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Near field travel-time solutions for Anatolia

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Abstract: *It is possible to use two methods in the near field travel-time solutions. These are* ***single-station*** *and* ***two-station travel-time methods****. Input data for these methods are travel times of many events at the single station and the differences of arrival-times at the couple of station lying on the same great circle with an event, respectively. In order to determine Pn-wave velocity and broad crustal structure beneath Anatolia, we have applied single-station method for various directions with an expanded data set, and composed the results with previous information obtained from both method. Data set relating to 84 events ($m_b \geq 4.6$ and occurred since 1977) recorded at 22 stations have been used for computations. Pn-wave velocity has been determined as approximately 8.00 km/s. Thickness of crust is also 38 km as convenient with the previous investigations.*

Key Words*: Seismic Wave Velocity, Single-Station Method, Anatolia.*

INTRODUCTION

As it is well known, overall knowledge about the Earth's interior have been begun to be collected at the beginning of 20th century with introduction to instrumental seismology. Especially, Deep Seismic Sounding (DSS) studies in which synthetic explosions or nuclear tests are used as a source have obtained more precise and detailed information. It is necessary to well know structure of the Earth's interior, specially crust and upper-mantle, in the investigation of either earthquakes or ore-bed. Today, crust and upper-mantle structure have been investigated in detail in many places of the world such as USA, old USSR, Japan, Europe countries and oceans. Unfortunately, these kind of studies could not be performed in Anatolia. For that reason, seismologists have obligated to use earthquake data.

Osmansahin and Sayil (1996) have computed Pn-wave velocity by using single-station and two-station travel-time methods from the first arrivals at the stations located in the north and west Anatolia for profiles approximately in the direction of E-W. To make a contribution to information about crust and upper-mantle structure in Anatolia, we have computed Pn-wave velocity for reciprocal profiles in the direction of E-W and N-S increasing the number of events and stations, and tried to determine the thickness of crust taking account existent knowledge.

COMPUTATION OF Pn-WAVE VELOCITY

Osmansahin and Sayil (1996) and Osmansahin (2000) have been explained in detail single-station and two-station methods for travel-time solutions. A brief definitions of single-station method that has been used in this study are given below.

Single-Station Travel-Time Method

Travel-time of any wave for a medium between source and station can be computed by the following equation:

$$t_i = t_i^a - t_i^o \tag{1}$$

Where t_i^a and t_i^o are arrival-time and origin-time, respectively. In single-station travel-time method for near field earthquakes, Pn-wave travel-times for a set of event and station are determined from equation (1). In order to avoid the travel-time differences arising from the focal depth differences, depth correction which is defined as

$$t_i^{\mathrm{cor}} = (h-d)\frac{\sqrt{V_{P_n}^2 - V_{P_l}^2}}{V_{P_l} V_{P_n}} \tag{2}$$

should be done for each value (Osmansahin and Sayil, 1996). Where *h* is focal depth, *d* is the reference depth where all the focuses would be located, V_{Pj} and V_{Pn} are P-wave velocity in the crust and upper-mantle, respectively. Then, depth corrected travel-times are plotted versus epicentral distances and Pn-wave velocity is computed from slope of the line that best fits to the graphics.

DATA

Osmansahin and Sayil (1996) and Osmansahin (2000) have explained all the important criteria about the focal parameters that have to be taken account while the data are chosen for a near field travel-time solutions. In order to obtain better resolved Pn-wave time readings for the single-station travel-time method, following main criteria should be secured:

- Epicentral distance should be approximately between 1.5°-11.5°,
- Focal depth should be about less than 40 km (inside of crust),
- Magnitude should be great enough ($m_b \geq 4.5$),
- Azimuthal coverage of the events should be convenient. Namely, the events should be locate on the same direction with the station. This is not important if there is no lateral heterogeneity.

Taking account these criteria, data set of 22 stations (Table 1) and 84 events (Table 2) have been used in the analysis. Locations of the events and stations are shown on the map in Fig. 1.

