P-waves reflected from the "20° discontinuity" beneath the Mediterranean region

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Summary. — The observed travel-times of the *P*-waves for twenty shallow, intermediate, and deep earthquakes, with epicenters in the Mediterranean area, are used in order to analyze some characteristics of the upper mantle.

A first order discontinuity, identificable as the "20° discontinuity", is found at a depth of 505 ± 16 km in the area underneath the Mediterranean basin. The velocity contrast is equal to 12% (above $V = 8.9$ km/sec; below $V = 9.97$ km/sec).

Assuming that this discontinuity gives rise to reflected *P*-waves (*PdP*), the travel times of these waves are calculated for various hypocentral depths.

The observation of impulses identified as *PdP* on the seismograms of Messina supports this hypothesis.

This result and its implications are discussed in the contest of the conclusions of various authors who locate a *P*-wave velocity-discontinuity at different depths between 400 and 580 km.

Finally, particular emphasis is given to the regional character of the analyzed structures in question.

Riassunto. — Al fine di caratterizzare alcune strutture del mantello superiore, si sono utilizzati i tempi di tragitto delle onde *P* osservate per venti terremoti superficiali, intermedi e profondi, con epicentro nell'area del Mar Mediterraneo.

Una discontinuità di prima specie, identificabile come « discontinuità 20° », risulta per il mantello sottostante il bacino del Mediterraneo alla profondità di 505 ± 16 km; il salto di velocità è pari al 12% (al disopra $V = 8.90$ km/sec; al disotto $V = 9.97$ km/sec).

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Nella ipotesi che detta discontinuità dia luogo ad onde P riflesse (PdP), se ne sono calcolati i tempi di tragitto per varie profondità ipocentrali.

L'osservazione sui sismogrammi di Messina di impulsi identificabili come PdP conforta la precedente ipotesi.

I risultati sono discussi anche in relazione alle conclusioni di vari ricercatori che localizzano, fra i 400 ed i 580 km di profondità, discontinuità di velocità per le onde P.

Particolare risalto è dato infine al carattere regionale delle strutture in questione.

Introduction

The many studies of the travel times of P-waves generated by earthquakes or atomic explosions have not succeeded in eliminating certain uncertainties concerning the structure of the earth's mantle between 200 and 700 kilometers of depth. On the contrary, the proliferation of studies of the subject has produced such a variety of velocity models, often quite different, so that, in general, our picture of the detailed structures of the upper mantle is rather confused.

Fundamentally, most scientists are agreed that the upper mantle contains two discontinuities for P-waves. The deeper of these two discontinuities is located at the depth of 650 km (Hoffmann et al., 1961; Niazi and Anderson, 1965; Johnson, 1967; other researchers) [10,17,12] and the other, more superficial, at different depths between 400 and 580 km, according to the various authors (Jeffreys, 1952; Hoffmann et al., 1961; Girlanda and Federico, 1966; Johnson, 1967; Lewis and Meyer, 1968; other researchers) [11,10,9,12,14].

In recent years, Caloi (1967) [4], from the study of deep earthquakes (deeper than 600 km) and at such epicentral distances that cannot cause confusion with reflected waves of different origin (pP, PcP, ...) has determined the depth of the "20° discontinuity" (515 km). The procedure adopted is based on seismic phases which Caloi attributed to P-waves reflected below the discontinuity.

In addition, Adams (1968) [1], Engdahl and Flinn (1969) [6] and others have observed some seismic phases preceding the $P'P'$-waves on the seismograms and these have been interpreted as $P'P'$-waves reflected from discontinuity surfaces located in the upper mantle. Therefore, though the depth of some abrupt changes in the structure of the upper mantle has not yet been determined with sufficient precision, the observed seismic phases can be interpreted as supporting the idea that there exist considerable variations in the properties of the material which makes up the most superficial zone of the earth's mantle.

On the other hand, Federico (1971) (7) has identified on the seismograms at Messina impulses (*PdP*) attributable to *P*-waves reflected off the "20° discontinuity". The same author, in a recent study (Federico, 1975) (8) by means of a systematic application of the Wadati-Masuda procedure, has deduced higher velocities for the *P*-waves below the "20° discontinuity" than those previously calculated (Girlanda and Federico, 1966) (9). These results, which support the hypothesis formulated by Federico concerning the consistency of the *PdP*-impulses observed at Messina, seem to imply that the "20° discontinuity" is a first order discontinuity, with a velocity contrast of about 14%.

However, it should be noted that both for the calculation of *PdP* wave travel-times, and for the application of the Wadati-Masuda procedure, the value adopted for the depth of the discontinuity was 536 km. This value was initially obtained (Girlanda and Federico, 1966) (9) using the travel times for a single earthquake (Sicily, 23 December 1959; $H = 09^h29^m04^s$; $h = 77$ km; 14.6° E; 37.7° N).

Considering the different values which various authors attribute to the depth of the more superficial discontinuity ($400 \leqslant h_d \leqslant 580$ km), considering the possible regional diversity of the depth of this discontinuity, and considering the variations in the travel times observed for the *PdP* waves identificable on the seismograms, some doubts concerning the depth value $h_d = 536$ km would appear to be justified.

The aim of the present essay is, therefore, to produce a new value for the depth of the discontinuity in question, using more numerous observation data. This is done with the additional aim of establishing the size of possible variations in the depth of the "20° discontinuity" in the upper mantle which lies beneath the Mediterranean region.

