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Supplementary Scientific Report

Pn TIME-TERM SURVEY NORWAY-SCOTLAND 1967

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ABSTRACT

Shot charges ranging from 135 kg to 1360 kg were used in this seismic Pn refraction survey between the west coast of Norway, Shetland, and the Scottish mainland in 1967. The apparent velocity showed signs of increasing with distance and therefore the time-terms have been calculated from equations of the form

$$t_{ij} = a_i + b_j + \Delta_{ij}/V_o - V_1\Delta_{ij}^2/V_o^2$$

The velocity parameters found are as follows:

$V_o = 8.12 \pm 0.16$ km/sec; $V_1 = 0.00011 \pm 0.00014$ sec^{-1}

The calculated Pn time-terms and their 95% confidence limits are given in tabular form and they are also shown graphically along some selected profiles.

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FOREWORD

This is a report on a joint program undertaken by the Geophysical Laboratories, Edinburgh, and the Seismological Observatory, Bergen. The author has prepared the report at the Geophysical Laboratories while on leave from the Seismological Observatory, holding a NATO Science Fellowship which was granted by the Royal Norwegian Council for Scientific and Industrial Research. The Royal Norwegian Navy provided the depth-charges used and undertook all of the shooting program. This work was excellently performed by the officers and crew of KNM-"Valkyrien" under Commander J.L.R. Möller. The Norwegian Broadcasting Corporation transmitted special timing signals for this project. One photographically recording unit for recording the shot-times on board the shooting ship was put to our disposal by the Department of Seismology of the Geodetic Institute, Copenhagen. Tape recordings from the Eskdalemuir array station were put to our disposal by the Data Analysis Centre for Seismology of U.K. Atomic Energy Authority.

The author acknowledges with thanks all the above-mentioned support to the project, as well as the assistance of the staff of the two cooperating institutes.

INTRODUCTION

The recent interest in the geology of the northern part of the North Sea is not only due to the possibility of discovering oil or gas, as has already been done in the southern part. The area covers the continental shelf along a profile where the crust changes eastwards from the oceanic structure in the Atlantic to the continental structure of the Baltic Shield. This profile is of particular importance because several institutes in the countries concerned have shown keen interest in exploring the crust by geophysical methods. Some surveys are already completed or are under way although there are still some gaps.

The potential prospects for early achievement of a well-explored crust along such a profile were recognised at the Ninth Assembly of the European Seismological Commission, held in August 1966 in Copenhagen. The Sub-Commission for Explosion Work in Northern Europe has established two Working Groups which have a bearing on these prospects (Garland, 1967). The Working Group for the North Sea is to promote further seismic coverage in the North Sea. The Working Group for the Atlantic-Ladoga Profile is to promote the same for that area, and especially to encourage cooperative programmes involving long range shots along the profile. This will give long range observations along a section where the crust will soon be well understood, and thus contribute much to the study of the Upper Mantle.

No deep crustal refraction survey has been undertaken so far in the northern part of the North Sea between Norway and Scotland, although separate surveys have been undertaken within the two countries. The results of such surveys in Norway have been given by Sellevoll (Sörnes and Sellevoll, 1967). In Scotland such work has been published for the southern part only (Agger and Carpenter, 1964). The lastmentioned published body of data for southern Scotland has been merged with additional data obtained further to the south, and an interpretation of the combined data has been given by Parks (1967).

Seismic surveys investigating only the upper crustal layers have been undertaken frequently during recent years in the northern part of the North Sea, mainly for prospecting purposes, but very few have so far been published. In 1959 the first of such surveys in this area was published, but included only one survey point in the northern and one in the middle part of the North Sea (Ewing and Ewing, 1959).

The present project was designed to provide essential information which has been lacking for the northern part of the North Sea, in order that effective planning could be made for a detailed long profile from the Atlantic into the Baltic Shield.

THE SHOOTING PROGRAM

The data for the shots are given in Table 1 and the general layout is shown in Fig. 1. The shooting program was performed by KNM-"Valkyrien". The 910 kg and 1360 kg charges consisted, respectively, of 40 and 60 canisters of Nitramon WW-EL contained within a steel framework together with some boosters and primers dispersed within the assembly. They were fired electrically on the sea bottom by control from the ship, after the ship had withdrawn a distance of about half a kilometer. The 135 kg shots were depth-charges containing TNT. They were dropped from the ship at full speed and adjusted to explode at a depth of 61 m. The depth of detonation was kept constant at 61 m to obtain homogeneous results without any danger that a charge could reach the bottom at any shotpoint without exploding. The ship reached on the average a distance of 250 m before detonation.

Timing of the electrically-fired shots was obtained in two ways, firstly by recording the electric firing current, and secondly by recording the direct water-wave. An electronic clock on board the ship was kept within a few milliseconds of standard time by constantly watching a built-in stroboscope which showed the difference between the clock and the continuous standard timing signals from radio stations. For most of the time the station used was Potsdam (DIZ), which appeared to give the best radio reception. One-second, ten-second and minute pulses from the electronic clock were recorded by a photographically recording six-channel oscillograph at a paper speed of 70 mm/sec. During most of the operation in the open sea the radio reception was so good that the radio timing signals gave a nice clean recording envelope and were recorded directly instead of the electronic clock. Along with these timing signals the electric high-voltage current to the caps in the Nitramon charges and the output from a hydrophone in an outside-hull water-tank were recorded at different gains. For the depth charges only the output of the hydrophone was recorded. As the distance from the ship to the shotpoint could always be estimated to within ± 20 m and the sound velocity of the sea water in the area would be very close to 1480 m/sec., it was possible to calculate the shot times to within an overall accuracy of ± 0.05 sec for most of the shots. Due to practical difficulties the shot times of two of the depth charges were missed, and for similar reasons, two more shot times are given only to the nearest tenth of a second; these two are estimated to be correct to within ± 0.1 sec.

