BOLLETTINO DI GEOFISICA TEORICA ED APPLICATA VOL. XXXIV, N. 133 - MARCH 1992

A. BOTTARI, B. FEDERICO and E. STILLITANI

BODY-WAVE VELOCITY MODEL IN THE UPPER MANTLE OF THE SOUTHERN TYRRHENIAN REGION

Abstract. This modelling of propagation velocity for body waves in the upper mantle of the Southern Tyrrhenian region, the subject of previous studies, was done with the ray-tracing method. The results of previous analyses provided the elements needed for a suitable model of the crust-mantle velocity to be used in the methodology. The velocities of the body waves in the mantle of the analysed region were determined with an iterative version of the ray-tracing methodology, together with other statistical procedures. The results obtained show a gradually increasing trend for P wave velocities, whereas for the S waves an almost uniform trend was found for the whole region. Apart from the fact that the ray-tracing analysis does not show great variations of velocity, which is related to the presence of a lithospheric body, these results lead to the conclusion that the zone of mantle investigated is anomalous in terms of its kinematic quantities. A comparison with other velocity models found in the literature confirms this anomalous nature of the kinematic quantities for the mantle of the Southern Tyrrhenian basin.

INTRODUCTION

Kinematic analyses of body waves in the mantle are well-known in the literature, following classical procedures (Bullen, 1953; Gutenberg, 1953) and calculation methods derived from them (Jeffreys and Bullen, 1948; Herrin, 1968), particularly for zones which are considered anomalous (Kaila, 1969; Kaila et al., 1971; Ritsema, 1972). Nevertheless, such procedures have some inconsistencies, as shown by a critical analysis (Bottari et al., 1989) which followed the introduction of a computational method suitable for velocity models of the P and S waves. The velocity modelling was carried out for two different regions of deep seismicity: the Japanese islands (Honshu) and the Southern Tyrrhenian. The main difficulty was the need to overcome the conditioning of those methodologies proposed in literature, which usually use the travel-time standard pertaining to spherically symmetrical terrestrial models, and with velocities for P and S waves generally increasing with depth. The assumptions of this procedure contrast with the assumed anomaly of propagation which characterizes mantle zones with lithospheric bodies (Morita, 1963; Utsu, 1967, 1971; Le Tourneau et al., 1972; Kaila et al., 1974), as given by the plate tectonic theory generally adopted for zones with middle and deep seismicity.

RESEARCH METHOD

In a mantle zone where there is a lithospheric body, the propagation of elastic energy radiating from the focus of a deep earthquake is influenced by the structural configuration of the system which has been crossed. Consequently, part of the energy is propagated through the lithospheric body and part externally (Fig. 1). Thus, this circumstance must be taken into account to obtain the best criteria for the research method. In particular, by correlating the distribution of the earthquakes with the position of the hypothesized lithospheric body (Fig. 2), the seismic stations

---

Manuscript received August 12, 1991; accepted December 15, 1991.

Istituto Geofisico e Geodetico, Università, Messina (Italy).

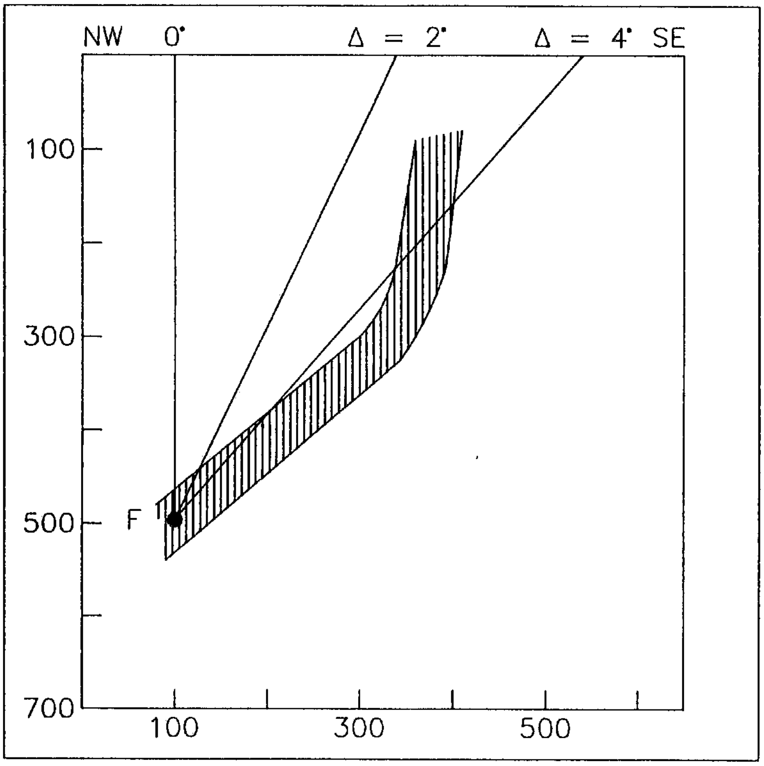

Fig. 1 — Schematic section of the hypothesised slab, which is compatible with the physiogeographic characteristics proposed by Anderson and Jackson (1987). F is the focus of deepest analysed earthquakes; D=2° is the limit of the epicentral distances assumed in a previous study (Bottari et al., 1989); D=4° is new limit assumed in the present analysis.

can be distinguished according to epicentral distances. The stations nearest to the epicentre record the waves travelling externally to the lithospheric body, while those furthest from the epicentre can record the waves travelling through the hypothesized lithospheric body.

