Travel time analysis of P waves arising from six underground nuclear explosion at Novaya Zemlya

A. BOTTARI (*) - B. FEDERICO (*)

Received on June, 14 th, 1977

SUMMARY. - The analysis of the travel times of the P waves generated by six underground nuclear explosions in Novaya Zemlya shows notable early arrivals ($\sim$ 4 sec) at the Fennoscandia stations. These observations, together with a marked linear dependence of the travel times on the epicentral distance throughout the interval $8.5 \leq \Delta^0 \leq 20.4$, were evaluated with the aim of producing a satisfactory model for the upper mantle of the Baltic zone. In particular, there appears a considerable mantle zone with almost uniform velocity, or at least, with not of increasing velocity. This mantle zone is delimited above by a discontinuity at the 86 km depth ($v = 8.45$ km/sec), and delimited below by the « 20^0 discontinuity » ($h = 507$ km; $v = 10.36$ km/sec).

The proposed model is amply verified on the basis of the foreseen travel times compared with the corresponding ones, observed from a fair number of impulses associated with teleseismic *Pn*, noticeable as far as 40^0, and from phases reflected and refracted on the discontinuity at 507 km.

RIASSUNTO. - L'analisi dei tempi di tragitto delle onde P generate da sei esplosioni nucleari sotterranee in Novaya Zemlya mostra dei chiari primi arrivi (4 sec) alle stazioni site in Fennoscandia. Queste osservazioni, unitamente ad una marcata dipendenza lineare dei tempi di tragitto dalla distanza epicentrale nell'intervallo $8.5 \leq \Delta^0 \leq 20.4$, sono state valutate nell'intento di produrre un modello soddisfacente per il mantello superiore della zona baltica. In particolare, vi appare una considerevole zona di mantello con velocità pressoché uniforme, o, almeno, senza alcun incremento di velocità. Questa parte di mantello è delimitata superiormente da una discontinuità ad una profondità di 86 km $v = 8.45$ km/sec) e, inferiormente, dalla « discontinuità 20^{0}" ($h = 507$ km; $v = 10.36$ km/sec).

Il modello proposto è ampiamente verificato e in base ai tempi di tragitto previsti con quelli loro corrispondenti, osservati da un discreto numero di impulsi associati alle *Pn* telesismiche, percettibili fino a 40^0, e dalle fasi riflesse e rifratte sulla discontinuità a 507 km.

(*) Istituto Geofisico e Geodetico, Università di Messina - (Italy).

INTRODUCTION.

It is generally agreed that the fine structure of the upper mantle cannot be assimilated to a single type for the whole of the earth' s sphere. This consideration, already expressed by various authors, has been recently emphasized by Bottari and Federico (1975) (5), who, availing themselves of the support of a vast amount of seismological observations, have studied the upper mantle in the Mediterranean area, with particular regard to the « 20^0 discontinuity ». Similarly, following much research the upper mantle in the Fennoscandia zone presents peculiar structures of no less seismological interest (Tryggvason, 1961; BÅTH, 1966, 1971; Sellevoll and Pomeroy, 1968; et al. ([14], [2], [4], [13]). In fact, in addition to what has already discovered, we consider remarkable both the sharp discontinuity of the seismic parameter corresponding to the epicentral distance 20.8^0, and the notable early arrivals of the first arrivals at the Fennoscandia stations in concomitance with some underground explosions in Novaya Zemlya.

OBSERVATION DATA AND ANALYSIS.

This work was commenced as a result of the mentioned observations, or more precisely, as a result of the following two: the explosions in Novaya Zemlya give rise in Messina to seismograms with clear phases between *P* and *PP* which are not identifiable with known phases; the first arrrivals at the Fennoscandia stations show notable early arrivals with respect to standard travel-times.

With the aim of analysing and interpreting these observations, the statistical epicenters of 6 nuclear explosions were determined (Table 1, col. 3), assuming as provisional coordinates — for calculation purpose — those published by the I. S. C. of Edinburgh. Also utilized were the initial times of the *P* of around hundred stations more favorably located than Novaya Zemlya. The times elaborated are, however, relative to stations with epicentral distance greater than 20^0, with the purpose of obtaining focal locations as for as possible independent of the propagation anomalies which exist in the upper mantle

TABLE 1

N^0	Nuclear Explosion Date	Latitude (N) Longitude (E) Origin Time (I. S. C.)	Latitude Longitude Origin Time	Residual Standard Deviation (sec)
1	OCT 27, '66	$73^0\ 24.0'$ $54^0\ 33.0'$ $05^h\ 57^m\ 57.9^s$	$73^0\ 24'\ 55''$ $54^0\ 48'\ 14''$ $05^h\ 57^m\ 59.9^s$	0.86
2	OCT 21, '67	$73^0\ 24.0'$ $54^0\ 25.2'$ $04^h\ 59^m\ 58.4^s$	$73^0\ 24'\ 06''$ $54^0\ 58'\ 35''$ $05^h\ 00^m\ 00.1^s$	0.71
3	OCT 14, '69	$73^0\ 24.0'$ $54^0\ 30.0'$ $07^h\ 00^m\ 06.4^s$	$73^0\ 22'\ 20''$ $54^0\ 49'\ 30''$ $07^h\ 00^m\ 08.2^s$	0.76
4	OCT 14, '70	$73^0\ 18.0'$ $54^0\ 54.0'$ $05^h\ 59^m\ 57.3^s$	$73^0\ 20'\ 10''$ $54^0\ 57'\ 10''$ $05^h\ 59^m\ 59.6^s$	0.55
5	SEP 27, '71	$73^0\ 24.0'$ $54^0\ 54.0'$ $05^h\ 59^m\ 55.4^s$	$73^0\ 24'\ 07''$ $54^0\ 55'\ 06''$ $05^h\ 59^m\ 57.5^s$	0.71
6	AUG 28, '72	$73^0\ 24.0'$ $54^0\ 45.0'$ $05^h\ 59^m\ 56.5^s$	$73^0\ 26'\ 59''$ $54^0\ 30'\ 52''$ $05^h\ 59^m\ 59.3^s$	0.77

and in particular in the crustal and sub-crustal structures of the Fennoscandia zone. The statistical procedure was carried out using the standard travel-time of both Jeffreys-Bullen (1967) (8) and Herrin et al. (1968) (7). The final explosion locations are not appreciably different in either case, but it was thought expedient to take for the epicentral coordinates those arrived at using the Herrin's travel-times, given that, with respect to these, the standard deviations of the observational residuals are smaller (Table 1, col. 3, 4).

With respect to the definitive space-time coordinates, the $T(\Delta)$ present a different trend according to the distance range:

— In the range $8.5 \leq \Delta^0 \leq 20.8$ the initial times of the *P* still show notable early arrivals (Table 2), and approximate well with the linear equation (Fig. 1)

