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A REPORT SUMMARIZING ON THE VELOCITY OF EARTHQUAKE WAVES AND THE STRUCTURE OF THE EARTH'S CRUST IN THE BALTIC SHIELD

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Abstract

A preliminary summary has been made of the data collected in Finland and Scandinavia on the velocities of earthquake waves as well as of the explosions seismic investigations carried out in different areas and the results obtained in earthquake research. The data on variations in the thickness of the earth's crust in the same region have also been summarized.

1. *Introduction*

During the past ten years, many reports have been published on explosion-seismic and earthquake studies carried out in different parts of Fennoscandia. The basis of the present report consists of these previously published research data, to wich have been added the results of explosion-seismic research into the crustal structure made in the past three years (some of the research projects still being incomplete). The observations collected are mostly from Finnish and Norwegian territory, but sufficient data are available from other areas as well as to make a summary of this kind feasible. A bibliography of publications dealing with the matters under review is appended.

2. *Wave velocities and the crustal thickness as calculated on the basis of explosion-seismic and earthquake research conducted in Finland*

In the past ten years, ten explosion-seismic research projects have been carried out in southern and western Finland. Registrations have been obtained from twenty different lines, although the results are not yet all quite complete. The lengths of the lines have varied between 22 and 600 km, and some of the investigation lines have extended out to sea, in the Gulf of Bothnia.

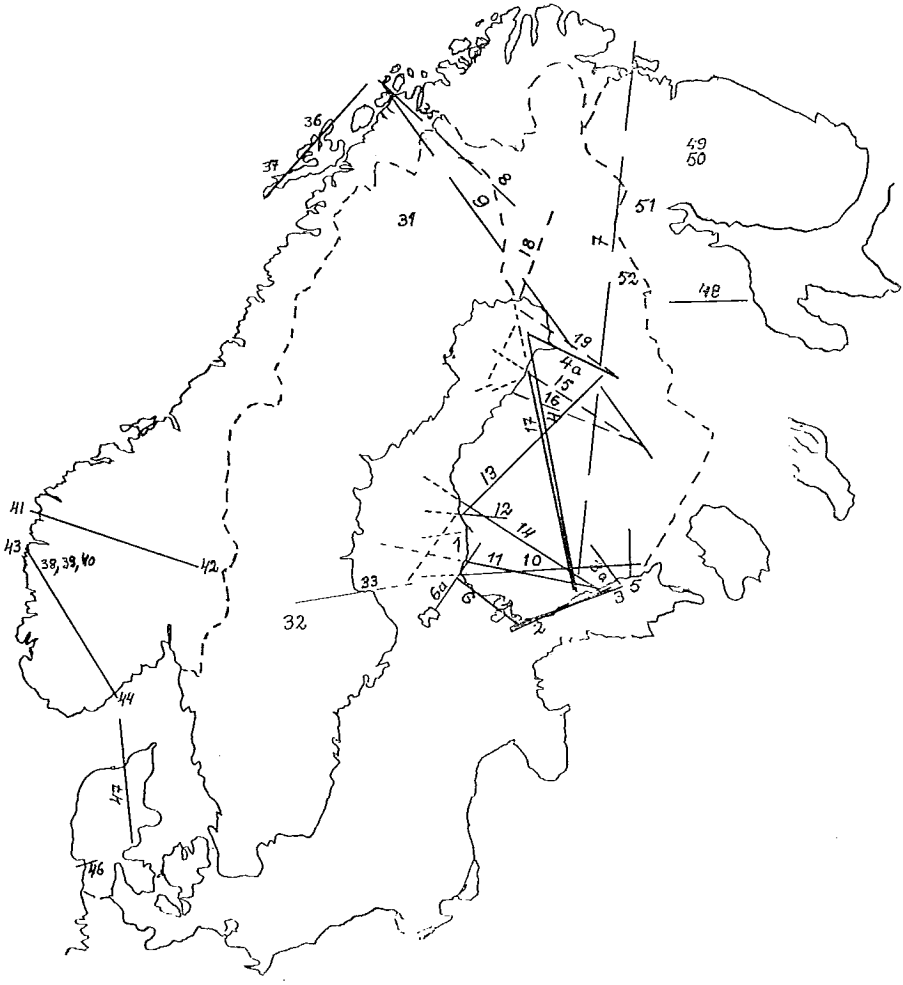

Fig. 1. Location of the investigation lines. References are given in Table 1.

