P and *S*-wave compatible crustal models for the western Ionian basin

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Received on June 19th, 1982

Abstract

We assume a four layers stratified crustal model with homogeneous layers and spherical simmetry for the earth's crust of the Western Ionian basin like a similar crustal model formerly proposed for the Southern Tyrrenian basin and the Messina Straits area.

To define the *P*-wave velocity in the upper layer of the model we analize the travel-times of the *T*-waves produced by shots fired in the region concerned. Such waves are recorded in different and conveniently grouped seismic stations. The observed travel-times are essential to define the *P*-phase refracted at the base of the first crustal layer of the model and subsequently the following refracted phases.

The thickness of the layers and the corrispondent velocities are calculated by determining the δt_i and $\delta \Delta_i$ contributions (travel-time and angular distance) following the relation relative to the seismic parameter p_i:

$$\Sigma_i \ a_i = 2 \quad \Sigma_i \Sigma t_i - 2 \, p_i \ \Sigma_i \ \delta \Delta_i$$

where a_i is the intercepted time of the observed travel-time curve. A similar procedure allows to define a crustal model also for *S*-waves.

Finally the elastic constants μ, λ, K, σ and ρ density in the crustal layers are calculated.

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Riassunto

Si propone per la regione del mare Ionio occidentale un modello di crosta a quattro strati e simmetria sferica a completamento di analogo modello già proposto per l'area del Tirreno meridionale e lo Stretto di Messina.

Per la determinazione della velocità delle onde P nello strato più superficiale sono esaminati i tempi di tragitto delle onde T prodotte da esplosioni effettuate nell'area di studio. Tali onde sono state chiaramente registrate sui sismogrammi di stazioni sismiche opportunamente raggruppate. I tempi di tragitto rilevati costituiscono il dato essenziale per la definizione della fase P rifratta alla base del primo strato e, successivamente, degli strati più profondi.

Lo spessore degli strati e le corrispondenti velocità di propagazione sono determinati mediante il calcolo dei contributi δt_i, $\delta \Delta_i$ (tempo di tragitto e distanza angolare) avvalendosi della relazione $\Sigma_i a_i = 2 \Sigma_i \delta \Delta t_i - 2 p_i \Sigma_i \delta \Delta_i$ ove a_i e p_i indicano rispettivamente il tempo intercetto di ciascuna dromocrona osservata ed il parametro del raggio sismico.

Analoga procedura è adottata per la definizione di un modello di crosta compatibile con le onde S.

Infine sono calcolati i valori delle costanti elastiche, μ, λ, K, σ e della densità ρ per ciascuno strato evidenziato.

Introduction

In October 1977 and until January 1978 the Royal Society Etna Research carried out a seismic array study on the Etna area in order to identify a possible anomalous propagation body identifiable with a magma chamber. The research was mainly based on the recording of seismic waves produced by four shots fired at the Ionian Sea and required the installation of a temporary seismic network made up of four sub-arrays with stations based in the North at Castiglione, in the East at Moscarello, in the South at San Vito and in North-West at Cesarò. About thirty stations were set up by the "Grandi Profili Group" of the Italian National Research Council along the line from Acireale to the northern coast of Sicily, and the Mt. Veneretta and Orti stations were installed by the Messina University Geophysical Institute. These stations completed the set of seismic equipments officially used.

The sea-shots were actually recorded by other stations of the Seismic Network of the Messina Straits, too, and the high qualitative standard of the seismograms together with the favourable position of the shot-points have encouraged the authors of this paper to analyse the travel-times of the *P* and *S* waves.

The main purpose of the Operators of the Seismic Network of the Messina Straits (briefly MSSN) is the same as that of most of the seismological observatories operating in high seismic risk areas, i.e. the detailed study of local seismic activity. Research concerning the identification and characterization of the active faults and the modelling of the genesis of earthquakes is fundamental. In this context, primary importance is given to the definition of a local crustal model suitable for a reliable location of the seismic phenomena originating in the Messina Straits area. This problem has been partly resolved for the Tyrrhenian sector by assuming a model having four plane and parallel crustal layers (h_1 = 2 Km, v_1 = 3.0 Km · sec^{-1}; h_2 = Km, v_2 = 4.5 Km · sec^{-1}; h_3 = 18 Km, v_3 = 5.8 Km · sec^{-1}; h_4 = 13.5 Km, v_4 = 6.4 Km · sec^{-1}; v_5 = 7.8 Km · sec^{-1}) and a concentric spherical layer-model (h_1 = 2 Km, v_1 = 3.0 Km · sec^{-1}; h_2 = 4 Km, v_2 = 4.5 Km · sec^{-1}; h_3 = 16.6 Km, v_3 = 5.85 Km · sec^{-1}; h_4 = 15.9 Km, v_4 = 6.5 Km · sec^{-1}; v = 7.8 Km · sec^{-1}). In the definition of this model we have used several hundred travel-times, mostly concerning the earthquakes which occurred in the Patti Gulf in 1978 (Bottari et al., 1979; Bottari and Federico, 1981).

Considering the complexity of the structure of the crust in this site of the Calabro-Peloritan Arc, characterized by variations in the Moho level and in the velocity of the seismic waves in direction orthogonal to it (Morelli and Giese, 1975; Cassinis et al., 1979; Shutte, 1979), we found it necessary to characterize a crustal model which was compatible with the seismic wave propagation in the Ionian sector.

The crustal models proposed by various authors following deep seismic explorations in Calabria and Sicily are an important element, but they do not solve the seismological problem. In fact less detail than that normally required in the modelling of the seismic crustal profiles, is acceptable, but the crustal model to be assumed must necessarily have an "areal" validity (Jeffreys and Bullen, 1940; Bottari and Girlanda, 1974).

This analysis of longitudinal and transversal seismic phases gives some interpretative elements which are useful for the characterization of the propagation beneath the Mount Etna area. The results reported in the literature on this area, in fact following the seismic array study, show a high degree of disagree ment.