TABLE 2

N^{0}	Station Code	Nuclear Explosion Date	Angular Distance (deg)	Travel Times of *Pn* obser. (sec)	Standard *TT* of *Pn* by *H* (1) (sec)	Standard *TT* by *J — B* (2) (sec)
1	KEV	OCT 27, '66	9.457	134.6	136.81	140.51
2		OCT 21, '67	9.506	134.8	137.48	141.12
3		OCT 14, '69	9.459	134.6	136.84	140.53
4		OCT 14, '70	9.490	134.6	137.26	140.96
5		SEP 27, '71	9.490	134.8	137.26	140.96
6		AUG 28, '72	9.383	133.7	135.80	139.49
7	KRK	OCT 27, '66	8.617	123.1	125.38	128.88
8		OCT 21, '67	8.662	123.3	125.99	129.50
9	KBS	OCT 21, '67	11.380	160.0	162.89	166.87
10		OCT 14, '70	11.425	160.6	163.50	167.48
11		SEP 27, '71	11.369	159.2	162.74	166.72
12		AUG 28, '72	11.255	158.7	161.20	165.17
13	TRO	OCT 27, '66	11.841	166.1	169.13	173.14
14		OCT 14, '69	11.846	165.7	169.20	173.21
15		OCT 14, '70	11.883	165.8	169.70	173.71
16		SEP 27, '71	11.873	166.1	169.56	173.57
17		AUG 28, '72	11.758	165.7	168.01	172.01
18	KIR	OCT 30, '61	12.504	175.0	178.08	182.05
19		OCT 27, '66	12.531	174.6	178.45	182.42
20		OCT 21, '67	12.578	175.2	179.08	183.05
21		OCT 14, '69	12.531	174.9	178.45	182.42
22		OCT 14, '70	12.561	175.2	178.85	182.62
23		SEP 27, '71	12.562	174.8	178.86	182.83
24		AUG 28, '72	12.455	174.4	177.42	181.40
25	SOD	OCT 27, '66	11.123	155.5	159.42	163.37
26		OCT 21, '67	11.166	155.6	160.00	163.96
27		OCT 14, '69	11.115	155.5	159.31	163.26
28		OCT 14, '70	11.139	155.6	159.63	163.59
29		SEP 27, '71	11.150	155.7	159.78	163.74
30		AUG 28, '72	11.056	154.7	158.51	162.46
31	OUL	OCT 21, '67	13.086	180.1	185.93	189.84
32		OCT 14, '69	13.034	180.0	185.23	189.15
33		OCT 14, '70	13.053	180.4	185.49	189.40
34		SEP 27, '71	13.071	180.2	185.73	189.64
35	KJN	OCT 27, '66	13.396	185.6	190.09	193.93

TABLE 2 - Continued

36	KJN	OCT 21, '67	13.432	185.4	190.57	194.40
37	KJF	OCT 14, '69	13.379	185.4	189.86	193.70
38		OCT 14, '70	13.393	184.1	190.05	193.89
39		SEP 27, '71	13.418	184.7	190.38	194.22
40		AUG 28, '72	13.342	185.7	189.36	193.21
41	UME	OCT 27, '66	15.557	212.7	218.76	222.24
42		OCT 21, '67	15.599	213.0	219.31	222.79
43		OCT 14, '69	15.548	213.1	218.64	222.12
44		OCT 14, '70	15.571	212.8	218.94	222.42
45		SEP 27, '71	15.584	213.2	219.11	222.69
46		AUG 28, '72	15.492	211.7	217.91	221.40
47	NUR	OCT 27, '66	17.201	234.4	239.84	243.21
48		OCT 21, '67	17.235	234.6	240.26	243.64
49		OCT 14, '69	17.183	234.7	239.62	242.99
50		OCT 14, '70	17.194	234.0	239.75	243.13
51		SEP 27, '71	17.221	234.2	240.09	243.46
52		AUG 28, '72	17.150	233.9	239.21	242.58
53	SKA	OCT 30, '61	17.926	246.0	248.86	252.28
54		OCT 27, '66	17.942	244.0	249.06	252.48
55		AUG 28, '72	17.868	243.7	248.14	251.55
56	UPP	OCT 30, '61	19.611	267.0	268.83	272.53
57		OCT 27, '66	19.537	265.5	267.98	271.68
58		OCT 21, '67	19.577	265.8	268.44	272.14
59		OCT 14, '69	19.525	265.7	267.84	271.54
60		OCT 14, '70	19.544	265.3	268.06	271.76
61		SEP 27, '71	19.562	265.7	268.27	271.96
62		AUG 28, '72	19.476	264.9	267.28	270.97
63	APP	OCT 14, '69	19.941	270.0	272.64	276.32
64	HFS	OCT 14, '69	20.344	275.4	277.09	280.58
65		OCT 14, '70	20.368	276.4	277.35	280.83
66		SEP 27, '71	20.379	275.5	277.47	280.94
67		AUG 28, '72	20.285	275.7	276.44	279.96

(1) H = Herrin et al. (1968) (7).

(2) $J-B$ = Jeffreys and Bullen (1967) (8).

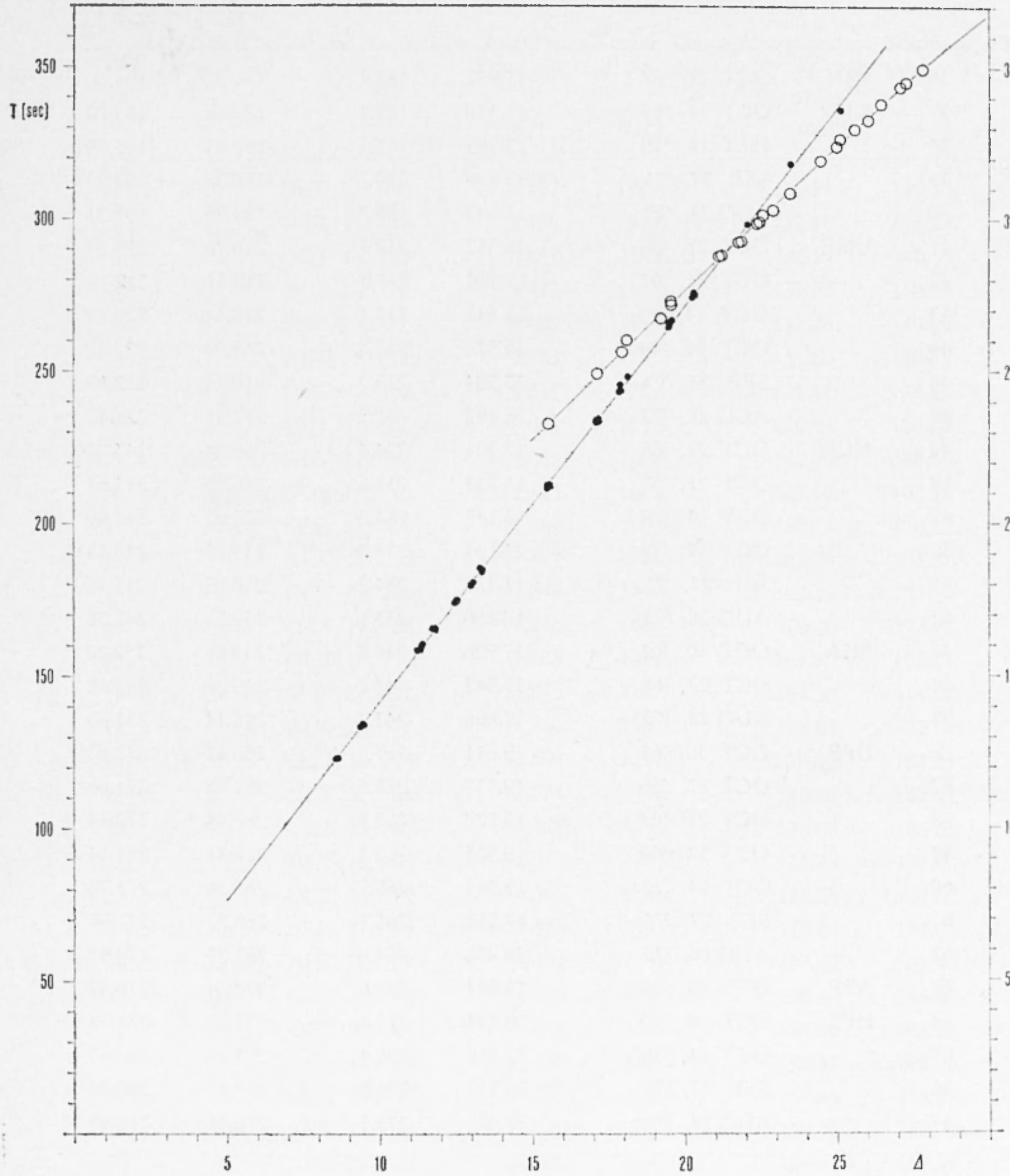

Fig. 1 — Travel times (spots) and least-square fits (lines) for *P*-wave first arrivals at Fennoscandia stations (black spots) and other stations with $\Delta \geq 20^{0}.4$ (white spots).

$$T=(11.51\pm0.36)+(12.9821\pm0.0244)\,\Delta \qquad [1]$$

revealing an apparent velocity of 8.56 km/sec, corresponding to a true velocity of 8.52 km/sec, under the Mohorovičić's discontinuity (r= =6336 km).