COMPUTING PROCEDURE FOR THE h_d

The depth of the "20° discontinuity" (h_d) has been calculated using observed travel-times for the *P*-waves for 20 earthquakes. The earthquakes used were chosen according to the following criteria:

1. Location of the epicenter in the Mediterranean basin or in an immediately adjacent zone.

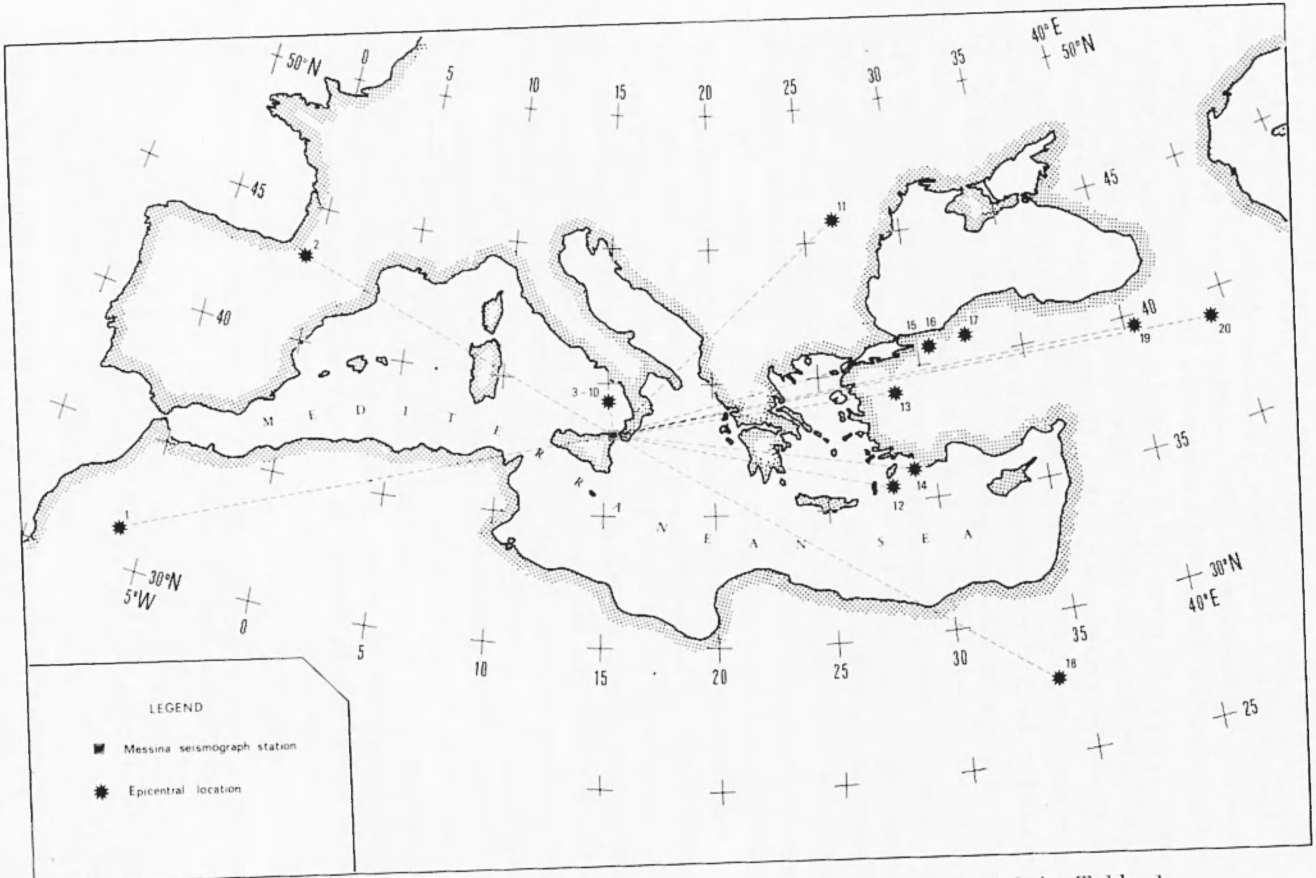

Fig. 1 – Map of the epicentral locations relating to the earthquakes listed in Table 1.

2. Good readings from a sufficient number of stations.

3. Satisfactory precision in the values of the focal parameters, particularly those of the focal depth and origin-time.

The spatial and temporal coordinates for the hypocenters of the earthquakes considered, together with information relative to criteria 1. and 2. are given in Table 1. A map of the Mediterranean region, with the distribution of the epicenters is schematized in Figure 1.

The procedure followed for the determination of the discontinuity level (R_d) is similar to a stripping in three phases, and, in particular, similar to that originally employed by Girlanda and Federico (1966)(9). The detailed description of the procedure is, however, omitted, and the exposition is limited to a short synthesis of the method followed; the application of the method was made using a computer program. The procedure includes the reduction of the observed travel-times for the P-waves to the surface of the discontinuity, relative to the epicentral interval $20^\circ \leqslant \Delta \leqslant 90^\circ$, according to the following scheme:

1. Reduction of the travel times to the Mohorovicic discontinuity ($R_M = 6331$ km; $h_M = 40$ km), using, for the average value of the P-wave velocity in the crust, the value 6.34 km/sec.

2. Reduction of the travel times already reduced to R_M (point 1) to the median spheric surface of the astenospheric channel ($R_A = 6291$ km; $h_A = 80$ km) using the following velocity law:

$$V = 6931.5175 - 2.2015r + 0.000175r^2 \qquad [1]$$

with $6291 \leqslant r \leqslant 6331$ km. The relation [1] is compatible with the values proposed by Gutenberg (1960) for the P-wave velocity relative to the depth range 40 to 80 km.

