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

A. Bottari (*) - B. Federico (*)

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SUMMARY. - The analysis of the travel times of the P waves generated by six underground nuclear explosions in Novaya Zemlya shows notable early arrivals (> 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 < Δ° < 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° 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°, 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 < Δ° < 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° » (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°, 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) (1), 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° discontinuity». Similarly, following much research the upper mantle in the Fennoscandia zone presents peculiar structures of no less seismological interest (Tryggvason, 1961; Bath, 1966, 1971; Sellevoll and Pomeroy, 1968, et al. (10, 12, 14, 19). 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°, 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 arrivals 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°, with the purpose of obtaining focal locations as for as possible independent of the propagation anomalies which exist in the upper mantle.
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) (7) and Herrin et al. (1968) (8). 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)
| No | Station Code | Nuclear Explosion Date | Angular Distance (deg) | TT of Pn by H (sec) | Standard TT by J — B (sec) |
|----|--------------|------------------------|------------------------|---------------------|---------------------------|
| 1  | KEV          | OCT 27, '66            | 9.457                  | 136.81              | 140.51                    |
| 2  |              | OCT 21, '67            | 9.506                  | 137.48              | 141.12                    |
| 3  |              | OCT 14, '69            | 9.459                  | 136.84              | 140.53                    |
| 4  |              | OCT 14, '70            | 9.490                  | 137.26              | 140.96                    |
| 5  |              | SEP 27, '71            | 9.490                  | 137.26              | 140.96                    |
| 6  |              | AUG 28, '72            | 9.383                  | 135.80              | 139.49                    |
| 7  | KRK          | OCT 27, '66            | 8.617                  | 125.38              | 128.88                    |
| 8  |              | OCT 21, '67            | 8.662                  | 125.99              | 129.50                    |
| 9  | KBS          | OCT 21, '67            | 11.380                 | 162.89              | 166.87                    |
| 10 |              | OCT 14, '70            | 11.425                 | 163.50              | 167.48                    |
| 11 |              | SEP 27, '71            | 11.369                 | 162.74              | 166.72                    |
| 12 |              | AUG 28, '72            | 11.255                 | 161.20              | 165.17                    |
| 13 | TRO          | OCT 27, '66            | 11.841                 | 169.13              | 173.14                    |
| 14 |              | OCT 14, '69            | 11.846                 | 169.20              | 173.21                    |
| 15 |              | OCT 14, '70            | 11.883                 | 169.70              | 173.71                    |
| 16 |              | SEP 27, '71            | 11.873                 | 169.56              | 173.57                    |
| 17 |              | AUG 28, '72            | 11.758                 | 168.01              | 172.01                    |
| 18 | KIR          | OCT 30, '61            | 12.504                 | 178.08              | 182.05                    |
| 19 |              | OCT 27, '66            | 12.531                 | 178.45              | 182.42                    |
| 20 |              | OCT 21, '67            | 12.578                 | 179.08              | 183.05                    |
| 21 |              | OCT 14, '69            | 12.531                 | 178.45              | 182.42                    |
| 22 |              | OCT 14, '70            | 12.561                 | 178.85              | 182.62                    |
| 23 |              | SEP 27, '71            | 12.562                 | 178.86              | 182.85                    |
| 24 |              | AUG 28, '72            | 12.455                 | 177.42              | 181.40                    |
| 25 | SOD          | OCT 27, '66            | 11.123                 | 159.42              | 163.37                    |
| 26 |              | OCT 21, '67            | 11.166                 | 160.00              | 165.96                    |
| 27 |              | OCT 14, '69            | 11.115                 | 159.31              | 163.26                    |
| 28 |              | OCT 14, '70            | 11.139                 | 159.63              | 163.59                    |
| 29 |              | SEP 27, '71            | 11.150                 | 159.78              | 163.74                    |
| 30 |              | AUG 28, '72            | 11.056                 | 158.51              | 162.46                    |
| 31 | OUL          | OCT 21, '67            | 13.086                 | 185.93              | 189.84                    |
| 32 |              | OCT 14, '69            | 13.054                 | 185.23              | 189.13                    |
| 33 |              | OCT 14, '70            | 13.053                 | 185.49              | 189.40                    |
| 34 |              | SEP 27, '71            | 13.071                 | 185.73              | 189.64                    |
| 35 | KIN          | OCT 27, '66            | 13.396                 | 190.09              | 193.93                    |
|   |   |   |   |
|---|---|---|---|
| 36 | KJN | OCT 21, '67 | 13.452 | 185.4 | 190.57 | 194.40 |
| 37 | KJF | OCT 14, '69 | 13.379 | 185.4 | 189.86 | 193.70 |
| 38 |   | OCT 14, '70 | 13.395 | 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 | 242.38 |
| 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 | 17.888 | 243.7 | 248.14 | 251.55 |
| 56 | UPP | OCT 30, '61 | 19.611 | 267.0 | 268.83 | 272.55 |
| 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 |   | OCT 14, '69 | 20.344 | 275.4 | 277.09 | 280.58 |
| 65 |   | OCT 14, '70 | 20.368 | 276.6 | 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). (2).
(2) $B =$ Jeffreys and Bullen (1967) (4).
Fig. 1 — Travel times (spots) and least-square fits (lines) for P-wave first arrivals at Fennoscandia stations (black spots) and other stations with $\Delta \geq 20^\circ.4$ (white spots).
revealing an apparent velocity of 8.56 km/sec, corresponding to a true velocity of 8.52 km/sec, under the Mohorovicic’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 (Pentiila, 1965; Sellevoll and Pomeroy, 1968; Bath, 1971; Kanestrom, 1973) ([1], [11], [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) ([2]), for the velocity in the sub-Moho, then the travel time equation of the \( P \)-waves refracted on the Mohorovicic discontinuity results as follows