The fit relative to [1] is completely reliable, given the extremely contained uncertainties of the straight line parameters. It follows that the value of 8.52 km/sec for the velocity in the sub-Moho is irreconcilable in consideration of the values present in literature (Pentiilä, 1965; Sellevoll and Pomeroy, 1968; Båth, 1971; Kanestrom, 1973) ([12], [13], [1]), all of which are in the 7.8 - 8.2 km/sec interval. If therefore, we adopt for the thickness of the crust h_c, and the mean velocity in it v_c, the most recurrent values in Fennoscandia literature ($h_c=35$ km, $v_c=6.1$ km/sec), and assume the value 8.15 km/sec (Pentiila, 1969) ([12]), for the velocity in the sub-Moho, then the travel time equation of the P-waves refracted on the Mohorovičić discontinuity results as follows

$$T=7.65+13.5686\,\Delta \qquad [2]$$

The travel-times compatible with [2] result for $\Delta^0>7$ longer than the corresponding ones deduced using [1]. Furthermore, it not being possible to have data on the epicentral range 2-8^0, the hypothesis that the first impulses in the range 8.5 to 20.8^0 are referible to seismic rays which have followed a deeper refractory horizon than the base of the crust, was put forward. In order to individuate this horizon, the condition of zeroing the known term was imposed for [1], adopting the above mentioned values of thickness and velocity for the crust and below it. The above conditions is satisfied at the level $r_s=6285$ km, to which belongs the true velocity of 8.45 km/sec.

The observation that the first impulses recorded are distributed along a single straight line in an apreciably wide interval of 8.5 - 20.8^0, leads to the belief that the medium underlying the level $r_s=6285$ km is very homogeneous. So much so that the velocity $v\,(r)$ is uniform, or at least doesn't increase with an increase in depth. Such a model agrees with the results of the teleseismic Pn of Båth (1966, 1967) ([2], [3]) and those of numerous other researchers which localize widespread discontinuities between depths of 80 and 100 km (Adams, 1968; Massé and Alexander, 1974) ([1], [10]).

The hypothesis that, below the level $r_s=6285$ km, the P-wave velocity can be taken to be uniform was examined closely by approximating the travel-times observed reduced to the level r_s, by means of an equation of the type $T_s=2\,r_s/v\ \sin \Delta_s/2$, which as is known, represents the travel-time curve in a homogeneous spheric medium. In Table 3 are reported some Δ and T couples of [1] contained in the interval $8 \leq \Delta^0 \leq 21$, and the corresponding Δ_s and T_s reduced to $r_s=6285$ km; the velocity values deducible from the equation $v=2\,r_s/T_s\ \sin \Delta_s/2$, and the travel-times $T_s{}^*=2r_s/\bar{v}\ \sin \Delta_s/2$, $\bar{v}$ being the mean value of the velocities given in column 5; the value of the seismic ray parameter $p\,(\Delta)$, and the maximum depth reached by the seismic rays (Col. 8).

From the relations

$$T_s{}^* = \frac{2\,r_s}{\bar{v}} \sin \frac{\Delta_s}{2} \qquad [3]$$

$$p = \frac{r_s}{\bar{v}} \cos \frac{\Delta_s}{2} \qquad [4]$$

with $\bar{v}=(8.44 \pm 0.01)$ km/sec, are calculated the corrections in crust and in the layer $(6285 \leq r \leq 6336$ km) to raise the couples Δ_s, T_s from the r_s level to the earth's surface. The new couples Δ', T' thus deduced (Table 3, col. 9 and 10) approximate the linear equation

$$T = 11.95 + 12.9491\,\Delta \qquad [5]$$

with a standard deviation of the observational residuals of $\sigma=0.71$ sec, totally consistent with the corresponding value of $\sigma=0.70$ sec, obtained for [1].

In the interval $20.8 \leq \Delta^0 \leq 95$, the travel-times observed concord excellently with the standard ones, and they are represented by the polynomial

$$T=(68.73 \pm 0.96)+(11.043 \pm 0.061)\,\Delta-(0.03363 \pm 0.00118)\,\Delta^2+$$
$$-(0.0000122 \pm 0.0000070)\,\Delta^3 \qquad [6]$$

This results confirms the acceptable quality of the statistical determination of the explosion location, and indicates, relatively to the velocity

TABLE 3

Δ (deg)	T (sec)	Δ_s (deg)	T_s (sec)	v (km/sec)	$T_s{}^*$ (sec)	$p(\Delta)$ (sec/rad)	h (km)	Δ' (deg)	T' (sec)
8	115.368	4.1488	53.864	8.447	53.939	744.5772	90.12	8.0447	116.023
9	128.350	5.1488	66.846	8.446	66.932	744.3135	92.34	9.0290	128.812
10	141.332	6.1488	79.828	8.445	79.920	743.9931	95.04	10.0101	141.551
11	154.314	7.1488	92.810	8.444	92.902	743.6161	98.22	10.9883	154.254
12	167.296	8.1488	105.792	8.442	105.877	743.1824	101.88	11.9636	166.909
13	180.278	9.1488	118.774	8.440	118.844	742.6922	106.02	12.9364	179.522
14	193.260	10.1488	131.756	8.438	131.801	742.1453	110.63	13.9067	192.095
15	206.242	11.1488	144.738	8.436	144.749	741.5420	115.72	14.8747	204.629
16	219.225	12.1488	157.721	8.434	157.686	740.8822	121.29	15.8408	217.127
17	232.207	13.1488	170.703	8.431	170.610	740.1659	127.33	16.8050	229.589
18	245.189	14.1488	183.685	8.428	183.522	739.3933	133.85	17.7675	242.017
19	258.171	15.1488	196.667	8.425	196.420	738.5644	140.84	18.7290	254.413
20	271.153	16.1488	209.649	8.422	209.302	737.6793	148.31	19.6890	266.779
21	284.135	17.1488	222.631	8.418	222.169	736.7379	156.24	20.6470	279.116

law of the P, a gradual return to normality below the 20.8^0 discontinuity.

The sharp incline different of the travel-time curves [1] and [6] which intersect in correspondence to the epicentral distance 20.8^0 poses the depth of the « 20^0 discontinuity » as our first objective. To this end, only the data from Baltic Shield stations ($15 \leq \Delta^0 \leq 25$) were utilized. If we consider that, with respect to the source of the P waves the mean azimuth of the Fennoscandia stations is consistent with that for Messina, it was deemed expedient to consider the observational data of only the azimuthal sector having its vertix in Novaya Zemlya and its opening within the azimuthal range $220 \leq \alpha^0 \leq 260$. From the examination of the observations sent us, we find successive impulses to the first arrivals, as in Uppsala (18.17^0, 260.8^s; 19.54^0, 271.2^s; 19.56^0, 272.1^s; 25.73^0, 343.5^s), Skalstugan (17.16^0, 248.1^s; 17.96^0, 257.0^s; 25.09^0, 355.7^s), Uddeholm (19.26^0, 267.5^s), Delary (22.08^0, 299.1^s; 23.46^0, 318.3^s), Umea (15.57^0, 232.8^s), which are consistent with the travel-times of [6] extrapolated to the distance of 15^0. Within the bounds of the azimuthal sector chosen, and with the travel-times menzioned above, the travel-time curve of the P in the interval $15 \leq \Delta^0 \leq 95$, can be represented by the equation

$$T = (70.25 \pm 1.85) + (10.971 \pm 0.141)\,\Delta - (0.03271 \pm 0.00336)\,\Delta^2 + \\ - (0.0000158 \pm 0.0000246)\,\Delta^3 \qquad [7]$$

On the other hand, the very close alignment of the first impulses in the distance interval $8 - 20.4^0$, and the sharp discontinuity of the seismic ray parameter in the proximity of 20.8^0, suggest that the mantle zone with uniforme velocity underlying the discontinuity at 86 km has as its bottom limit the « 20^0 discontinuity ». Furthermore, the « 20^0 discontinuity » depth was determined, relative to the Baltic Shield, by limiting the reduction procedure to only the Fennoscandia stations ($15 \leq \Delta^0 \leq 25$), and elaborating the observation data according to a procedure already introduced for the study of the « 20^0 discontinuity » in Europe and the Mediterranean Basin (Girlanda and Federico, 1966; Bottari and Federico, 1975) ([6], [5]). In this case the procedure was suitably modified to adapt it to the peculiar features of the area under study. This calculation method provides for the utilization of the travel times associated with the seismic rays having points of maximum depth below the discontinuity, and a knowledge of the velocity laws in the crust and in the mantle overlying the discontinuity itself.