T — WAVE ANALYSIS

The data here used were taken from the seismograms of the stations of the four sub-array of the Etna array, installed by the Geopghysics Department of Cambridge University (U. K.) and by the MSSN of the Geophysics Institute of Messina University. Each sub-array has a base station with three short period seismometric components and 3 or 4 out-stations, 10-15 Km from the base station, equipped only with vertical component. The MSSN stations have only vertical components except Ganzirri where there is a seismometric tern.

The positions of the sea-shots sites and of the seismic stations are shown in the map of Fig. 1 and the relative geographical coordinates are reported in Tables 1 and 2.

The seismograms allow us to obtain sufficiently clear data in nearly all the stations, and in many of them we get clear records of the *T*-phase. The Ganzirri seismograms for the first and second shot fired give us the following information:

i) the Ganzirri-shot point distance for the first explosion is 76.0 Km and the seismic ray path is completely in the sea, since the path between the coast and the station is insignificant (1.5%) compared with the sea-path (98.5%). The travel-time observed, on both the vertical and the horizontal (E-W) components is 50.6 sec. This is compatible with a propagation velocity of 1.5 Km $\cdot$ sec^{-1}, and can be identified with the velocity of the sound waves channelled in the SOFAR;

ii) the Ganzirri-shot point distance for the second explosion is 90.5 Km with the ray path partially on land and no longer irrelevant, as we can see in the map of Fig. 1. The travel-times

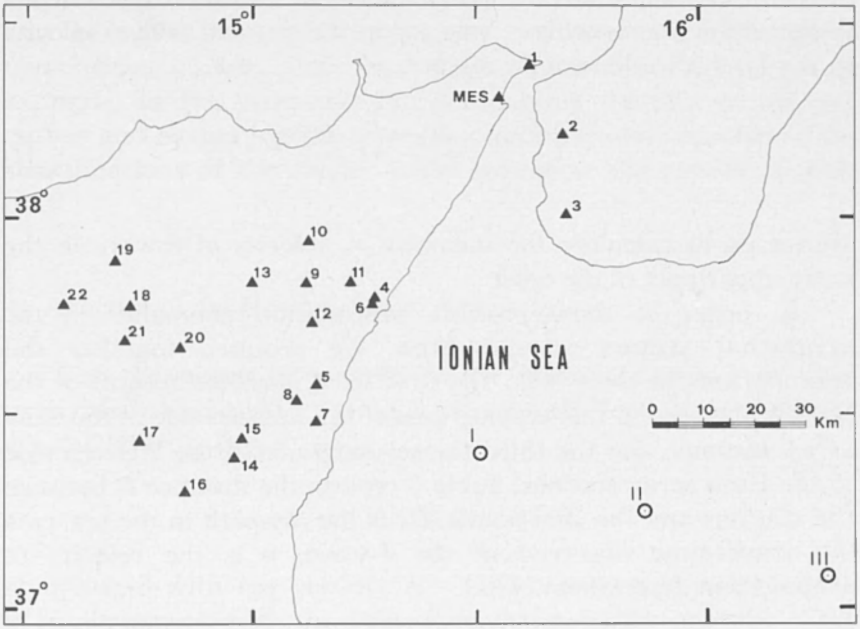

Fig. 1 - Map of the seismic stations and three shocks fired in the Jonian Sea.

observed for a clear *T*-phase present on the vertical and horizontal (E-W) components are 55.0 and 54.6 sec, respectively. The average velocity compatible with these times is 1.65 km $\cdot$ sec^{-1}, which is greater than the velocity calculated for the first explosion, probably because the ray-path is different. On the seismograms concerning the second explosion, after the impulse attributed to the *T*-phase, we find another less-evident impulse (Fig. 3) with a travel time of 59.7 sec, on the vertical component and 58.5 sec on the E-W component. The corresponding velocities are 1.52 and 1.55 Km $\cdot$ sec^{-1}, which can robably be attributed to the diffracted *T*-phase.

These observed elements, together with those seen from the *T*-phase records at Castiglione, Martino, San Vito and Mount Veneretta (Figs. 4, 5, and 6) enable us to use a procedure for the determination of the velocity of the *P* waves in the most upper crust. In fact, once we have the distances D_1 and D_2 covered by the longitudinal waves with v_1 velocity in the sea and with v velocity in the land, the elementary relation.

$$t_T = \frac{D_1}{v_1} + \frac{D_2}{v} \quad [1]$$

allows us to calculate the unknown v, velocity of P-wave in the most upper part of the crust.

In order to show possible propagation anomalies in the azimuthal sectors around Etna, we grouped together the seismograms in three sets. The first set groups the records of the MSSN; the second the seismograms of the Eastern side of the Etna array stations, and the third the seismograms of the Western side of the Etna array stations. Table 3 reports the distance D between the stations and the shot-points, D_1 is the ray-path in the sea, t_T is the travel-time observed of the T-wave, v is the velocity of propagation determined by [1].

First layer: geometrical and seismological parameters

Once we know the travel-times of refracted longitudinal phase at the base of the most superficial crustal layer and the velocity there, the velocity v_1 in the most superficial layer, obtained by the observation of the T-phase, allows us to determine for each of the three groups of seismograms studied the travel-time curves of the direct P waves and the thickness of the first layer.

In the analysis of the first arrivals and of the later impulses to be found in the records, we followed the criterion of considering the clearest ones, without discriminating their type.

