On time-distance curves for P_n waves in the Friuli earthquake of 6 May 1976

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Abstract

Results obtained in the study of the arrival times of the P_n phase for the Friuli earthquake of 6 May 1976 ($H = 20^h 00^m 15^s,5$; $\varphi = 46^\circ 16' 30''$ N; $\lambda = 13^\circ 06' 00''$ E; $M = 6.3$) with respect to the epicentral distance are reported. Particular emphasis is given to the fact that the travel-time curves relative to the P_n waves and the corresponding equations are only valid for selected alignment. By plotting the time-distance curves it was possible to derive the depth of the lower surface of the upper mantle for different zones; the results thus obtained exibit significant differences.

Riassunto

Sono esposti i risultati ottenuti dallo studio dei tempi di arrivo della fase P_n del terremoto del Friuli del 6 maggio 1976 ($H = 20^h 00^m 15^s.5$, $\varphi = 46^\circ 16' 30''$ N, $\lambda = 13^\circ 06' 00''$ E, $M = 6.3$) in relazione alla distanza

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epicentrale. E' evidenziato in particolare il fatto che le dromocrone per le onde P_n e le corrispondenti equazioni valgono limitatamente al-l'allineamento prescelto. Le dromocrone tracciate hanno poi permesso di ricavare la profondità della superficie inferiore del mantello superiore in diverse zone; i risultati ottenuti indicano differenze significative.

Introduction

Travel-time curves characteristic of the event are obtained for different phases of an earthquake as recorded by nearby stations; a number of accurate investigations have been carried out in this respect. It is our purpose to show how the time-distance curve relative to the same phase of a given event varies with the chosen alignments. Owing to the considerable number of available data, this study was carried out for the P_n phase of the Friuli earthquake which took place on 6th May, 1976 (φ = 46°16'30"N; λ = 13°06'00"E) at $20^h00^m15^s,5$ (Biagi, Caloi, Migani, Spadea, 1976).

In Table 1 the recording times obtained with the seismograms of the considered stations, as well as the corresponding epicentral distances are given. The locations of the various seismic stations and the chosed alignments are shown in Fig. 1; the travel-time graphs obtained are those in Fig. 2. As it is possible to see, in some plots, starting from a given value of the epicentral distance Δ, the plot is no longer linear but bends towards the x-axis, thus showing that, for greater distances, the seismic ray penetrates layers in which the longitudinal waves have increasing velocities.

For the drawn travel-time curves the most probable values of the parameters v_{P_n} and K appearing in the equation

$$t = \frac{\Delta}{v_{P_n}} + k \qquad [1]$$

describing the linear part of the curves, were derived analytically. The results obtained are reported in Table 2.

The values of the differences δt between the times calculated from equation [1] for the various zones and those observed are given in Table 3. For zone e), the study was carried out using