The positions of the four shots close to the shore, nos. 1, 2, 35 and 36, were determined graphically using sightings of buoys and landmarks as reference points. They are estimated to be accurate to ± 50 m. Similar principles were also used for the shots 3, 4 and 5 with the aid of radar and Decca. The accuracy is estimated to be better than ± 400 m. For the rest of the shots the positions were determined by the Decca Navigator system only, the North Scottish Chain. The Decca system on the west coast of Norway did not come into operation until later in the year. Geographical coordinates were worked out by the navigational officers on board at once from Decca indicators read visually. At the dropping time of the charges the Decca indicators were also photographed successfully for most of the shots for later checking. The positions along the profile running between Shetland and the Scottish mainland are estimated to be correct within ± 200 m. For the shots along the profile east of Shetland the accuracy decreases eastwards and might be of the order of a few kilometers in the worst case for no. 6. A buoy with radar reflectors was put out at the common shotpoint by another ship, "H.U. Sverdrup", which was intended to undertake a short range refraction survey in the area of shotpoint nos. 6, 7 and 8, one week before the present survey. This should have given independent position readings by several methods, among them LORAN C. After the setting-out operation the weather forced "H.U. Sverdrup" to abandon the planned survey. Therefore she unfortunately did not return to fix the coordinates by other instruments, and thus only Decca readings from one Chain by the two ships are available.

THE RECORDING STATIONS

The data for the station sites are given in Table 2 and they are also shown in Fig. 1. The positions of the temporary field stations are estimated to be correct to within ± 50 m. The field stations at the selected sites in Norway could not be expected to achieve satisfactory reception of the continuous standard time radio stations. Therefore the Norwegian Broadcasting Corporation transmitted some extra timing signals especially for this project. Those shots which were expected to be recorded by these stations were timed to coincide with either these extra signals or the ordinary radio signals transmitted on all of the domestic network. Most of the seismograms obtained by the field stations in Norway have therefore radio timing signals along with the built-in electronic clock.

A description of the three-component photographically recording field-stations used at the sites 1, 2, 3, 6 and 7 and of the permanent array-station at Lillehammer, site 12, is given in an earlier report (Sörnes and Sellevoll, 1967). At Bergen and Uskedalen, sites 4 and 5, a three-component set of Willmore seismometers were recorded on a 14-channel FM one-inch wide magnetic tape at a speed of 3¾ in./sec. using the same amplifiers as designed for the photographically recording sites. The World-Wide Network Standard-Stations at Kongsberg, site 11, which at the time of this survey was operating with a magnification of 100,000 at 1 cps, did also record some of the shots.

Two three-component field-stations recording on magnetic tape were operated by the Geophysical Laboratories in Shetland and Aberdeenshire, sites 8 and 9. They are described, together with the play-back facilities at Edinburgh, by Parks (1966). The Eskdalemuir array station, site 10, is described by Truscott (1964).

It should be noted that the station sites 1, 3 and 6 were very near the shots 2, 1 and 35 (+36) respectively, re. Fig. 1. The shots 1 and 2 are practically repetitions of the Fedje and Flora shot-points of the 1965 program in Norway.

TIME-TERM CALCULATIONS

Preliminary time-term interpretations were carried out by an available time-term computer program written by Dr S. Crampin and Dr R. Parks (Parks, 1967). This program solves a_i and b_j and V by the least-square method from a system of simultaneous equations of the form

$$t_{ij} = a_i + b_j + \Delta_{ij}/V$$

where t_{ij} are the travel times of a particular refracted phase and Δ_{ij} are the distances between the i-th shot and the j-th station. The time-terms a_i and b_j are characteristics of the layers above the refractor at the individual sites. A time-term might be regarded as being the time lost by the wave between the surface and the refractor in question. First the time-terms are solved as a function of the velocity setting the last b to zero, and afterwards the velocity is solved using the calculated time-terms. The computer programming is facilitated very much by using matrix notations for the calculations which also has the advantage that the variance and covariance coefficients become easily available during the calculations for estimating the uncertainties of the solutions. Here only a reference to one of the available papers outlining the time-term method will be given (Willmore and Bancroft, 1961).

In the present study three recording sites were very close to shots and therefore would have approximately the same time-term as the nearby shot. A modified version of the above program was written to use such information, $a_i = b_j$, in the least-square process instead of setting the last b to zero. This program was particularly useful for the first runs of a small selected body of data. Even though this small body of data was selected as being the most reliable, it appeared to be unstable to small alterations in the input data. The judgement of the available data by successive additions is facilitated very much by achieving as soon as possible a reliable and stable (but not necessarily large)body of data.