\[ T = 7.65 + 13.5686 \Delta \]  

The travel-times compatible with [2] result for \( \Delta^2 > 7 \) longer than the corresponding ones deduced using [1]. Furthermore, it not being possible to have data on the epicentral range 2-8\(^\circ\), the hypothesis that the first impulses in the range 8.5 to 20.8\(^\circ\) 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 appreciably wide interval of 8.5 - 20.8\(^\circ\), 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 Bath (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 $r_s = 6285\, \text{km}$, 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 $T_s = 2 \frac{r_s}{v} \sin \Delta_s/2$, which as is known, represents the travel-time curve in a homogeneous spheric medium. In Table 3 are reported some $\Delta$ and $T$ couples of [1] contained in the interval $8 \leq \Delta \leq 21$, and the corresponding $\Delta_s$ and $T_s$ reduced to $r_s = 6285\, \text{km}$; the velocity values deducible from the equation $v = \frac{2 r_s}{T_s \sin \Delta_s/2}$, $\Delta_s$ and $T_s^* = 2r_s/v \sin \Delta_s/2$, $\bar{v}$ being the mean value of the velocities given in column 5; the value of the seismic ray parameter $\rho(\Delta)$, and the maximum depth reached by the seismic rays (Col. 8).

From the relations

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

$$\rho = \frac{r_s}{v} \cos \frac{\Delta_s}{2}$$  \[4\]

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

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

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

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

$$T = (68.73 \pm 0.96) + (11.043 \pm 0.06) \Delta - (0.03363 \pm 0.00118) \Delta^2 +$$

$$- (0.0000122 \pm 0.0000070) \Delta^3$$  \[6\]