In order to calculate better the alignments of the first phases observed and the later ones, we chose an intermediate velocity of propagation v_r among the most probable ones, and we assumed it as the reduction velocity for the calculation of the reduced travel-times $t_r = t - \Delta v_r^{-1}$, with t the travel-time observed, Δ the distance in Km and v_r the reduction velocity, in Km · sec^{-1}. The reduced travel-times plotted versus the distance, are almost straight inea discriminated according to the slope. For every alignment obtained, through further conversion from reduced travel-times to original travel-times, we determine the relative travel-time curves. This method is reported in detail, as an example, in the procedure for determining the first travel-time curves and evaluating the respective thickness and velocities of the stratifications of the model. Later we report the results in table only.

a) *Analysis of the Messina Straits station data*

For the group of records of the Messina Straits, the most probable travel-time curve for the direct *P*-waves in the first crustal layer, called P_1, is

$$t_{P_1} = (43.88 \pm 0.99)\ \Delta \qquad [2]$$

compatible with the velocity $v_1 = (2.53 \pm 0.05)$ Km · sec^{-1}, which is in agreement with the value determined by the analysis of the *T*-phase.

The most probable travel-time curve of the*P*-waves refracted on the base of the first layer, called P_2, is determined by linear fit of eight observed travel-times represented by the equation

$$t_{P_2} = (24.71 \pm 0.32)\ \Delta + (2.34 \pm 0.22) \qquad [3]$$

compatible with the apparent velocity $v_2 = 4.5$ Km · sec^{-1}.

For the calculation of the thickness of the first spherical layer of the crustal model and of the true velocity at its base, the following relations must be satisfied

$$2\ \delta t - 2_{p_1}\ \delta\ \Delta = 2.344 \text{ sec}, \qquad [4]$$

being

$$2\ \delta\ \Delta = 2\ (\cos^{-1} \frac{p_1}{\eta_0} - \cos^{-1} \frac{p_1}{\eta_*}) \qquad [5]$$

and

$$2 \ \delta t = 2 \left[(\eta_{o}^{2} - p_{1}^{2}) - (\eta_{*}^{2} - p_{1}^{2})^{1/2} \right] \qquad [6]$$

where

$$\eta_o = R_o \cdot v_1^{-1} = 6371 \cdot 2.53^{-1} \quad (R_o = \text{average earth radius})$$

$$\eta_* = R_* \cdot v_2^{-1} \ (R_* = \text{level to be determined})$$

and p_1 is the seismic ray parameter, in sec $\cdot$ Δ^{-1} (with Δ in degrees). Equation [4] is satisfied for $R_* = 6367.39$ km, with a corresponding thickness $h_1 = (4.49 \pm 0.08)$ Km $\cdot$ sec^{-1}, for the P-waves beneath it.

b) *Analysis of the East-Etna station data*

With the same procedure as in a), we determine the travel-time curves for the P-waves. A fit is operated on 30 observed travel-times and results

$$t_{P_1} = (42.42 \pm 0.78) \ \Delta \qquad [7]$$

compatible with the velocity (2.62 ± 0.49) Km $\cdot$ sec^{-1}.

The equation of P_2 deduced from a fit of 14 observed travel-times is

$$t_{P_2} = (23.45 \pm 0.40) \ \Delta + (2.93 \pm 0.25) \qquad [8]$$

corresponding to the apparent velocity $v_2 = 4.74$ Km $\cdot$ sec^{-1}. Since the value of p_1 ray parameter is 23.455 sec $\cdot$ Δ^{-1} and the intercept time a_1 is 2.93 sec, condition [2] is satisfied for $R_* = 6366.4$ Km, corresponding to the thickness $h_1 = 4.6$ Km for the first layer and the true velocity $v_2 = (4.63 \pm 0.11)$ Km $\cdot$ sec^{-1}, below it.

c) *Analysis of the West-Etna station data*

A linear fit of 5 travel-times of impulses observed establishes for the most probable travel-time curve of *P*-waves the equation

$$t_{P_1} = (42.16 \pm 0.007)\ \Delta \qquad [9]$$

corresponding to the velocity $v_1 = (2.64 \pm 0.05)$ Km · sec^{-1}, for the direct *P*-waves. Successively we calculate the travel-time curve of the *P*-waves refracted on the bottom of the first layer from a fit of 17 travel-times observed. We obtain the equation

$$t_{P_2} = (24.00 \pm 2.61)\ \Delta + (2.03 \pm 0.39), \qquad [10]$$

compatible with the apparent velocity of the refracted *P*-waves, $v_2 = 4.63$ Km · sec^{-1}. Since $p_1 = 23.996$ sec · Δ^{-1} and $a_1 = 2.04$ sec, condition [2] is satisfied for $R_* = 6367.3$ Km. It follows that the thickness of the first layer is $h_1 = 3.7$ Km and the true velocity of the *P*-waves below it is $v_2 = (4.63 \pm 0.72)$ Km · sec^{-1}.

P-WAVES REFRACTED AND CRUSTAL MODELS

The typical repetitive characteristic of the procedure used in the definition of the seismic phases and the parameters of the crustal models leads to a schematic presentation of the results obtained for the three areas studied.

a) *Messina Straits area*

The travel-time curve for the refracted *P*-waves on the botton of the second layer, shortly called P_3, on the basis of the analysis of 10 observed travel-times has equation

$$t_{P_3} = (18.31 \pm 0.32)\ \Delta + (5.81 \pm 0.24). \qquad [11]$$

In an analogous way we obtain

$$t_{P_4} = (15.80 \pm 0.64)\ \Delta + (6.77 \pm 0.56). \qquad [12]$$

$$t_{P_n} = (13.66 \pm 0.70)\ \Delta + (9.12 \pm 0.58). \qquad [13]$$

for the successive P_4 and P_n-waves refracted respectively on the bottom of the third layer and on the Mohorovicic discontinuity. A refracttor horizon at the $R_* = 6355.5$ Km level corresponds to the travel-time curve of the P_* with parameter $p = 18.3104$ sec $\cdot\ \Delta^{-1}$ and an intercept time $a_2 = 5.81$ sec. It follows that the thickness of the second layer is $h_2 = 10.8$ Km, with a value of the true velocity of the P-waves below it $v_3 = (6.06 \pm 0.15)$ Km $\cdot$ sec^{-1}.