Taking in to account [7] and following the above indicated procedure, we obtain the cancellation of the known polinomial term at the depth $h=506.57$ km ($r=5864.43$ km) which level was arrived at by extrapolation of the travel-time curves of equations

$$T=3.55+9.9058\,\Delta-0.0003840\,\Delta^3 \text{ by } r=5891 \text{ km}$$

$$T=0.88+9.8866\,\Delta-0.0009087\,\Delta^3 \text{ by } r=5871 \text{ km.}$$

The couples Δ and T reduced to the level $r=5864.43$ km, can be given by the equation

$$T=9.8804\,\Delta-0.0009168\,\Delta^3 \qquad [8]$$

from which follows

$$p=9.8804-0.00275050\,\Delta^2 \qquad [9]$$

On the other hand, from the relation

$$V=\frac{r}{\frac{180}{\pi}\left(\frac{d\,T}{d\,\Delta}\right)_{\Delta=0}} \qquad [10]$$

we obtain for the velocity of the dilatation waves below the discontinuity the value $V=10.36$ km/sec, which, confronted with the above analogous value $V=8.45$ km/sec, shows a marked contrast in velocity through the discontinuity

$$\frac{V+}{V-}=\frac{8.45}{10.36}=0.815$$

therefore, the research on the Fennoscandia seismograms of the impulses relative to the P waves reflected ($P\,dP$) seems justified. Towards this end and in line with the proposed model for the Fennoscandia mantle, the curve of the $P\,d\,P$ calculated was determined, and we proceded to identify these phases in the seismograms. The travel-time equation of the $P\,d\,P$ calculated is

$$T=(123.58\pm0.10)+(0.7435\pm0.0026)\,\Delta^2-(0.021973\pm0.000207)\,\Delta^3+$$
$$+(0.00025022\pm0.00000418)\,\Delta^4 \qquad [11]$$

The elements which allow the comparison between the reflected phase calculated and that identified in the seismograms are reported in Table 4 (Col. 8 and 9). Other examples of reflected waves are shown in the Figg. 7, 8, 9, 10, 11, 12, and 13.

TABLE 4

Nuclear Explosion Date	Station Code	Angular Distance (deg)	*Pn TT* observed (sec)	Residual (*Pn*) (sec)	*P TT* observed (sec)	Residual (*P*) (sec)	*P d P TT* observed (sec)	Residual (*P d P*) (sec)
OCT. 14, '69	KIR	12.5306	174.9	+ 0.7			205.1	+ 2.8
	UPP	19.5250	255.7	+ 0.7	273.2	+ 1.8	281.9	+ 2.5
	DEL	23.4521	318.3	+ 2.2	308.6	— 0.5	325.0	+ 0.1
OCT. 14, '70	KIR	12.5615	175.2	+ 0.5	(202.4)	(0.3)	202.4	— 1.2
	UME	15.5705	212.8	— 0.8	(232.8)	(0.3)	232.8	— 2.8
	UPP	19.5439	265.3	0.0	271.2	— 0.4	278.1	— 1.9
SEP. 27, '71	KIR	12.5617	174.8	+ 0.2	(199.8)	(— 2.3)	199.8	— 3.8
	UPP	19.5619	255.7	+ 0.2	272.0	+ 0.2	279.4	— 0.9
	DEL	23.4988	315.4	— 1.2	308.7	— 0.8	324.5	— 0.8
AUG. 28, '72	UPP	19.4758	254.9	+ 0.5	271.1	+ 0.2	278.7	— 0.6
SEP. 12, '73	KIR	12.5924	175.3	+ 0.3	(202.8)	(0.4)	202.8	— 1.1
	UME	15.6078	212.9	— 1.2	(232.9)	0.0	233.9	— 2.1
	UPP	19.5831	265.8	+ 0.1	273.3	+ 1.3		
SEP. 27, '73	SKA	17.1660	236.3	+ 1.9	248.1	— 0.2	252.7	— 0.5
AUG. 14, '74	KIR	19.8991	272.3	+ 2.5	276.6	+ 1.5	283.6	— 0.5
	UME	22.1820	300.0	+ 0.5	298.0	+ 1.0	311.0	+ 0.8
	SKA	25.0909	335.7	— 1.5	326.8	+ 2.4	347.0	+ 3.2
	UPP	25.7337	348.9	+ 3.3	332.8	+ 2.4	354.5	+ 3.3
	UDD	27.0008	359.8	— 2.2	345.9	+ 3.8	364.8	— 1.3

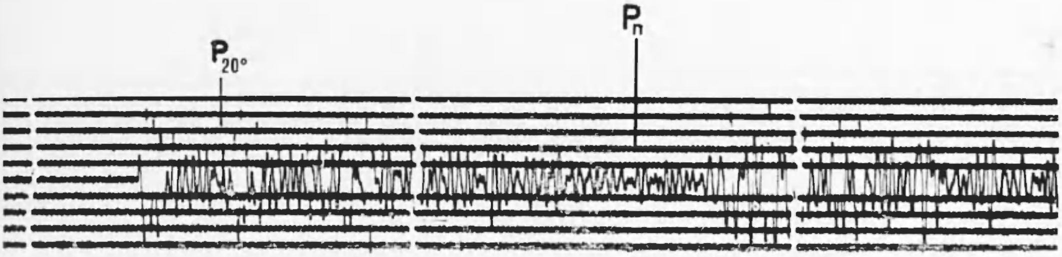

Fig. 2 — MES seismogram for the October 14, 1970 New Zemlya underground nuclear explosion, showing clear impulses of P_{20^0} and Pn.

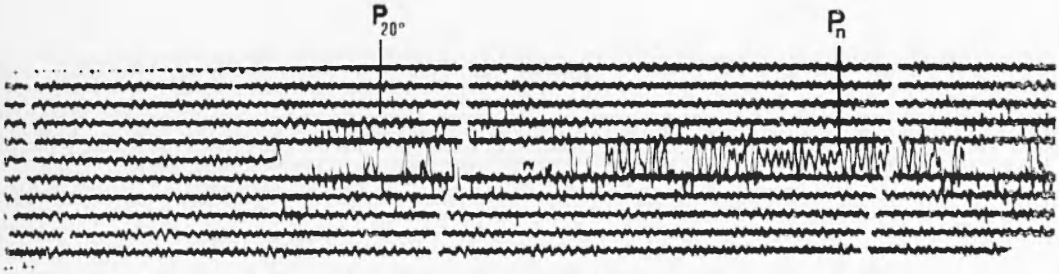

Fig. 3 — Record illustrating P_{20^0} and Pn at MES station for the September 27, 1971, New Zemlya nuclear explosion.