A previous analysis (Bottari et al., 1989) was carried out in the basin of the Southern Tyrrhenian, limiting the area of investigation to that part of the crust not crossed by the hypothesized lithospherical slab (Fig. 1). Limiting the choice of data to the stations with $D \leq 2°$, it was possible to approximate the route of the seismic rays along an almost vertical and rectilinear course. The results obtained were then verified through the calculation of the travel times for zero epicentral distances ($D=0$), corresponding with the vertical propagation of the seismic rays. The values determined for the Tyrrhenian region ($V_p=8.2$ km/s, $V_s=4.7$ km/s) are shown to be congruent with the hypothesis of an almost homogeneous crust for the propagation of the body waves. Thus, the need to adopt the most suitable technique to vertically investigate a sector of earth crust became apparent: namelly, ray-tracing. Moreover, the area of investigation was extended beyond the limit previously considered for the epicentral distances ($D \leq 2°$), applying the ray-tracing procedure in order to verify possible important variations of the kinematic parameters corresponding to the assumed slab (Fig. 1). In conformity with the spatial distribution of the foci in relation to the hypothesized slab for the region under study, the limit of the investigated area was extended to $D=4°$.

The algorithm applied assumes a crust mantle system of spherical symmetry as a reference model; the velocity of the seismic waves for each layer was interpolated between the surfaces bordering the layer. Taking into account what had been deduced in the previously mentioned study, it was considered correct to adopt a model with uniform velocity for the mantle. Knowing the distribution of the velocities in the layers traversed (crust and mantle), it was possible to

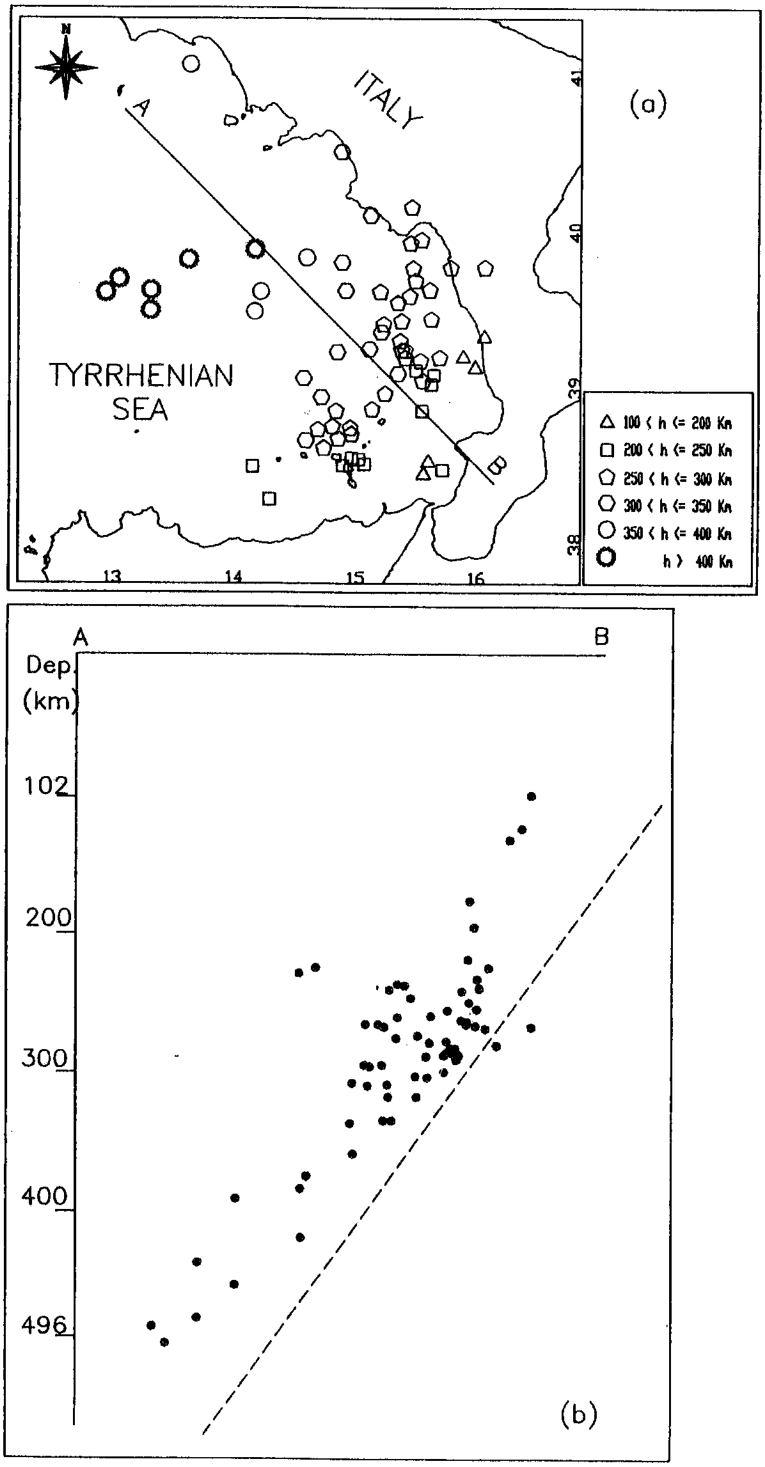

Fig. 2 — Cross-section of investigated area along the line AB (NW-SE). (a) epicentral distribution of analysed earthquakes; (b) comparison of hypocentral distribution with the hypothesised slab orientation (dashed line) in the region.