Table 1. Velocities and crustal thicknesses obtained in explosion-seismic studies.

No.	Line	Direction	km	Pg1	Pg2	Pb	Pn	Sg1	Sg2	Sb	Sn	C	M	References
1	Pori	W-E	70	5.72				3.34				18		Vesanen *et al.*, Penttilä *et al.* 1960
2	Porkkala—Kotka	W-E	150	5.73	5.95	6.37	8.23		3.52	3.72	4.67	21	29	Penttilä *et al.* 1960, Penttilä 1965
2a	Porkkala—Hanko	E-W	85									19	27	
3	Kotka	E-W	230	5.89	6.21	6.65	8.23		3.55	3.96	4.67	21	38	Penttilä 1962, 1963, 1965
3a	Kotka rapakivi gr.	SE-NW	50	5.73	6.13			3.30	3.48					Penttilä 1962, 1963, 1965
4	Hailuoto	N-S	550	5.80	6.17	6.77	8.39	3.28	3.52	3.73	4.69	18	36	Penttilä 1962, 1963, 1965
4a	Hailuoto—KJN	W-E	200		6.00		7.90							
5	Hamina rapakivi	N-S	65	5.79	6.03									Penttilä 1962, 1963
6	Katanpää	SW-NE	500			6.85	8.20					21	38	Penttilä 1966
6a	Katanpää	NW-SE	200	5.85	6.05	6.40	8.00					19	37	Penttilä 1966
6b	Kauttua rapakivi	SN-NE	81	5.83	6.02									Penttilä, MS
6b	Ahvenanmaa rapakivi	NE-SW	85	5.86	6.05	6.50	8.05							Penttilä, MS
7	Nowaya—Zemlya	N-S	1900				8.20			3.90	4.60			Penttilä 1962
8	Tromsö—SOD	NW-SE	300		5.95	6.70	8.18					14	33	Sellevoll *et al.* 1964
9	Tromsö—Joensuu	NW-SE	1000		6.23	6.72	8.23		3.55	3.85	4.62	24	40	Penttilä 1966
10	Katanpää—Luumäki	W-E	450		6.07	6.60	8.00					15	41	Penttilä 1967
11	Pyhäranta—Porvoo	NW-SE	400		6.07	6.51	8.03		3.51	3.76	4.64	12+18	42	Luosto 1966, 1967
11a	Sea line	NW-SE	25	5.85		6.64								
12	Ahlainen—Tampere	W-E	250	5.95	6.15	6.60	7.90					18	42	
12a	Sea line	W-E	25	5.82										
13	Siipyy—KJN	SW-NE	550	5.90	6.15	6.75	8.00					18	42	
13a	Sea line	SW-NE	25	5.92										
14a	Sea line	NW-SE	25	5.83										
15a	Sea line	NW-SE	25	5.96										
16a	Sea line	NW-SE	22	5.79										
17a	Sea line	N-S	22	5.97										
18a	Sea line	SW-NE	22	5.99										

Table 2. Velocities and crustal thicknesses obtained in earthquake studies.

No.	Study	km	Pg1	Pg2	Pb	Pn	Sg1	Sg2	Sb	Sn	C	M	References
21	Northern Fennoscandia	650	5.70		6.30	8.10	3.40		3.70	4.50		35	Vesanen *et al.* 1960
22	Northern Fennoscandia	1000	5.79		6.60	8.12	3.41		3.77	4.53		34	Porkka 1960
23	Kuusamo	1000	5.70	6.00	6.70	8.10	3.40	3.50	3.90	4.60	23	35	Penttilä 1960, Miyamura *et al.* 1964
24	Bothnian Bay	550		5.95	6.73	8.20		3.47	3.75	4.32	19	35	Korhonen 1966
25	Kuopio	550	5.46	5.92	6.50	8.10	3.31	3.50	3.89	4.56	22	31	Talvitie 1967
26	Sodankylä	900	5.94	6.08	6.64	7.90					19	34	Kataja, MS

Figure 1 shows the location of the investigation lines as well as those lines along which the explosions set off in the Norwegian Sea off Tromsö during two summers were registered, along with the nuclear blasts occurring in the vicinity of Novaja Zemlya. The figure further shows the boundary of the positive and negative Bouguer gravity anomaly, revealing that the investigation lines have been situated almost without exception in the negative anomaly area.

