3	23 ms	limestone	3,50 km/s	40,3 m	*78,6 m*
b_1	26 ms	water	1,43 km/s	18,6 m	
b_2	21 ms	till	2,10 km/s	22,1 m	
b_3	22 ms	limestone	3,50 km/s	38,5 m	*79,2 m*
c_1	42 ms	water	1,43 km/s	30,0 m	
c_2	17 ms	clay	1,60 km/s	13,6 m	
c_3	21 ms	limestone	3,50 km/s	36,8 m	*80,4 m*

Fig. 12. Control of adopted sound velocities. In order to check the adopted velocities (Table 6), a portion of a continuous seismic reflection profile was studied in detail. The interval times were measured at three points (a, b and c) from an hypothetical datum line. The depth to the acoustic boundary O_1 was calculated at each point. The surface O_1 was found to be almost horizontal, a result that was expected, and that the rise of O_1 below b_2 is only a velocity high. If the interval b_2 is interpreted as being a reefstructure, with an assumed velocity of 4,0 km/sec (Flodén 1975), a depression of approximate 20 m would, in that case, be present below the structure, a result that is unlikely.

However, this assumption implies that the clay has a velocity of approximately 1,6 km/sec and the till a velocity of approximately 2,1 km/sec. The latter velocity was recorded at station 1 (Table 6) in a sediment interpreted as till.

Recorded velocities between approximately 3 and 4 km/sec have been divided into two groups. The first group has only two recorded values, 4,08 and 4,14 km/sec, and is believed to be associated with hard layers in the Ordovician limestone of only limited extension. The second velocity group with values between 3,29 and 3,77 km/sec is tentatively accepted as the general velocity in Ordovician calcareous layers. This is in good accordance with values found in the Baltic Sea (Flodén 1975). The mean value, adjusted to 3,5 km/sec, has been used for all calculations of Ordovician strata above the acoustic boundary O_1 (cf. Fig. 12).

It should be noted that it is only possible to measure the velocity of the Cambrian strata at locations where the uppermost part of the bedrock consists of Cambrian sediments. This depends on the presence in most parts of the investigated area of high-velocity layers overlaying the Cambrian strata. Refraction station number 8 was located under this assumption. A velocity of 2,51 km/sec was recorded and, adjusted to 2,5 km/sec, was used for the calculation of the thickness of the Cambrian strata.

Velocities in the Jotnian sandstone were expected to be in the order of 5 km/sec (Flodén 1975). Results of that magnitude were obtained at five stations. At stations 4, 5, 6 and 10, the recorded velocities were 4,80, 4,77, 4,76 and 4,79 km/sec, respectively. At station 9, a somewhat lower velocity was recorded, 4,68 km/sec. For calculations of Jotnian strata, a value of 4,8 km/sec has been used.

Velocities assumed to be associated with the crystalline basement have been recorded in the range of 5,49 and 6,23 km/sec.

General geological setting

The Bothnian Sea forms a depression in the pre-Cambrian Baltic Shield. It is to a large extent filled with late pre-Cambrian (Middle and possibly also Late Riphean) and Early Paleozoic (Cambro-Ordovician) sedimentary rocks (Fig. 13).

The adjoining land area consists of pre-Cambrian igneous and metamorphic rocks but with a few exceptions. Jotnian sandstone (Middle Riphean), tectonically preserved, forms fairly large areas near Gävle in Sweden (Gorbatschev 1967) and near Björneborg in Finland (Laitakari 1925). Jotnian bedrock is also present in the region of Nordingrå, 40 km N of Härnösand (Sobral 1913). Westergård (1939) reported the occurrence of Lower Cambrian clay at Holmudden, 10 km NE of Gävle. The clay rests on a light reddish sandstone different from the underlying reddish Jotnian sandstone (cf. below). Cambrian sandstone in minor fissure fillings is found in SW Finland (Tanner 1911, Asklund 1926 and Martinsson 1956). Early Paleozoic sediments are also present in Lake Lumparen on Åland (Sauramo 1943).

Sedimentary rocks in the SW Bothnian Sea

The Gävle Bay area

From studies of erratics Wiman (1893) pointed out that two different types of red sandstone are present in the Gävle area. The most common type is a reddish quartzitic sandstone with yellowish white spots and stripes developed along its bedding planes. This sandstone, considered to be of Jotnian age, is commonly referred to as Gävle Sandstone. On the mainland the Gävle Sandstone, accompanied by conglomerates and dolerites, extends in a long and narrow area from Gävle and southwestwards. The sandstone is downfaulted and constitutes remnants of a formation that once covered a much larger area.

The second type of red sandstone that Wiman (op. cit.) identified in the Gävle area is described as light reddish to white and containing kaolin. This sandstone has been found in situ only in the drilling at Holmudden (Westergård 1939), 10 km NE of Gävle.

The reddish, quartzitic Jotnian sandstone was here found to be covered by more than 7 meters of a light reddish to grey-white sandstone containing kaolin. At the base of the sandstone, and also on top of it, a thin polymict conglomerate was found. The age of this light reddish sandstone has not been determined definitively. Westergård (1939) and Lundegårdh (1967) consider it to be Late Riphean or Early Cambrian.