Similarly the travel-time curve of the refracted P-waves at the base of the third layer with parameter $p_3 = 15.8058$ sec $\cdot\ \Delta^{-1}$ and and intercept-time $a_3 = 6.77$ sec, a refractor is defined at a level $R_* = 6353.5$ Km. The thickness of the third layer is $h_3 = 2.0$ Km and the P-wave velocity below it is $v_4 = (7.02 \pm 0.40)$ Km $\cdot$ sec^{-1}.

Finally, a refractor at the level $R_* = 6340.6$ Km (Mohorovicic discontinuity) corresponds to the travel-time curve of the P_n-waves, of parameter $p_4 = 13.6632$ sec $\cdot\ \Delta^{-1}$, and intercept-time $a_4 = 9.12$ sec. Therefore the thickness of the fourth layer is $h_4 = 12.56$ Km and the true velocity of the P-waves on the Moho is $v_n = (8.12 \pm 0.58)$ km $\cdot$ sec^{-1}.

The same procedure used for the data of the East and West Etna stations characterizes the following sets of travel-time curves.

b) *East-Etna area:*

$$t_{P_3} = (18.68 \pm 0.62)\ \Delta + (5.32 \pm 0.36)$$

$$t_{P_4} = (15.17 \pm 0.25)\ \Delta + (7.06 \pm 0.22) \qquad [14]$$

$$t_{P_n} = (13.39 \pm 0.18)\ \Delta + (9.81 \pm 0.51)$$

c) *West-Etna area:*

$$t_{P_3} = (19.24 \pm 0.41)\ \Delta + (4.68 \pm 0.04)$$

$$t_{P_4} = (16.52 \pm 0.22)\ \Delta + (5.88 \pm 0.25) \qquad [15]$$

$$t_{P_n} = (13.70 \pm 0.49)\ \Delta + (9.11 \pm 0.67)$$

Table 4 summarizes the values of the geometrical and seismological rameters of the three crustal models worked out.

The complete set of data of the *P*-waves observed in the three areas studied is compatible with an average crustal model for the Western Ionian basin, called briefly WIB_P. The main elements of this model are obtained by the average of the parameters of the *P*-wave travel-time curves and they are reported in detail in Table 8 and Figure 8.

Travel-time analysis of the *S*-waves

Initially we determined the travel-time curves of the *S*-waves refracted on the discontinuities of the models deduced from *P*-wave travel-time analysis, assuming the Poisson coefficient $\sigma = 0.25$ and therefore $v_P \cdot v_S^{-1} = \sqrt{3}$. The calculated *S*-wave travel-times are then compared with those observed on the recorded impulses, which are chosen according to the same criteria as in the discrimination of *P*-phases (Tab. 5). Analogously to the characterization the *P*-compatible crustal models, we carried out the determination of the *S*-compatible crustal models for the three areas studied (Tab. 6).

The complete set of the data of the *P* and *S*-waves determined allows to characterize the values of the main elastic parameters μ, λ and K (Bullen, 1064) and ρ density (Birch, 1961; Trifunac and Brune, 1970), which are reported in detail in Table 7.

Finally,Table 8 summarizes the characteristics of a *P*-waves and *S*-waves average crustal models (indicated briefly WIB_P and WIB_S respectively) compatible with the Western Ionian basin and Table 9 reports the values of the correspondent elastic parameters.

TABLE 1

Shot point coordinates

Shot-point Number	Origin Time (hr min sec)			Latitude N (deg min sec)			Longitude E (deg min sec)		
I	10	08	04.48	37	35	06.4	15	29	52.1
II	12	38	15.10	37	28	37.4	15	51	36.0
III	15	38	53.00	37	22	03.4	16	15	57.4
IV	20	08	17.86	37	11	00.4	16	53	08.2

TABLE 2

Seismic station coordinates

Station Number	Stations	Latitude N (deg)	Longitude E (deg)	Altitude (m)
1	Ganzirri	38.26444	15.60639	80
2	Orti	38.15347	15.68917	460
3	Martino	38.01781	15.70603	590
4	Monte Veneretta	37.86945	15.26417	760
5	Moscarello base	37.71175	15.13703	247
6	Moscarello North	37.84708	15.25690	299
7	Moscarello South	37.63750	15.13928	295
8	Moscarello West	37.68307	15.09525	750
9	Castiglione	37.88314	15.12085	621
10	Castiglione North	37.95592	15.11820	900
11	Castiglione East	37.89922	15.21162	770
12	Castiglione South	37.81149	15.06422	481
13	Castiglione West	37.88582	15.00128	643
14	San Vito base	37.58843	14.93097	442
15	San Vito North	37.72767	14.94522	720
16	San Vito South	37.53217	14.85987	141
17	San Vito West	37.61482	14.75923	430
18	Cesarò base	37.84281	14.72194	1150
19	Cesarò North	37.91022	14.70313	1600
20	Cesarò East	37.77030	14.85100	930
21	Cesarò South	37.78664	14.71585	1026
22	Cesarò West	37.85019	14.57602	1320