3. A further reduction of the travel times to four pre-chosen levels ($r_1 = 5971$ km, $h_1 = 400$ km; $r_2 = 5921$ km, $h_2 = 450$ km; $r_3 = 5871$ km, $h_3 = 500$ km; $r_4 = 5821$ km, $h_4 = 550$ km) using the velocity law:

$$V = \beta + \sqrt{\alpha - A \log r} \qquad [2]$$

where the numerical values of the constants are $\beta = 7.511472$, $\alpha = 233.1888556$ and $A = 61.365372$ (Girlanda and Federico, 1966)(9).

The depth level of the discontinuity, inside the two contiguous levels of the 4 pre-chosen, is obtained by reducing to zero the known term of the polynomial which approximates the curve of the reduced travel times (point 3.).

Both the observed travel times of the P-waves and the P-waves reduced travel-times were approximated using complete polynomials of the 3° order, and the respective values of the coefficients of which A, B, C, D and A_d, B_d, C_d, D_d are given in Table 2. The values for the depth level of the discontinuity obtained, using the procedure described above and applied to the 20 earthquakes considered, are given in Table 3.

Identification of the PdP phase

The estimations of the level R_d of the discontinuity and of its depth h_d, as well as the P-wave velocity above V_{d+} and below V_{d-} the discontinuity (Table 3), give the following average values:

$$R_d = (5866 \pm 16)\ \text{km} \qquad h_d = (505 \pm 16)\ \text{km} \qquad [3]$$

$$V_{d+} = (8.902 \pm 0.027)\ \text{km/sec}; \qquad V_{d-} = (9.983 \pm 0.145)\ \text{km/sec} \qquad [4]$$

The small size of the standard error for R_d and for h_d deserves, however, a few remarkes. The sign of the cubic coefficient D is in fact, sometimes positive, sometimes negative (Table 2). In the first case, for obvious reasons connected with the apparent velocity of the P-waves, the values of h_d which result are below the average value 505 km, while in the second case h_d is higher than the average value ($h_d > 505$ km). Because the sign of the coefficient in question depends essentially on the travel times for remote stations, systematic early or late arrivals for these stations conditions the sign of D. It follows that the small uncertainty of $\pm$ 16 km, apart from any possible physical fluctuation in the discontinuity level, is to be attributed, for the most part, to the shape of the travel-time curves for the most remote stations.

The h_d depth of 505 km, attributable to all of the mantle underneath the Mediterranean region, was introduced into the calculations of the PdP-wave travel-time for different values of the hypocentral depth. The procedure adopted is that described by Federico (1971) (7), and the results obtained are given in Table 4. In this Table are also given the coefficients of the polynomial of the type:

$$T_{PdP} = \alpha + \beta\Delta^2 + \gamma\Delta^3 + \delta\Delta^4 \qquad [5]$$

with which the travel-time curves of the P-waves reflected from the 505-km discontinuity were approximated.

The estimated times for the *PdP*-waves provided a standard model used in order to recognize on the seismograms impulses attributable to these reflected *PdP*-phases. The observations were obviously limited to those earthquakes for which the recordings obtained at Messina, in addition to offering clear signals, do not, for reason of epicentral distance or focal depth, present the possibility of being superimposed or masked by other seismic phases.

The data used for the recognition of the *PdP*-waves, together with observation data relative to the seismograms examinated, are summarized in Table 5. The best conditions for seismographic analysis were found, in general, for earthquakes whose epicentral distances for Messina lie in the range 6° to 13°.

Several photograms which reproduce *PdP*-impulses, substantially in agreement with the proposed model, are given in Figures 2, 3, 4, 5, 6 and 7.

Discussion of the results

The impulses observed on the seismograms and identified as *PdP*-waves, support the hypothesis of the existence of a *P*-wave velocity-discontinuity located underneath the Mediterranean region at the depth of 505 km. This value, although it does not substantially differ from that previously determined by Girlanda and Federico (1966) (9), does constitute, because of the number and variety of earthquakes studied, a more solid element in the description of the mantle's structure under the Mediterranean basin.

The agreement between the calculated and the observed travel-times for the *PdP*-waves is satisfactory. The residuals are on average of the order of —0.3 sec ($\pm$ 1.4). When one considers the uncertainties connected with the origin-time of the earthquakes considered, the difficulties of isolating a single seismic phase in the body of a recording, and the possible changes in the depth level of the discontinuity in the studied area, the results obtained can be considered as acceptable. The width of the interval of the residuals obtained reflects, in fact, both the average uncertainty of the estimated depth of the discontinuity and the difference between the calculated level and the depth of the discontinuity corresponding to the reflection zone of the *PdP*-waves which emerge at Messina.

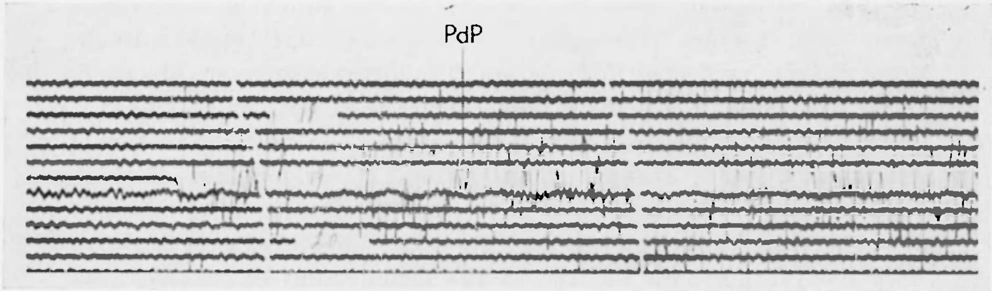

Fig. 2 – Earthquake of 1965 March 9, originating in Aegean basin, recorded at Messina station by a Sprengnether seismograph (vertical component, short period). *PdP* arrival indicated.