On land, in the Gävle Bay area, Paleozoic rocks have only been found in situ in the Holmudden boring. More than 11 m of blue-green, very hard, clay of Lower Cambrian age was here found to overlie the possibly Late Riphean sandstone (Westergård 1939). On the island of Limön, in the inner part of the Gävle Bay, a large ice-transported thin wedge of Ordovician limestone constitutes the NE part of the island. The limestone was believed to be in situ until an excavation and

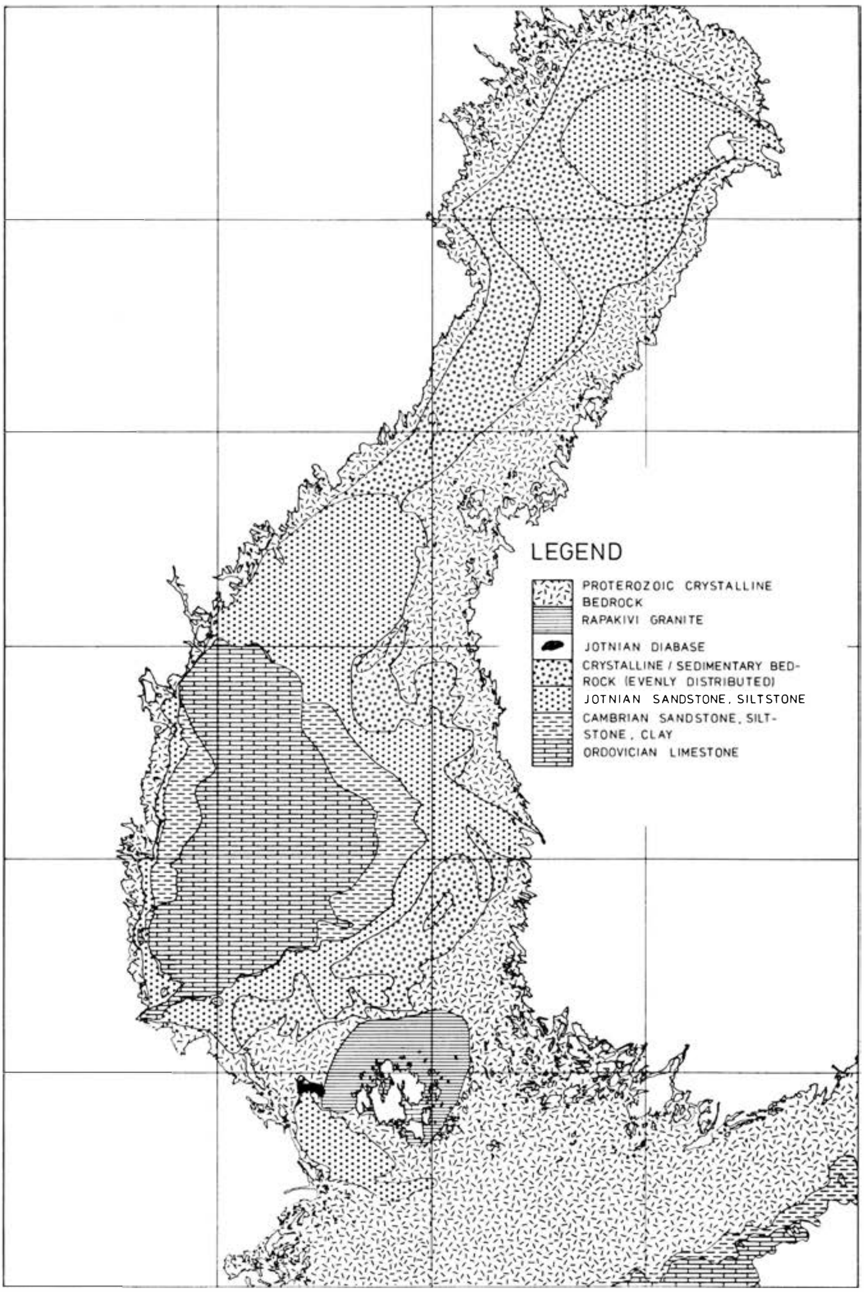


Fig. 13. General geological setting. After Axberg & Flodén (1977).

a boring pierced the limestone plate (Westergård op. cit.) and revealed it to be only 3—4 m thick and underlain by till deposits of Quaternary age. On the small island of Granskär, 3 km W of the island of Limön, the condition seems to be similar to that of the island of Limön. An excavation by Asklund, reported on by Westergård (1939), was terminated at a depth of 4,5 m while still in beds of Ordovician age. However, it seems likely that the limestone partly constituting the island of Granskär is part of an ice-transported plate.

The Port Authority of Gävle carried out in 1965 a refraction seismic investigation in the area NE of the harbour (H. Lundqvist, personal com-

Fig. 15. Map of the bedrock distribution in the SW Bothnian Sea.
1 — Ordovician strata above the acoustic boundary O_1
2 — Strata between the acoustic boundaries C_1 and O_1 (mainly Lower Cambrian)
3 — Jotnian sandstone
4 — Proterozoic crystalline bedrock.
The broken line between the Jotnian sandstone and the crystalline bedrock indicates that minor outliers of Jotnian sandstone may occur within the area marked as crystalline bedrock.

munication, 1978). Sound velocities ranging between 3 and 4 km/sec were registered. The results of this refraction seismic investigation were used for planning of the dredging activities carried out during 1965—1967. During the dredging, limestones were scraped off the bottom. This information indicates the presence of a limestone bed close to the harbour, either in situ or allochthonous.