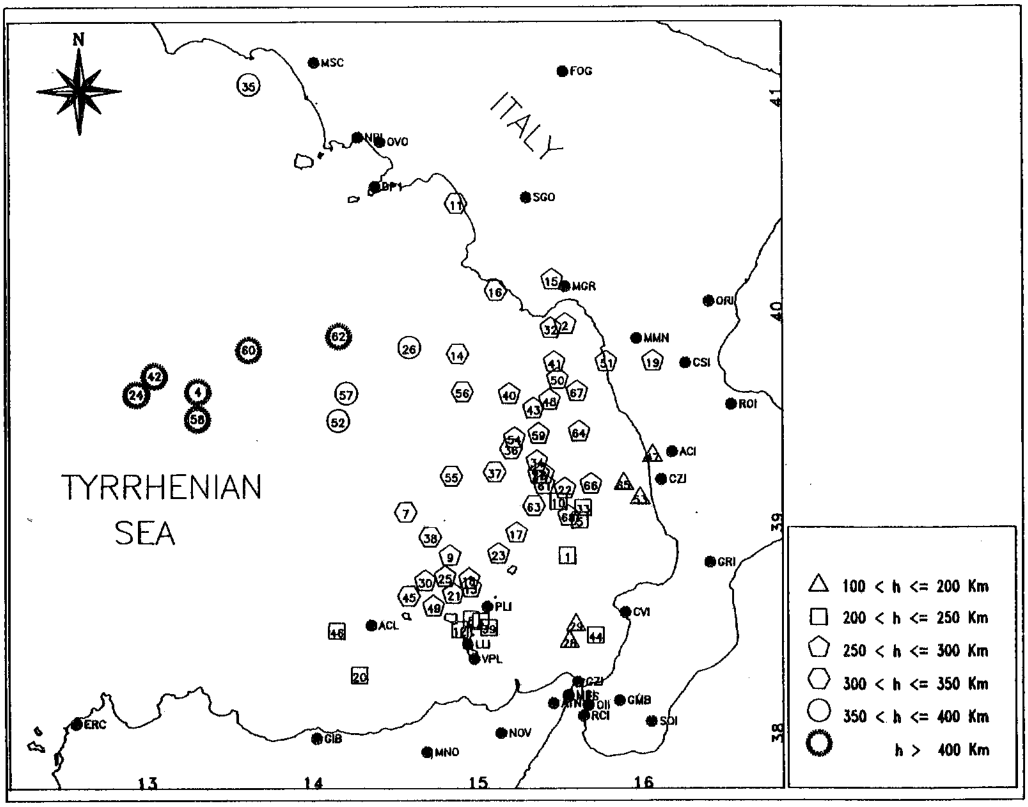

Fig. 3 — Epicentral map and representation of the seismic stations near the investigated area. The earthquakes are numbered as in table 1 and are represented with different symbols according to focal depth; each station is given with its international code.

determine partially rectilinear routes, which travel from the seismic source, and the relative travel times.

DATA AND PROCEDURE

A data set of 68 earthquakes, from the last forty years in the Southern Tyrrhenian basin, were analaysed; $100 \leq h \leq 500$ km is the range of focal depths (Table 1).

The epicentral distribution is denser near the coast of the Calabro-Peloritan Arc and extends in the WNW direction. The hypocentral depth shows a gradual increase in the same direction (Fig. 3).

The choice of seismic stations for each earthquake was done, making sure that the epicentre-station distance was not greater than four degrees, and in conformity with the structural hypothesis adopted for the investigated region.

The values to attribute to the geometrical and kinematical quantities of the earth model (crust - mantle spherical symmetry) were deduced from previous studies carried out in the area (Bottari et al., 1987; Locardi, 1988; Bottari et al., 1989), and used in the application of the ray-tracing method (Doornbos, 1988).

In particular, remembering that in the Southern Tyrrhenian basin the thickness of the crust shows a gradual thinning towards the centre of the basin (Morelli et al., 1975; Schütte, 1978; Morelli, 1981; Nicolich, 1981; Locardi, 1988) more realiable thicknesses were assigned to the crust (Locardi, 1988). Attributing to each of these values a weight given by the number

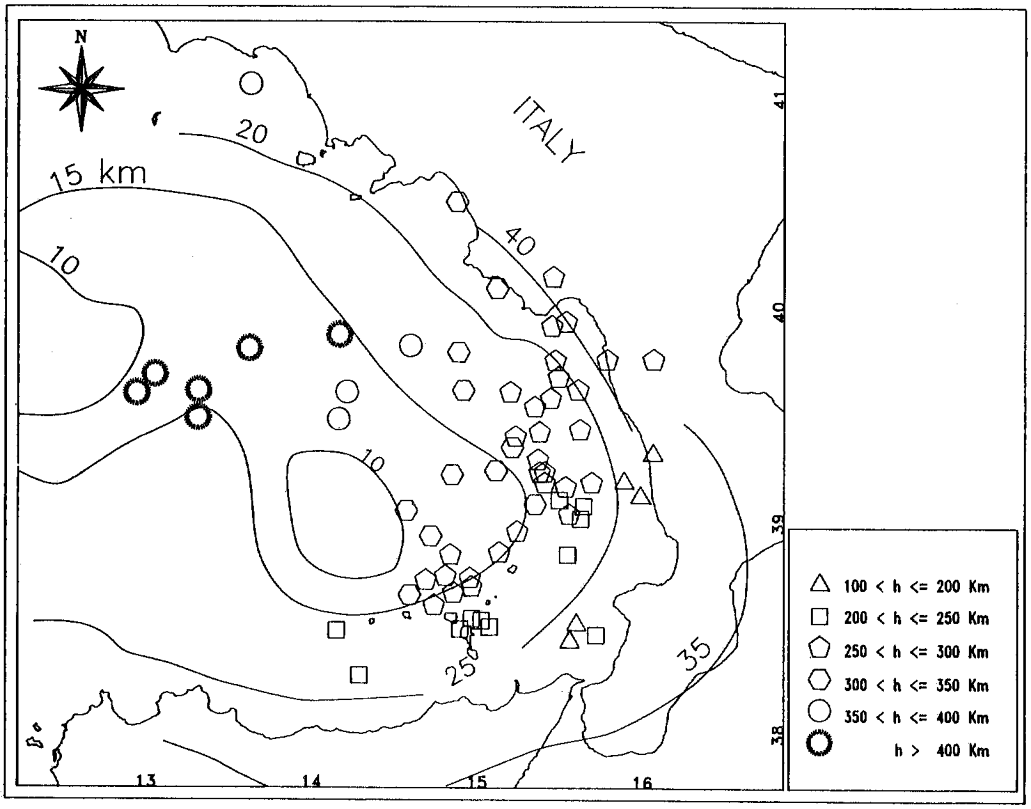

Fig. 4 — Map of the Moho discontinuity as derived for the investigated area by Locardi (1988). A comparison of the map with the epicentral distribution is useful to calculate the value of crustal thickness for the model.

of earthquakes associated with it (Fig. 4), and by using its average, the average value of 20 km was obtained for the thickness of the crust.