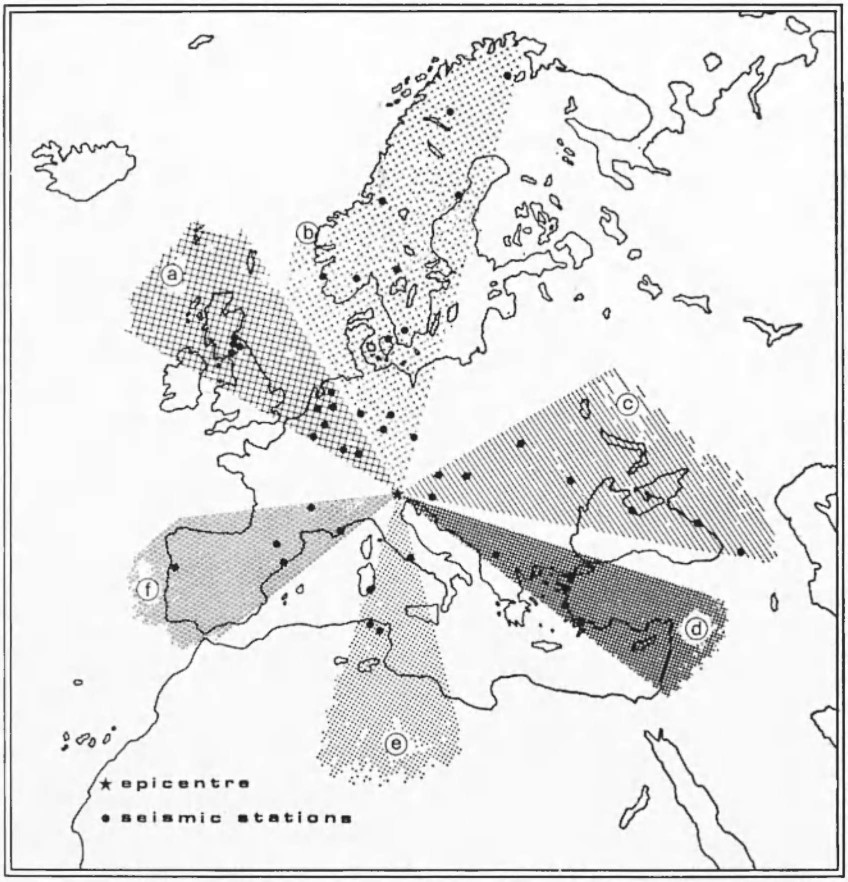

FIG. 1 - Location of the seismic stations with the indication of the various zones. Zone a): Stuttgart and Karlsruhe (West Germany); Dourbes (Belgium); Winterswijk, Witteveen and De Bilt (Holland); Eskdalemuir, Broadlaw, Auchinoon, Black Hill and Amulree (Great Britain). Zone b): Pruhonice (Czechoslovakia); Moxa, Leipzig and Gottingen (East Germany); Copenhagen (Denmark); Delary, Uddeholm, Skalstugan, Umea and Kiruna (Sweden); Kongsberg and Bergen (Norway); Kevo (Finland). Zone c): Sopron and Budapest (Hungary); Lvov Kishinev, Simferopol, Sochi and Bakuriani (U.S.S.R). Zone d): Zagreb and Skopije (Yugoslavia);) Athens (Greece); Ezine, Edincik, Instanbul and Bakuriani (U.S.S.R). Zone d): Zagreb and Skopije Cagliari (Italy); Sidi Tabet and Zaghouan (Tunisia). Zone f): Monaco (Monaco); St. Sauveur en Rone and Moulis (France); Fabra (Spain); Porto (Portugal).

TABLE 1

SEISMIC STATIONS	Δ (km)	t_{Pn}	SEISMIC STATIONS	Δ (km)	t_{Pn}	SEISMIC STATIONS	Δ (km)	t_{Pn}
1 Amulree	1621	20 03 38,9	17 Fabra	1033	20 02 39,8	33 Rome	497	20 01 20,7
2 Athens	1270	20 02 53,5	18 Gottingen	628	20 01 38,8	34 St. Souver R.	673	20 01 45,0
3 Auchinoon	1567	20 03 33,1	19 Instanbul	1408	20 03 08,5	35 Sidi Tabet (KCH)	1050	20 02 31,4
4 Bakuriani	2478	20 05 13,2	20 Izmir	1445	20 03 13,6	36 Simferopol	1640	20 03 44,8
5 Bergen	1650	20 03 43,7	21 Karlsruhe	466	20 01 19,4	37 Skalstugan	1929	20 04 16,6
6 Black Hill	1596	20 03 33,3	22 Kevo	2727	20 05 32,4	38 Skopie	822	20 02 00,5
7 Broadlaw	1541	20 03 29,8	23 Kiruna	2439	20 05 07,3	39 Sochi	2111	20 04 36,2
8 Budapest	471	20 01 18,5	24 Kishinev	1206	20 02 51,5	40 Sopron	309	20 00 56,3
9 Cagliari	850	20 02 07,0	25 Kongsberg	1507	20 03 24,9	41 Stuttgart	405	20 01 11,2
10 Copenhagen	1047	20 02 30,8	26 Leipzig	564	20 01 31,0	42 Uddeholm	1538	20 03 38,7
11 De Bilt	868	20 02 10,0	27 Lvov	905	20 02 12,4	43 Umea	2003	20 04 25,2
12 Delary	1134	20 02 39,4	28 Monaco	529	20 01 27,8	44 Winterswijk	786	20 01 59,1
13 Dourbes	762	20 01 56,5	29 Moulis	1021	20 02 18,0	45 Witteveen	864	20 02 09,1
14 Edincik	1365	20 03 03,6	30 Moxa	498	20 01 22,4	46 Zaghouan	1126	20 02 40,8
15 Eskdalemuir	1521	20 03 27,2	31 Porto	1834	20 04 06,2	47 Zagreb	227	20 00 48,4
16 Ezine	1291	20 02 54,3	32 Pruhonice	427	20 01 13,3			

the reliable data from only 4 stations, up to an epicentral distance of 1126 km. The 4 experimental points show quite-clearly the existence in the time-distance curve of two parts having different slopes. Assuming that the P_n waves under the crust involve layers of always increasing velocities, the travel-time graph can reasonably be represented by the line of Fig. 2e. For the two stations that allowed the identification of the bending in the curves, the times of arrival of the P_n waves differ by —$1^s.5$ and —$2^s.8$ respectively from those calculated from equation [1] with the values of the parameters corresponding to zone e) in the Table.