TABLE 3

SEISMIC STATION DATA

Data Source	Station	Shot Number	D (Km)	D_1 (Km)	e_E (sec)	M_1 (Km·sec^{-1})
Messina Straits Stations	Ganzirri	I	76.0			
		II	90.5			
	Orti	I	65.6	53.1	40.1	2.64
		II	76.6	50.1	43.3	2.54
		III	100.9	71.0	59.0	2.57
	Martino	I	51.9	43.4	32.3	2.61
		II	61.7	50.0	38.1	2.50
	Mt. Veneretta	I	37.4	34.1	24.2	2.77
		II	68.2	64.0	44.3	2.57
Eastern Etna Stations	Moscarello base	I	34.8	28.4	21.8	3.23
		II	68.9	6.2	44.8	2.04
					44.6	2.17
					44.2	2.46
	Moscarello North	I	36.0	33.8	33.3	2.97
		II	67.2	64.2	43.7	3.46
		III	106.2	100.3	69.3	2.43
	Moscarello South	I	28.3	20.8	16.6	2.77
		II	64.4	62.3	42.4	2.49
		III	106.7	100.0	69.4	2.47
	Moscarello West	I	37.2	27.8	21.7	2.95
		II	71.3	61.9	45.8	2.08
		III	109.2	99.9	70.6	2.33
	Castiglione base	I	46.8	31.8	26.3	2.92
					26.1	3.04
					26.2	3.00
	Castiglione North	I	53.0	33.0	28.7	3.00
	Castiglione East	I	43.0	33.4	25.8	2.73
	Castiglione South	II	79.3	61.3	46.9	2.97
	Castiglione West					

continued Table 3

Data Source	Station	Shot Number	D (Km)	D_1 (Km)	e_E (sec)	M_1 (Km·sec^{-1})
	San Vito base	I	50.0	29.8	29.7	2.05
		II	83.0	55.0	46.9	2.72
		III	120.6	100.6	74.8	2.59
					77.0	2.01
					74.2	2.80
Eastern	San Vito North	II	82.5	61.5	49.3	2.55
Etna					50.5	2.22
Stations		III	120.3	99.2	73.8	2.75
	San Vito South	I	56.6	30.6	32.6	2.13
		II	88.6	65.6	52.9	2.51
		III	125.8	103.8	75.6	3.42
	San Vito West	I	65.2	29.2	36.6	3.22
		II	98.4	61.4	53.6	2.91
	Cesarò base	I	74.1	27.6	37.3	2.46
					37.8	2.48
					37.4	2.94
		II	118.2	71.8	63.2	3.02
					66.5	2.48
					64.4	2.81
		III	146.2	100.2	81.6	3.12
					81.6	3.12
Western	Cesarò North	I	78.8	27.6	42.8	2.10
Etna					31.8	2.48
Stations					36.8	2.55
		II	123.6	76.1	67.0	2.81
		III	150.5	102.5	87.8	2.47
	Cesarò East	II	94.8	62.2	54.8	2.45
		III	132.8	100.8	79.8	2.53
	Cesarò South	II	106.7	50.1	58.6	2.44
		III	144.6	99.6	84.0	2.56
	Cesarò West	I	86.4	28.1	38.2	2.99
					40.5	2.58
		II	120.6	46.4	64.2	2.58
		III	158.5	101.5	87.4	2.89

TABLE 4

P-WAVE CRUSTAL MODELS

Area	R (Km)	H (Km)	Layer	h (Km)	V_P (Km · sec^{-1})
A_1	6371.0 6367.3	0.0 3.7	I	3.7	2.53 ± 0.05
	6367.3 6355.5	3.7 15.5	II	11.8	4.49 ± 0.08
	6355.5 6353.5	15.5 17.5	III	2.0	6.06 ± 0.15
	6353.5 6340.6	17.5 30.4	IV	12.9	7.02 ± 0.40
	6340.6	Moho			8.12 ± 0.58
A_2	6371.0 6366.4	0.0 4.6	I	4.6	2.62 ± 0.49
	6366.4 6357.8	4.6 13.2	II	8.6	4.63 ± 0.11
	6357.8 6352.6	13.2 18.4	III	5.2	5.94 ± 0.27
	6352.6 6334.7	18.4 36.3	IV	17.9	7.31 ± 0.17
	6334.7	Moho			8.25 ± 0.15
A_3	6371.0 6367.3	0.0 3.7	I	3.7	2.64 ± 0.05
	6367.3 6358.8	3.7 12.2	II	8.5	4.63 ± 0.72
	6358.8 6355.2	12.2 15.8	III	3.6	5.76 ± 0.13
	6355.2 6338.0	15.8 32.2	IV	16.4	6.71 ± 0.15
	6338.0	Moho			8.08 ± 0.41

Note: R = geocentric level; H = discontinuity depth; h = layer thickness; V_P = *P*-wave velocity; A_1 = Messina Straits area; A_2 = Eastern Etna area; A_3 = Western Etna area.

TABLE 5

S-WAVE TRAVEL-TIMES

Data Source	Travel - Times Calculated (sec)	Travel - Times Observed (sec)	Seismic Parameter (sec · Δ^{-1})
Messina Straits Stations	$t_{S_1} = 73.15\ \Delta$	$t_{S_1} = (76.13 \pm 0.53)\ \Delta$	76.1285
	$t_{S_2} = 40.12\ \Delta + 4.40$	$t_{S_2} = (41.84 \pm 0.87)\ \Delta + (3.93 \pm 0.53)$	41.8437
	$t_{S_3} = 31.70\ \Delta + 9.60$	$t_{S_3} = (32.24 \pm 0.20)\ \Delta + (9.21 \pm 0.11)$	32.2410
	$t_{S_4} = 27.45\ \Delta + 11.22$	$t_{S_4} = (28.79 \pm 1.35)\ \Delta + (11.64 \pm 0.52)$	28.7947
	$t_{S_5} = 23.99\ \Delta + 15.90$	$t_{S_5} = (23.97 \pm 0.78)\ \Delta + (15.47 \pm 0.58)$	23.9712
Eastern Etna Stations	$t_{S_1} = 73.64\ \Delta$	$t_{S_1} = (71.84 \pm 5.96)\ \Delta$	71.8433
	$t_{S_2} = 40.70\ \Delta + 5.07$	$t_{S_2} = (41.54 \pm 0.28)\ \Delta + (4.56 \pm 0.32)$	41.5468
	$t_{S_3} = 32.35\ \Delta + 9.25$	$t_{S_3} = (32.27 \pm 0.57)\ \Delta + (9.36 \pm 0.39)$	32.2766
	$t_{S_4} = 26.15\ \Delta + 12.42$	$t_{S_4} = (26.59 \pm 1.24)\ \Delta + (11.76 \pm 0.86)$	26.5955
	$t_{S_5} = 23.28\ \Delta + 16.61$	$t_{S_5} = (23.65 \pm 0.59)\ \Delta + (16.14 \pm 0.39)$	23.6536
Western Etna Stations	$t_{S_1} = 73.15\ \Delta$	$t_{S_1} = (72.73 \pm 0.89)\ \Delta$	72.7318
	$t_{S_2} = 41.62\ \Delta + 4.03$	$t_{S_2} = (42.38 \pm 0.73)\ \Delta + (3.74 \pm 0.67)$	42.3882
	$t_{S_3} = 33.43\ \Delta + 8.13$	$t_{S_3} = (33.96 \pm 0.63)\ \Delta + (7.51 \pm 0.78)$	33.9695
	$t_{S_4} = 28.66\ \Delta + 10.22$	$t_{S_4} = (29.74 \pm 0.72)\ \Delta + (9.18 \pm 0.81)$	29.7443
	$t_{S_5} = 24.20\ \Delta + 15.72$	$t_{S_5} = (23.17 \pm 0.03)\ \Delta + (17.21 \pm 0.02)$	23.1695

