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Travel Time Residuals in Southeastern Europe

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Abstract—The Pn travel time relative residuals, in respect to a crustal model of the Aegean area, have been determined for 103 permanent seismological stations in southeastern Europe, western Turkey and the Middle East. The values of these residuals are considered to depend mainly on the crustal thickness beneath the seismological stations. Based on these values seven regions with different crustal thickness, varying between 31 Km and 42 Km, have been defined. The crust in these regions is continental. A region with very high negative residuals has been defined in the Middle East (Egypt, Israel, Lebanon). These negative residuals are attributed to different crustal structure of the eastern Mediterranean (oceanic crust with an extra thick sedimentary layer) and not the crustal thickness at the station sites.

Independently from the interpretation, these Pn residuals can be used successfully to considerably improve (up to 2 Km) the determination of the earthquake foci locations.

Key words: Travel-time residuals; Southeastern Europe.

1. Introduction

The analysis of travel-time residuals of seismic waves is a traditional seismic method for studying the structure of the crust as well as of the upper mantle.

The time residuals, R, representative of the seismological stations, have been considered by many authors and are defined in the present study as the difference of the theoretical travel times of the seismic waves from the observed ones:

$$R = t_0 - t_c \tag{1}$$

where t_0 is the observed travel time and t_c is the theoretical travel time, measured in seconds.

Absolute residuals are based on accurately determined seismic foci (nuclear explosions, etc). In the present study residuals, relative to the model applied, are used.

For the present paper's study area several authors have used travel time residuals to get information on its crustal and upper mantle structure.

Delibasis and Galanopoulos (1965) investigated the P-wave residuals at the

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seismological station of Athens and showed that the positive residuals from western Greece are due to the continental crust related to the Alpine orogeny, while the negative residuals from northeastern Greece are due to a thinner crust.

Economides (1972) studied the azimuthal dependence of station residuals for the area of Greece, trying to estimate the crustal thickness in this area.

Several other studies performed on this area have dealt with the correlation between P-wave residuals and crust and/or upper mantle structure (Agarwal *et al.*, 1976; Gregersen, 1977; Koch, 1982; Scarpa, 1982; Tassos, 1984).

Panagiotopoulos and Papazachos (1985) used 23 very shallow earthquakes ($h = 1$–14 Km) in northern and central Greece, accurately located by networks of portable seismographs and by the joint epicenter method, to determine the travel times of the Pn-waves from the foci of these earthquakes to the sites of 54 permanent stations in the Balkan region. Time delays of Pn-waves have been calculated for each of these permanent stations with respect to the mean travel-time curve of these waves in the central and eastern part of the area. The present study is an extension of that work.

2. *Data and Method*

Panagiotopoulos and Papazachos (1985) calculated travel time residuals of Pn waves for 54 stations in the Balkan region by using information from shocks of two seismic sequences which occurred in 1978 and 1981 in northern Greece (Thessaloniki) and in central Greece (Alkyonides gulf), respectively. To improve the values of the residuals for these stations, and to determine such residuals for almost all stations which usually record Pn waves of relatively strong earthquakes ($M_S \geqslant 4.5$) located in the Aegean and surrounding areas, Pn travel times of 378 earthquakes have been used in the present study.

These earthquakes can be separated into two groups. The first group includes earthquakes which have $M_S \geqslant 4.5$ and belong to a seismic sequence (aftershocks or foreshocks), and the second group includes independent events which have $M_S \geqslant 5.0$. There are 10 such seismic sequences with their locations denoted by black hexagons in Figure 1, and 91 other events denoted by circles in the same figure. All of these earthquakes occurred in the Aegean and surrounding area between 1970 and 1982, and each of them has been clearly recorded by several stations.

The following procedure has been applied to determine an average residual of Pn waves for each of the stations which clearly recorded a considerable number of earthquakes.