It soon appeared that the shots between 2^{o}E and 3^{o}E, shots 6, 7, 8 and 34 gave very little consistent data and were excluded. This might be caused by an unknown anomaly in the area or by the fact that these are the shots which might have the greatest location errors.

The results obtained in the 1965 program were useful to identify which readings did belong to the P_n group for the stations in Norway. For the stations in Shetland and Aberdeenshire playouts of the vertical seismometer at a paper speed of 2 cm per second recording time, were made into seismogram montages, which proved very useful to identify phases.

The results of the preliminary calculations were that the solution combining all the data gave an increased velocity compared with, for example, the solution for all connections west of 2°E (shot 9 and all connections to the west), or with the solution for all connections east of 4°E (shot 5 and all connections to the east). The residual versus distance for the combined solution also showed a negative-positive-negative tendency and it thus was clear that the time-term program would require to take into account an increase in apparent velocity with distance. Another modified version of the time-term program was then written using the equation

$$t_{ij} = a_i + b_j + \Delta_{ij}/V_o - V_1 \Delta_{ij}^2/V_o^2$$

which also was used by Smith et. al. (1966). Their notation has been used to facilitate comparisons with the known parameters of similar studies. The apparent velocity, V_a, in the case of the above travel-time relation is

$$V_a = \frac{V_o^2}{V_o - 2V_1\Delta}$$

and

$$\frac{dVa}{d\Delta} = 2V_1\left(\frac{V_o}{V_o - 2V_1\Delta}\right)^2$$

which shows that for small distances the apparent velocity will have an approximate linear increase with distance. The rate of change of the apparent velocity will for small distances be just above $2V_1$. Functions to evaluate for example the velocity distribution of a medium exhibiting a travel-time relation of the form $t = A\Delta - B\Delta^2$ as well as for several other similar forms are given in a summarizing paper by Bullen (1966). He described a method of successive approximations which can be applied to the formula used here.

The uncertainties given for the presented solution are the 95% confidence limits calculated by the standard formulas quoted by Smith et. al. (1966).

After the modifications were introduced in the program the KDF9 computer of the Edinburgh Computing Centre could handle data sets for 36 sites. Because the full data set which was found consistent comprised 39 sites, three sites had to be left out in each run. It appeared that the solutions changed only marginally when the exchanging sites were chosen among the sites with only two or three connections. Therefore it was not found necessary to run the full data set on a larger computer. The results are presented for example in the figures as if they arose from a single combined solution.

The final values for the velocity parameters are as follows:-

$$V_o = 8.12 \pm 0.16 \text{ km/sec}$$

$$V_1 = 0.00011 \pm 0.00014 \text{ sec}^{-1}$$

The observational data used are given in Table 3. The Pn time-term results are presented in Table 4. The residuals versus distance are shown in Fig. 2. The time-terms along some selected profiles are shown in Figs. 3, 4, 5 and 6.

DISCUSSION

The calculated value of V_1 is not different from zero at more than about 90% confidence level. In spite of this, the use of an increasing apparent velocity was preferred because it gave a smaller sum of the squared residuals, and the residuals were more evenly distributed relative to distance. The discontinuities relative to independently determined time-terms at some sites were also smaller and subsets of data involving only shortrange connections gave lower velocities as mentioned previously. The present study makes use of recordings of 135 kg depth-charges up to distances of almost 800 km from Eskdalemuir and Lillehammer. The signal-to-noise ratios for these recordings are of course very low and they increase the uncertainty values of the solutions. For observations over such a long range of distance, it is hardly surprising that the first-arrival curve as revealed by time-term analysis shows signs of curvature. In the Lake Superior area, however, some of the time-term investigations did not show any curvature at about the same distances (Berry and West, 1966).

The results have been affected to some extent by the uneven distribution of the weights in the data. It is only the two array stations on the outskirts of the surveyed area, Eskdalemuir and Lillehammer, sites 10 and 12, which have all of the long-range and most of the medium-range observations. The influence of such facts is quite difficult to predict.

Direct comparisons with other studies are possible for the Pn time-terms of three of the sites used in the present study. This is the case for the Eskdalemuir array station and for the Flora and Fedje shotpoints of the Norwegian shot program in 1965.

The latest available value of the Pn time-term for the Eskdalemuir array station from other studies using different sets of data is 3.04 $\pm$ 0.71 sec. obtained by a constant velocity of 8.09 $\pm$ 0.17 km/sec. (Parks, 1967).

The present study indicates a higher Pn velocity and a higher value for the time-term, 3.35 ± 0.22. Without allowing for an increasing apparent velocity the time-term for Eskdalemuir, as well as for all the other sites, will be assigned a still higher value.

The values of the Pn time-term which can be calculated for the Flora and Fedje shotpoints based on the model deduced from the 1965 data are 3.64 sec and 3.04 sec respectively, corresponding to 2.97 sec and 2.94 sec of the present study (Sörnes and Sellevoll, 1967).

The values for the time-terms of these two sites obtained by using a constant velocity were higher than those by using an increasing velocity, but also in that case there was very little difference between them. One of the reasons why the presented solution is preferred is that the time-term values for the three sites mentioned above as a whole shows smaller discontinuities relative to the values from the independent studies.