The velocity values for the seismic body waves in the crust layers of the investigated region were derived from a study carried out by Bottari et al. (1987). Giving each velocity value a weight equal to the thickness of the layer, and using the average, the values of 6.28 km/s and 3.63 km/s were obtained for the velocities of propagation for P and S waves, respectively (see Bottari et al., 1987).

The velocity values in the mantle were those calculated in a previous study by Bottari et al. (1989); the velocity is 8.2 km/s for P waves and 4.7 km/s for S waves. The mantle zone crossed by seismic waves was defined each time by the focal depth of each earthquake. From the data set available, the thickness of the mantle reaches 476 km.

The calculation procedure adopted was based on an iterative process which minimizes the difference between the calculated travel time and the observed travel time for each station, varying only the velocities of propagation of seismic waves in the mantle by steps of 0.01 km/s.

The elaboration of the available data (ISC, 1952-1987) was carried out using as inputs, for each ray-tracing application, the epicentral distances of the seismic stations, the focal depth of the earthquake, the travel times recorded by each station for the P phase and, if possible, for the S phase. Based on the data input and the terrestrial model used, the computer program calculates the velocity of propagation in the mantle (for P and S waves), the seismic ray parameter and the travel time for each earthquake and each station.

Thus two sets of propagation velocity values in the mantle for P and S waves are to be associated with each earthquake which after averaging give one velocity value for the P waves

Table 1 — List of analysed earthquakes.

In columns 7 and 8 the values of velocity for P. and S waves calculated for each earthquake by a ray-tracing method are listed.

N	Date d m y	Lat. deg.	Lon. deg.	Dep. km	T_0 h m s	v_p km/s	v_s km/s
01	10-09-52	38°86	15°55	220	04 17 03	7.89	4.42
02	26-12-52	39°96	15°55	265	23 55 55.6	7.94	4.46
03	23-11-54	38°55	15°02	239	13 00 55	7.93	4.44
04	17-02-55	39°63	13°27	438	19 31 33	8.22	4.58
05	01-02-56	39°03	15°63	234	15 10 50.6	7.90	4.42
06	03-01-60	39°25	15°41	284	20 19 37.4	7.99	4.48
07	25-03-62	39°07	14°56	338	21 38 26.1	8.08	4.51
08	01-06-63	38°56	14°96	238	20 36 03.8	7.91	4.44
09	14-04-64	38°86	14°83	296	06 35 27.5	8.02	4.49
10	04-10-64	39°12	15°50	243	01 46 50.2	7.93	4.45
11	23-12-65	40°53	14°87	310	15 29 06.9	8.03	4.49
12	03-02-66	38°51	14°89	242	13 23 28.2	7.93	4.44
13	02-06-67	38°71	14°96	262	20 20 22.1	7.96	4.54
14	22-04-68	39°82	14°88	319	21 09 48	8.06	4.50
15	01-10-68	40°17	15°47	289	16 31 02.5	8.01	4.48
16	29-03-69	40°12	15°12	319	01 32 39.7	7.84	4.38
17	02-04-69	38°97	15°24	261	01 38 02.1	7.94	4.45
18	13-04-69	38°75	14°95	277	05 45 43.1	7.97	4.45
19	17-02-70	39°78	16°09	269	07 32 01.6	7.96	4.46
20	02-04-70	38°29	14°28	226	21 26 39.5	7.79	4.35
21	29-01-70	38°68	14°85	269	11 09 23	8.02	4.49
22	05-06-70	39°18	15°54	267	09 20 55.6	8.06	4.51
23	03-04-71	38°87	15°13	275	04 03 56.1	7.98	4.47
24	21-08-71	39°61	12°89	484	03 59 04.0	8.33	4.63
25	20-12-73	38°76	14°80	267	17 44 35.5	8.03	4.46
26	24-01-74	39°85	14°58	360	13 19 23.4	8.10	4.52
27	22-07-74	39°25	15°38	257	07 19 32.7	7.95	4.45
28	12-04-75	38°45	15°56	178	16 47 03.4	7.71	4.34
29	10-08-75	38°53	15°60	197	20 55 50.9	7.73	4.34
30	21-09-76	38°74	14°68	296	15 01 50.0	8.29	4.54
31	28-06-77	36°60	14°70	267	07 12 49.0	8.46	4.75
32	30-12-77	39°94	15°46	292	18 08 50.7	7.99	4.64
33	25-06-78	39°09	15°65	241	15 36 55.2	8.02	4.54
34	22-08-78	39°31	15°37	279	18 03 04.7	7.96	4.19
35	27-12-78	41°08	13°56	392	17 46 10.4	8.12	4.60
36	25-03-79	39°37	15°21	305	11 36 25.9	8.13	4.72
37	25-07-79	39°26	15°11	304	00 18 11.2	8.12	4.62
38	21-09-79	38°95	14°71	311	23 47 35.8	8.17	4.84
49	04-02-80	38°52	15°07	248	02 30 24.7	8.09	4.66
40	31-08-80	39°63	15°2	290	07 22 28.2	8.20	4.46
41	12-10-80	39°78	15°48	289	18 08 32	7.92	—
42	13-10-80	39°70	13°00	496	03 44 49.1	8.40	—
43	10-05-81	39°56	15°35	289	02 44 42	8.18	4.61
44	03-09-81	38°48	15°72	226	23 29 19.3	7.92	4.44
45	11-10-81	38°67	14°58	309	23 48 56.9	8.20	4.63
46	30-03-82	38°50	14°14	230	02 16 55.3	8.50	4.79
47	16-05-82	39°33	16°08	102	16 09 10.3	7.45	4.44
48	02-06-82	39°60	15°45	284	09 31 07.9	7.92	4.55
49	21-06-82	38°62	14°73	297	04 18 37.5	8.13	4.59
50	13-09-82	39°7	15°5	264	19 50 56.9	7.98	4.43
51	14-02-83	39°78	15°80	282	02 08 24.8	7.96	6.88
52	10-10-83	39°50	14°14	385	22 01 41.9	8.18	4.70
53	31-10-83	39°13	16°0	126	23 28 35.2	7.74	4.54
54	21-03-84	39°42	15°23	280	01 12 43.7	7.99	4.52
55	15-07-84	39°24	14°84	336	10 02 59.6	8.09	4.76
56	22-08-84	39°64	14°91	336	14 53 46.5	8.17	—
57	22-10-84	39°63	14°19	376	18 24 55.8	8.27	5.31
58	30-12-84	39°50	13°27	478	07 37 06.7	8.24	—
59	08-01-86	39°44	15°38	287	15 04 48.8	8.07	—
60	10-03-86	39°83	13°58	454	16 03 55.8	8.31	—
61	01-04-86	39°20	15°41	287	03 55 56.4	8.18	5.21