TABLE 2

ZONE	v_{P_n} (Km/sec)	K (Km/sec.)
a	7,94 ± 0,04	4,9 ± 0,5
b	8,22 ± 0,03	6,6 ± 0,5
c	7,91 ± 0,05	6,5 ± 0,9
d	8,43 ± 0,05	6,5 ± 0,9
e	7,60	—0,1
f	8,24 ± 0,04	8,3 ± 0,6

As is possible to note in Table 2, the velocities of the P_n waves for the Friuli earthquake here dealt with turn out to be, for the various sectors, 7.6 km/sec., 7.91 km/s., 7.94 km/s., 8.22 km/s., 8.24 km/s., 8.43 km/s. The values of V_{P_n} found in previous earthquakes in Europe, limitedly to only one alignment, are well in agreement with one among the values above. But, on the basis of the effected research, it is impossible to consider a single well defined value of the velocity as being valid for the P_n waves of a given earthquake; and this testifies the considerable non-uniformity in the Earth stratifications, at least as far as the most external ones are considered . It follows that the travel-

TABLE 3

ZONE	Seismic stations	Δ (Km)	δ *t* (sec.)
a	STUTTGART	405	+ 0,2
	KARLSRUHE	466	— 0,3
	DOURBES	762	— 0,1
	WINTERSWIJK	786	+ 0,3
	WITTEVEEN	864	+ 0,1
	DE BILT	868	— 0,2
b	PRUHONICE	427	+ 0,7
	MOXA	498	+ 0,3
	LEIPZIG	564	+ 0,3
	GOTTINGEN	628	— 0,3
	COPENHAGEN	1047	— 1,3
	DELARY	1134	+ 0,7
	KONGSBERG	1507	+ 0,3
	UDDEHOLM	1538	+ 0,4
	BERGEN	1650	+ 0,9
	SKALSTUGAN	1929	0,0
	UMEA	2003	+ 0,5
c	SOPRON	309	+ 0,9
	BUDAPEST	471	— 0,8
	LVOV	905	+ 0,2
	KISHINEV	1206	—0,9
	SIMFEROPOL	1640	+ 0,6
d	ZAGREB	227	+ 0,5
	SKOPIE	822	— 0,1
	ATHENS	1270	— 0,8
	EZINE	1291	+ 0,8
	EDINCIK	1365	+ 0,2
	ISTANBUL	1408	+ 0,5
	IZMIR	1445	— 0,2
f	MONACO	529	+ 0,2
	ST. SOUVER R.	673	+ 0,5
	MOULIS	1021	— 0,3
	FABRA	1033	— 0,7
	PORTO	1834	+ 0,3