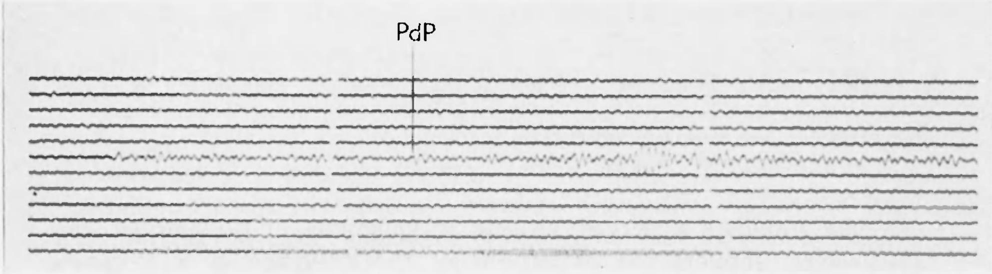

Fig. 3 – Earthquake of 1965 March 22, originating in Aegean basin, recorded at Messina station by a Sprengnether seismograph (vertical component, short period). *PdP* arrival indicated.

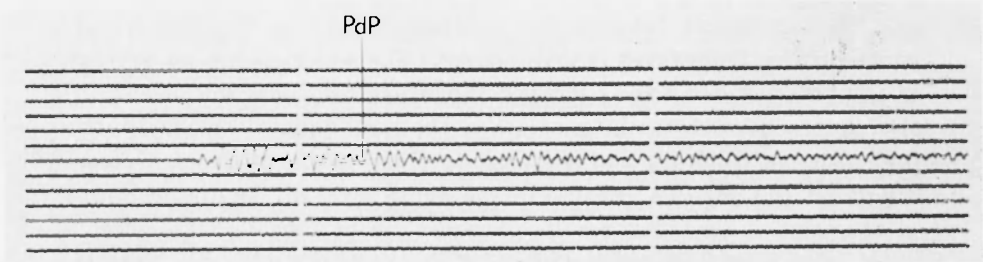

Fig. 4 – Earthquake of 1965 June 13, originating in Turkey, recorded at Messina station by a Sprengnether seismograph (vertical component, short period). *PdP* arrival indicated.

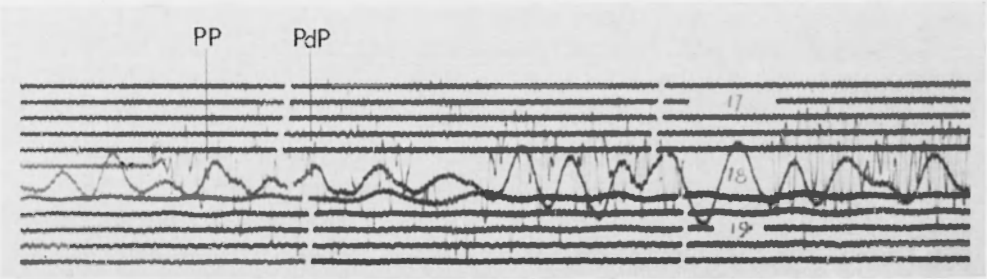

Fig. 5 – Earthquake of 1967 July 22, originating in Turkey, recorded at Messina station by a Sprengnether seismograph (vertical component, short period). *PdP* arrival indicated.

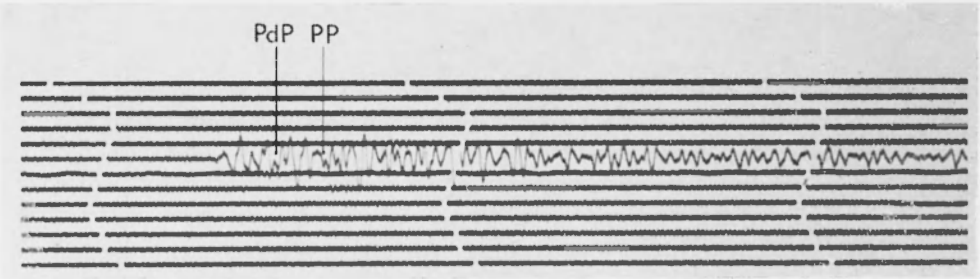

Fig. 6 – Earthquake of 1967 July 26, originating in Turkey, recorded at Messina station by a Sprengnether seismograph (vertical component, short period). *PdP* arrival indicated.

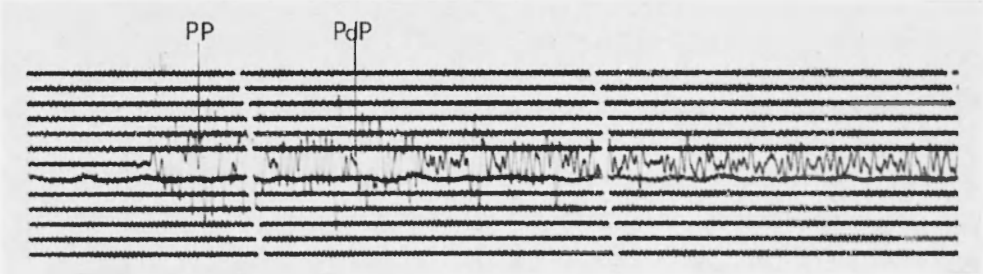

Fig. 7 – Earthquake of 1969 March 28, originating in Turkey, recorded at Messina station by a Sprengnether seismograph (vertical component, short period). *PdP* arrival indicated.