This results confirms the acceptable quality of the statistical determination of the explosion location, and indicates, relatively to the velocity
| $\Delta$ (deg) | $T$ (sec) | $\Delta t$ (sec) | $\Delta t^*$ (sec) | $p(\Delta t)$ (sec) | $T_1$ (sec) | $T_2$ (sec) | $T_3$ (sec) | $h$ (km) | $d$ (deg) | $\Delta d$ (deg) |
|----------------|-----------|------------------|-------------------|--------------------|-----------|-----------|-----------|--------|--------|--------|
| 8              | 41,988    | 53,864           | 8,447             | 53,939             | 74,5772   | 90,12     | 116,023   | 128,812 | 141,551 | 141,524 |
| 9              | 51,688    | 66,864           | 8,446             | 66,952             | 74,5135   | 95,34     | 100,901   | 128,812 | 141,551 | 141,524 |
| 10             | 61,388    | 79,828           | 8,445             | 79,920             | 74,3951   | 95,04     | 100,701   | 141,551 | 141,524 | 141,524 |
| 11             | 71,088    | 92,810           | 8,444             | 92,902             | 74,3166   | 95,22     | 100,501   | 141,551 | 141,524 | 141,524 |
| 12             | 80,788    | 105,792          | 8,442             | 105,877            | 74,2584   | 95,40     | 100,301   | 141,551 | 141,524 | 141,524 |
| 13             | 90,488    | 118,844          | 8,440             | 118,984            | 74,2242   | 95,60     | 100,101   | 141,551 | 141,524 | 141,524 |
| 14             | 100,188   | 131,931          | 8,438             | 131,981            | 74,1543   | 95,80     | 100,001   | 141,551 | 141,524 | 141,524 |
| 15             | 109,888   | 144,820          | 8,436             | 144,974            | 74,1032   | 96,00     | 100,001   | 141,551 | 141,524 | 141,524 |
| 16             | 119,588   | 157,712          | 8,434             | 157,766            | 74,0522   | 96,20     | 100,001   | 141,551 | 141,524 | 141,524 |
| 17             | 129,288   | 170,601          | 8,432             | 170,610            | 74,0022   | 96,40     | 100,001   | 141,551 | 141,524 | 141,524 |
| 18             | 138,988   | 183,485          | 8,430             | 183,522            | 73,9522   | 96,60     | 100,001   | 141,551 | 141,524 | 141,524 |
| 19             | 148,688   | 196,367          | 8,428             | 196,467            | 73,9022   | 96,80     | 100,001   | 141,551 | 141,524 | 141,524 |
| 20             | 158,388   | 209,249          | 8,426             | 209,349            | 73,8522   | 97,00     | 100,001   | 141,551 | 141,524 | 141,524 |
| 21             | 168,088   | 222,131          | 8,424             | 222,031            | 73,8022   | 97,20     | 100,001   | 141,551 | 141,524 | 141,524 |
law of the $P$, a gradual return to normality below the 20.8° discontinuity.

The sharp incline different of the travel-time curves [1] and [6] which intersect in correspondence to the epicentral distance 20.8° poses the depth of the «20° discontinuity» as our first objective. To this end, only the data from Baltic Shield stations (15° ≤ δ ≤ 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 vertex in Novaya Zemlya and its opening within the azimuthal range 220° ≤ α ≤ 260°. From the examination of the observations sent us, we find successive impulses to the first arrivals, as in Uppsala (18.17°, 260.8 s; 19.54°, 271.2°; 19.56°, 272.1°; 25.73°, 345.5°), Skalstugan (17.16°, 248.1°; 17.96°, 257.0°; 25.09°, 355.7°), Uddeholm (19.26°, 267.5°), Delary (22.08°, 299.1°; 23.46°, 318.3°), Umea (15.57°, 232.8°), which are consistent with the travel-times of [6] extrapolated to the distance of 15°. Within the bounds of the azimuthal sector chosen, and with the travel-times mentioned above, the travel-time curve of the $P$ in the interval 15° ≤ δ ≤ 95°, can be represented by the equation

$$T = (70.25 ± 1.85) + (10.971 ± 0.141) \Delta - (0.03271 ± 0.00336) \Delta^2 +$$

$$- (0.0000158 ± 0.0000246) \Delta^3$$  [7]