Based on the Holmudden and Limön borings, the excavations and the rich occurrence of erratics, Westergård (1939) concluded the following Paleozoic sequence was present in the Gävle Bay area:

Limbata Limestone
Planilimbata Limestone
Lower *Didymograptus* clay
Ceratopyge Limestone
Ceratopyge Shale
Obolus Conglomerate
Lower Cambrian Sandstone
Lower Cambrian clay

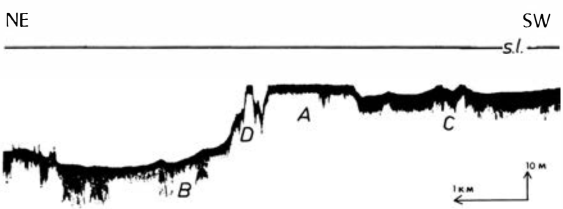


Fig. 14. Echo-sounding profile obtained in the inner part of the Gävle Bay (location in Fig. 10). D—A mark an area interpreted as consisting of remnants of Paleozoic sedimentary bedrock. B indicates an uneven bedrock topography with rather thick Quaternary clays deposited on top of the bedrock. At C the profile intersects a minor ridge interpreted as a terminal moraine (Axberg, in prep.).

In the inner part of the Gävle Bay (location given in Fig. 10), a profile, reproduced in Fig. 14, was obtained by a 30 kHz echo-sounder. The echosounding was carried out parallel to the ordinary continuous reflection seismics. Due to the shallow water conditions, the seismic records from this area tend to be distorted and of poor quality. The left portion, constituting the northeastern part of the echosounding profile, is characterized by an uneven bedrock topography (B in Fig. 14). The bottom gives a rather smooth impression depending on the presence of fairly thick Quaternary clays deposited on top of the bedrock. From morphological reasons and indications found in the seismic records, the bedrock in this part of the profile has been interpreted as being a pre-Cam-

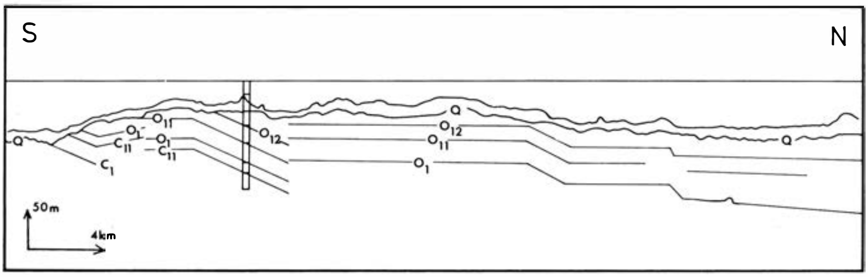


Fig. 16. Schematized geological section based on a continuous seismic reflection profile (S7504 0710 —1040) obtained near to the Västra Banken lighthouse (location in Fig. 10). A simplified version of the Västra Banken core is inserted. The letters with subscripts refer to acoustic boundaries identified.

brian sedimentary rock, probably Jotnian sandstone.

Between the markings B and D on the profile, the bedrock rises approximately 35 m and exhibits a very flat surface towards the SW (D—A in Fig. 14). This portion traverses the area where the dredging, previously mentioned, was carried out, and is interpreted as consisting of remnants of Paleozoic sediments. The bedrock surface, which only has a thin cover of Quaternary deposits, is acoustically very hard and bear a good resemblance to Ordovician limestones recorded in other areas. In the right part of the echo-sounding profile, the relief of the bedrock is partly masked by a layer of till on top of which clay is deposited. At the marking C, the profile intersects a minor ridge interpreted as a terminal moraine (Axberg, in prep.).

The described echo-sounding profile cannot contribute to an indisputable interpretation on the bedrock distribution in the inner part of the Gävle Bay. However, combined with other available data, it supports the interpretation given in the map shown in Fig. 15.

In the vicinity of Gävle the SW—NE Bönan fault forms the boundary between the crystalline bedrock on land and the sedimentary bedrock in the inner part of the Gävle Bay. This boundary follows in large a SW—NE direction, but is to some extent interrupted by the interaction of NW—SE tectonic lines.

The Finngrunden shoal area

This region constitutes the southern part of a long and rather broad, shallow area that reaches from the Swedish coast in the south to the Eystrasalt Bank in the central part of the Bothnian Sea. This long N—S area was named the Central Ridge by Winterhalter (1972). The NW limit of the Finngrunden shoal area coincides with the NE prolongation of the Bönan fault. To the south, the shoal area is limited by the boundary between Jotnian and Paleozoic sediments (cf. Fig. 15). The fact that Jotnian sediments are missing in the two Finngrunden cores indicates early unstable conditions within this region (cf. Fig. 3 and p. 60). Features in the continuous seismic reflection profiles recorded during the present investigation, indicate that considerable tectonic movement has occurred, especially in the southern part of the Finngrunden shoal area.

A simplified geological section is reproduced in Fig. 16. The section is based on a seismic reflection profile running from south to north and passing 200 m east of the Västra Banken lighthouse (location in Fig. 10). This is a key section for the correlation of the registered acoustic boundaries with the Västra Banken core. In this way it has been possible to establish a tentative acoustic stratigraphy for the present area.

The bedrock is covered by a comparatively thin layer, 10—15 m thick, of Quaternary deposits, mainly glacial drift. The thickness of these unconsolidated sediments increases slightly towards the north. The bedrock is influenced by tectonic movements, two faults and several joints have been observed. The faulting has caused down-thrusting and tilting of a block, probably of SW—NE extension, penetrated by the Västra Banken drilling.