TABLE 6

S-WAVE CRUSTAL MODELS

Area	R (Km)	H (Km)	Layer	h (Km)	V_S (Km · sec^{-1})
A_1	6371.0 6367.6	0.0 3.4	I	3.4	1.46 ± 0.03
	6367.6 6357.2	3.4 13.8	II	10.4	2.66 ± 0.05
	6357.2 6354.8	13.8 16.2	III	2.4	3.43 ± 0.02
	6354.8 6341.8	16.2 29.2	IV	13.1	3.86 ± 0.07
	6341.8	Moho			4.62 ± 0.15
A_2	6371.0 6366.7	0.0 4.3	I	4.3	1.54 ± 0.18
	6366.7 6357.4	4.3 13.6	II	9.3	2.67 ± 0.02
	6357.4 6352.9	13.6 18.1	III	4.4	3.43 ± 0.08
	6352.9 6337.7	18.1 33.3	IV	16.1	4.14 ± 0.27
	6337.7	Moho			4.65 ± 0.16
A_3	6371.0 6367.4	0.0 3.5	I	3.5	1.53 ± 0.04
	6367.4 6359.2	3.5 11.7	II	8.2	2.62 ± 0.06
	6359.2 6356.9	11.7 14.1	III	2.3	3.27 ± 0.08
	6356.9 6336.9	14.1 34.1	IV	19.9	3.73 ± 0.14
	6336.9	Moho			4.77 ± 0.01

Note: R = geocentric level; H = discontinuity depth; h = layer thickness; V_S = *S*-wave velocity; A_1 = Messina Straits area; A_2 = Eastern Etna area; A_3 = Western Etna area.

TABLE 7

PHYSICAL PARAMETERS OF THE CRUSTAL LAYERS

Area	Layer	V_P (Km · sec^{-1})	V_S (Km · sec^{-1})	ρ (g · cm^{-3})	$\mu \cdot 10^{-10}$ (dyn · cm^{-2})	$\lambda \cdot 10^{-10}$ (dyn · cm^{-2})	K 7 10^{-10} (dyn · cm^{-2})	
	I	2.54	1.46	1.54	3.28	3.37	5.56	0.25
	II	4.49	2.66	2.13	15.07	12.80	22.85	0.23
A_1	III	6.06	3.44	2.60	30.77	33.95	54.96	0.26
	IV	7.01	3.86	2.89	43.06	55.90	84.60	0.28
	—	7.96	4.62	3.18	67.88	65.75	111.00	0.25
	I	2.62	1.54	1.56	3.74	3.26	5.75	0.23
	II	4.73	2.67	2.19	15.72	17.74	28.22	0.27
A_2	III	5.93	3.44	2.56	30.27	29.53	49.70	0.25
	IV	7.35	4.14	2.99	51.25	59.03	93.19	0.27
	—	8.23	4.65	3.25	70.59	79.28	126.35	0.26
	I	2.64	1.52	1.56	3.67	3.67	6.11	0.25
	II	4.63	2.62	2.17	14.91	16.70	26.60	0.26
A_3	III	5.76	3.27	2.51	26.83	29.82	47.71	0.26
	IV	6.71	3.73	2.80	38.93	48.19	74.14	0.28
	—	8.08	4.77	3.20	73.11	63.00	111.74	0.23

TABLE 8

WESTERN IONIAN BASIN: *P* AND *S*-WAVE CRUSTAL MODELS

P / *S*	*R* (Km)	*H* (Km)	Layer	*h* (Km)	*V* ($Km \cdot sec^{-1}$)
WIB *p*	6371.0 6367.0	0.0 3.9	I	3.9	2.53
	6367.0 6357.7	3.9 13.2	II	9.3	4.62
	6357.7 6351.9	13.2 19.0	III	5.8	5.92
	6351.9 6340.0	19.0 30.6	IV	11.6	7.02
	Moho	30.6			8.09
WIB_S	6371.0 6367.3	0.0 3.7	I	3.7	1.51
	6367.3 6352.2	3.7 12.8	II	9.1	2.65
	6358.2 6354.9	12.8 16.1	III	3.3	3.38
	6354.9 6338.3	16.1 32.7	IV	16.6	3.90
	Moho	32.7			4.70

Note: WIB *p* = *P*-waves compatible crustal model; WIB_S = *S*-waves compatible crustal model; *R* = geocentric level; *H* = discontinuity depth; *h* = layer thickness; *V* = velocities of the *P* and *S*-waves in the layers and at the Mohorovicic discontinuity.