First, the arrival times of the Pn waves at the stations for which residual have been determined by Panagiotopoulos and Papazachos (1985) were corrected by adding these residuals. Then, the foci of all earthquakes were determined by using all the individual arrival times listed in the bulletin of the International Seismological Center

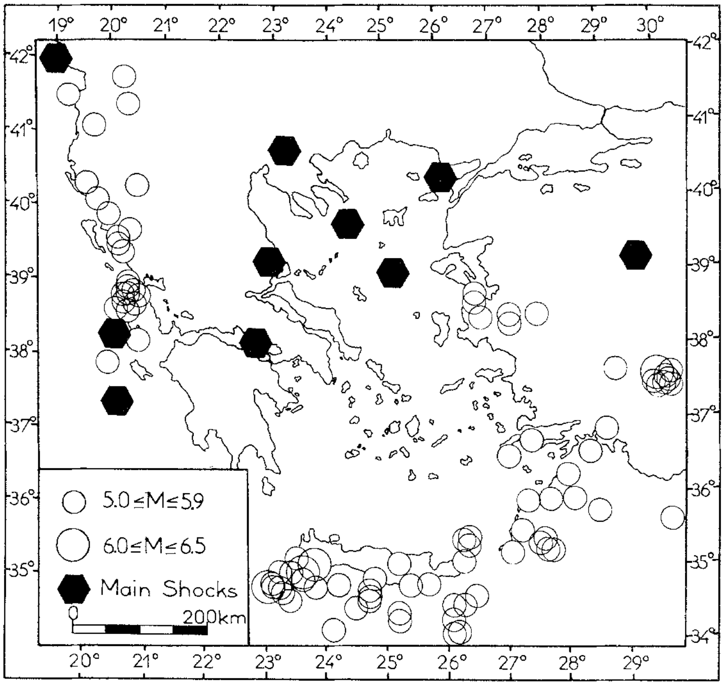

Figure 1
Map of epicentres of the main shocks of the ten seismic sequences (black exagons) and of the 91 other earthquakes (white circles) which occurred in the period 1970–1982 and which generated the Pn waves of which residualŝ are studied in the present paper.

(ISC) for epicentral distances up to 1285 Km. The HYPO 71 computer program (Lee and Lahr 1975) has been used for these determinations. A two layer crustal model (d_1 = 19 Km, V_1 = 6.0 Km/s, d_2 = 12 Km, V_2 = 6.6 Km/s, V_n = 7.9 Km/s) which represents the crustal structure of the Aegean region has also been used. This is the same model used by Panagiotopoulos and Papazachos (1985) and is in agreement with results derived by Makris (1977) on the basis of deep seismic exploration. In the cases of the stations for which a time residual has already been applied, the total travel time residual is the sum of its value and the value given in the output list of HYPO 71.

By applying the method described above the frequency diagrams of all Pn residuals, which correspond to different earthquakes, were made for each station. These diagrams have the form of a normal distribution around the mean value R. Three such diagrams for the stations DMK (Turkey), SKO (Yugoslavia) and VLS (Greece) are shown in Figure 2. The mean residuals are −1.1 s, 0.0 s and 1.5 s for the stations DMK, SKO and VLS, while the corresponding standard deviations are 0.5 s, 0.7 s and 0.7 s, respectively.