The lowermost part of the Ordovician strata, consisting of a thin sequence of shale and sandstone (cf. Fig. 6), cannot be separated from the underlying Lower Cambrian beds with the methods used in the present investigation (Fig. 11). The Ordovician sequence above the acoustic boundary O_1 (p. 51) consists predominantly of limestone The sequence has been divided by the acoustic boundaries O_{11} and O_{12} (p. 51) into three parts. The lower part, between the acoustic bounda-

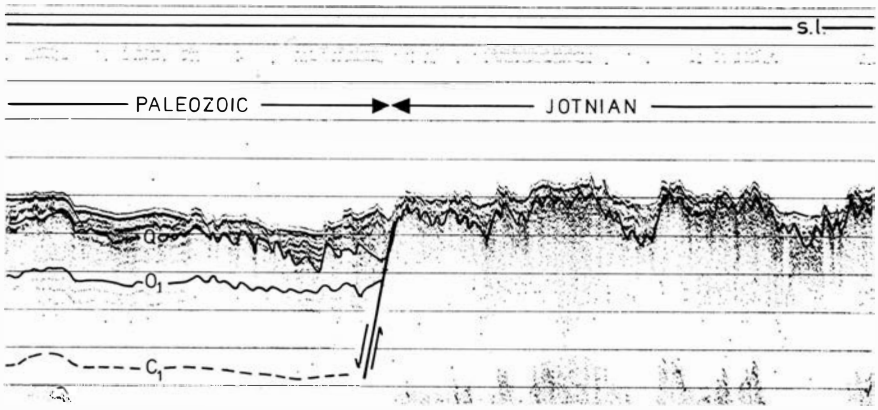


Fig. 17. Part of a continuous seismic reflection profile (S7322 0520—0600) across the Paleozoic/Jotnian boundary (location in Fig. 10). The Paleozoic rocks are downfaulted about 70 m. The two way travel-time (TWT) between the horizontal scale-lines is 12,5 ms. The horizontal scale, depending on the ship speed etc., is approximately 1:72.000.

ries O_1 and O_{11}, represents Lower and Middle Arenigian limestones. Between O_{11} and O_{12} the beds consist of Upper Arenigian limestones. The uppermost division of the Ordovician strata, above the acoustic boundary O_{12}, consists of limestones from the lowermost part of Llanvirnian.

The total thickness of the Ordovician beds in the section increases towards the north. The largest part of this increase occurs between O_1 and O_{11}. This might be explained by the appearance of stratigraphical units missing in the Västra Banken core, i.e. the *Ceratopyge* Stage. The thickness between O_{11} and O_{12} seems to be rather constant within this section. An increasing thickness towards the north is found not only between O_1 and O_{11}, but also for the layers above O_{12}. This is probably caused by an addition of younger stratigraphical units (cf. the section in Fig. 16).

The occurrence in the Lower Cambrian sequence of a 2—3 m thick arkosic bed, containing relatively high amounts of $CaCO_3$, has made it possible to establish the acoustic boundary C_{11}. The Lower Cambrian series of strata is thus divided into two parts — a lower part between the sub-Cambrian peneplain, C_1, and the acoustic boundary C_{11}, and an upper part between C_{11} and O_1. The latter part includes also the non-calcareous Ordovician strata (cf. Fig. 11).

In the seismic profile, on which this section is based, it is not possible to trace the sub-Cambrian peneplain and C_{11} further to the north than to the site of the Västra Banken lighthouse.

Judging from the Västra Banken core, the Cambrian was deposited directly on crystalline rocks of Svecofennian age. The sub-Cambrian peneplain outside the shoal area of Finngrunden seems, however, to have been formed in Jotnian sandstone, as indicated by the presence of Jotnian sandstone at all refraction stations outside the shoal area (Table 6).

As shown by the map in Fig. 15, Jotnian sediments cover the area south of the Finngrunden shoals. A portion of a continuous seismic reflection profile across the Paleozoic/Jotnian boundary is given in Fig. 17.

To illustrate the bedrock conditions near the Finngrunden drilling site, a schematic section was

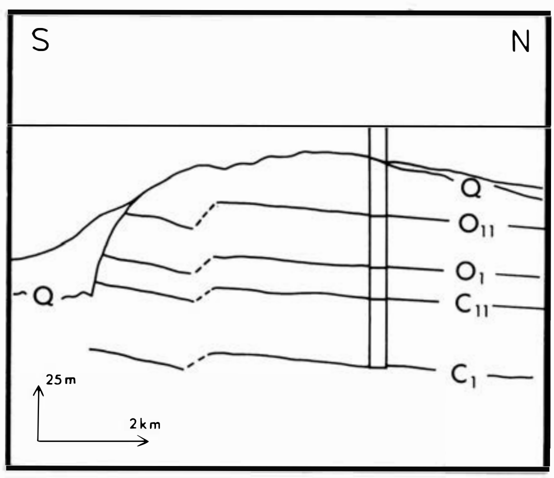


Fig. 18. Schematic geological section based on a continuous seismic reflection profile (S7322 1000—1050) obtained near the Finngrunden ligthouse (location in Fig. 10). A simplified version of the Finngrunden core is inserted. The letters with subscripts refer to acoustic boundaries identified.

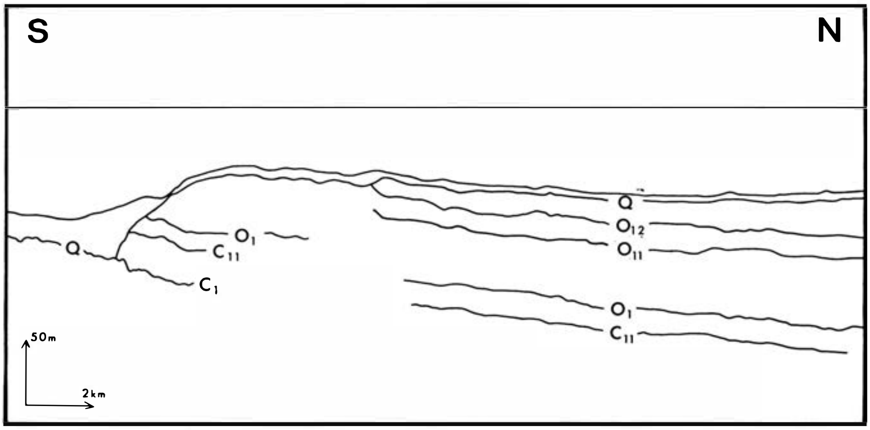


Fig. 19. Geological section based on a continuous seismic reflection profile (S7505 1500—1640) obtained 9 km east of the section in Fig. 18 (location in Fig. 10). The letters with subscripts refer to acoustic boundaries identified.