At present no attempt has been made to describe the crustal layers throughout the area in more detail than the Pn time-terms do. The former report on the 1965 program describes the crust in Norway (Sörnes and Sellevoll, 1967). The present survey supplements the data for that part, but over the greater part of the area of the present survey very little information is available for the upper layers. The shot closest to the station in Shetland is at a distance of 45 km, but the station in Aberdeenshire is at a distance of 103 km from the closest shot with known shot-time. It is felt that crustal interpretations which at present have to be based on several assumptions should be deferred in the meantime, because the necessary information on the upper layers in the western part of the area may soon become available as the result of some British investigations.

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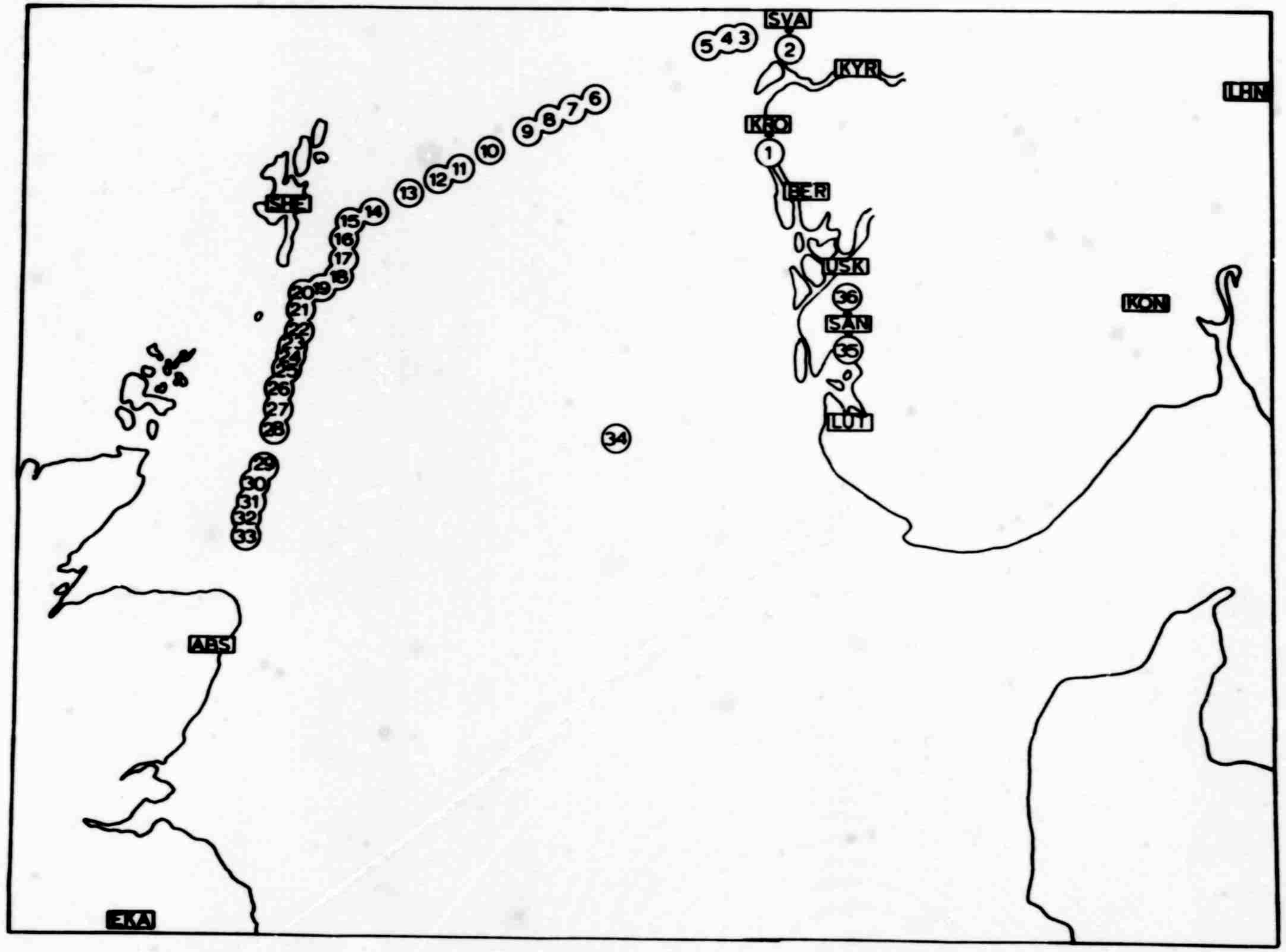
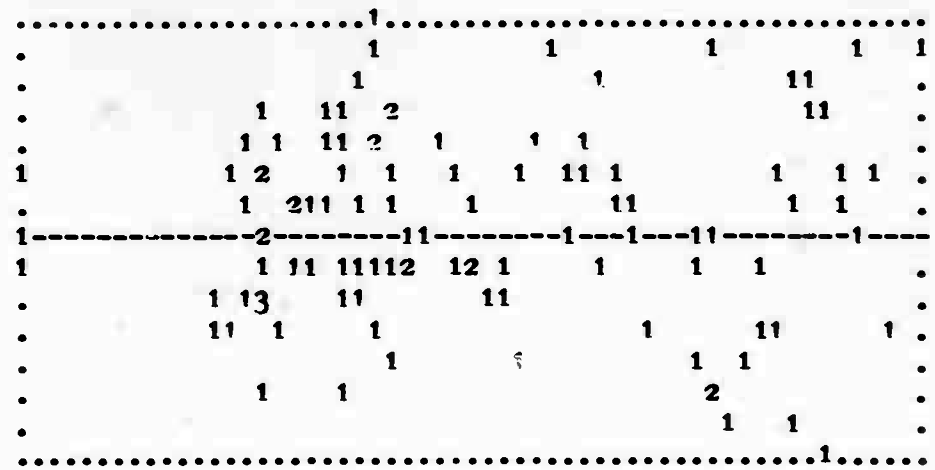