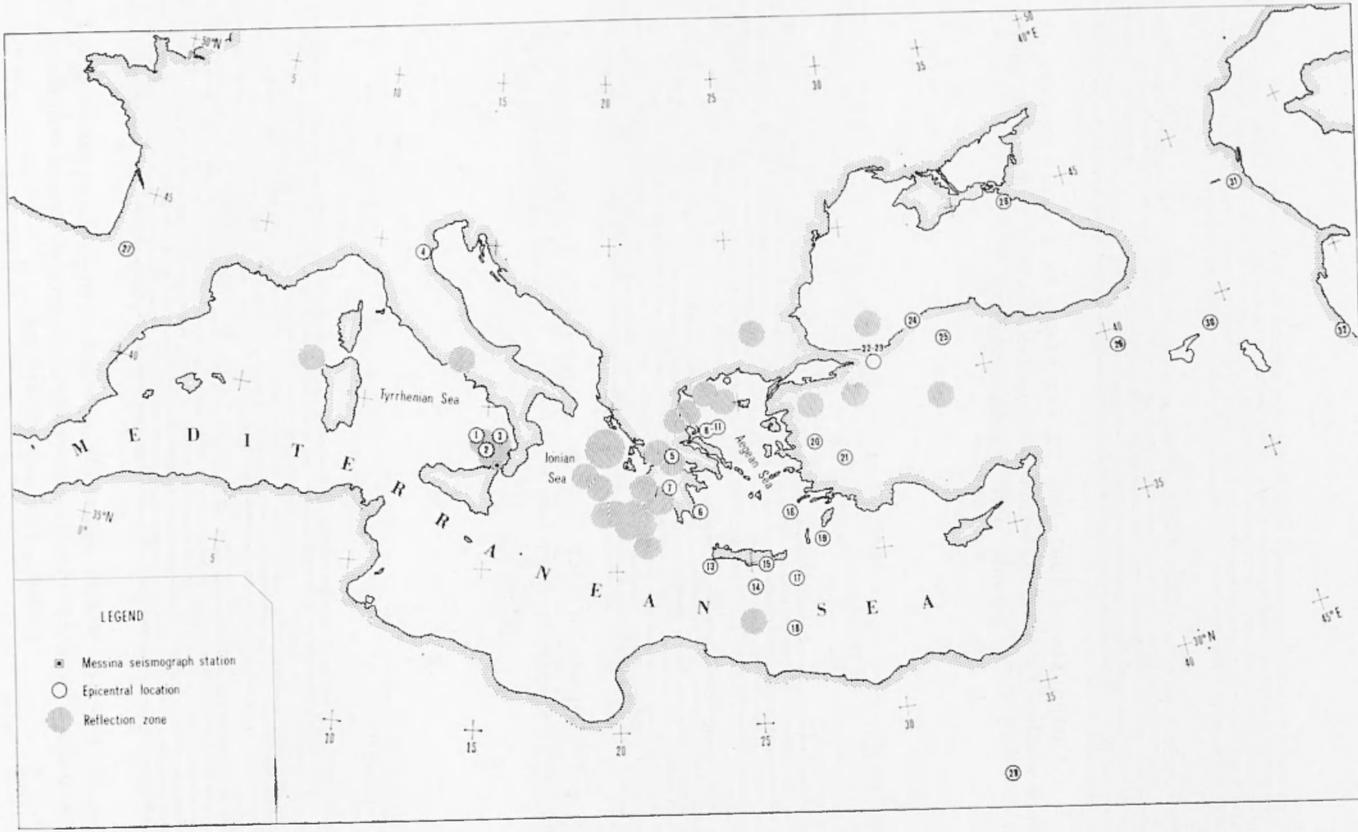

Fig. 8 – Map of the reflection zones on the 505-km discontinuity for *P*-waves originating from the earthquakes listed in Table 6 and emerging at Messina.

On the basis of a comparison of the results obtained it isn't possible to discover substantial differences between the reflecting level corresponding to the central Mediterranean basin (Tyrrhenian and Ionian basins) and those corresponding to the eastern Mediterranean basin (Aegean basin). The values of h_d and of the residuals associated with the *PdP*-waves possess, in fact, the same degree of relative and reciprocal homogeneity.

The velocity contrast of the *P*-waves above and below the 505 km discontinuity, which is approximately 12% ($\pm$ 1.2), is more consistent with the recent estimation (Federico, in press)

$$c_v = (V_{d-} - V_{d+})/V_{d+} = 0.14$$

than with the previous estimation (Girlanda and Federico, 1966) [9] that is $c_v = 0.07$.

The results obtained, and the argument set forth above, imply the following conclusions:

In the upper mantle in the Mediterranean area there is a first order discontinuity at the depth of 505 km for the *P*-wave velocity

The velocity contrast is such that, when the epicentral distance the focal depth the released energy and the clarity of the recording are suitable, it is possible to observe, on the seismograms, a phase which can be attributed to *P*-waves reflected from the discontinuity itself.