drawn (Fig. 18). This section is based on a seismic reflection profile obtained very close to the Finngrunden lighthouse tower (location in Fig. 10). Like the previously described section (p. 56) this is a key section at the attempt to correlate the drilling results with the registered acoustic boundaries.

In this section Quaternary deposits are only found in the northern and southern ends. The Quaternary deposits are 2—3 m thick in the northern part, while towards the southern end they may thicken to as much as 30 m. The thick layer of Quaternary sediments in the southern part of the section has made the sea bottom topography smooth, although the Paleozoic bedrock surface is developed as a scarp in this part of the investigated area (cf. also Fig. 19). This configuration of the Paleozoic/Proterozoic boundary is tentatively interpreted as due to the combined action of tectonic and erosional forces.

Good correlation between the Finngrunden core and the tentative acoustic stratigraphy (p. 51) has been established. The thickness of the sequence between O_{11} and Q is of the same magnitude as the thickness between Q_{11} and Q_{12} found in other profiles from the Finngrunden shoal area (Figs. 16 and 20). This may indicate that the exposed bedrock at the Finngrunden lighthouse is preserved owing to a surface bed resistant to erosion.

The Ordovician series of strata above the acoustic boundary O_1 is divided into two parts by O_{11}, representing the top of the *Limbata* Limestone. The thickness of the Arenigian limestones between O_1 and O_{11}, corresponding to the lower part of this stage, is approximately 20 m in the southern part of the section. Towards the north, the thickness increases gradually to a maximum of almost 25 m.

The Västra Banken and the Finngrunden cores revealed the thickness of Cambrian strata to be 8 m greater in the latter boring. This is also true in the seismic reflection profiles obtained close to the two boring sites. It is noteworthy that the entire increase in thickness is found between C_1 and C_{11} (cf. p. 61).

From the Finngrunden drilling it is evident that the bedrock underlying the Paleozoic sediments consists of crystalline rocks of Svecofennian age. The seismic reflection profile, on which the section in Fig. 18 is based, indicates Jotnian sandstone to be present south of the Paleozoic/Proterozoic

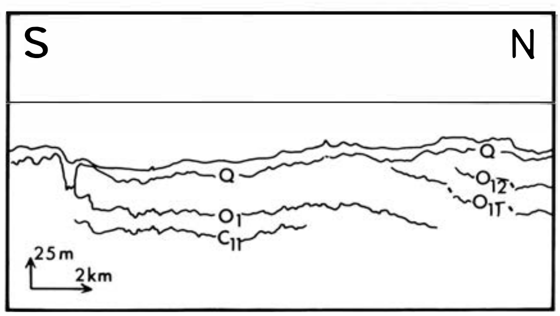


Fig. 20. Geological section based on a continuous seismic reflection profile (S7505 2110—2220) obtained close to the profile in Fig. 17 (location in Fig. 10). The letters with subscripts refer to acoustic boundaries identified.

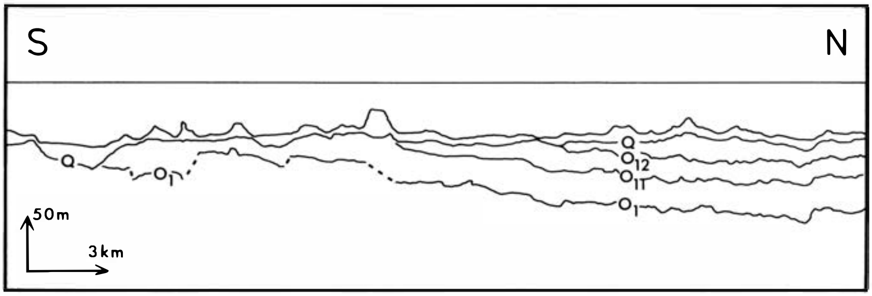


Fig. 21. Geological section based on a continuous seismic reflection profile (S7504 0020—0240) obtained 16 km west of the section in Fig. 16 (location in Fig. 10). The letters with subscripts refer to acoustic boundaries identified.

boundary (cf. Fig. 15). A weak reflector in the assumed Jotnian sandstone has been observed 135 m below the bedrock surface. Considering this, and the fact that results from the examination of the pre-Cambrian part of the Finngrunden core (p. 42) indicate the presence of a major fault not far from the drill site, it is assumed that a fault with a vertical displacement of more than 110 m terminates the Paleozoic sequence southwards. This fault is situated 5 km south of the Finngrunden drilling site and has an assumed direction of SW—NE. Further to the NE, the fault becomes less prominent. In the section in Fig. 19, the vertical displacement is about 25 m, while further to the north (Fig. 22), the displacement is less than 10 m.

Another fault, almost parallel to the former, is found 7 km westwards. The Paleozoic sequence is there downfaulted 65—70 m as illustrated in Figs. 17 and 20. The section in Fig. 20, located between the two Finngrunden drilling sites, shows also tectonic disturbance in its northern part, probably resulting from the influence of movements along the fault just north of the Västra Banken lighthouse.