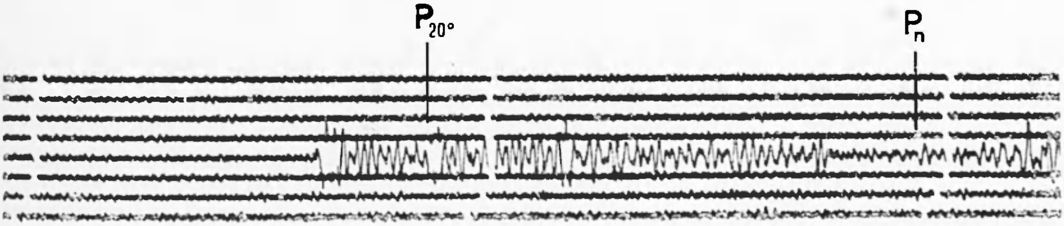

Fig. 4 — MES seismogram of the New Zemlya underground explosion of August 27, 1972. P_{20^0} and Pn impulses are indicated.

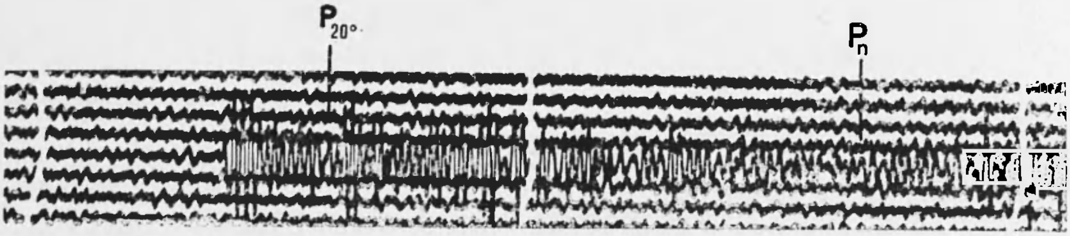

Fig. 5 — Record illustrating P_{20^0} and *Pn* at Messina station for the August 29, 1971 New Zemlya underground nuclear explosion.

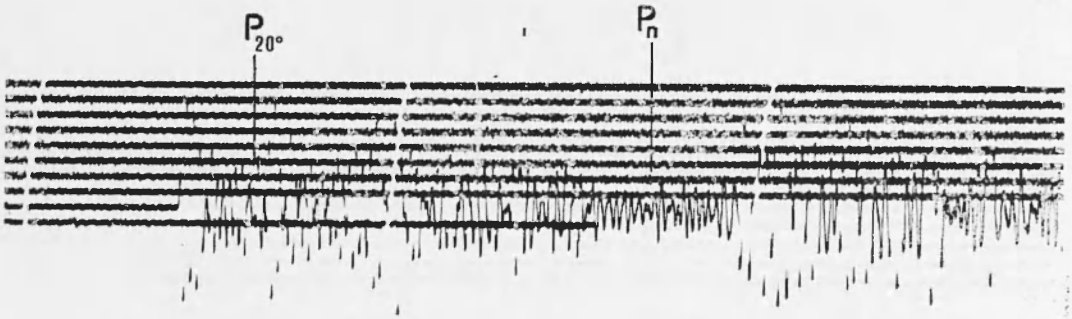

Fig. 6 — Seismogram showing P_{20^0} and *Pn* arrivals at Messina station for the nuclear explosion at New Zemlya of September 12, 1973.

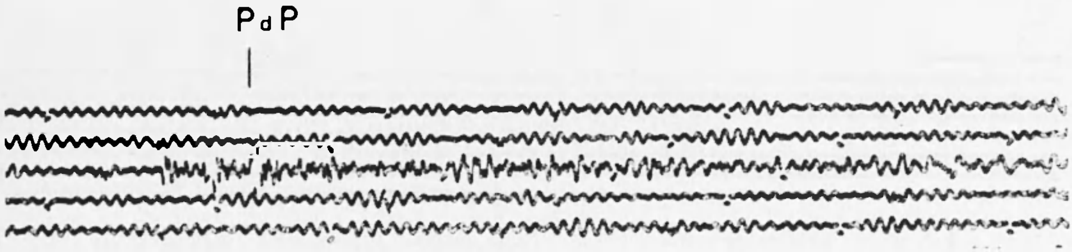

Fig. 7 — KIR seismogram for the October 14, 1969 New Zemlya nuclear explosion, showing a clear impulse of *P d P*.

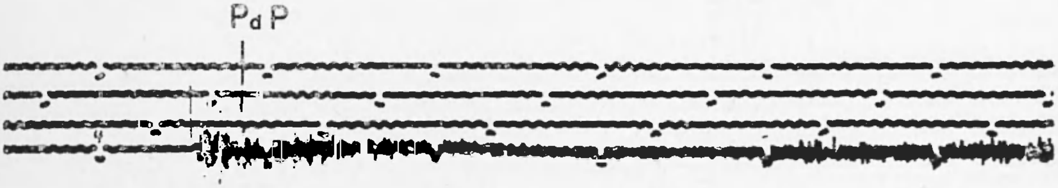

Fig. 8 — Record illustrating PdP at UPP station for the October 10, 1969 New Zemlya underground nuclear explosion.

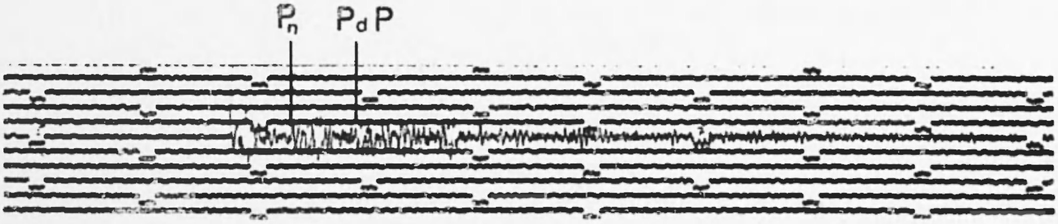

Fig. 9 — UPP seismogram of the New Zemlya underground nuclear explosion of August 15, 1974. Impulses of the PdP and Pn phases are indicated.

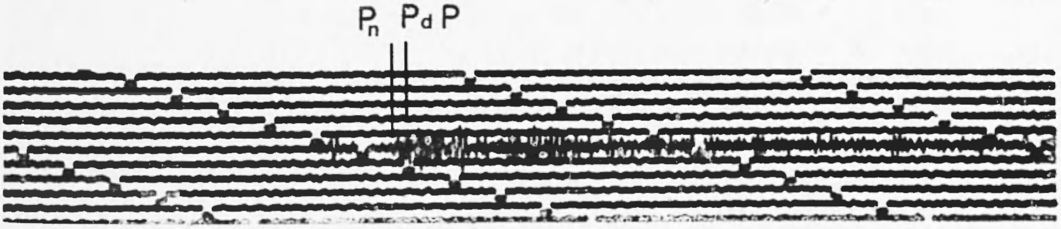

Fig. 10 — UDD seismogram for the August 15, 1974 New Zemlya nuclear explosion, showing impulses of Pn and PdP phases.

Fig. 11 — Record illustrating *Pn* and *P d P* at SKA station for the August 15, 1974 New Zemlya underground nuclear explosion.

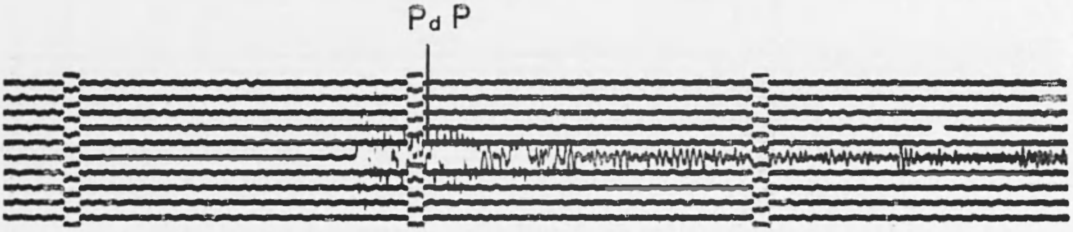

Fig. 12 — UME seismogram for the August 15, 1974 New Zemlya nuclear explosion, showing clear impulse of *P d P* phase.