The results obtained up to now are presented in Table 1, including the directions and lengths of the lines, the wave velocities and the depths of the Conrad and the Moho; the literary references are likewise given. Corresponding results obtained in the earthquake studies are given in Table 2. Tables 3 and 4 give the combined results obtained from investigation lines of different lengths in the form of mean values. In explosion-seismic studies slightly higher velocities seem generally to be registered than in earthquake studies. The tables further show how the velocities increase with distance from the sourace.

Table 5 records the mean values obtained in several investigations of explosions set off in different areas. The Pg1 velocity appears to increase from the Gulf of Finland to the main body of the Gulf of Bothnia and onward to the northern expanse of the gulf. This is likewise true of the Pb velocity. The Pg2 velocity is everywhere the same, while the Pn velocity is lower in the region of the Gulf of Bothnia than it is in

Table 3. Mean wave velocities obtained for explosions along lines of differen tlengths

km	Pg1	Pg2	Pb	Pn	Sg1	Sg2	Sb	Sn	References
200	5.84	6.04	6.42	8.09	3.32	3.50	3.72	4.67	1, 2, 3b, 5, 6b, 11a—18a
550	5.88	6.12	6.68	8.14	3.28	3.53	3.82	4.67	3a, 4, 6, 8, 10, 11, 12, 13
2000		(6.22)	7.72	8.22		3.55	3.88	4.61	7, 9
Means	5.86	6.08	6.64	8.15	3.30	3.53	3.80	4.65	

Table 4. Mean wave velocities obtained for earthquakes along lines of different lengths.

km	Pg1	Pg2	Pb	Pn	Sg1	Sg2	Sb	Sn	References
650	5.60	5.95	6.50	8.15	3.36	3.49	3.78	4.46	21, 24, 25
1000	5.75	6.00	6.65	8.15	3.41	3.50	3.84	4.56	22, 23
Means	5.68	5.98	6.58	8.15	3.38	3.50	3.81	4.51	

Table 5. Mean wave velocities obtained for explosions set off in different regions.

Region	Pg1	Pg2	Pb	Pn	Sg1	Sg2	Sb	Sn	References
Gulf of Finland	5.80	6.08	6.51	8.32	3.30	3.52	3.84	4.67	2, 3a, 3b, 5
Bothnian Sea	5.85	6.08	6.61	8.03	3.34	3.51	3.80	4.64	1, 6, 10, 11, 12, 13, 12a, 13a, 14a
Bothnian Bay	5.89	6.08	6.77		3.28	3.52	3.73	3.69	4, 16a, 17a, 18a
N. Finland		6.08	6.71	8.20		3.55	3.88	4.61	7, 8, 9
Means	5.85	6.08	6.65	8.15	3.30	3.53	3.81	4.65	

southern and northern Finland. Such differences are not observed so distinctly in the velocities of the S waves — but this is probably to some extent due the fact that only a few S velocities have been computed.

On the basis of the practically equal mean values yielded by both the regional registration lines and the lines of different lengths, the velocities of the different waves in Finnish territory may be assued to be on the average as follows:

Vpg1	= 5.85	km per sec	Vsg1	= 3.30	km per sec
Vpg2	= 6.08	»	Vsg2	= 3.52	»
Vpb	= 6.65	»	Vsb	= 3.80	»
Vpn	= 8.15	»	Vsn	= 4.65	»

Tables 1 and 2 also give the values obtained for the depths of the Conrad and Moho. The depths obtained for the Moho in explosionseismic investigations have been over 40 km in the region of the Gulf of Bothnia and 37—38 km in southern Finland, while earthquake observations made in northern Finland have given depths of 34—35 km. In the first explosion-seismic study made on the shore of the Gulf of Finland (PENTTILÄ [33]) and in the Kuopio earthquake investigation (TALVITIE [50]), smaller values were also obtained, values probably connected with the positive Bouguer gravity anomaly of these areas. Correspondingly, Moho depth values exceeding 40 km are obtained in the most markedly negative gravity-anomaly area. The thickness of the crust calculated from surface wave observations between Kevo and Nurmijärvi, Finland, is 42 km (LUOSTO [17], NOPONEN [22]). According to Noponen, the average difference in thickness between the results obtained for Kevo—Oulu and Oulu—Nurmijärvi does not exceed 1.6 km. In the region of the Gulf of Bothnia the depth obtained for the Conrad has mostly been

18 km, in southern Finland 19—21 km, in eastern Finland 22—23 km, and in northern Finland 23 km. The values for eastern and northern Finland are based on earthquake studies. Accordingly, the granite layer appears to grow thinner from east to west, but the greatest variations in thickness seem to occur in the basalt layer.