The section given in Fig. 19 represents the eastern part of the Finngrunden shoal area. The southern portion of the section shows the Paleozoic/Proterozoic boundary. In this part of the section, the sub-Cambrian peneplain is clearly detectable, while further to the north, faulting and increasing thickness of the sediments made it impossible to follow the peneplain. In the central part of the section, north of the fault, the Paleozoic sequence grows thicker, from 110 m to 135 m in the north, assuming a constant thickness between C_1 and C_{11}. A large portion of this increased thickness is located between the acoustic boundaries O_1 and O_{11}.

The area north and west of the Finngrunden shoals

A major fault runs in N—S direction along the coast between Gävle and Söderhamn, and further northwards. It is composed of a series of faults of NW—SE and NE—SW directions. The western limit of the Jotnian sandstone extension seems to be very close to the coast line, in some cases even situated inside the outer islets. On the map in Fig. 15 this limit is drawn only approximately as the seismic reflection profiles, due to navigational reasons, were terminated while still on Jotnian sandstone.

The western limitation of the Paleozoic sequence can be followed clearly in the seismic reflection profiles. From Gävle and approximately 30 km towards the NE the Paleozoic/Proterozoic boundary follows the extension of the Bönan fault (p. 56). From there on, the boundary runs parallel to one of the main tectonic directions, NW—SE, with some N—S interruptions (Figs. 13 and 21). Further towards the north the boundary parallels the coast line with only local NW—SE and NE—SW deviations.

Within the north-westerly part of the investigated area, the Paleozoic sequence is uplifted (Fig. 22). The dip of the sub-Cambrian peneplain is here to the east instead of the gentle westerly dip normally found in the Bothnian Sea (Winterhalter 1972).

Outliers, possibly of Paleozoic age, have been noted in the area west of the island of Storjungfrun, approximately 20 km SE of Söderhamn. The seismic reflection profile across this area resembles acoustically those obtained in areas interpreted as consisting of limestones. Accordingly this area is marked as Ordovician on the bedrock map in Fig. 15.

An E—W section across the Bothnian Sea

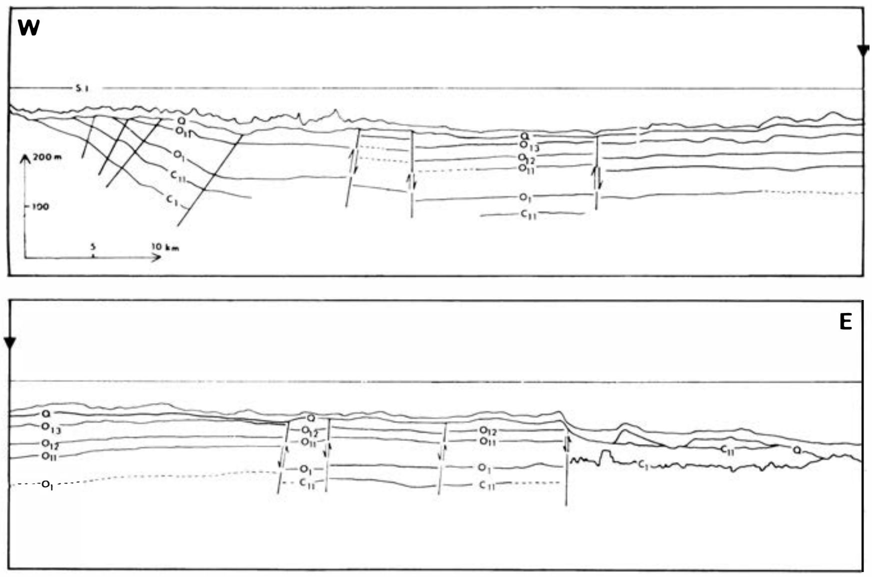


Fig. 22. Geological section based on a continuous seismic reflection profile (S7507 1746—0500) obtained from the Swedish coast and eastwards (location in Fig. 10) as far as the Paleozoic/Proterozoic boundary (cf. bedrock map in Fig. 15). The letters with subscripts refer to acoustic boundaries found. The acoustic boundary O_{13} has not been noted in the southern part of the studied area. Due to the absence of boreholes in this part of the Bothnian Sea, it is not possible at present to correlate this boundary stratigraphically. Hence O_{13} is not included in the list of acoustic boundaries (p. 51).

within the northern part of the investigated area is given in Fig. 22. A new acoustic boundary, O_{13}, is marked in the section. This boundary has not been noted in the southern part of the investigated area and, due to the lack of drilling in this part of the Bothnian Sea, it is not at present possible to correlate this boundary stratigraphically. It should, however, be mentioned that erratic boulders of the lower Middle Ordovician *Platyurus* and *Schroeteri* Limestones have been found in the vicinity of Gävle (e.g. Westergård 1939) and also that samples from the Sylen shoal were found to consist of limestones from the uppermost part of Middle Ordovician (Winterhalter 1967).

The section in Fig. 22 illustrates also that the tectonic influence is greater towards the flanks than in the middle part of the Paleozoic bedrock area. The considerable disturbance to the east along the Paleozoic border is clearly shown by the section in Fig. 23, in which numerous faults and joints have been registered. This section also demonstrates an increasing thickness of the Paleozoic sequence towards the north.

Concluding remarks

It is evident that without the possibility of correlating the acoustic boundaries with the two Finngrunden shoal borings, the outcome of the present investigation would have been limited.

The established acoustic stratigraphy is, however, only relevant in the proximity of the drilling sites, a fact that stresses the necessity of further borings in the Bothnian Sea.