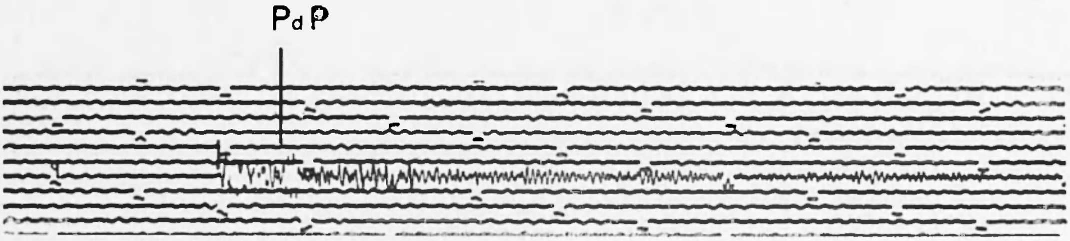

Fig. 13 — Seismogram showing *P d P* arrival (KIR station) of the underground nuclear explosion of August 15, 1974.

TELESEIMIC Pn AND P_{20^0} PHASES.

From a fair number of recordings kindly furnished us by various observatories, we can find, up to distances of around 40^0, clear impulses whose travel times have the same trend of the Pn, initially caracterized by the relation [1], (Table 4, col. 4 and 5; table 5, col. 9 and 10).

In addition, the notable impulses observed at Messina (Figg. 2, 3, 4, 5 and 6) 13 sec after the first arrivals, already mentioned in the preceding paragraph of this paper, are adequately confirmed in the numerous seismograms of other stations, and are interpretable as P refracted on the « 20^0 discontinuity » (P_{20^0}). The observed data relative to this phase, and those calculated in line with the crust-mantle model previously defined, are reported in Table 5 (Col. 3 and 5).

In this connection we emphasize that for this refracted phase the relating travel-time equation has been obtained excluding the observational data of Messina. In fact, at this station, the travel times exhibit systematically considerable early arrivals as well as the observed first arrivals (P waves). This concomitance is revealing the disagreement of the model adopted with the travel times observed at Messina.

The impulses of the P_{20^0} recorded concord with the equation of the travel times

$$T = 77.69 + 9.8804\,\Delta \qquad [12]$$

which was obtained by assigning to the « 20^0 discontinuity » the calculated depth (506.57 km) and to the seismic ray parameter the value corresponding limit incidence on the same discontinuity ($p = 9.8803962$ sec/Δ^0). Furthermore, in column 7 are shown the travel times calculated by the simple linear fit of the data observed

$$T = 77.11 + 9.8970\,\Delta$$

which is consistent with [12] as clearly indicated by the two residual populations (Col. 6 and 8). A fair number of impulses of the Pn phase are reported in Figg. 2, 3, 4, 5, 6, 14, 15, 16, 17, 18, 19, 20, 21, 22; analogously examples of P_{20^0} are reported in Figg. 2, 3, 4, 5, 6, 16, 17, 18, 19, 22, 23, and 24.

TABLE 5

N^0	Station Code	Angular Distance (deg)	T_{ob} (P_{20^0}) (sec)	T_{ob} (P_{20^0})—$p\Delta$ (sec)	T_c (P_{20^0}) (sec)	Residual (P_{20^0}) (sec)	T_c' (P_{20^0}) (sec)	Residual (P_{20^0}) (sec)	P_n — TT observed (sec)	Residual (P_n) (sec)
1	KHC	30.1620	376.8	78.788	375.70	— 1.10	375.62	— 1.18	404.3	+ 1.2
2	BRA	30.2543	375.3	76.376	376.61	+ 1.31	376.54	+ 1.24	40[illegible].5	— 1.7
3	BRA	30.2847	375.7	76.475	376.91	+ 1.21	376.84	+ 1.14	[illegible]0	— 2.7
4	SRO	30.3387	—	—	—	—	—	—	403.9	— 1.5
5	SRO	30.3506	377.2	77.324	377.56	+ 0.36	377.49	+ 0.29	402.2	— 3.3
6	BUD	30.4881	379.2	77.966	378.92	— 0.28	378.83	— 0.35	410.5	+ 3.2
7	DUD	30.4992	379.1	77.756	379.03	— 0.07	378.96	— 0.14	407.4	0.0
8	STU	31.6622	390.4	77.565	390.52	+ 0.12	390.47	+ 0.07	421.2	— 1.3
9	STU	31.6819	389.6	76.570	390.72	+ 1.12	390.67	+ 1.07	—	—
10	WLS	32.4743	398.7	77.841	398.55	— 0.15	398.51	— 0.19	431.9	— 1.2
11	WLS	32.4919	399.2	78.167	398.72	— 0.48	398.68	— 0.52	430.5	— 2.8
12	NEU	33.8826	413.4	78.627	412.46	— 0.94	412.45	— 0.95	454.8	— 1.4
13	NEU	33.9218	414.1	78.939	412.85	— 1.25	412.83	— 1.27	449.3	— 2.5
14	VOU	34.7104	420.1	77.148	420.64	+ 0.54	420.64	—0.54	—	—
15	MNY	36.0347	434.9	78.863	433.72	— 1.18	433.75	— 1.15	—	—
16	RMP	37.2487	445.7	77.668	445.72	+ 0.02	445.76	+ 0.06	495.4	+ 0.3
17	RMP	37.2886	447.0	78.574	446.11	— 0.89	446.16	— 0.84	498.0	+ 2.4
18	RMP	37.3175	445.7	76.988	446.40	+ 0.70	446.44	+ 0.74	497.2	+ 1.2
19	NPL	37.8228	450.7	76.996	451.39	+ 0.69	451.44	+ 0.74	450.9	0.0
20	NPL	37.7902	451.6	78.218	451.07	— 0.53	451.12	— 0.48	502.8	— 0.7
21	NPL	37.8544	451.9	77.884	451.70	— 0.20	451.76	— 0.14	—	—
22	NPL	37.8668	450.8	76.661	451.83	+ 1.03	451.88	+ 1.08	505.1	+ 2.0
23	MES	40.0664	466.9	—	473.31	+ 6.41	473.40	+6.50	531.2	— 0.1
24	MES	40.0664	467.5	—	473.56	+ 6.06	473.65	+ 6.15	532.5	+ 0.8
25	MES	40.1005	467.3	—	473.90	+ 6.60	473.98	+ 6.68	532.8	+ 0.7
26	MES	40.1110	468.6	—	474.00	+ 5.40	474.09	+ 5.49	533.1	+ 0.9
27	TOL	43.4614	507.5	78.084	507.10	— 0.40	507.25	— 0.25	—	—
28	PTO	43.5689	507.8	77.322	508.16	+ 0.36	508.31	+ 0.51	—	—

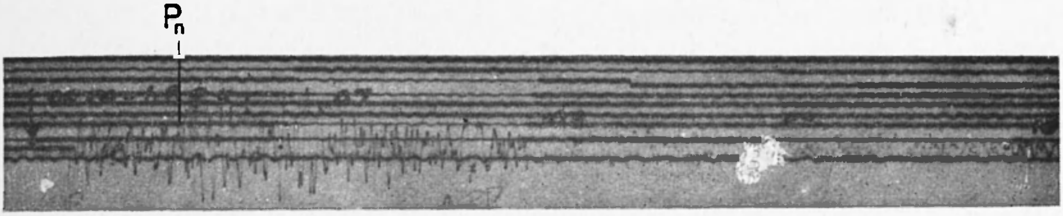

Fig. 14 — BRA seismogram for the September 27, 1971 New Zemlya underground nuclear explosion, showing a clear impulse of *Pn*.