Fig. 1 Map of shots and stations



RANGE OF X AXSIS IS 0.00 TO 836.36
RANGE OF Y AXSIS IS -0.512 TO 0.461

Fig. 2 The residuals versus distance

Fig. 3 Pn time-terms on the profile south of Shetland

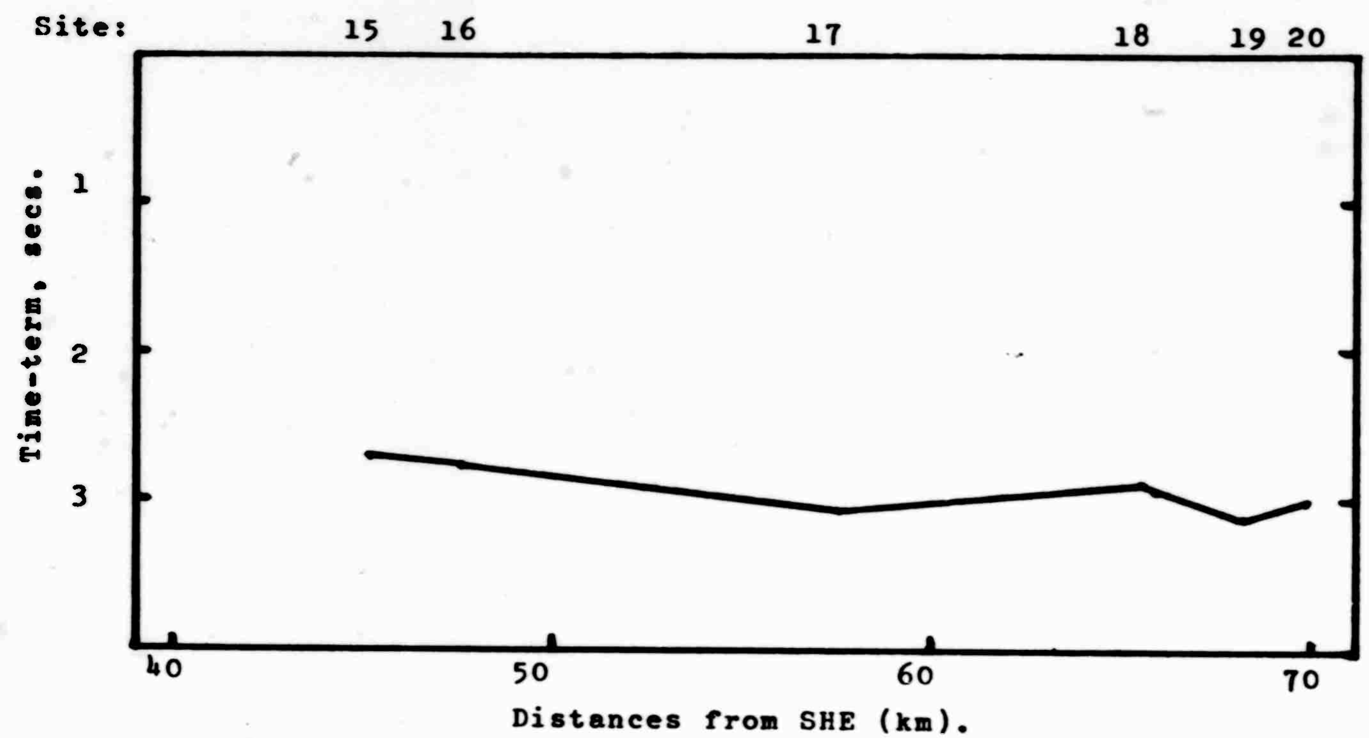


Fig. 4 Pn time-terms near Shetland

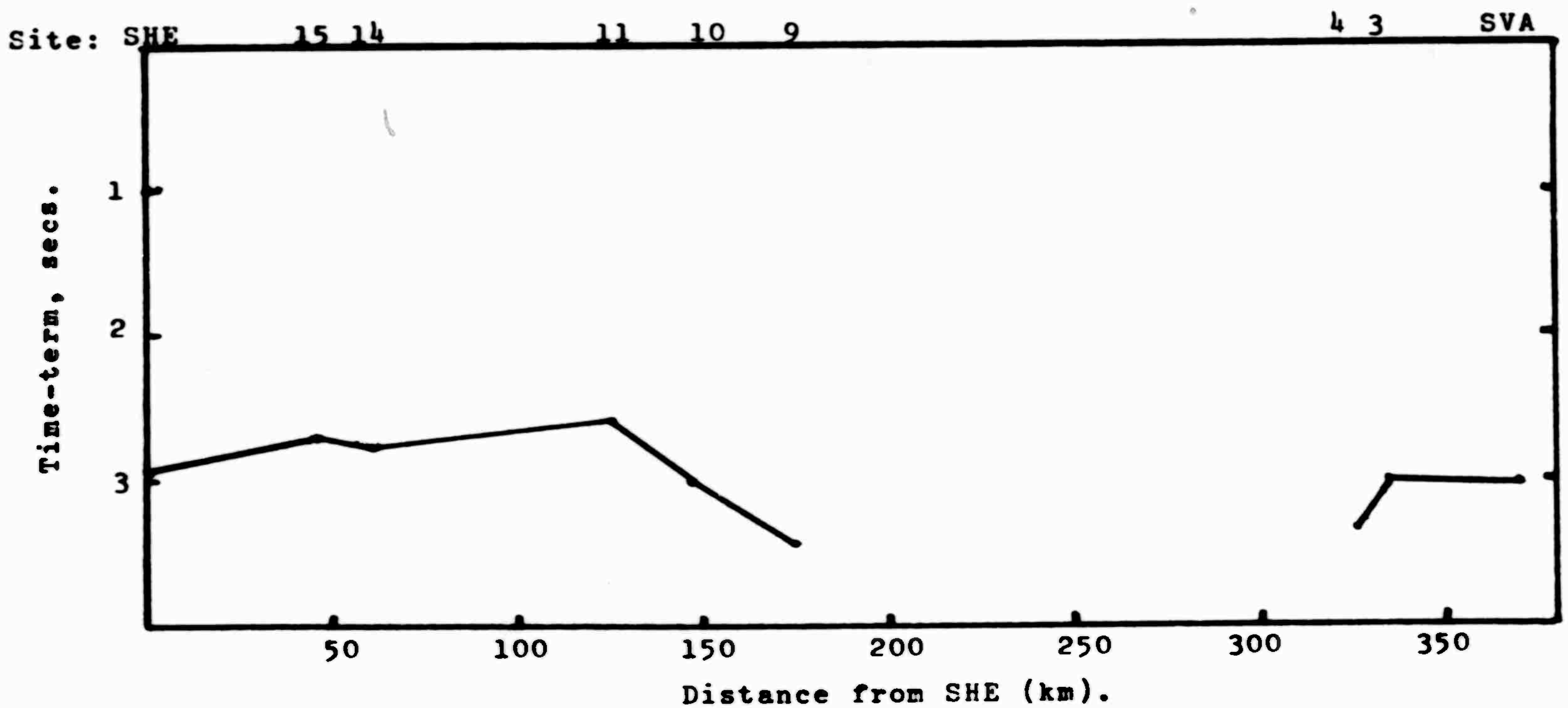


Fig. 5 Pn time-terms on the profile east of Shetland

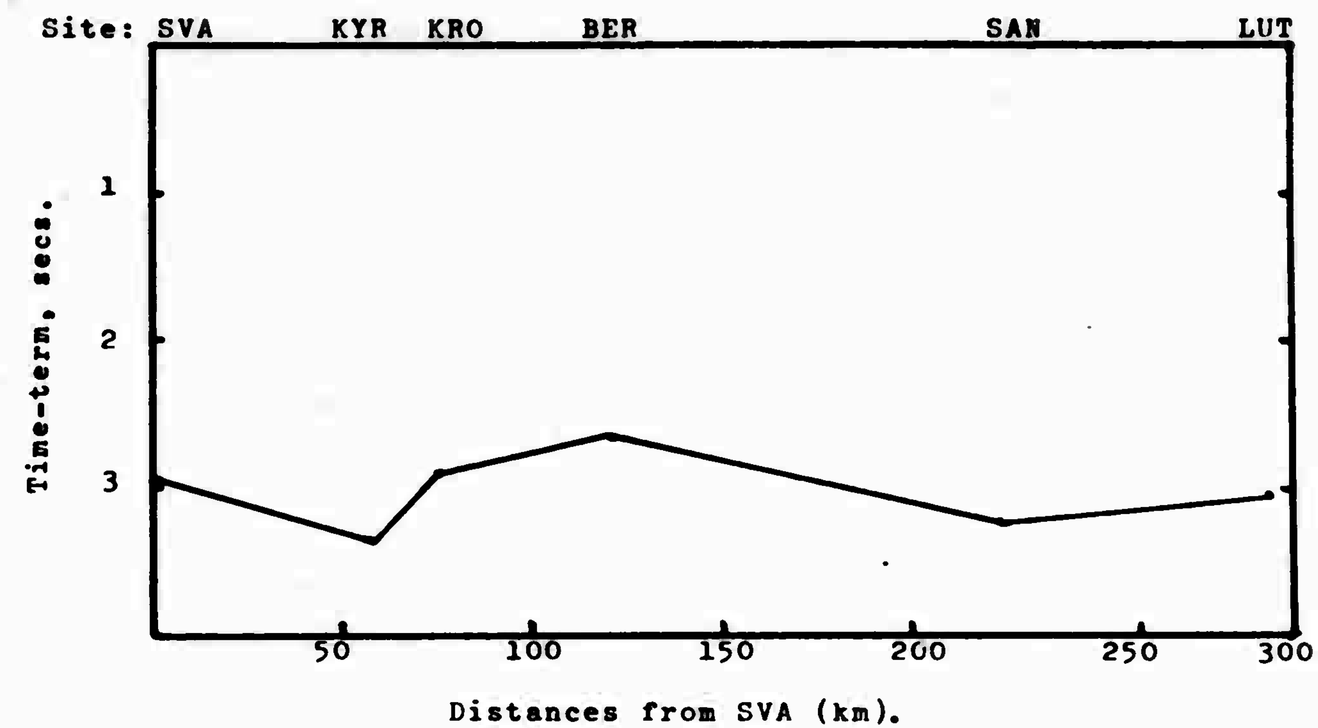


Fig. 6 Pn time-terms on the Norwegian coast

Table 1 Data for the shots

No	Date	Soundings (m)	Shot depth (m)	Charge (kg)	Latitude	Longitude	Shot time(GMT)
1	3	103	103	1360	60°49.52'N	04°49.75'E	11 59 36.33
2	3	86	86	1360	61°28.41'N	05°06.53'E	17 29 36.32
3	4	182	61	135	61°21.92'N	04°31.25'E	04 58 50.69
4	4	293	61	135	61°20.55'N	04°19.21'E	05 59 46.51
5	4	348	61	135	61°18.25'N	04°03.81'E	06 59 38.15
6	4	123	123	910	60°58.79'N	02°37.00'E	11 59 26.8
7	4	123	123	910	60°54.90'N	02°20.14'E	17 29 13.88
8	5	123	123	1360	60°50.83'N	02°02.65'E	04 58 04.87