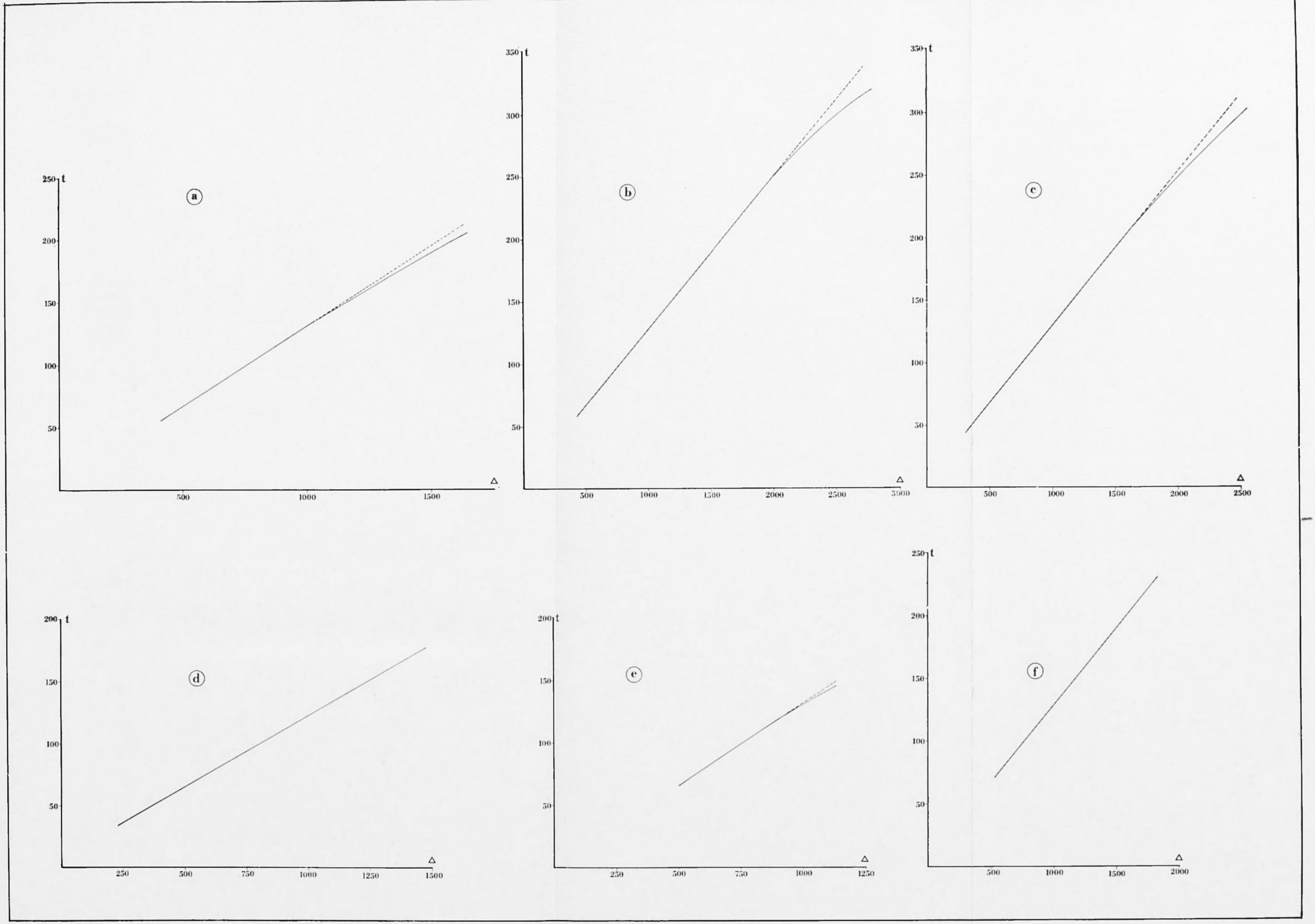

FIG. 2 - Observed time-distance curves for P_n waves in the zones a), b), c), d), e), f) shown in, fig. 1, △ is expressed in Km. and t in sec.

time curves of the P_n waves, as well as the corresponding equations, are only valid for a given event and limitedly to a chosen alignment; as a consequence, any attempt to construct a table for the times of arrival of the P_n phase (and not only for this!) for close earthquakes is useless. Thus, for example, for an epicentral distance of 1000 km, relationship [1], with the values of the parameters corresponding to zone a), gives a travel time equal to $130^s.8$ whereas, using the values corresponding to zone b), one has a time of $128^s.2$ and the deviation is by far greater than the uncertainty which is generally ascribed to the observed times.

All the drawn time-distance curves, at least in a first part, are nearly linear, considering the small variation with the depth of the elastic properties of the materials in the superficial layer of the Earth's crust. The bending towards the axis of the distances, observed in some cases, allowed the evaluation of the depth of the layer below, at which both the elastic characteristics and the density undergo a sharp variation.

Under the assumption of a density steadily increasing with the depth, a method developped by Caloi (1933, 1935) was used. If e , ϑ and R indicate the emergency angle of the seismic ray at the surface, the angular epicentrel distance of the origin (assumed on the surface) and the Earth's radius, respectively, one has

$$h = R\,(1 - \sqrt{\rho}) \qquad [2]$$

where

$$\rho = 1 - \frac{\sin e \sin \theta/2}{\cos\,(e - \theta/2)} \qquad [3]$$

h being the depth of the lower limiting surface of the layer at which the P_n waves have approximately constant velocity. The value of $\hat{e}$ can be deduced using Benndorf's principle expressed by the formula $v_o = V \cos \hat{e}$, where v_o is the effective velocity of the P_n waves in the superficial layers and V is the apparent velocity of the same waves for a given epicentral distance.

In Table 4 the values of ϑ and V derived from the travel-time curves in the points at which the curve begins to bend towards the x-axis, as well as the values of h calculated using equation [2] and supposing R equal to 6367 Km are reported.

Obviously, the values found for the depths are only approximate. Their order of magnitude, however, is reasonable. In conclusion, the study carried out seems to indicate that the whole Earth's crust (i.e. including the upper mantle) tends to grow thinner corresponding to Western Europe southwards and, still more, westwards. All this is in excellent agreement with the results obtained geologically concerning the Middle Atlantic ridge and the lithologic plates.

TABLE 4

ZONE	$\vartheta°$	V (Km/s)	h (Km)
a	9.5	8.33	82
b	18.0	8.55	140
c	15.0	8.39	143
e	8.5	8.33	104

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