On the other hand, the very close alignment of the first impulses in the distance interval 8°–20.4°, and the sharp discontinuity of the seismic ray parameter in the proximity of 20.8°, suggest that the mantle zone with uniforme velocity underlying the discontinuity at 86 km has as its bottom limit the «20° discontinuity». Furthermore, the «20° discontinuity» depth was determined, relative to the Baltic Shield, by limiting the reduction procedure to only the Fennoscandia stations (15° ≤ δ ≤ 25°), and elaborating the observation data according to a procedure already introduced for the study of the «20° discontinuity» in Europe and the Mediterranean Basin (Girlanda and Federico, 1966; Bottari and Federico, 1975) (°, ′). 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 into account \([7]\) and following the above indicated procedure, we obtain the cancellation of the known polynomial 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

\[
T = 3.55 + 9.9058 \Delta - 0.0003840 \Delta^3 \quad \text{by} \quad r = 5891\ km
\]

\[
T = 0.88 + 9.8866 \Delta - 0.0009087 \Delta^3 \quad \text{by} \quad r = 5871\ km.
\]

The couples \(\Delta\) and \(T\) reduced to the level \(r = 5864.43\) km, can be given by the equation

\[
T = 9.8804 \Delta - 0.0009168 \Delta^3
\]

from which follows

\[
p = 9.8804 - 0.00275050 \Delta^2
\]

On the other hand, from the relation

\[
V = \frac{\dot{T}}{\dot{\Delta}} = \frac{d\ T}{d\ \Delta} \bigg|_{\Delta=0}
\]

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

\[
\frac{V+}{V-} = \frac{10.36}{8.45} = 0.815
\]

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 \(P\ dP\) calculated was determined, and we proceeded to identify these phases in the seismograms. The travel-time equation of the \(P\ dP\) calculated is

\[
T = (123.58\pm0.10) + (0.7435\pm0.0026) \Delta^2 - (0.021973\pm0.000207) \Delta^3 +
\]

\[
+ (0.00025022\pm0.00000418) \Delta^4
\]

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.
| Nuclear Explosion Date | Station Code | Angular Distance (deg) | $P_dTT$ observed (sec) | Residual ($P_dTT$) (sec) | $P_dTT$ observed (sec) | Residual ($P_dTT$) (sec) | $P_dP$ observed (sec) | Residual ($P_dP$) (sec) |
|------------------------|--------------|------------------------|-----------------------|--------------------------|-----------------------|--------------------------|-----------------------|--------------------------|
| OCT. 14, '69           | KIR          | 12.5306                | 174.9                 | + 0.7                    | 273.2                 | + 1.8                    | 205.1                 | + 2.8                    |
|                        | UPP          | 19.5250                | 255.7                 | + 0.7                    | 308.6                 | − 0.5                    | 325.0                 | + 0.1                    |
| OCT. 14, '70           | KIR          | 12.5615                | 175.2                 | + 0.5                    | 202.4                 | (0.5)                    | 202.4                 | − 1.2                    |
|                        | UPP          | 15.5703                | 212.8                 | − 0.5                    | 232.8                 | (0.3)                    | 232.8                 | − 2.8                    |
| SEP 27, '71            | KIR          | 12.5617                | 174.8                 | + 0.2                    | 199.8                 | (− 2.3)                  | 199.8                 | − 3.8                    |
|                        | UPP          | 19.5619                | 235.7                 | + 0.2                    | 272.0                 | + 0.2                    | 279.4                 | − 0.9                    |
| AUG. 28, '72           | UPP          | 19.4758                | 234.9                 | + 0.5                    | 271.1                 | + 0.2                    | 278.7                 | − 0.6                    |
| SEP. 12, '73           | KIR          | 12.5924                | 175.3                 | + 0.5                    | 202.8                 | (0.4)                    | 202.8                 | − 1.1                    |
|                        | UMP          | 15.6078                | 212.9                 | − 1.2                    | 232.9                 | 0.3                      | 233.9                 | − 2.1                    |
| SEP. 27, '73           | S+ A         | 17.1660                | 256.3                 | + 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                    |
|                        | UMP          | 22.1820                | 300.0                 | + 0.5                    | 298.0                 | + 1.0                    | 311.0                 | + 0.8                    |
|                        | S+ A         | 25.0909                | 335.7                 | − 1.5                    | 326.8                 | + 2.4                    | 347.0                 | + 5.2                    |
|                        | UPP          | 25.7337                | 348.9                 | + 3.3                    | 332.8                 | + 2.4                    | 354.5                 | + 3.3                    |
|                        | UDD          | 27.0008                | 359.8                 | − 2.2                    | 345.9                 | + 3.9                    | 364.8                 | − 1.3                    |
Fig. 2 — MES seismogram for the October 14, 1970 New Zemlya underground nuclear explosion, showing clear impulses of $P_{\text{ge}}$ and $Pn$.