9	5	132	132	910	60°46.20'N	01°44.60'E	06 59 14.82
10	5	136	61	135	60°39.17'N	01°17.60'E	08 30 03.87
11	5	132	132	1360	60°32.40'N	00°55.00'E	11 58 59.83
12	5	130	61	135	60°28.17'N	00°38.18'E	13 28 58.10
13	5	161	61	135	60°22.85'N	00°16.23'E	14 29 04.04
14	5	121	121	910	60°15.43'N	00°11.30'W	17 29 00.10
15	5	113	61	135	60°11.25'N	00°29.20'W	18 28 58.46
16	5	131	61	135	60°03.71'N	00°33.56'W	18 59 01.26
17	5	138	61	135	59°55.52'N	00°33.10'W	19 28 59.87
18	5	131	61	135	59°48.36'N	00°37.20'W	19 58 59.5
19	5	117	61	135	59°43.51'N	00°50.00'W	20 29 04.00
20	5	120	61	135	59°41.15'N	01°04.20'W	20 59 02.94
21	5	127	61	135	59°34.66'N	01°05.60'W	21 29 01.01
22	5	123	61	135	59°25.15'N	01°06.27'W	21 59 00.86
23	5	115	61	135	59°19.80'N	01°11.83'W	22 28 57.06
24	5	112	61	135	59°16.00'N	01°12.40'W	22 59 03.84
25	5	105	61	135	59°10.91'N	01°15.65'W	23 28 58.89
26	5	105	61	135	59°03.34'N	01°20.71'W	23 59 01.90
27	6	109	61	135	58°55.37'N	01°21.75'W	00 29 03.15
28	6	113	61	135	58°47.38'N	01°24.38'W	00 59 03.89