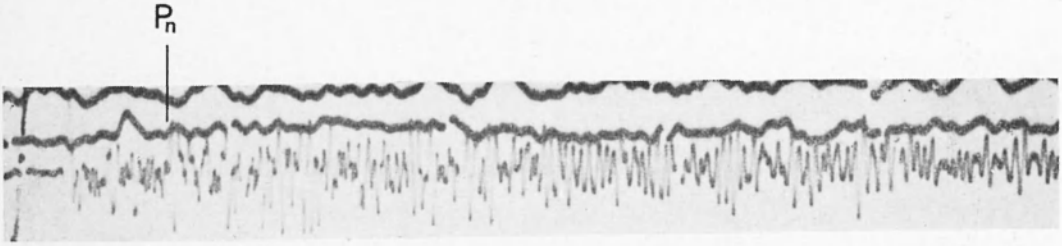

Fig. 15 — SRO seismogram (Horizontal component) for the September 27, 1971 New Zemlya nuclear explosion, showing a clear impulse of *Pn*.

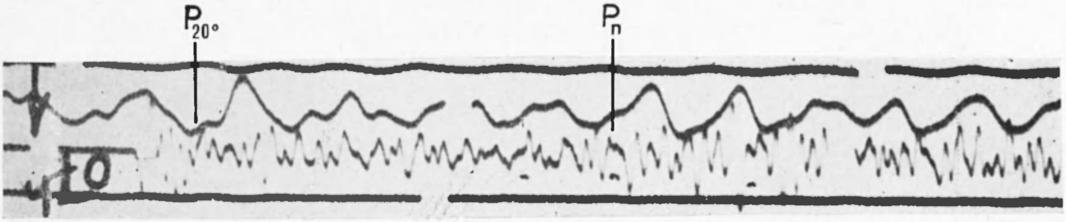

Fig. 16 — BUD seismogram of the New Zemlya underground nuclear explosion of September 27, 1971. The impulses of the $P_{20°}$ and *Pn* phases are indicated.

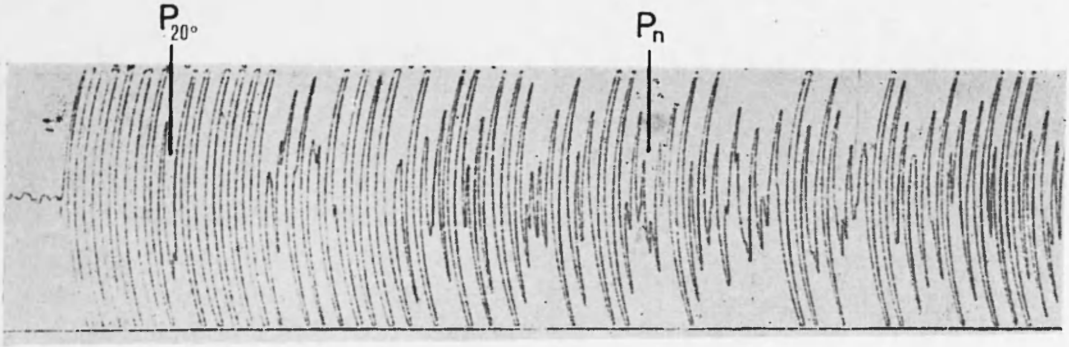

Fig. 17 — WLS seismogram for the September 27, 1971 ,New Zemlya underground nuclear explosion, showing imulses of P_{20^0} and Pn.

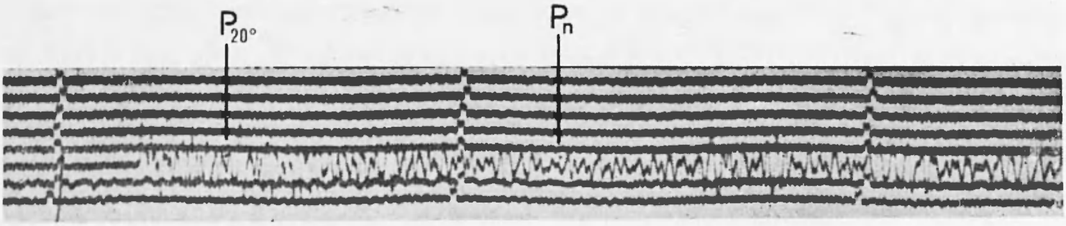

Fig. 18 — Record illustrating P_{20^0} and Pn arrivals at RMP station for the August 28, 1972 New Zemlya underground nuclear explosion.

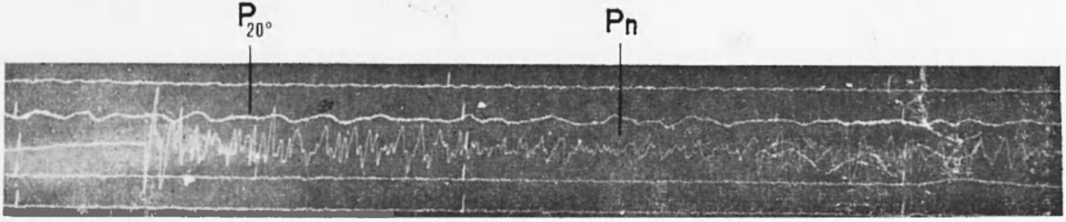

Fig. 19 — NPL seismogram of the New Zemlya underground nuclear explosion of August 27, 1972. The impulses of P_{20^0} and Pn are indicated.

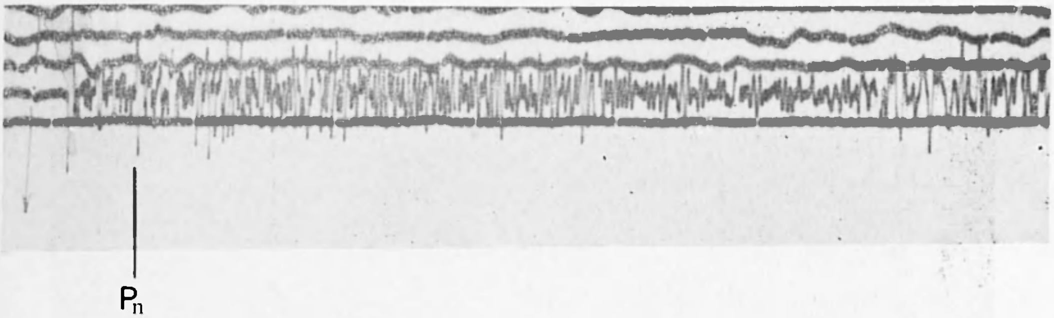

Fig. 20 — Record illustrating *Pn* arrival at SRO station for September 12, 1973 New Zemlya underground nuclear explosion.

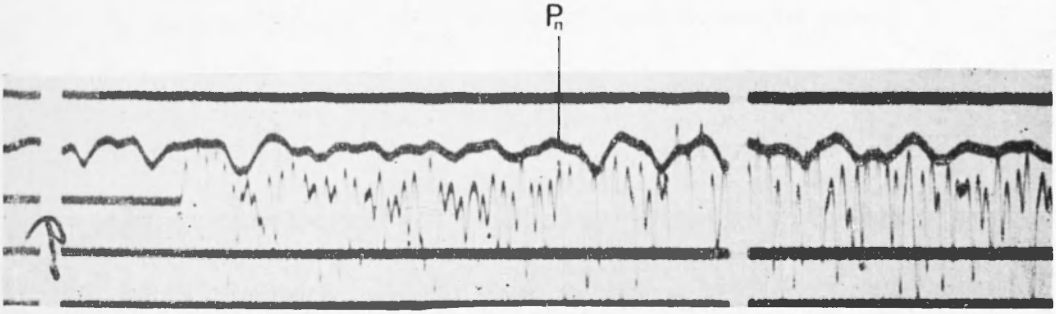

Fig. 21 — Seismogram of the BUD station showing *Pn* impulse for the September 12, 1973 New Zemlya nuclear explosion.