Fig. 3 — Record illustrating $P_{\text{ap}}$ 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. $P_{20^\circ}$ and $Pn$ impulses are indicated.
Fig. 5 — Record illustrating $f_{20}$ and $Pn$ at Messina station for the August 29, 1971 New Zemlya underground nuclear explosion.

Fig. 6 — Seismogram showing $P_{20}$ 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 $PdP$. 
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Fig. 8 — Record illustrating $P_d P$ 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 $P_d P$ and $Pn$ phases are indicated.

Fig. 10 — UDD seismogram for the August 15, 1974 New Zemlya nuclear explosion, showing impulses of $Pn$ and $P_d P$ phases.
Fig. 11 — Record illustrating $P_n$ 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 (KJR station) of the underground nuclear explosion of August 15, 1974.
TELESEMIC $P_n$ AND $P_{20\circ}$ PHASES.

From a fair number of recordings kindly furnished us by various observatories, we can find, up to distances of around 40°, clear impulses whose travel times have the same trend of the $P_n$, initially characterized 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) 15 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° discontinuity» ($P_{20\circ}$). 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 $P_{20\circ}$ recorded concord with the equation of the travel times

$$T = 77.69 + 9.8804 \Delta$$

which was obtained by assigning to the «20° 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°). 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 $P_n$ phase are reported in Figg. 2, 3, 4, 5, 6, 14, 15, 16, 17, 18, 19, 20, 21, 22; analogously examples of $P_{20\circ}$ are reported in Figg. 2, 3, 4, 5, 6, 16, 17, 18, 19, 22, 23, and 24.
| No | Station Code | Angular Distance (deg) | \(T_{ob} (P_{201})\) (sec) | \(T_{ob} (P_{201}) - \Delta\) (sec) | \(T_c (P_{201})\) (sec) | Residual \(T_c (P_{201})\) (sec) | Residual \(T_c (P_{201}) - TT\) observed (sec) | Residual \(P_e - TT\) (sec) |
|----|--------------|------------------------|-----------------------------|-----------------------------------|-----------------------------|-------------------------------------|-----------------------------------------------|-----------------------------------------------|
| 1  | KHC          | 30.1620                | 376.8                       | 78.788                            | 375.70                      | -1.10                               | 375.62                                         | -1.18                                         |
| 2  | BRA          | 30.2543                | 375.3                       | 76.376                            | 376.61                      | +1.31                               | 376.54                                         | +1.24                                         |
| 3  | BRA          | 30.2847                | 375.7                       | 76.475                            | 376.91                      | +1.21                               | 376.84                                         | +1.14                                         |
| 4  | SRO          | 30.3387                | -                           | -                                 | -                           | -                                   | -                                             | -                                             |
| 5  | SRO          | 30.3506                | 377.2                       | 77.324                            | 377.56                      | +0.36                               | 377.49                                         | +0.29                                         |
| 6  | BUD          | 30.4881                | 379.2                       | 77.966                            | 378.92                      | -0.28                               | 378.83                                         | -0.33                                         |
| 7  | DUD          | 30.4992                | 379.1                       | 77.756                            | 379.15                      | -0.07                               | 378.96                                         | -0.14                                         |
| 8  | STU          | 31.6622                | 390.4                       | 77.565                            | 390.52                      | +0.12                               | 390.47                                         | +0.07                                         |
| 9  | STU          | 31.6819                | 389.6                       | 76.570                            | 390.72                      | +1.12                               | 390.67                                         | +1.07                                         |
| 10 | WLS          | 32.4743                | 398.7                       | 77.841                            | 398.35                      | -0.15                               | 398.51                                         | -0.19                                         |