When it is considered that analogous estimations proposed by various seismologists give values for h_d which lie between 400÷580 km, and that these different values in general result from the adoption of different methods and from their application to observations relative to different areas (Table 7), the most likely hypothesis appears to be that the different depth values determined also reflect physical changes in the discontinuity depth for different regions. In our opinion, therefore, the hypothesis of the universality of the "20° discontinuity" should be excluded. On the contrary, it seems more reasonable to suppose that the zone of the earth's mantle with large-scale lateral inhomogenities extends below the depth of 250 km. The data given in Table 6 offer several elements in support of that. In addition, this idea constitutes a generalization of the results obtained by Adams (1968) [1] relative to the structural changes encountered in the most external 250 km of the earth's upper mantle.

TABLE I

Earthquake hypocentral data

Event No.	Date	Locality	Origin-Time (hr min sec)	Latitude (deg)	Longitude (deg)	Depth (km)
1	28 Aug 67	Morocco	21 15 35.9	31.49 N	6.06 W	33 *
2	13 Aug 67	Pyrenees	22 07 47.8	43.20 N	0.67 W	15 *
3	25 Mar 62	Tyrrhenian Sea	21 38 26.1	39.06 N	14.56 E	338 **
4	23 Dec 65	Tyrrhenian Sea	15 29 06.9	40.53 N	14.87 E	310 **
5	21 Apr 68	Tyrrhenian Sea	21 09 48.0	39.82 N	14.88 E	319 **
6	1 Jun 63	Tyrrhenian Sea	20 36 03.8	38.56 N	14.96 E	238 **
7	29 Mar 69	Tyrrhenian Sea	01 43 39.7	40.12 N	15.12 E	319 **
8	2 Apr 69	Tyrrhenian Sea	01 38 02.1	38.97 N	15.24 E	261 **
9	3 Jan 60	Tyrrhenian Sea	20 19 34.5	39.25 N	15.41 E	284 **
10	1 Feb 56	Tyrrhenian Sea	15 10 50.6	39.06 N	15.63 E	234 **
11	2 Oct 66	Romania	11 21 45.2	45.77 N	26.50 E	141 *
12	30 May 68	Dodecanese Islands	17 40 26.0	35.45 N	27.88 E	27 *
13	25 Mar 69	Turkey	13 21 34.2	39.25 N	28.44 E	37 *
14	14 Jan 69	Turkey	23 12 06.2	36.11 N	29.19 E	22 *
15	30 Jul 67	Turkey	01 31 01.8	40.72 N	30.52 E	18 *
16	22 Jul 67	Turkey	16 56 58.0	40.67 N	30.69 E	33 *
17	3 Sep 68	Turkey	08 19 52.6	41.81 N	32.39 E	5 *
18	31 Mar 69	Egypt	07 15 54.4	27.61 N	33.91 E	33 *
19	26 Jul 67	Turkey	18 53 01.1	39.54 N	40.38 E	30 *
20	29 Mar 68	NW. Persia	17 01 55.6	39.24 N	44.23 E	17 *

* Values from the Bulletin of the International Seismological Centre, Edinburgh-Scotland
** Values from Bottari and Lo Giudice (1975)(3)

TABLE 2

Polynomial coefficients of the curves relating to the P travel-times and P travel-times *"reduced"* to the "20° discontinuity".

No.	Earthquake Source	N_T SD	A A_d	B B_d	$C \times 10^3$ $C_d \times 10^3$	$D \times 10^6$ $D_d \times 10^6$
1	Morocco	56 (1.26)	65.044 0	11.151 10.279	—36.438 —30.836	8.991 —7.272
2	Pyrenees	102 (1.07)	65.023 0	11.293 10.374	—38.444 —32.250	16.387 —2.267
3	Tyrrhenian Sea	28 (0.91)	49.180 0	10.505 10.009	—26.640 —24.225	—48.735 —50.205
4	Tyrrhenian Sea	28 (0.80)	44.551 0	10.987 10.344	—36.318 —31.957	10.832 —2.649
5	Tyrrhenian Sea	27 (0.87)	47.847 0	10.720 10.143	—31.507 —28.308	—15.276 —23.300
6	Tyrrhenian Sea	38 (1.35)	46.636 0	11.083 10.399	—36.600 —32.181	6.644 —5.868
7	Tyrrhenian Sea	40 (1.25)	45.280 0	10.917 10.297	—35.165 —31.240	4.830 —6.112
8	Tyrrhenian Sea	70 (0.90)	49.901 0	10.811 10.196	—31.974 —28.643	—15.908 —23.630
9	Tyrrhenian Sea	43 (1.21)	44.359 0	11.182 10.465	—40.352 —35.074	34.988 —18.319
10	Tyrrhenian Sea	42 (0.94)	45.390 0	11.277 10.537	—40.006 —34.775	26.433 —10.734

cont. Table 2

No.	Earthquake Source	N_T SD	A A_d	B B_d	$C \times 10^3$ $C_d \times 10^3$	$D \times 10^6$ $D_d \times 10^6$
11	Romania	60 (0.98)	53.298 0	11.341 10.452	—41.669 —34.916	40.370 18.020
12	Dodecanese I.	87 (1.05)	63.814 0	11.206 10.351	—36.088 —30.933	—3.288 —16.750
13	Turkey	105 (0.93)	60.161 0	11.421 10.471	—41.123 —34.233	31.485 9.707
14	Turkey	111 (1.37)	62.231 0	11.400 10.459	—40.525 —33.869	28.187 7.656
15	Turkey	55 (0.74)	73.695 0	10.713 10.000	—27.478 —24.933	—49.351 —50.871
16	Turkey	45 (1.14)	71.163 0	10.729 9.995	—27.729 —24.485	—47.410 —51.553
17	Turkey	99 (1.11)	69.481 0	11.110 10.242	—35.427 —30.235	—0.285 —13.865
18	Egypt	91 (1.33)	67.156 0	11.042 10.204	—33.859 —29.085	—12.136 —23.528
19	Turkey	43 (0.97)	73.194 0	10.637 10.075	—26.314 —25.497	—53.017 —47.605
20	NW. Persia	99 (0.99)	70.986 0	10.904 10.115	—31.525 —27.602	—23.110 —31.039

SD is the standard deviation (in sec) of the *P*-wave residuals relating to the N_T travel times utilized in the computing procedure.