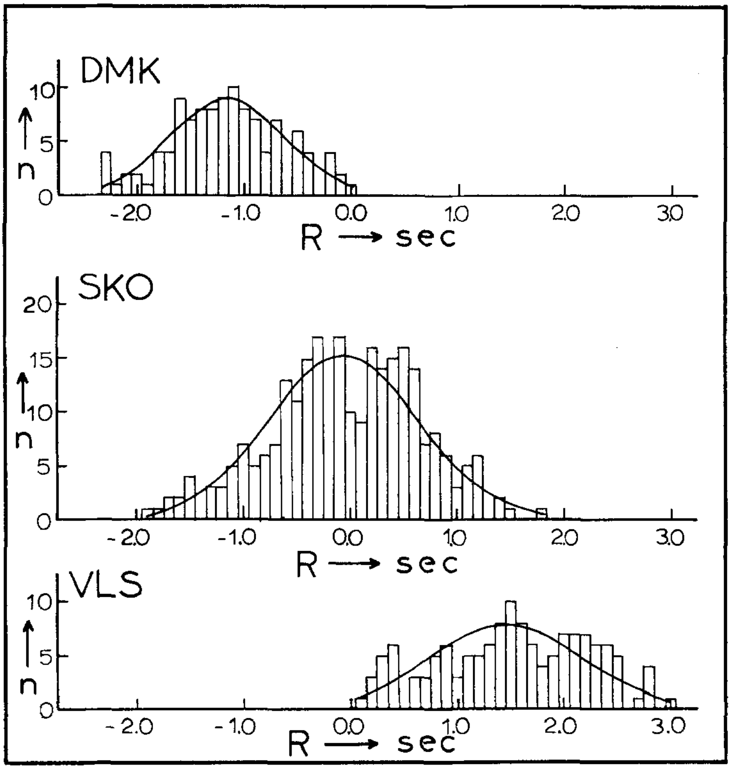

Figure 2
Frequency diagram of the Pn travel time residuals for three permanent seismological stations.

Table 1 gives the mean values determined for the Pn residuals, R, the corresponding standard deviations, σ_n, and the number of observations, n (number of earthquakes) for 103 permanent seismological stations in Albania, Austria, Bulgaria, Czechoslovakia, Greece, Hungary, Italy, Romania, Turkey, USSR, Egypt, Israel and Lebanon. This table shows that the mean residuals vary between -8.4 s and $+1.6$ s. It must be remembered that the mean Pn residual for each station listed in Table 1 expresses the crustal conditions (crustal thickness) in that station's region relative to the crustal conditions in the Aegean area. These residuals can be used to correct the arrival times of Pn waves only in the cases of earthquake foci determinations based on the crustal model, which was mentioned above and holds for the Aegean area.

3. *Geographical Distribution of the Residuals*

Figure 3 shows the distribution of the mean Pn residuals, $\bar{R}$, which are listed in Table 1, excluding the mean residuals of the Middle East stations KSA, HLW, EIL and JER (near the southeastern coast of the eastern Mediterranean) which have large

Table 1

The code name, and the mean residual, $\bar{R}$, with standard deviation, σ_n, calculated from n observations, for each seismic station

No	*Station*	$\bar{R}$	σ_n	n	Country
1	KBN	1.3	0.3	20	Albania
2	SDA	1.6	0.6	43	„
3	SRN	0.4	0.5	34	„
4	TIR	1,5	0.6	90	„
5	VLO	1.5	0.8	92	„
6	VKA	−0.9	1.0	9	Austria
7	DIM	−0.2	0.6	80	Bulgaria
8	KDZ	−0.3	0.7	194	„
9	PVL	−0.1	0.8	179	„
10	SOF	0.7	0.9	144	„
11	BRA	−0.7	1.8	4	Czechoslovakia
12	NIE	−0.3	1.0	7	„
13	APE	0.0	0.6	89	Greece
14	ARG	0.6	0.7	127	„
15	ATH	0.3	0.7	275	„
16	GRG	0.2	0.4	51	„
17	ITM	1.3	0.7	123	„
18	JAN	1.2	0.7	147	„
19	KNT	0.2	0.3	50	„
20	KZN	1.2	0.8	97	„
21	LIT	0.3	0.6	44	„
22	NPS	0.1	0.7	106	„
23	OUR	−0.2	0.5	40	„
24	PAIG	−0.3	0.6	17	„
25	PLG	0.2	0.5	153	„
26	PRK	0.1	0.7	180	„
27	PTL	0.3	0.6	182	„
28	RLS	1.2	0.7	86	„
29	SOH	0.2	0.4	44	„
30	SRS	−0.4	0.3	41	„
31	THE	0.2	0.4	42	„
32	VAM	0.5	1.0	132	Greece
33	VLS	1.5	0.7	140	„
34	BUD	−0.7	0.7	52	Hungary
35	JOS	−1.0	1.1	11	„
36	SRO	−0.7	1.0	11	„
37	UZH	−0.7	0.8	16	„
38	ACI	0.8	0.7	12	Italy
39	ALP	0.5	0.5	38	„
40	AQU	0.8	0.6	6	„
41	BRT	0.2	0.5	45	„
42	CRN	1.0	1.0	8	„
43	DPS	−0.9	0.5	57	„
44	DUI	1.1	0.5	88	„
45	FIR	−0.6	0.8	20	„
46	GIB	−0.3	0.6	15	„
47	LCI	−0.3	0.4	28	„
48	LLI	−0.6	0.9	9	„
49	MES	−0.9	0.6	48	„