The tectonic pattern in the SW Bothnian Sea seems to be complicated. The strongest tectonic influence is found within a zone, 10—15 km wide, along the Paleozoic/Proterozoic boundary (cf. Figs. 15, 22, and 23).

As indicated in the seismic profiles, the Finngrunden shoal area seems to be divided in at least two tectonic blocks with a SW—NE direction. The absence of Jotnian bedrock in the two Finngrunden cores indicates that the Finngrunden shoals form an anomalous region in the SW Bothnian Sea. This is also supported by the fact that the *Ceratopyge* Stage, frequently found as erratics on the Swedish coast, is missing in the cores.

A gentle increase in thickness towards the north of the entire Paleozoic sequence is indicated in the seismic profiles (e.g. Figs. 16 and 21). Minor variations of thickness of the beds are probably caused by local lithological changes and associated changes in the propagation of sound. In Fig. 23, an increase in thickness between C_{11} and O_1 has been registered between the markings A and B. It seems unlikely that this thickening, from 20 to 35 m, is due to a decrease in sound velocity.

The relative position of C_{11} versus C_1 and O_1 varies in several regions within the investigated area (e.g. Figs. 19 and 23). As C_{11} represents an arkosic bed in the clayey and silty Lower Cambrian sediments, the relative position of C_{11} may be of paleogeographical significance.

Summary of results

Per Thorslund and Stefan Axberg

With due regard to previous research, predominantly based on erratics from the sedimentary bedrock of the Bothnian Sea, the following main results have been obtained from the investigation of the two cores from the Finngrunden banks.

The Lower Cambrian sequence in the eastern part of the marine area has been made available for records of its thickness and lithology. An increasing thickness in an easterly direction is found, and the sediments, rich in clayey matter, are less sandy in that direction. Seismic reflection profiling data have shown that this sequence is much thicker in the areas east and northeast of the banks, and very likely the content of sandstone beds is more abundant there. From the composition of the sequence in the cores, it is evident that most of the erratics of Lower Cambrian beds spread on the neighbouring southern mainland and islands derive from these areas, probably also from a comparatively narrow area along and outside the Swedish coast (cf. Winterhalter 1972 p. 35, Fig. 19; and p. 55).

Coarse, arkosic beds intercalated in the clayey sediments comparatively high above the base of the sequence, indicate the presence during early Cambrian times of land areas with exposed crystalline rocks not very far from the shore of the Bothnian Sea. Middle and Upper Cambrian beds are missing.

Dictyonema Shales are recorded for the first time in the Tremadocian beds of the Bothnian Sea area. It is noteworthy that *Ceratopyge* beds, i.e. shales and limestone, found as erratics, are not present in the sequence of the cores. This implies that there is a comparatively high degree of variation in the completeness of the Tremadocian series of strata within the marine area (cf. Thorslund 1960 p. 101). It also means that the discontinuity surface at the top of the *Obolus* Sandstone denotes a stratigraphical gap between the Tremadocian and the Arenigian parts of the sequence in the bedrock of the Finngrunden Banks.

The lighthouse of Finngrundet (Östra Banken) is located on Lower Ordovician limestone in the neighbourhood of a fault, Jotnian or post-Jotnian of age, which took place long before the transgression of the Cambrian sea as documented by the great depth of the weathering in the crystalline basement of the core sequence.

Owing to the scarcity of porous beds in the Finngrunden banks, the content of asphaltic matter is very small in the sequence of the cores. Consequently, the rather commonly occurring erratics of dark, asphaltic sandstone derive from the area north of the banks.

The seismic investigation was carried out during 1973 and 1976 from R/V Strombus. Approximately 2600 km of continuous seismic reflection profiles and 10 seismic refraction stations were shot. Penetration of the sedimentary rocks in the order of 200 m was occasionally obtained, however, the normal depth of penetration rarely exceeds 100—150 m in this area.

The term acoustic stratigraphy is introduced as it is believed that boundaries derived from acoustic investigations are often falsely regarded as chronostratigraphical boundaries.

The investigation has provided new details on the distribution of the Paleozoic rocks in the SW Bothnian Sea. Their western limit coincides with a large fault line extending northwards from Gävle. The Finngrunden banks are shown to form an anomalous region, where the Jotnian sediments are missing and the Paleozoic sequence is reduced in thickness. The tectonic pattern is shown to be complicated with lineaments in the main NE—SW and NW—SE directions.

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Plate 1. Some parts of the core at Västra Banken.