| 11 | WLS          | 32.4919                | 399.2                       | 78.167                            | 398.72                      | -0.48                               | 398.68                                         | -0.52                                         |
| 12 | NEU          | 33.8826                | 413.4                       | 78.627                            | 412.46                      | -0.94                               | 412.54                                         | -0.95                                         |
| 13 | NEU          | 33.9271                | 414.1                       | 78.939                            | 412.85                      | -1.23                               | 412.85                                         | -1.27                                         |
| 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                               | 433.71                                         | -1.15                                         |
| 16 | RMP          | 37.2487                | 445.7                       | 77.668                            | 445.72                      | +0.02                               | 445.74                                         | +0.06                                         |
| 17 | RMP          | 37.2886                | 447.0                       | 78.574                            | 446.11                      | -0.89                               | 446.16                                         | -0.84                                         |
| 18 | RMP          | 37.3175                | 445.7                       | 76.988                            | 446.40                      | +0.70                               | 446.14                                         | +0.74                                         |
| 19 | NPL          | 37.8228                | 450.7                       | 76.996                            | 451.39                      | +0.69                               | 451.44                                         | +0.74                                         |
| 20 | NPL          | 37.7902                | 451.6                       | 78.218                            | 451.07                      | -0.53                               | 451.12                                         | -0.48                                         |
| 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                                         |
| 23 | MES          | 40.0664                | 466.9                       | -                                 | -                           | -                                   | -                                             | -                                             |
| 24 | MES          | 40.0664                | 467.5                       | -                                 | -                           | -                                   | -                                             | -                                             |
| 25 | MES          | 40.1005                | 467.3                       | -                                 | -                           | -                                   | -                                             | -                                             |
| 26 | MES          | 40.1110                | 468.6                       | -                                 | -                           | -                                   | -                                             | -                                             |
| 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                      | +0.56                               | 508.31                                         | +0.51                                         |
TRAVEL TIME ANALYSIS OF P WAVES ARISING ETC.

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

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

Fig. 16 — BUD seismogram of the New Zemlya underground nuclear explosion of September 27, 1971. The impulses of the $P_{*0}$ and $P_n$ phases are indicated.
Fig. 17 — WLS seismogram for the September 27, 1971 New Zemlya underground nuclear explosion, showing impulses of $P_{20}$ and $P_n$.

Fig. 18 — Record illustrating $P_{20}$ and $P_n$ 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 $P_{20}$ and $P_n$ are indicated.
Fig. 20 — Record illustrating $P_n$ arrival at SRO station for September 12, 1973 New Zemlya underground nuclear explosion.

Fig. 21 — Seismogram of the BUD station showing $P_n$ 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 $P_{gr}$ and $P_n$ phases are indicated.
Fig. 23 — NPL seismogram for the October 14, 1970 New Zemlya underground nuclear explosion, showing clear impulse of the $P_{20^o}$ phase.

Fig. 24 — Seismogram obtained at NPL station for the September 27, 1971 New Zemlya underground nuclear explosion. The $P_{20^o}$ 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 $9 \leq \Delta^o \leq 20.4$, 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° discontinuity».

(iii) the proposed model is confirmed by the observation of Pn waves noticeable as far as 40° and of P waves reflected (P d P) and refracted (P o) on the «20° discontinuity».

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