TABLE 3

Depth level and P-wave velocity for the 505 km discontinuity inferred from the study of twenty earthquakes

No.	Earthquake Source	R_d km	h_d km	V_{d+} km/sec	V_{d-} km/sec	V_{d+}/V_{d-}
1	Morocco	5866	505	8.913	9.960	0.895
2	Pyrenees	5875	496	8.898	9.884	0.900
3	Tyrrhenian Sea	5844	527	8.940	10.191	0.877
4	Tyrrhenian Sea	5872	499	8.895	9.908	0.898
5	Tyrrhenian Sea	5854	517	8.932	10.074	0.885
6	Tyrrhenian Sea	5887	484	8.871	9.880	0.898
7	Tyrrhenian Sea	5865	506	8.906	9.942	0.896
8	Tyrrhenian Sea	5864	507	8.909	10.038	0.888
9	Tyrrhenian Sea	5878	493	8.885	9.804	0.906
10	Tyrrhenian Sea	5892	479	8.863	9.760	0.908
11	Romania	5875	496	8.897	9.811	0.907
12	Dodecanese I.	5879	492	8.845	9.913	0.896
13	Turkey	5884	487	8.876	9.808	0.905
14	Turkey	5884	487	8.875	9.819	0.904
15	Turkey	5840	531	8.947	10.193	0.878
16	Turkey	5864	507	8.908	10.240	0.870
17	Turkey	5862	509	8.913	9.988	0.892
18	Egypt	5855	516	8.923	10.015	0.891
19	Turkey	5866	505	8.906	10.161	0.876
20	NW. Persia	5851	520	8.930	10.095	0.885

TABLE 4

Polynomial coefficients of the PdP travel-time curves for the 505 km discontinuity and for various focal depths

Depth	$\alpha \times 10^{-3}$	β	$\gamma \times 10$	$\delta \times 10^3$
0	0.12263	0.768249	—0.24462073	0.307095848
40	0.11633	0.790028	—0.25989177	0.338044206
80	0.11128	0.819906	—0.28074782	0.380498816
100	0.10863	0.838537	—0.29453318	0.410043777
150	0.10252	0.878953	—0.32383710	0.472390698
200	0.09644	0.929180	—0.36238728	0.558999751
250	0.09046	0.988439	—0.41068351	0.674349542
300	0.08456	1.057987	—0.47049442	0.825410704
350	0.07875	1.141227	—0.54718361	1.033720410
400	0.07299	1.242337	—0.64718219	1.326739332
450	0.06729	1.395432	—0.83357267	1.993635632
500	0.06166	1.523406	—0.96163276	2.392609283

Table 5

PdP travel-times for various focal depths

h (Km) → / $\Delta°$	0	40	80	100	150	200	250	300	350	400	450	500
0	122.63	116.33	111.28	108.63	102.52	96.44	90.46	84.57	78.75	72.99	67.29	61.66
1	123.38	117.10	112.07	109.44	103.37	97.34	91.41	85.58	79.84	74.17	68.60	63.09
2	125.51	119.29	114.34	111.76	105.79	99.88	94.10	88.44	82.89	77.47	72.23	67.02
3	128.91	122.77	117.93	115.42	109.60	103.87	98.30	92.89	87.63	82.53	77.76	72.97
4	133.44	127.40	122.70	120.27	114.63	109.13	103.82	98.70	93.77	89.07	84.79	80.49
5	139.00	133.05	128.51	126.17	120.74	115.49	110.46	105.65	101.09	96.79	93.00	89.22
6	145.40	139.60	135.22	132.99	127.78	122.79	118.05	113.56	109.35	105.46	102.10	98.83
7	152.62	146.94	142.74	140.60	135.62	130.88	126.43	122.25	118.38	114.85	111.86	109.07
8	160.53	154.97	150.94	148.90	144.13	139.64	135.46	131.57	128.01	124.80	122.08	119.72
9	169.04	163.60	159.72	157.77	153.21	148.95	145.01	141.38	138.08	135.15	132.63	130.65
10	178.07	172.73	169.00	167.13	162.76	158.71	154.98	151.57	148.49	145.78	143.41	141.76
11	187.53	182.28	178.69	176.90	172.69	168.82	165.27	162.05	159.14	156.60	154.38	153.03
12	197.36	192.20	188.72	186.99	182.93	179.21	175.81	172.73	169.97	167.57	165.53	(164.47)
13	207.49	202.40	199.03	197.35	193.41	189.82	186.54	183.58	180.92	178.65	(176.92)	
14	217.88	212.85	209.56	207.92	204.08	200.60	197.41	194.54	191.19	189.87		
15	228.48	223.49	220.27	218.66	214.91	211.50	208.39	205.61	203.18	(201.26)		
16	239.23	234.28	231.11	229.53	225.85	222.51	219.48	216.79	214.52			
17	250.12	245.20	242.08	240.51	236.89	233.62	230.67	228.11	(226.07)			
18	261.12	256.22	253.14	251.59	248.03	244.83	242.00	(239.61)				
19	272.21	267.33	264.29	262.76	259.27	256.16	(253.48)					
20	283.37	278.52	275.52	274.03	270.62	(267.64)						
21	294.61	289.79	286.86	285.40	(282.11)							
22	305.93	301.16	(298.31)	(296.92)								
23	317.34	(312.65)										
24	(328.87)											