No	Station	$\bar{R}$	σ_n	n	Country
50	MNS	0.8	0.5	52	„
51	MSI	−0.2	0.6	12	„
52	NPL	−0.8	0.6	9	„
53	OII	−1.0	0.6	47	„
54	ORI	0.2	0.6	33	„
55	OVO	0.5	0.7	36	„
56	PRG	0.6	0.6	20	„
57	PRT	−0.7	1.0	7	„
58	PTC	1.2	0.4	16	„
59	RCI	−0.3	0.6	32	„
60	RMP	0.5	0.8	70	„
61	SGG	0.5	0.4	33	„
62	TRI	−0.6	0.8	74	„
63	ARR	0.1	0.8	29	Romania
64	BAC	−0.7	0.9	18	„
65	BUC	0.4	1.3	55	„
66	FOC	0.0	1.1	11	„
67	GZR	−0.1	0.6	24	„
68	IAS	−1.1	0.6	12	„
69	ISR	−0.2	0.6	4	„
70	LOT	−0.1	0.5	23	„
71	MLR	0.1	0.9	60	„
72	VRA	−0.9	1.0	9	„
73	VRI	−0.2	1.1	61	„
74	ALT	0.4	0.6	44	Turkey
75	BCK	1.3	0.9	43	„
76	CIN	−0.2	0.6	28	„
77	DMK	−1.1	0.5	120	„
78	DRB	0.1	0.7	20	„
79	DST	−0.1	0.5	45	„
80	EDC	−0.3	0.6	76	„
81	ELL	0.3	1.7	50	„
82	EZN	−0.3	0.7	72	„
83	GPA	−0.4	0.6	65	„
84	ISK	−0.8	0.6	105	„
85	IST	−0.4	0.6	50	„
86	IZM	0.1	0.7	81	„
87	KAS	−0.2	0.7	31	„
88	MGN	−0.6	0.7	51	„
89	YER	0.2	0.7	60	„
90	KIS	−1.1	0.8	22	U.S.S.R.
91	SIM	−0.7	0.6	31	„
92	BLY	1.4	0.5	45	Yugoslavia
93	CEY	0.3	0.5	54	„
94	LJU	0.2	0.5	60	„
95	OHR	0.5	0.7	167	„
96	SKO	0.0	0.7	268	„
97	SSA	−0.5	0.5	50	„
98	VAY	0.1	0.6	216	„
99	ZAG	−0.3	1.6	14	„
100	HLW	−8.4	1.2	15	Egypt
101	EIL	−8.0	1.2	19	Israel
102	JER	−8.2	1.2	11	„
103	KSA	−6.5	0.6	5	Lebanon

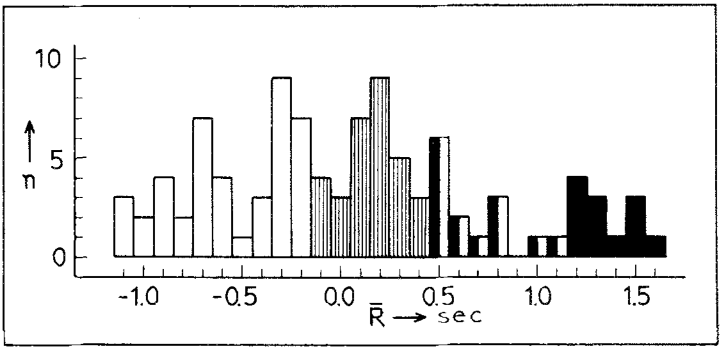

Figure 3
Frequency diagram of mean Pn residuals for the first 99 permanent seismological stations listed in Table 1.

negative values (between -6.5 s and -8.4 s). The residuals in Figure 3 are divided into four groups, denoted by four different symbols: black, half black and half white, dashed and white. This grouping is not arbitrary but is related to the geographical distribution of the corresponding stations. Thus, each of the mean residuals of Table 1 belongs to one of the following five intervals: (1.6 s, 1.2 s), (1.1 s, 0.5 s), (0.4 s, -0.1 s), (-0.2 s, -1.1 s) and (-6.5 s, -8.4 s).