A. Core portion with the boundary between pegmatite and Cambrian sandstone.

B. Core portions with arkosic beds, from the basal part of the Cambrian sequence.

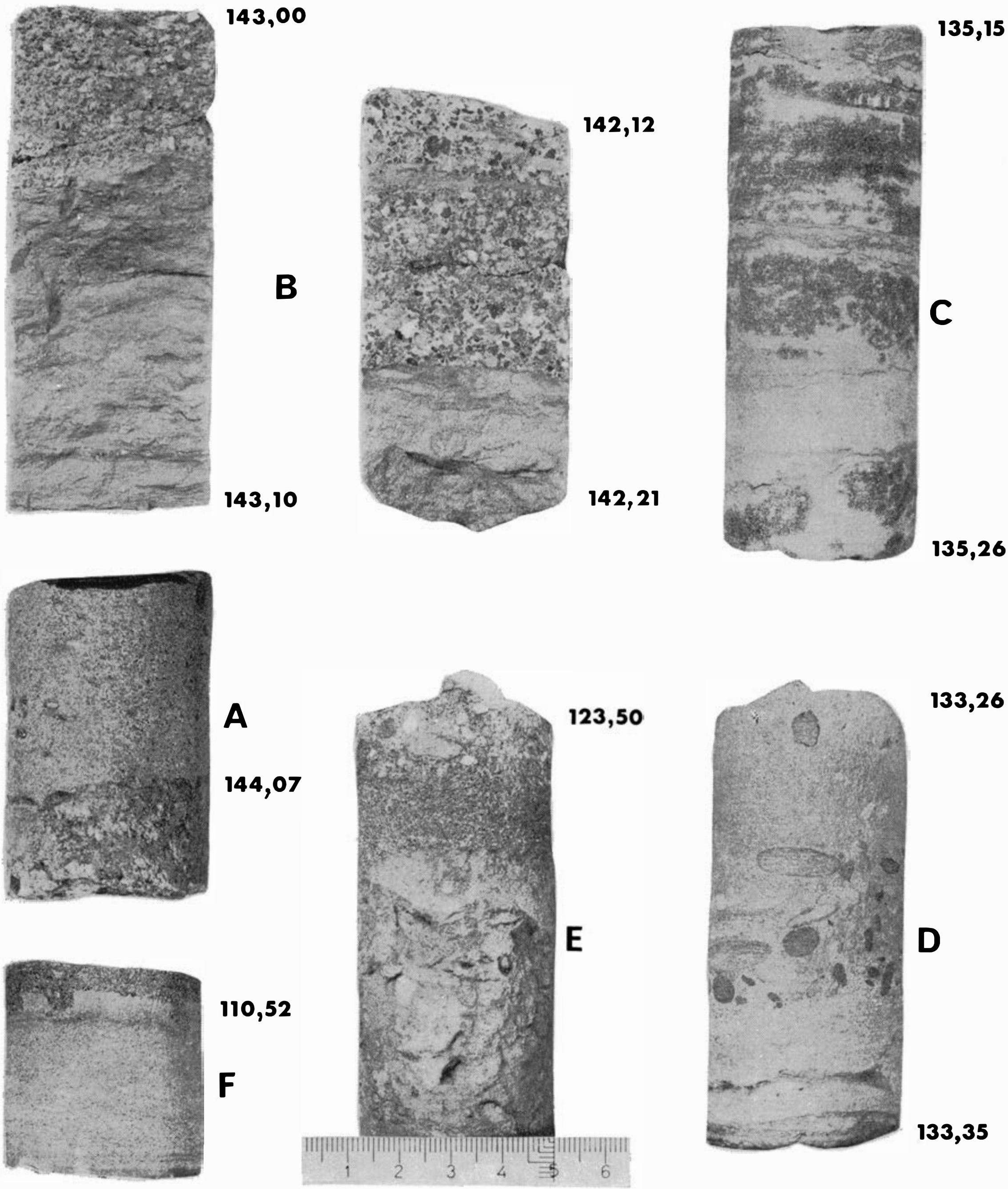
C. Sandstone, partly stained with oil.

D. Conglomeratic sandstone with phosphorite pebbles.

E. Core portion with "crow rock" sandstone in the lower part and a conglomerate with a large fragment of feldspar on top.

F. Discontinuity surface at the top of the *Obolus* Sandstone.

Plate I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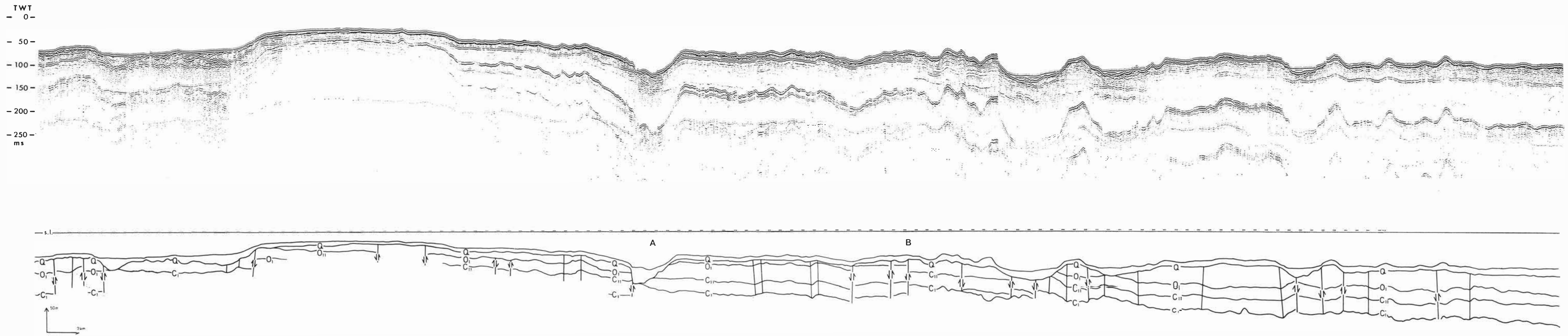

Fig. 23. Geological section based on the continuous seismic reflection profile (S7607 0400—1020) reproduced together with the section. The letters with subscripts refer to acoustic boundaries identified. The profile runs west of and parallel to the Paleozoic/Proterozoic boundary (cf. Figs. 10 and 15). Numerous faults and joints have been noted in the profile. The left portion of the section is from the Finngrunden shoal area, while the right part extends northeasterly to the northern limit of the investigated area. The local variations in sediment thickness are probably caused by lithological changes and associated changes in the propagation of sound.

From A to B the increase in thickness between C_{11} and O_1 is of such magnitude that it seems unlikely that a decrease in sound velocity (from assumed 2,5 km/sec to 1,5 km/sec) is the cause of the thickening.