ANALAYSIS

P_n-wave velocity beneath Anatolia has been estimated by performing single-station travel-time method explained above. In the application of single-station travel-time method, data of stations located in east and west Anatolia have been used to construct reciprocal profiles in the directions of E-W and N-S (Table 2). Travel-times have been computed by the equation (1) with origin-time and arrival-time taken from ISC. Focal depth corrections have been done by the equation (2) for the velocity values of 6.1 (Kalafat *et al.*, 1992) and 8.0 km/s in crust and upper-mantle, respectively. Corrected travel-times have been plotted versus epicentral distances, and Pn-wave velocity has been computed from the slope of

Table 1. Stations used in analysis.

#	STATION	LAT. (°N)	LONG. (°E)
1	ANTO (Ankara)	39.9167	32.8167
2	CTT (Catalca)	41.1473	28.4297
3	DMK (Demirköy)	41.8214	27.7573
4	DST (Dursunbey)	39.6055	28.6280
5	EDC (Edincik)	40.3468	27.8634
6	EZN (Ezine)	39.8258	26.3253
7	GPA (Golpazari)	40.2889	30.3094
8	HRT (Hereke)	40.8217	29.6680
9	ISK (Istanbul)	41.0656	29.0592
10	KAS (Kastamonu)	41.3717	33.7667
11	KVT (Kavak)	41.0806	36.0464
12	TBZ (Trabzon)	40.9944	39.7761
13	ALT (Altintas)	39.0552	30.1103
14	BCK (Bucak)	37.4608	30.5890
15	ELL (Elmali)	36.7483	29.9085
16	IZM (Izmir)	38.3978	27.2625
17	YER (Yerkesik)	37.1347	28.2828
18	LEN (Leninakan)	40.7667	43.8500
19	ERE (Erivan)	40.2000	44.5000
20	NAK (Nakhjavan)	39.2000	45.4000
21	TAB (Tabriz)	38.0675	46.3267
22	MSL (Mosul)	36.3478	43.1111

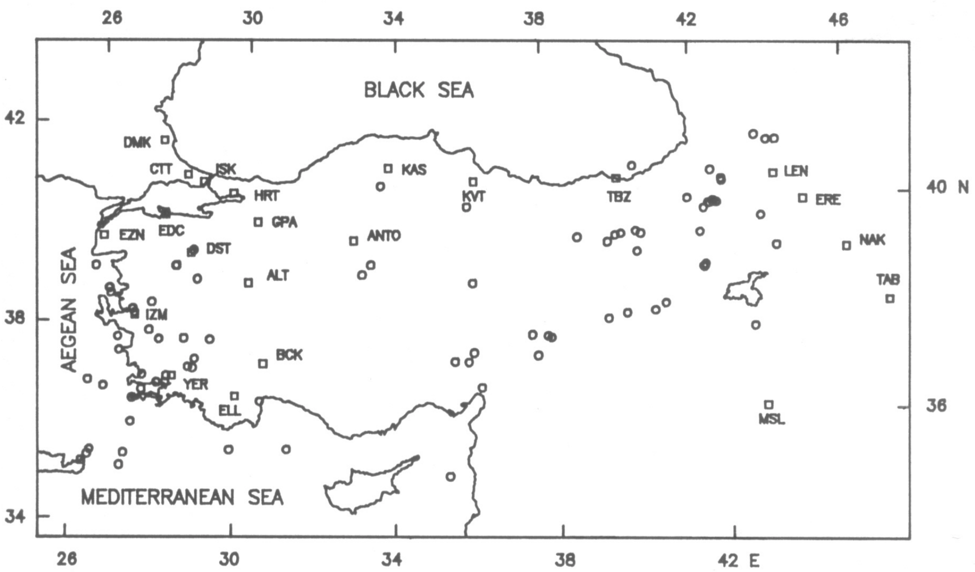

FIG. 1. Location of the events (O) and stations (☐). Some of the events located in the same place.

Table 2. Earthquake parameters used in application (from ISC). In the station number section, the numbers indicate the stations (in Table 1) from which the first arrival-time readings were used.