In computing some sort of mean value, the fact has been taken into account that these studies have mainly dealt with the Bouguer gravity-anomaly area. Hence, two results specifically pertaining to the positive anomaly area have been omitted. Considering, in addition, that the thickest basalt layers seem to occur in the areas of the thinnest granite layers, the following mean values have resulted:

Granite layer	21 ± 3 km
Basalt layer	20 ± 4 km
Crustal thickness	39 ± 3 km

Table 6. Velocities of earthquake waves, depths of Conrad and Moho in Sweden, Norway, Denmark and Baltic Shield area of USSR, as registered in explosion-seismic and earthquake studies.

	Region	km	Pg	Pb	Pn	Sg	Sb	Sn	C	M	References
31	Kiruna	10	5.65						19	34	Båth *et al* 1962
32	S.Sweden	113	6.00		8.12						Dahlman 1967
33	S.Sweden	500	6.00	6.65	8.15				16	38	
34	Nor. coast	1400	5.98	6.35	8.29	3.54	3.79	4.70	12	39	Dahlman 1967
35	Tromsö	300	5.95	6.70	8.18				14	33	Sellevoll *et al* 1966
36	Lofoten Is.N	300	6.10	6.66	8.25				17	31	Sellevoll 1967
37	Lofoten Is.S	300	6.00	6.66	8.26				9	30	» »
38	W.Norway		5.50								Sellevoll *et al* 1964
39	W.Norway								16	24	Kvale 1960
40	W.Norway		5.50	6.43	8.10						Sellevoll 1958
41	Flora	380	6.10	6.45	8.25				13	36	Sellevoll 1967
42	Åsnes	380	6.10	6.55	8.20				18	36	» »
43	Fedje	350		6.50	8.25				0	32	» »
44	Grimstad	350	6.00	6.50	8.25				17	35	» »
45	Expl. in Norway		6.13	6.60	8.20	3.58		4.66	19	38	» »
46	Denmark	40	6.03								Hjelme 1961
47	Denmark		6.10	6.60	8.10				8	29-32	Hirschleber 1966
48	Kemi USSR.	200	6.10	6.70	8.10				10-15	34-38	Litvinenko 1960
49	Kola pen.		5.70	6.60					20	52	Panasenko 1960
50	Kola pen.		5.70	6.60					16-17	51	Panasenko 1963
51	Tolvantijärvi		5.63	6.69	8.18	3.32	4.12	4.65	19.5	50.4	» »
52	Kuusamo		5.76	6.65	7.90	3.42	3.92	4.50	19.6	49.0	» »

3. *Results of explosion-seismic and earthquake investigations carried out in Sweden, Norway, Denmark and the USSR in the region of the Baltic Shield*

Table 6 gives the results of corresponding studies made in the other Scandinavian countries and Soviet territory. The results are from numerous different explosion-seismic investigation lines and earthquake studies. The greatest deficiency pertains to the S-wave velocities, which are dealt in very few of the published papers.

Table 7 gives the regional averages for the velocities of the earthquake waves. The table includes the results from Finnish territory and, moreover, the mean wave velocities from explosions registered by the seismographic stations located in Fennoscandia, as computed by SELLEVOLL and DAHLMAN, of Norway, in 1965 [48]. In addition, the table gives the results and means of the registrations of the explosions set off in the vicinity of Tromsö along the line Tromsö-Joensuu.

4. *Conclusions*

In the light of the foregoing data, the following values may be regarded as the most general earthquake wave velocities in the region of the Baltic Shield:

Table 7. Regional mean velocities of earthquake waves in Baltic Shield, together with results of research into explosions set off in Norway.