TABLE 9

AVERAGE VALUES OF THE DENSITY AND ELASTIC PARAMETERS

Layer	ρ ($g \cdot cm^{-3}$)	$\mu \cdot 10^{-10}$ ($dyn \cdot cm^{-2}$)	$\lambda \cdot 10^{-10}$ ($dyn \cdot cm^{-2}$)	$K \cdot 10^{-10}$ ($dyn \cdot cm^{-2}$)	σ
I	1.53	3.51	2.78	5.11	0.22
II	2.16	15.20	15.70	25.90	0.25
III	2.50	29.20	21.10	50.60	0.26
IV	2.90	44.00	54.20	83.50	0.27
—	3.20	70.60	69.10	116.10	0.25

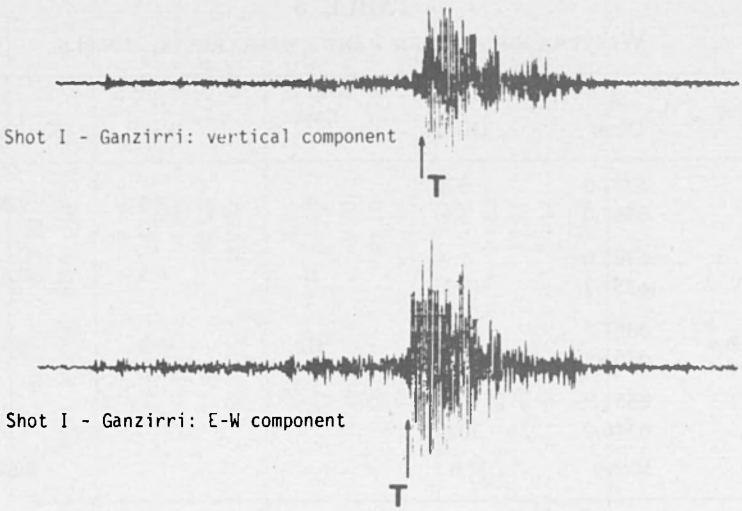

Fig. 2 - Ganzirri station records of the first shot fired. The travel-times of the indicated T-phase are 50.6 and 50.2 sec on the vertical and E-W components respectively.

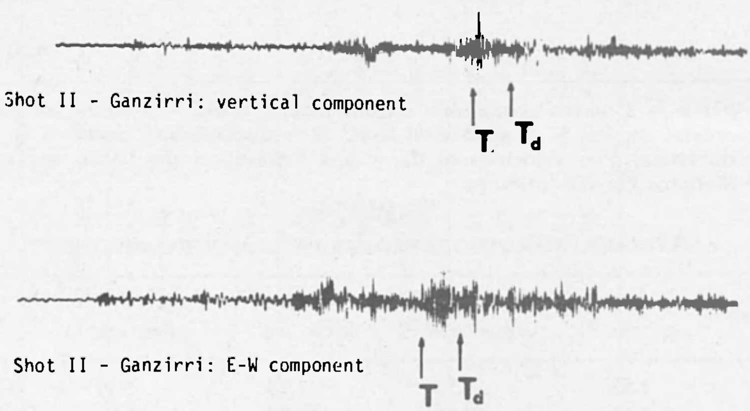

Fig. 3 - On the Ganzirri seismograms a "diffracted" T-phase (briefly T_d) follows the t-phase (t_T = 55.0, sec, t_{T_d} = 59.7 sec, on the vertical component; t_T = 54.6 sec, t_{T_d} = 58.5 sec, on the E-W component).

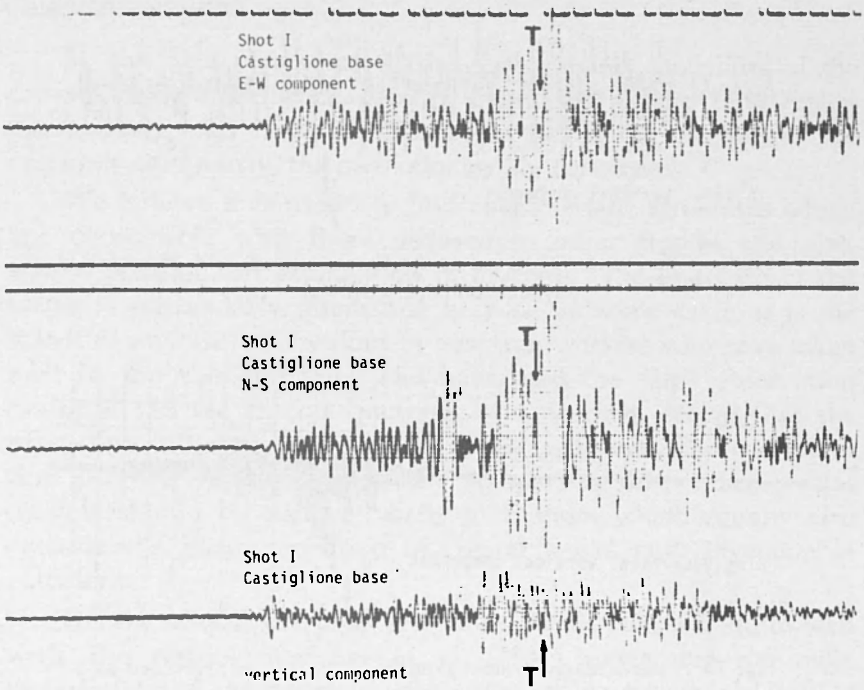

Fig. 4 - Records at the Castiglione base station: the *T*-phase impulses are well consistent.