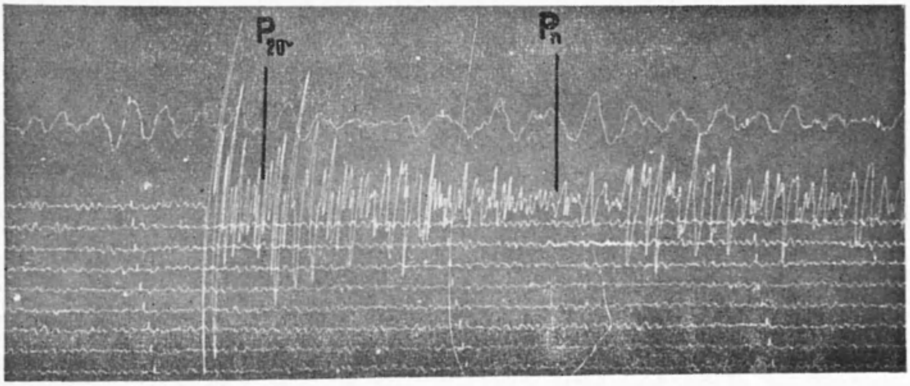

Fig. 22 — NPL seismogram of the New Zemlya underground nuclear explosion of September 12, 1973. The impulses of the $P_{20^{\circ}}$ an *Pn* phases are indicated.

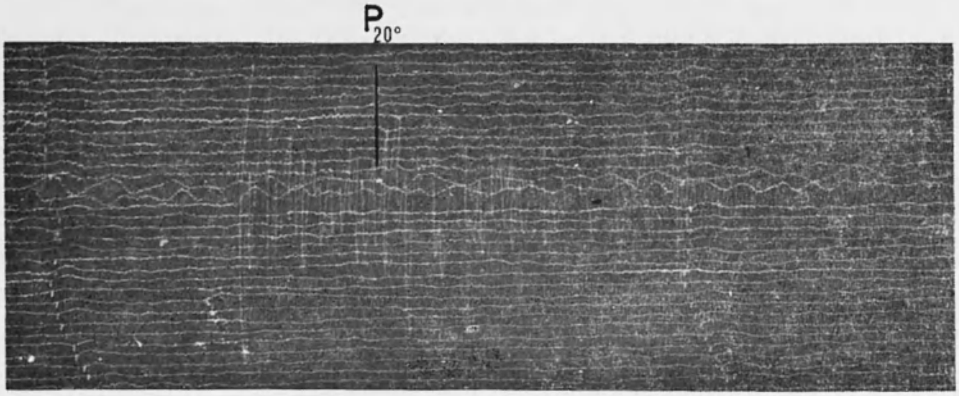

Fig. 23 — NPL seismogram for the October 14, 1970 New Zemlya underground nuclear explosion, showing clear impulse of the P_{20^0} phase.

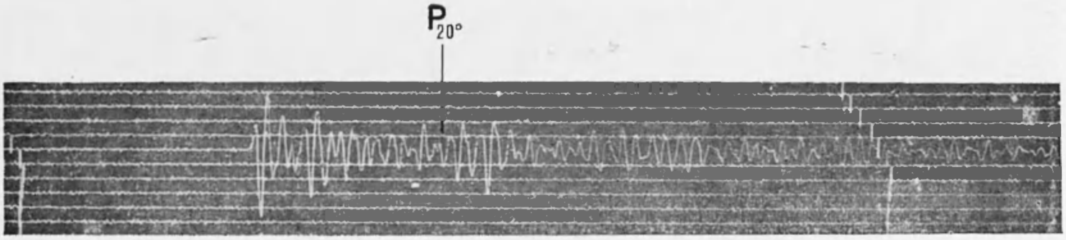

Fig. 24 — Seismogram obtained at NPL station for the September 27, 1971 New Zemlya underground nuclear explosion. The P_{20^0} phase is indicated.

CONCLUSIONS.

The analysis of the travel times of the *P* waves originating concomitantly with six underground nuclear explosions in Novaya Zemlya puts into evidence various observational elements and puts forward solutions which can be summarized as follows:

(i) the first arrivals in the distance range $9 \leq \Delta^0 \leq 20.4$, are noticeably early arrivals with respect to the standard travel-times of Herrin and Jeffreys-Bullen.

(ii) the travel times of the initial impulses result, for the entire distance interval corresponding to the Fennoscandia area, as being strictly linearly dependent on the distance and show an appreciably greater value for the apparent velocity than those reported in literature for the sub-Moho in the same region. We can therefore point out the existence of a refractory horizon located at a depth of 86 km, below which the velocity of the longitudinal waves can be considered uniform down to the level of the « 20^0 discontinuity ».

(iii) the proposed model is confirmed by the observation of *Pn* waves noticeable as far as 40^0 and of *P* vaves reflected (*P d P*) and refracted (P_{20^0}) on the « 20^0 discontinuity ».

ACKNOWLEDGEMENTS.

We thank Professor Markus Båth Director of the Seismological Institute, Uppsala, Sweden, for his keen interest and also for providing seismograms of the Swedish Network. The writers are indebted to all observatories which have provide to send records and observational data.

REFERENCES

(¹) ADAMS, R. D., 1968. - *Early reflection of P′ P′ as an indication of upper mantle structure.* « Bull. Seism. Soc. Am. », **58**, pp. 1933-1947.

(²) BÅTH, M., 1966. - *Propagation of Sn and Pn to teleseismic distances.* « Pure Appl. Geophys. » **64**, pp. 19-30.

(³) BÅTH, M., 1967. - *Observations of teleseismic Pn phases.* «Pure Appl. Geophys.», **66**, pp. 30-36.

(⁴) BÅTH, M., 1971. - *Average Crustal Structure of Sweden.* «Pure Appl. Geophys.», **88**, pp. 75-91.

(⁵) BOTTARI, A., FEDERICO, B., 1975. - *P-waves reflected from the « 20^0 discontinuity » beneath the Mediterranean region.* « Annali di Geofisica », **28**, pp. 77-96.

(⁶) GIRLANDA, A., FEDERICO, B., 1966. - *La « Dicontinuità 20^0 ».* « Annali di Geofisica », **19**, pp. 131-189.

(7) Herrin, E., E. P. Arnold, B. A. Bolt, G. E. Clawson, E. R. Engdahl, H. W. Freedman, D. W. Gordon, A. L. Hales, J. L. Lobdell, O. Nuttli, C. Romney, J. Taggart, and W. Tucker, 1968. - *1968 seismological tables for P phases.* « Bull. Seism. Soc. Am. », **58**, pp. 1193-1241.

(8) Jeffreys, H., K. E. Bullen, 1967. - *Seismological Tables.* Brit. Ass., Gray-Milne Trust.

(9) Kanestrom, R., 1973. - *A Crust-Mantle Model for Norsar Area.* « Pure Appl. Geophys. », **105**, pp. 729-740.

(10) Massé, R. P., S. S. Alexander, 1974. - *Compressional velocity distribution beneath Scandinavia and Western Russia.* « Geophys. J. R. Astr. Soc. », **39**, pp. 587-602.

(11) Penttilä, E., 1965. - *On Seismological Investigation of Crustal Structure in Finland.* Institute of Seismology, University of Helsinki, Publ. N⁰ 60.

(12) Penttilä, E., 1969. - *A report summarizing on the velocity of earthquake waves and the structure of the earth's crust in the Baltic shield.* « Geophysica », **10**, p. 11.

(13) Sellevoll, M. A., P. Pomeroy, 1968. - *A travel time study for Fennoscandia.* « Arbok for Univ. I Bergen, Mat. Naturv. » Serie, **9**, pp. 3-29.

(14) Tryggvason, E., 1961. - *Wave velocity in the upper mantle below the Artic-Atlantic Ocean and North West Europe.* « Annali di Geofisica », **14**, pp. 379-392.