#	Date	Time	Coordinate		Dep	Mag	Station Number				
	(d m y)	(h m s)	(°N)	(°E)	(km)	m_b	1*	2*	3*	4*	5*
1	24.02.1977	20:47:18.2	38.55	27.66	20	5.0				3,5,6,9,17	
2	28.03.1977	10:50:20.1	36.83	27.52	35	4.8				3-7,9,16	
3	05.10.1977	05:34:43.8	41.02	33.57	10	5.3	3,7,9,11	21			
4	27.10.1977	22:43:32.2	37.87	27.88	16	4.7				4,6,7	
5	09.12.1977	15:53:38.0	38.35	27.23	27	4.8				3-6,9,17	
6	16.12.1977	07:37:29.3	38.41	27.19	24	5.3				3-5,9,17	
7 !	11.01.1978	03:57:45.7	37.48	28.86	5	4.9				3,5,7,9,16	
8 !	04.07.1978	22:39:16.5	39.45	33.19	23	4.9	4,10-13,16	18,19			4&6
9	04.12.1978	03:12:37.6	38.07	37.43	37	5.0	11,14-16	21	12		
10	19.01.1979	23:36:58.8	39.91	39.60	11	4.9	3-7,10,13,15,17	18,19,21			
11	14.06.1979	11:44:45.1	38.79	26.57	15	5.9				2,3,5,9,15	
12	16.06.1979	18:41:59.4	38.72	26.64	11	4.9				2,3,5,9,15	
13	18.07.1979	13:12:02.3	39.66	28.65	7	5.2				9,15,16	
14	23.07.1979	11:41:55.1	35.48	26.37	36	5.2				3-7,9,16	
15	11.08.1979	22:30:29.2	35.40	26.34	40	4.8				3-7,9,16,17	
16	12.09.1979	16:14:54.0	38.41	39.80	35	4.9	9,14	18			
17	28.12.1979	03:09:08.1	37.52	35.85	39	5.1	8,10,15	21			13&6
18 !	02.05.1980	05:30:58.8	35.68	29.81	38	5.2				5,9,16	
19	11.07.1980	12:33:31.8	38.54	40.83	30	5.1	1,3,6,7,11,13,15,17		18		1&5,7
20	04.10.1980	15:12:06.6	37.00	28.80	26	5.0				2,3,5,7-9,13,16	
21	18.10.1980	03:14:10.4	39.91	40.31	37	5.1	1-3,6,7,9,11,13-17	19,21			7&5,1&6
22	19.12.1980	07:49:21.5	38.02	27.65	15	4.7				2,3,5,7-9	
23	27.03.1982	19:57:24.0	39.23	41.90	38	5.4	3,8,9,11,13-17	21	18		
24	25.05.1982	08:06:04.7	41.42	44.00	5	4.7	14		19		
25	29.05.1982	14:22:01.2	39.40	43.72	26	4.8	8		18		
26	07.06.1982	00:31:26.1	36.98	27.92	10	4.7				2,3,5,6,8,9,13,16	
27	13.10.1982	03:51:31.1	39.19	41.92	40	4.7	1,7-11	21	18,22		
28	26.12.1982	17:48:01.1	39.33	28.26	5	4.9				2,3,9,14,15	
29	27.12.1982	11:02:44.3	39.34	28.27	11	4.8				2,3,9,14,15	
30	14.04.1983	09:36:28.3	36.57	27.03	10	4.7				16	
31	20.04.1983	10:00:52.4	39.93	38.68	10	4.6	1,2,4,6,7,9,11,13	18			1&4,6
32	21.04.1983	16:18:57.2	39.31	33.06	36	4.7	5,8,10,13,16	19-21			
33	07.07.1983	21:31:10.7	36.69	30.54	7	4.7				3,5,7,9,13	
34 !	11.08.1983	05:26:30.1	35.72	31.28	33	4.8				4,7,15	
35	09.09.1983	17:59:45.4	35.48	27.23	35	5.0				3-6,8,13,16	
36 !	30.10.1983	04:12:28.1	40.35	42.18	14	6.0	3,5,8,9,11,13-15,17	21	22		11&9
37 !	01.11.1983	18:03:28.0	40.43	32.21	23	4.8	7,8,10,11,15	21	22		
38	02.11.1983	00:24:22.6	40.36	42.06	25	4.8	3,5,7-11,15	21	22		