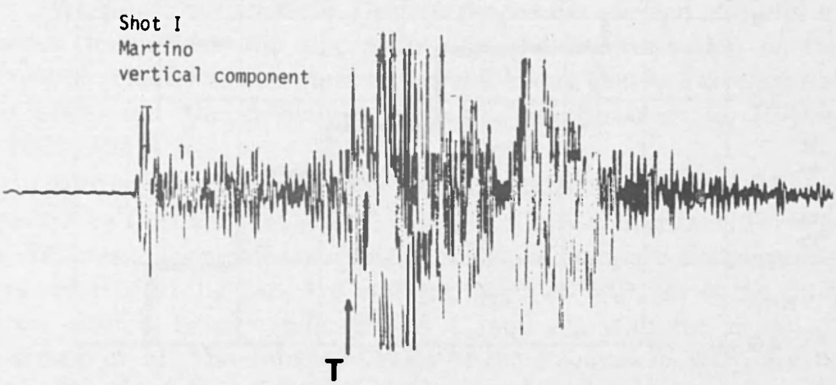

Fig. 5 - A sharp *T*-phase (t_T = 32.3 sec) recorded at the Martino station.

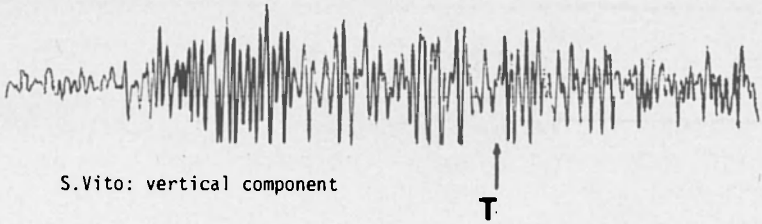

Fig. 6 - The T-phase observed at the S. Vito station: $t_T = 74.8$ sec, vertical component, III shot.

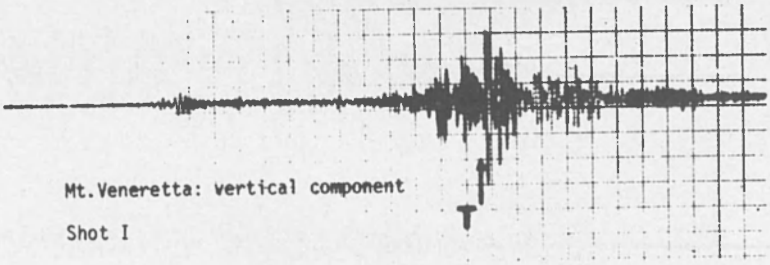

Fig. 7 - A particularly evident T-phase ($t_T = 24.2$ sec) recorded at the Mt. Veneretta station.

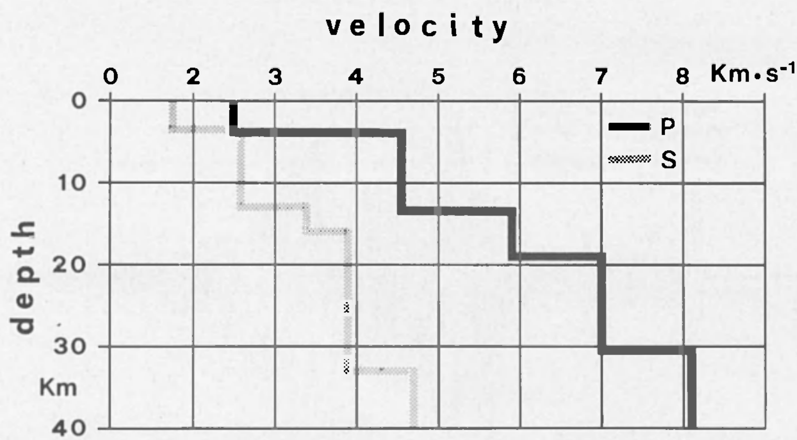

Fig. 8 - P and S-wave crustal models for the western Jonian sea basin.

Conclusive remarks

In the field of studies on the seismological modelling of the crustal structures in the Eastern Sicily and in the Etna region particularly, our study is different as far as the purpose of the research and, partly, the methodology are concerned.

We believe it is useful to find characteristic structures which are compatible with those deduced in other studies and also, where possible, an explanation of diversity. The existence of the latter is particularly interesting because, in some cases, it is the result of analyses carried out by research workers who have taken part in the shot-campaign and have used the same observation material. As far as this question, is concerned, seeing that the procedure followed by us did not allow us to take into consideration the low velocity layers, any comparison with other crustal models should be correct mostly with those which equally also exclude the characterization of crustal layers with inversion of velocity.

On the whole, the proposed model WIB_P concords quite well with the results of Sharp et al. (1981) concerning the most superficial and the deepest layers of the crust while it is clearly in contrast for the intermediate part. This diversity is also found in relation to less recent models (Cassinis et al., 1969; 1979) proposed for Eastern Sicily, in which the *P*-wave velocity of 5.5 $Km \cdot sec^{-1}$ is recurrent.

We point out that the *T*-phase procedure adopted is useful in order to restrict the uncertainty in the determination of the *P*-wave velocity in the most superficial layer. That is also essential to surmount the difficulties indicated by Sharp et al. (1980a, 1980b, 1981).

The comparison with the crustal model in three layers suggested by Colombi et al. (1979) is substantially concordant. There is a sufficient degree of correspondence if we compare the parameters relative to the 2nd, 3rd and 4th layers of WIB_P (or of the Etna area models briefly indicated as A_2 and A_3) with the model of Colombi et al. The velocity values of the *P*-waves in WIB_P are in fact close to those of the model quoted and remain constantly above them ($0.1 \div 0.4$ $Km \cdot sec^{-1}$).

The average level of the Mohorovicic discontinuity (−31 Km) is very close to the value proposed by COLOMBI et al. (−32 Km) but is unnegligibly deeper than the value estimated by SHARP et al. (−27 Km). In conclusion, the agreement between the various evaluations of the P_n velocities is excellent (all in the $8.0 \div 8.2$ Km · sec^{-1} interval). Nevertheless, the main diversities of the crustal models relative to the intermediate zone of the crust in the Etna area, require further studies also taking into account the considerable volcanological implications.

Finally, the WIB_S crustal model and the elastic parameters here characterized are useful elements for the modelling completion of the Western border of the Ionian Sea basin because of the approximate knowledge of the quoted parameters and the *S*-wave travel-times in most of the Mediterranean regions.

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