Figure 4 shows the distribution of the permanent seismological stations listed in

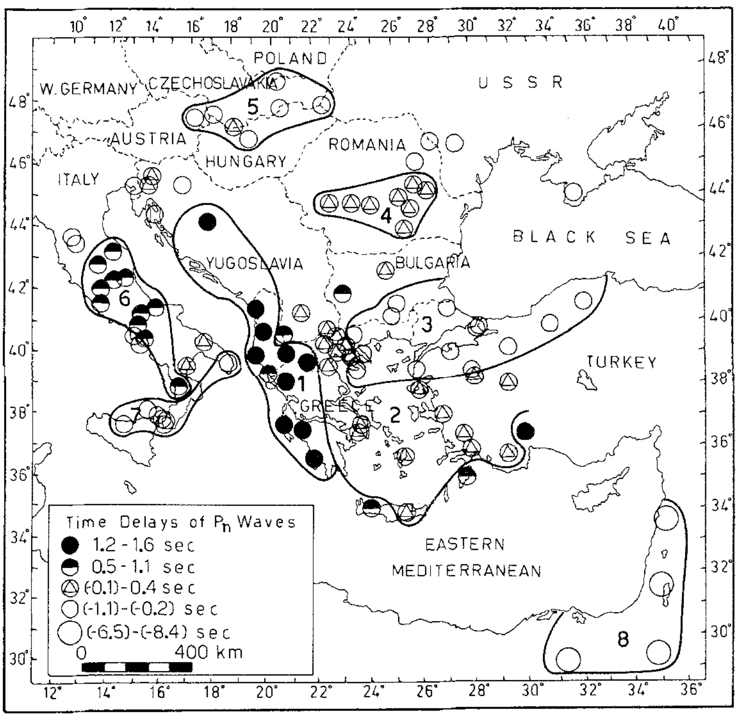

Figure 4
Map of the permanent seismological station in the investigated area. Five symbols are used to denote five corresponding ranges of Pn residuals.

Table 1. Five symbols have been used to denote stations with Pn residuals in the corresponding five intervals mentioned above. Therefore, Figure 4 shows the distribution of the Pn residuals in southeastern Europe, western Turkey, and Middle East; and expresses, in our opinion, the variation of crustal properties (mainly crustal thickness) in this area. However, independent of the interpretation of the geographical distribution of the Pn residuals, the values of these residuals can be used to correct the arrival times of Pn waves before these times are used for earthquake foci determination. Use of the residuals in this fashion has resulted in the drastic improvement of earthquake foci location, within a radius of 2 Kms (PAPAZACHOS *et al.*, 1984a, b; ROCCA *et al.*, 1985; KARAKAISIS *et al.*, 1984).

4. Discussion

Most of the studies concerning crustal structure deal with changes of seismic wave velocities in the crust. For earthquake prediction problems the question is to estimate temporal changes of P-residuals (Johnston *et al.*, 1982).

The main purpose of the present work is the derivation of Pn residuals for seismological stations in the area studied, in order to improve the earthquake foci determinations.