Table 1 — (continued)

N	Date d m y	Lat. deg.	Lon. deg.	Dep. km	T_0 h m s	v_p km/s	v_s km/s
62	21-06-86	39°9	14°14	420	18 10 53.9	8.25	—
63	11-08-86	39°10	15°35	301	22 49 05.1	8.08	5.41
64	08-09-86	39°45	15°63	256	22 22 14.1	8.09	4.51
65	19-09-86	39°2	15°9	134	12 36 45.1	7.50	4.71
66	20-10-86	39°2	15°7	270	19 18 56.0	7.98	—
67	27-10-87	39°64	15°62	268	18 20 33.9	8.15	4.52
68	15-12-87	39°05	15°56	251	07 35 42.2	8.09	4.77

and one for the S waves for each earthquake studied (Table 1).

Furthermore, by comparing the epicentral distribution with the focal depth, it is possible to group the earthquakes into zones. This permits an association of an average velocity value for the P and S waves to each hypocentral depth value. The velocity values are calculated from an average of the velocity values of earthquakes with the same focal depth.

The hypocentral distribution of the 68 earthquakes analysed suggested grouping them according to depth ranges; each range is characterized by a "population" of events (Table 2) which quantify its statistical significance.

RESULTS

The velocity trend with depth from a fitting of experimental points (velocity of each earthquakes for a fixed value of depth) was constructed for the ranges 2, 3, 4 (Table 2) which are statistically more significant. For each analysed data set, a linear regression is the best fit; the velocity diagrams for P and S waves, shown in Figure 5, prove this deduction.

The regression lines of the velocity trend for seismic body waves, for the same depth range, show that the velocity values are distributed around a mean value for the two data sets. The same regression lines also show a different trend of seismic body waves for each analysed sector. This can be seen from the different slope of the corresponding regression lines.

For each depth range, a typical propagation velocity value can be determined for the seismic body waves (P and S separately) by a grouping of the analysed earthquakes.

A graphic representation of the velocity trend of the seismic body waves was used with isovelocity curves for P waves (Fig. 6a) and S waves (Fig. 6b). The maps show an increasing trend towards the WNW direction, more marked for P waves than S waves; this WNW direction is the same as that of the hypocentral distribution; from this circumstance, particularly for P waves, an increasing velocity trend with depth is noted.

A comparison of the fits for all available experimental points, separately for P and S phases (Fig. 7), shows that the P phase regression line has a greater slope than the S phase. This means

Table 2 — Grouping of the analysed earthquakes according to depth range (columns 2, 3).

In the columns 4 and 5 the values of velocity for P and S waves in each depth range are listed.

N°	RANGE OF DEPTH (km)	POPULATION	Vp (Km/s)	Vs (km/s)
1	$100 \leq h \leq 200$	5	7.63 ÷ 0.139	4.47 ÷ 0.155
2	$200 \leq h \leq 250$	11	8.00 ÷ 0.187	4.50 ÷ 0.126
3	$250 \leq h \leq 300$	31	8.04 ÷ 0.107	4.54 ÷ 0.188
4	$300 \leq h \leq 350$	11	8.10 ÷ 0.091	4.71 ÷ 0.296
5	$350 \leq h \leq 400$	4	8.17 ÷ 0.076	4.78 ÷ 0.359
6	$400 \leq h \leq 500$	6	8.22 ÷ 0.141	4.61 ÷ 0.035