Region	Pg	Pb	Pn	Sg	Sb	Sn
Norwegian coast	5.88	6.45	8.22	3.58		4.65
S.Norway	6.05	6.53	8.23			
Denmark	6.07	6.60	8.10			
Sweden	6.00	6.50	8.19	3.54	3.79	4.70
Kola pen. (USSR)	5.70	6.64	8.04	3.37	4.02	4.58
Uhtua—Kemi (USSR)	5.90	6.68	8.10			
Gulf of Finland	6.08	6.51	8.22	3.52	3.84	4.67
Gulf of Bothnia	6.08	6.69	8.03	3.52	3.78	4.67
N.Finland	6.08	6.71	8.20	3.55	3.88	4.61
Mean values	6.05	6.60	8.15	3.55	3.82	4.65
Dahlman	5.98	6.35	8.29	3.54	3.79	4.70
Sellevoll	6.13	6.60	8.20	3.58		4.66
Penttilä	6.23	6.72	8.23	3.55	3.85	4.62
Mean values	6.11	6.56	8.24	3.56	3.82	4.66

Vpg = 6.10 km per sec		Vsg = 3.55 km per sec		0.24	(Poisson,
Vpb = 6.60	»	Vsb = 3.80	»	0.25	Constant)
Vpn = 8.20	»	Vsn = 4.65	»	0.26	

The greatest deviations from these mean values are seen in the smaller Pg and Pb velocities registered in the coastal region of Norway and the smaller Pg velocity registered in the region of the Kola Peninsula and the White Sea.

The thickness of the granite layer appears to be 18 km in the region of the Gulf of Bothnia and 19—21 km in southern Finland, while it increases in eastern and northern Finland to 22—23 km and thins down toward the Norwegian coast to 14—12 km. In the Kiruna area of Sweden it is 19 km, in southern Norway 13—18 km and in Denmark 8 km. The values obtained in the Soviet part of the Baltic Shield range between 10 and 20 km. The least thicknesses of the granite layer thus occur in the belt comprising the Gulf of Bothnia and the Skagerak as well as along the Norwegian coast.

The thickness of the basalt layer in Finnish territory has correspondingly been 24 km in the Gulf of Bothnia, 16—17 km in southern Finland and 12—16 km in eastern and northern Finland. In the region of Tromsö it is 19 km, at Kiruna 14—15 km and to the south 17 km, in the Skagerak 21 km and in the region of Kantalahti—Kola 26—30 km. The basalt layer would thus appear to be thickest in the belt covering the Skagerak, the Gulf of Bothnia and Kola Peninsula.

The total thickness of the earth's crust is also considerable in the region of the Gulf of Bothnia, i.e. over 40 km. From there it then thins down toward the east to values below 40 km and westward to the Norwegian coast, where it is about 30 km, and onward to the Norwegian Sea, where it is 10—12 km (BÅTH [1]). The greatest value for the crustal thickness, however, has been obtained in the centre of the Kola Peninsula, 50 km (PANASENKO [28]).

According to the foregoing, the following values have been obtained for the average thickness of the earth's crust in different areas:

Area	1st layer	2nd layer	Total crust
Coast (Norway)	15	17	32
Southern Norway	17	18	35
Denmark	8	23	31
Sweden	18	20	38

Finland	19	20	39
Kola Peninsula (USSR)	20	30	50
Uhtua (East Karelia, USSR)	13	24	37
Kemi (East Karelia, USSR)	17	17	34

If, then, the values obtained from the Norwegian coastal area and Denmark are omitted, the average crustal thickness in the Baltic Shield would be: 20 km + 17 km = 37 km. On the basis of the observations made by the seismographic stations of Fennoscandia on explosions set off in Norway, Sellevoll computed the thickness of the crust to be: 19 km + 19 km = 38 km. In the summary report published by MORELLI *et al.* [21], the depth of the Moho in the Gulf of Bothnia was given as 30 km, whereas in the present report the value has been raised to over 40 km. The depth values obtained for the Conrad, on the other hand, agree well. In Eurasia the average thickness of the earth's crust has been registered as 35 to 40 km (KOSMINSKAYA *et al.* [12]). In the Pacific coastal and western mountain region of the United States of America, the depth of the Moho has been measured to be 20 to 50 km, in the eastern seaboard and Appalachian regions 30 to 40 km, and in the Mid-western plains 40 to 50 km (PAKISER *et al.* [27]). The average thickness recorded for all the continents on the basis of the available data is 35 ± 2 km (LEE *et al.* [15]).

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