29	6	111	61	135	58°32.79'N	01°32.00'W	01 59
30	6	103	61	135	58°26.05'N	01°38.80'W	02 28 59.23
31	6	111	61	135	58°18.92'N	01°41.42'W	02 59 01.22
32	6	96	61	135	58°12.20'N	01°45.05'W	03 28 57.48
33	6	102	61	135	58°04.60'N	01°45.00'W	03 59
34	6	111	111	910	58°44.50'N	02°55.65'E	14 00 01.00
35	7	149	149	910	59°29.30'N	05°51.39'E	04 58 30.29
36	7	190	190	910	59°29.26'N	05°51.46'E	06 59 30.34

Table 2 Data for the station sites

Code	Name	Abbr	Coordinates (geographic)		Height (m)
1	Svanöy	SVA	61°28.58'N	05 05.04'E	10
2	Kyrkjebö	KYR	61°10.19'N	05 57.26'E	165
3	Krossöy	KRO	60°49.21'N	04 49.40'E	5
4	Bergen	BER	60°23,k3'N	05 19.33'E	20
5	Uskedalen	USK	59°55.84'N	05 51.16'E	50
6	Sandei	SAN	59°30.08'N	05 50.06'E	75
7	Lutsi	LUT	58°51.68'N	05 51.30'E	5
8	Shetland	SHE	60°17.79'N	01 16.43'W	100
9	Aberdeenshire	ABS	57°18.05'N	02 09.24'W	110
10	Eskdalemuir (B4)	EKA	55°19.90'N	03 09.60'W	300
11	Kongsberg	KON	59°38.57'N	09 37.55'E	200
12	Lillehammer (Z3)	LHN	61°02.57'N	10 52.48'E	505