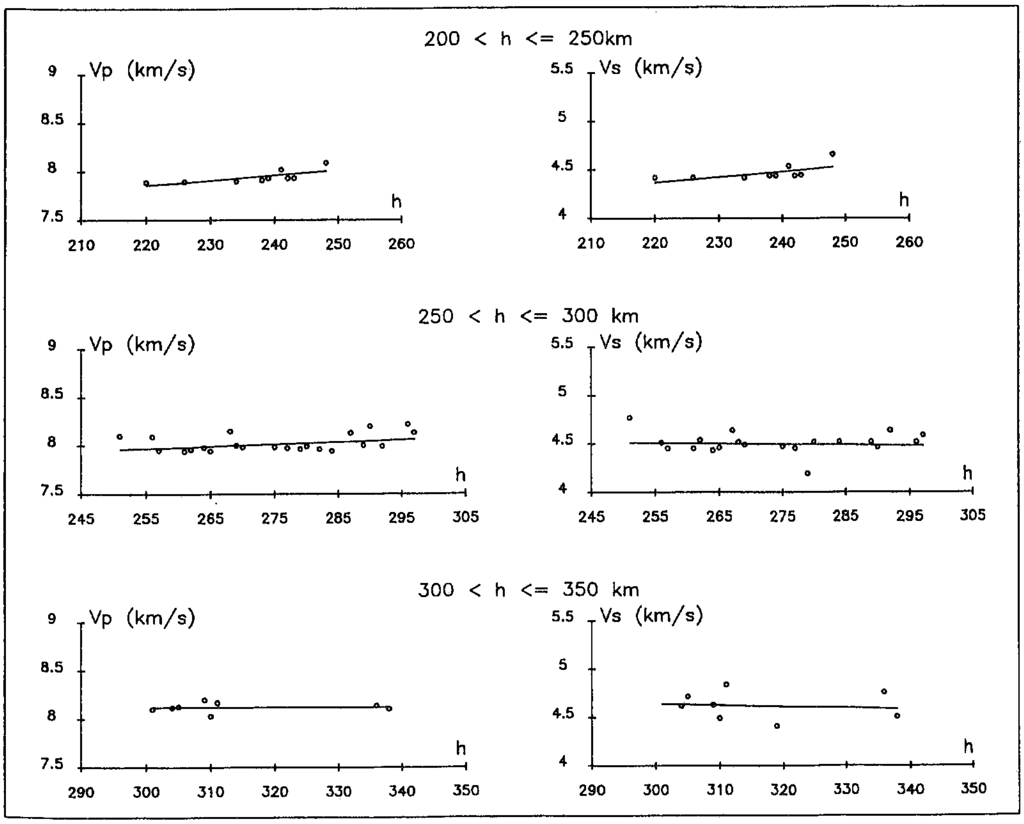

Fig. 5 — Graphic representation of velocity vs depth for the statistically more significant depth ranges.

that the trend of the body wave velocity is different with depth.

A comparison of the longitudinal wave velocity model obtained from the present analysis with the models proposed in the literature (Fig. 8), in particular with the classical model (Jeffreys and Bullen, 1948; Herrin, 1968) and more recent ones (Bottari and Lo Giudice, 1975), shows a much lower velocity value. However, the velocity trend for P waves is not greatly different from that of the comparison models. In fact, it is almost equal to that of a model proposed for the same region by Bottari and Lo Giudice (1975). With respect to the latter, in the range of depth 230 ± 480 km, the velocities are lower by 0.77 km/s.

Apart from this, there is no evidence that the seismic rays analysed with a ray-tracing procedure crossed a media substantially different from the one characterized in the previous study, considering the range of distances $0 \leq D \leq 2°$. On the basis of these results, the investigated mantle zone is considered anomalous. In short, the extension of the analysed range of epicentral distances does not show substantial difference of propagation for P and S waves with respect to the model initially considered.

CONCLUSION AND DISCUSSION

The modelling of velocity laws for seismic body waves in the upper mantle of the Southern Tyrrhenian region was carried out using a ray-tracing methodology. By using this means, the research was extended to a wider range of epicentral distances $(0 \leq D \leq 4°)$, compatibly with the spatial distribution of the earthquakes and with the hypothesis of the presence in the

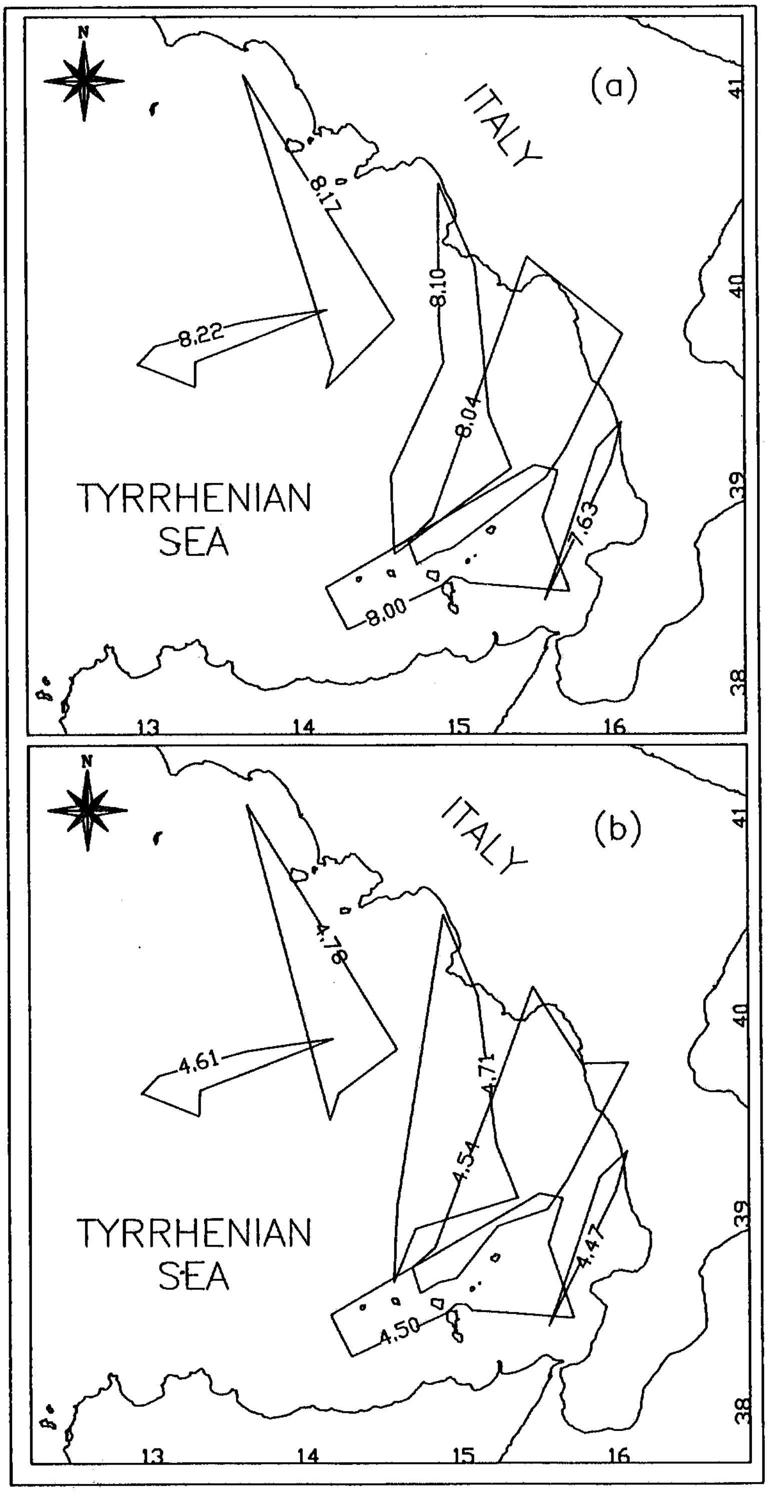

Fig. 6 — Maps of the isovelocities curves (km/s) for the upper mantle of Southern Tyrrhenian basin. (a): longitudinal waves; (b): transversal waves. An increasing velocity trend towards the WNW direction (direction of hypocentral distribution) is noted, and a positive gradient of velocity with depth, particularly for P waves.