TABLE 3

Data for the *PdP*-waves emerging at Messina and originating from Mediterranean earthquake sources

No.	Date Locality	Origin-Time hr min sec Depth (km)	Δ_{MES} (deg)	T'_{PdP} (sec)	T''_{PdP} (sec)	R (sec)
1	25 Mar 62 Tyrrhenian Sea	21 38 26.1 338	1.16	83.1	81.8	+1.3
2	1 Jun 63 Tyrrhenian Sea	20 36 03.8 238	0.59	89.5	92.5	—3.0
3	4 Oct 64 Tyrrhenian Sea	01 46 50.2 243	0.92	93.1	92.2	+0.9
4	30 Dec 67 Italy	04 19 20.5 33	6.95	145.6	147.6	—2.0
5	31 Mar 65 Greece	12 01 11.7 78	5.25	131.3	130.4	+0.9
6	2 Jan 66 Greece	23 12 18.0 12	6.05	143.5	144.0	—0.5
7	1 Sep 66 Greece	14 22 56.9 15	5.25	135.6	138.4	—2.8
8	29 Apr 64 Aegean Sea	04 21 05.1 20	6.47	145.9	145.9	0.0
9	9 Mar 65 Aegean Sea	17 57 54.4 18	6.56	144.0	146.9	—2.9
10	22 Mar 65 Aegean Sea	03 22 22.2 1	6.55	148.5	149.4	—0.9
11	31 Mar 65 Aegean Sea	20 08 25.5 33	6.78	147.0	146.3	+0.7
12	11 Apr 64 Aegean Sea	16 00 43.0 33	7.50	151.2	151.9	—0.7
13	19 Nov 66 Crete	07 12 38.0 17	7.10	152.0	151.0	+1.0
14	25 Aug 65 Crete	04 57 45.7 10	8.43	163.0	162.8	+0.2
15	17 Oct 64 Crete	09 50 28.0 18	8.55	160.0	162.7	—2.7
16	10 Jun 65 Crete	15 24 17.1 142	9.01	154.2	154.0	+0.2

No.	Date Locality	Origin-Time hr min sec Depth (Km)	Δ_{MES} (deg)	T'_{PdP} (sec)	T''_{PdP} (sec)	R (sec)
17	29 Jun 65 Crete	15 40 31.5 33	9.50	168.5	169.1	—0.6
18	9 May 66 Crete	13 08 16.9 9	9.55	172.0	172.2	—0.2
19	30 May 68 Dodecanese I.	17 40 26.0 27	10.26	176.5	177.0	—0.5
20	28 Mar 69 Turkey	01 48 29.5 4	10.14	178.7	178.9	—0.2
21	13 Jun 65 Turkey	20 01 50.8 33	10.87	183.2	182.0	+1.2
22	30 Jul 67 Turkey	01 31 01.8 18	11.84	191.0	193.5	—2.5
23	22 Jul 67 Turkey	16 56 58.0 33	11.96	194.0	192.7	+1.3
24	3 Sep 68 Turkey	08 19 52.6 5	13.39	211.4	210.9	+0.5
25	10 Dec 66 Turkey	17 08 33.0 13	14.17	217.0	218.1	—1.1
26	26 Jul 67 Turkey	18 53 01.1 30	19.36	271.9	272.6	—0.7
27	13 Aug 67 Pyrenees	22 07 47.8 15	13.28	209.0	208.5	+0.5
28	31 Mar 69 Egypt	07 15 54.4 33	18.65	265.1	264.3	+0.8
29	12 Jul 66 W. Caucasus	18 53 05.0 2	17.53	258.0	255.7	+2.3
30	29 Apr 68 W. Persia	17 01 55.6 17	22.36	307.8	308.0	—0.2
31	14 May 70 E. Caucasus	18 12 28.0 44	24.34	328.7	(328.3)	+0.4
32	11 Jul 70 Caspio Sea	22 41 15.6 65	26.32	351.5	(350.8)	+0.7

Δ_{MES} denotes the epicentral distance for the Messina station.

T'_{PdP}, T''_{PdP} indicate respectively the observed and estimated *PdP*-wave travel-times.

R denotes the residual $T'_{PdP}-T''_{PdP}$

TABLE 7

Depth values for the *P*-wave velocity-discontinuities between 400 and 580 km in the Upper Mantle

Region	Depth	Author
Nord America	410	Carder et al. (1966)(5)
Arizona (USA)	400	Johnson (1967)(12)
West of Lake Superior (USA)	450	Lewis Brian and Meyer(1968)(14)
Central and EN. America	431	Masse (1973)(15)
Europe	536	Girlanda and Federico (1966)(9)
NE. France	550	Mechler et al. (1974)(16)
Mediterranean region	505	Present Authors
China	515	Caloi (1967)(13)
India-China	580	Kaila et al. (1968)(2)
Antartica	420	Adams (1971)
Australia	520	Simpson et al. (1974)(18)
Atlantic-Indian Rise and Indian Ocean	520	Whitcomb and Don Anderson (1970)(19)

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