Table 3 The observational data used

Shot	Station	t	Δ
2	-1	0.00	0.00
9	1	30.64	196.48
11	1	36.02	248.35
14	1	44.79	316.95
35	1	33.78	225.63
35	1	33.67	225.54
11	2	40.89	282.60
14	2	48.90	350.31
1	-3	0.00	0.00
11	3	31.72	215.75
14	3	40.62	282.10
9	4	30.88	200.96
11	4	35.18	243.25
14	4	42.77	304.98
2	6	33.66	223.33
9	6	39.61	267.64
11	6	42.49	297.57
14	6	48.57	347.53
35	-6	0.00	0.00
1	7	33.75	226.24
2	7	41.97	293.97
3	7	41.60	288.67
4	7	41.80	289.31
9	7	45.32	313.66
11	7	46.52	334.96
14	7	52.01	375.26
1	8	47.87	339.81
2	8	51.32	370.42
9	8	27.53	173.83
30	8	32.25	208.55
31	8	33.58	221.98
32	8	35.25	234.77
35	8	56.28	409.09
35	8	56.11	409.00
1	9	74.64	560.41
2	9	81.92	620.95
9	9	61.10	446.40
11	9	55.02	401.76

(Cont.)

Table 3 (Cont.)

Shot	Station	t	Δ
14	9	48.44	348.36
15	9	47.00	335.71
16	9	45.45	321.14
17	9	43.82	306.80
18	9	42.11	292.98
19	9	40.87	280.79
20	9	39.64	273.07
21	9	38.23	261.06
22	9	36.47	243.81
23	9	35.07	232.86
24	9	34.00	225.90
25	9	32.82	215.98
26	9	30.90	201.17
27	9	29.25	186.59
28	9	27.17	171.60
35	9	70.64	527.59
1	10	100.82	771.30
2	10	108.63	836.36
3	10	104.48	807.54
4	10	104.22	799.07
9	10	88.51	670.95
10	10	85.27	648.22
11	10	83.10	628.08
14	10	76.35	576.20
15	10	74.94	563.63
16	10	73.41	549.07
17	10	72.13	534.71
18	10	70.00	520.89
19	10	68.95	508.70
20	10	67.82	500.79
21	10	66.80	488.82
22	10	64.71	471.66
23	10	62.70	460.66
24	10	62.35	453.73
25	10	60.91	443.79
26	10	59.02	428.95
27	10	57.53	414.44
28	10	55.37	399.49
30	10	50.40	357.58

(Cont.)

Table 3 (Cont.)

Shot	Station	t	Δ
31	10	48.73	344.15
32	10	47.90	331.17
35	10	92.91	711.70
35	10	92.86	711.70
1	11	42.60	296.51
35	11	33.32	214.13
35	11	33.17	214.08
1	12	47.11	328.88
2	12	45.13	313.19
3	12	49.08	343.52
4	12	50.61	354.12
9	12	68.09	496.35
10	12	71.13	522.55
11	12	73.23	545.01
14	12	81.22	611.08
15	12	83.42	628.96
16	12	84.10	636.33
17	12	84.78	640.00
18	12	85.40	647.50
19	12	87.42	661.65
20	12	89.31	675.68
21	12	89.94	680.77
22	12	90.99	687.33
23	12	92.19	695.79
24	12	92.56	698.87
25	12	93.66	705.27
26	12	94.70	715.17
27	12	95.85	722.06
28	12	96.41	730.60
30	12	100.27	760.82
31	12	101.03	769.32
32	12	102.52	778.48
35	12	47.71	327.82
35	12	47.66	327.81

Table 4 The Pn time-term results

Station/shot	time-term	confidence limit
SVA	2.97	±0.25
KYR	3.38	0.43
KRO	2.94	0.33
BER	2.66	0.36
SAN	3.24	0.27
LUT	3.07	0.27
SHE	2.94	0.27
ABS	3.05	0.23
EKA	3.35	0.22
KON	3.59	0.36
LHN	3.88	0.22
1	3.00	0.26
2	2.99	0.24
3	2.95	0.36
4	3.33	0.36
9	3.45	0.26
10	3.03	0.43
11	2.62	0.25
14	2.77	0.25
15	2.70	0.36
16	2.79	0.36
17	3.06	0.36
18	2.81	0.36
19	3.14	0.36
20	3.05	0.36
21	3.22	0.36
22	3.42	0.36
23	3.24	0.36
24	3.33	0.36
25	3.37	0.36
26	3.26	0.36
27	3.50	0.36
28	3.15	0.36
30	3.49	0.36
31	3.29	0.36
32	3.70	0.36
35	3.15	0.23

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13. ABSTRACT

Shot charges ranging from 135 kg to 1360 kg were used in this seismic Pn refraction survey between the west coast of Norway, Shetland, and the Scottish mainland in 1967. The apparent velocity showed signs of increasing with distance and therefore the time-terms have been calculated from equations of the form

$$t_{ij} = a_i + b_j + \Delta_{ij}/V_o - V_1\Delta_{ij}^2/V_o^2$$

The velocity parameters found are as follows:

$$V_o = 8.12 \pm 0.16 \text{ km/sec}; \quad V_1 = 0.00011 \pm 0.00014 \text{ sec}^{-1}$$

The calculated Pn time terms and their 95% confidence limits are given in tabular form and they are also shown graphically along some selected profiles.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
seismic refraction survey						
time-term survey						
upper mantle velocity						
the North Sea						
Norway						
Scotland						