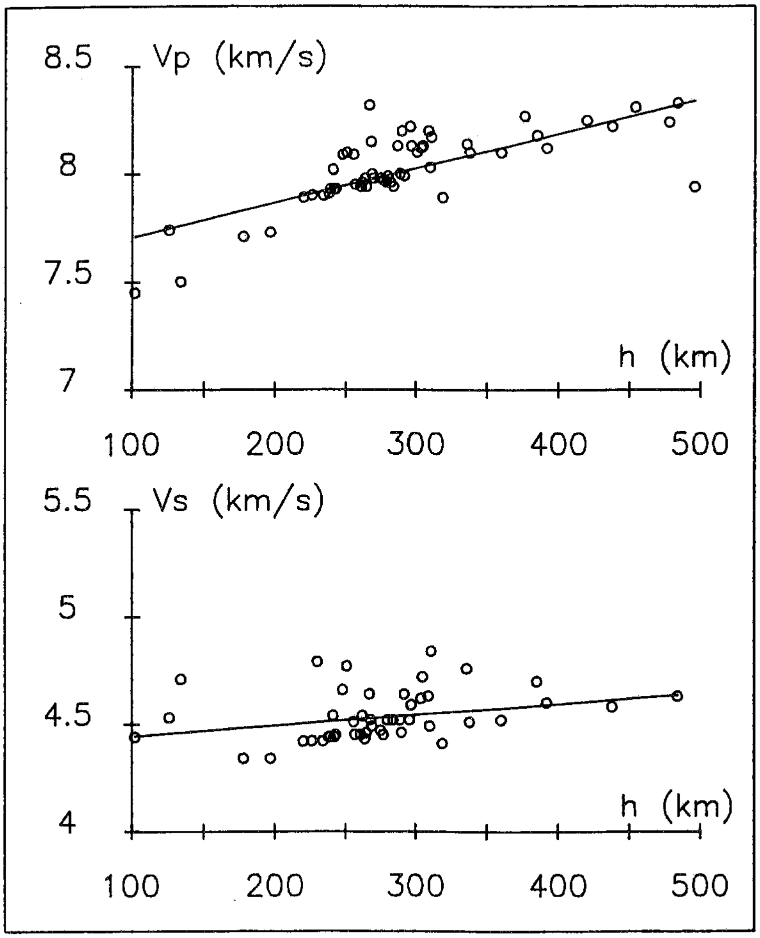

Fig. 7 — Graphic representation of velocity vs depth for the whole data set. The trend of velocity with depth is immediately seen: it is increasing for P waves and nearly uniform for S waves.

investigated region of a lithospsheric body in subduction. The adopted reference model, a spherical crust-mantle system, was derived from previous studies carried out in the same region. This model allowed a verification of the ray-tracing procedure employed.

For reasons of analysis, a grouping of depth ranges for the investigated mantle zone proved useful, each range with its own "population" of events which quantify its statistical significance. The trend of velocity with depth was determined for the most statistically significant ranges. A linear regression gave the best results for all analysed ranges, showing a distribution of experimental points around a mean value used as the characteristic value for each depth range.

The trend of the characteristic values suggested carrying out a total fit of the available data separately for P and S waves, in order to characterize the velocity trend throughout the investigated area. Once again, a linear regression is the best fit for the experimental data, and the regression line for the P waves shows a greater slope than for the S waves.

The velocity values for P waves increase gradually with depth: down to 400 km they are lower than the value assumed for the model, and between 400 and 500 km they are a little higher. The velocity values computed for S waves are not different from the assumed value for the model, and they fluctuate around the mean value 4.6 ± 0.13 km/s. The mantle velocity model, derived from the present analysis, is not substantially different from the one assumed; it is in accordance with other geophysical and geological characteristics of the area (Panza et

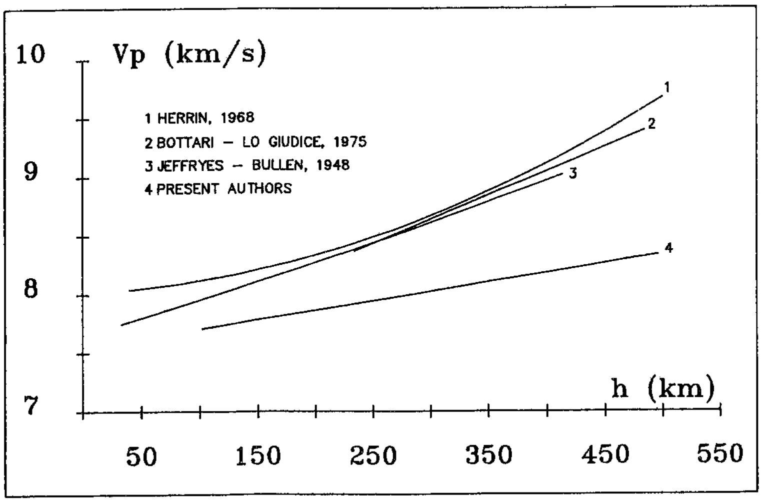

Fig. 8 — Comparison of the velocity model implemented by present analysis with some models proposed in the literature.

al., 1979, 1980, 1982; Suhadolc and Panza, 1989; Della Vedova et al., 1991), particularly for the S waves.

The results of the study confirm the hypothesis of uniform propagation for S waves, while the velocity of P waves slightly increases with depth.

Considering as anomalous a mantle that does not show the "normal" increasing velocity trend with depth, this region must be retained anomalous. It is also shown that the propagation of P and S waves for epicentral distances of 2° ≤ D ≤ 4° is not influenced by the assumed lithospheric body.