Possible causes for P-residuals include the following three factors (Calhaem, 1982): the crustal conditions below the station, the path properties, and the instrumental errors. Assuming that the mean instrumental errors are close to zero, an attempt was made to investigate any path dependence on the Pn residuals. For each station, PANAGIOTOPOULOS and PAPAZACHOS (1985) have compared residuals which resulted from seismic rays passing through different Pn paths. For this reason, they used portable instruments to determine earthquake foci for shocks of the two sequences mentioned above (Thessaloniki 1978 and Alkyonides 1981). These shocks were also recorded by permanent seismological stations in Greece and neighbouring countries. Because of the accurate foci location by the portable seismograph (RMS = 0.1 s, ERH = 1 Km, ERZ = 2 Km), they determined the travel times of the Pn-waves from the focus of each earthquake to each permanent station accurately. On the other hand, by knowing the epicentral coordinates of the earthquakes and the coordinates of the permanent station sites, they calculated the corresponding epicentral distances. Then they plotted the travel times as a function of distance, and observed that for the stations in the western part of southern Balkan region the travel times were higher by more than 1 s. Since the time delays for these stations resulted from different paths, they assumed that the crustal structure under these stations ought to be responsible for these delays. The obvious reason for these delays was the relatively large crustal thickness (45 Kms) along the well known mountain range of Dinarides–Hellenides (MAKRIS, 1977).

Most of the permanent stations of Figure 4 can be grouped into the eight regions shown in this figure, according to the values of Pn residuals.

Region 1 is characterized by strongly positive Pn residuals (1.2–1.6 s). It includes western Greece, Albania, western Yugoslavia, and is dominated by the Dinarides and the Hellenides mountain ranges. For this region a relative thick crust (42 Km) has been determined (MARKIS, 1977; CALCAGNILE *et al.*, 1982; PANAGIOTOPOULOS and PAPAZACHOS 1985), which is in excellent agreement with the interpretation that positive Pn residuals mean larger crustal thickness within the Aegean area.

Region 2 is characterized by almost zero values of Pn residuals. This region includes part of central-northern Greece, central-eastern Greece, central and southern Aegean and southeastern Turkey. A crustal thickness equal to that of the Aegean area (31 Km) is suggested by the almost zero values of the Pn residuals in this region. Residuals of the same order are observed in region 4 which covers a part of Romania. It probably means that this region has the same crustal thickness as the Aegean region.

Region 3 is characterized by Pn residuals between −1.1 s and −0.2 s. It means that in this region, which includes southeastern Bulgaria, the northernmost part of the Aegean area and northeastern Greece, as well as the northwesternmost part of Turkey (Marmara sea), the crustal thickness is slightly less than the normal one (Aegean crust) which dominates in the surrounding area (northeastern Bulgaria, region 2). This result is in good agreement with the results of previous research made by DATCHEV (1978) and PANAGIOTOPOULOS (1984), who proposed a rather thin crust in this region. Regions 5 and 7 are also characterized by negative Pn residuals of the same order.

Region 6 is characterized by positive Pn residuals between 0.5 s and 1.1 s. Such positive residuals are expected in this part of central Italy, dominated by the Apennines mountain range, because a relatively thick crust (38 Kms) has been determined in this region (CALCAGNILE *et al.*, 1982).

The four stations of region 8 are not far from the southeastern coast of the eastern Mediterranean and are characterized by very high negative Pn residuals. These residuals are from Pn waves of earthquakes which occurred in the convex side of the Hellenic Arc (Crete–Rhodos) and are recorded by these four stations (HLW, EIL, JER, KSA). We have used shocks that occurred in this area in order to avoid complex Pn paths passing through the subducted slab of the eastern Mediterranean lithosphere. In this case, a dependence of the residuals on the epicentral distance has been observed. This is probably due to the fact that the crustal structure in the eastern Mediterranean is much different from that of the Aegean region. It is well known that the crust in the eastern Mediterranean has features of oceanic affinity with an extra thick sedimentary layer (GASKELL *et al.* 1958; PAPAZACHOS, 1969; PAYO, 1967, 1969; RYAN, 1969; LORT, 1971, 1972; MAKRIS *et al.*, 1983). Due to this dependence on the epicentral distance, a reduction of these residuals to the mean epicentral distance (= 1060 Kms) has been made, and the values of the mean Pn residuals written in Table 1 and in Figure 4 correspond to this mean distance. It must be noted that these very high negative residuals (−6.5 s, −8.4 s) do not indicate an extra thin crust in the region of these four stations. In this case the residuals are due to the path properties.

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