The classical velocity models for longitudinal waves implemented by Jeffreys and Bullen (1948) and by Herrin (1968), generally valid for the whole terrestrial mantle, and the model proposed by Bottari and Lo Giudice (1975) for the Southern Tyrrhenian region in particular, are all useful elements for comparison with the model derived from the present analysis. In the latter much lower velocities and the same trend as the former for the same region are derived. Apart from the fact that, from the ray-tracing analysis, there is no evidence of the hypotesized lithospheric body, a comparison with the models proposed in the literature leads to the conclusion that the investigated mantle zone is anomalous in its kinematic quantities.

REFERENCES

Anderson H. and Jackson J.; 1987: *The deep seismicity of the Tyrrhenian sea*. Geophys. J.R. astr. Soc., **91**, 613-637.

Bottari A. and Lo Giudice E.; 1975: *On the waves velocity and plate tectonics implications for the Tyrrhenian deep earthquake zone*. Tectonophysics, **25**, 187-200.

Bottari A., Cannatelli D., Federico B. and Teramo A.; 1987: *A crustal model with spherical symmetry for Sicily. Travel time equations and stripping techniques*. In: Atti 6° Convegno annuale GNGTS, Esa, Roma, pp. 1125-1136.

Bottari A., Caruso V., Federico B. and Teramo A.; 1989: *The determination of the velocity of longitudinal and trasversal waves in the Mantle affected by lithospheric subduction*. Atti 8° Convegno annuale GNGTS, Esa, Roma, pp. 361-363.

Bullen K.E.; 1953: *An introduction to the theory of seismology*. University Press, Cambridge.

Della Vedova B., Marson I., Panza G.F. and Suhadolc P.; 1991: *Upper mantle properties of the Tuscan-Tyrrhenian area: a framework for its recent tectonic evolution*. Tectonophysics, **195**, 311-318.

Doornbos D.J.; 1988: *Seismological algorithms (computational methods and computer programs)*. Academic Press, London, pp. 75-85.

ISC, 1952-1987: *Bulletin*, Edinburg, Newburgy.

Gutenberg B.; 1953: *Wave velocities at depths between 50 and 600 kilometers*. Bull. Seism. Soc. Am., **43**, 223-232.

Herrin E.; 1968: *Introduction to "1968 seismological tables for P phases"*. Bull. Seism. Soc. Am., **58**, 1193-1242.

Jeffreys H. and Bullen K.E.; 1948: *Sesmological tables*. British Association for the Advancement of Sciences.

Kaila K.L.; 1969: *A new analytical method for finding the upper mantle velocity structure from P and S wave travel-time of deep earthquakes*. Bull. Seism. Soc. Am., **61**, 1549-1570.

Kaila K.L., Krishna V.G. and Narain H.; 1971: *Upper mantle P wave velocity structure in the Japan region*. Bull. Seism. Soc. Am., **61**, 1549-1570.

Kaila K.L., Krishna V.G. and Narain H.; 1974: *Upper mantle shear wave velocity structure in the Japan region*. Bull. Seism. Soc. Am., **64**, 355-374.

Le Tourneau N.J., Piermattei R. and Walker D.A.; 1972: *Mantle phases recorded at Guam for distances between 1° and 52°*. Ann. Geofis., **25**, 433-450.

Locardi E.; 1988: *The origin of Apenninic arcs*. Tectonophysics, 146, 105-123.

Morelli C.; 1981: *Gravity anomalies and crustal structures connected with the Mediterranean margins*. In: F.C. Wezel (ed), Sedimentary basins of Mediterranean margins, C.N.R., Tecnoprint, Bologna, pp. 33-53.

Morelli C., Giese P., Cassinis R., Colombi B., Guerra I., Luongo G., Scarascia S. and Schutte K.G.; 1975: *Crustal structure of southern Italy: a seismic refraction profile between Puglia-Calabria-Sicily*. Boll. Geof. Teor. Appl., **17**, 183-210.

Morita M.; 1963: *Difference between eastern and western Japan as exhibited in the deep earthquake under Kumanonda on June 30, 1931*. Kenshinjiho (Quart. J. Seism.), **9**, 231-251, (in Japanese).

Nicolich R.; 1981: *Crustal structures in the Italian peninsula and surrondings seas: a review of DSS data*. F.C. Wezel (ed), Sedimentary basins of Mediterranean margins, Tecnoprint, Bologna, pp. 3-17.

Panza G.F. and Calcagnile G.; 1979: *The upper mantle structure in Balearic and Tyrrhenian bathyal plains and the Messinian salinity crisis*. Palaeogeogr. Palaeoclimatol. Palaeoecol., **29**, 3-14.

Panza G.F., Calcagnile G., Scandone P. and Mueller St.; 1980: *La struttura profonda dell'area mediterranea*. Scienze, **141**, 60-69.

Panza G.F., Muller St., Calcagnile G. and Knopoff L.; 1982: *Delineation of the north Central Italian upper mantle anomaly*. Nature, **296**, 238-239.

Ritsema A.R.; 1972: *Deep earthquakes of the Tyrrhenian sea*. Geol. Mijbouw, **51**, 541-545.

Schütte K.G.; 1978: *Crustal structure of Southern Italy*. In; Closs H., Roeder D. and Schmidt K. (eds), Alps, Apennines and Hellenides, I.U.G.G. Sci. Rep. 38, Schweizerbart, Stuttgart, pp. 316-321.

Suhadolc P. and Panza G.F.; 1989: *Physical properties of the lithosphere-astenosphere system in Europe from geophysical data*. In: Boriani A., Bonafede M., Piccardo G.B. and Vai G.B. (eds), The lithosphere in Italy, Advances in earth Science research, Accad. Naz. Lincei, pp. 15-40.

Utsu T.; 1967: *Anomalies in seismic-wave velocity and attenuation associated with a deep earthquake zone*. J. Fac. Sci., Hokkaido Univ., Ser. 7 (Geophys.), **3**, 1-25.

Utsu T.; 1971: *Seismological evidence for anomalous structure of island arcs with special reference to the Japanese region*. Rev. Geophys. Space Phys., **9**, 839-890.