39	18.11.1983	01:15:37.5	39.79	39.43	37	5.0	3,4,6,7,9,10,13-17	18,20,21	22		11&10,7&5
40	19.11.1983	18:09:31.0	40.38	42.14	32	4.7	10-12	20,21			
41	24.11.1983	00:14:08.9	37.05	36.12	37	4.7	4,6-9,13-17				13&6
42	31.01.1984	15:51:34.3	37.03	28.00	15	4.9				3,5-8,13,16	
43	05.02.1984	00:20:19.7	37.21	28.67	30	5.0				2-5,7,13,15,16	
44	06.02.1984	04:03:26.3	37.09	28.15	26	4.9				3-6,8,9,13,16	
45	23.04.1984	12:11:35.5	37.84	26.87	27	4.8				2,4-9,17	
46	04.05.1984	21:35:02.9	37.89	29.24	27	4.7				2.4.5.7-9.15	
47	18.09.1984	13:26:02.2	40.90	42.24	10	5.3	3-5,7,9,12,14,15		22		11&8,9
48	18.10.1984	09:46:20.7	40.79	42.48	19	5.3	3,7,9,10,12,14,15		21,22		11&8,9
49	21.10.1984	18:04:26.4	40.76	42.49	21	4.7	4,7,9,10,12,15		21,22		11&8,9
50	26.10.1984	15:08:03.1	40.50	41.54	39	4.7	8,10-12,15	21	21,22		
51	18.12.1984	13:59:34.9	35.29	35.32	39	4.6	10,12	22			
52	23.01.1985	01:23:31.2	39.11	35.94	30	4.6	6,8,10-12	19	12		4&6
53	16.02.1985	21:33:29.6	39.83	41.80	10	4.8	10-12,15	21	12,22		
54	29.03.1985	09:24:08.4	38.80	26.57	26	4.8				2,3,5,9	
55	10.04.1985	08:35:08.5	36.80	27.54	20	5.0				3,16	
56	10.06.1985	11:41:54.5	40.60	35.80	10	4.8	4,6,7,9-12	20,21			
57	12.08.1985	02:54:44.2	39.95	39.77	29	4.9	1,2,5,7,9,10,16,17	18,20	22		
58	07.11.1985	08:26:21.7	40.37	42.29	15	5.1	3,11,12,14				
59	18.12.1985	05:46:00.8	39.20	26.17	17	5.0				3,16	
60	21.12.1985	05:05:36.5	37.55	35.47	33	4.6	8,10,14-17	20,22	12		
61	23.12.1985	20:08:58.8	36.81	26.62	25	4.9				3,6,16	
62	01.01.1986	06:09:06.3	39.14	41.83	36	4.8	7,8,12,15	20	12,18,22		
63	19.03.1986	15:29:11.5	37.55	26.93	18	4.7				2,4-6,8,9	
64	11.04.1986	04:10:34.4	40.01	43.34	33	4.9	10,11	21	22		12&10

Table 2. (continuation) Earthquake parameters used in application (from ISC). In the station number section, the numbers indicate the stations (in Table 1) from which the first arrival-time readings were used.

#	Date	Time	Coordinate		Dep	Mag	Station Number				
	(d m y)	(h m s)	(°N)	(°E)	(km)	m_b	1*	2*	3*	4*	5*
65	05.05.1986	03:35:38.0	38.02	37.79	4	5.7	1-6,9,11,14-16	18-20	12		1&2,3,8,9
66	13.05.1986	08:44:01.9	41.44	43.72	6	5.5	2,11,12		19,20,22		12&10,10&9
67	06.06.1986	10:39:47.0	38.01	37.91	11	5.5	2,4,6-12,15,16	18,19	12		
68	03.08.1986	01:33:24.5	37.19	37.16	38	5.0	2,4,6,9,13,15,16		12		13&6
69	19.08.1986	06:03:54.4	39.04	28.79	10	4.7				2,5,7,16,17	
70	03.09.1986	09:28:17.6	41.57	43.45	5	4.8			19,20,22		12&11
71	11.10.1986	09:00:10.9	37.94	28.56	5	5.4				2-8,13,15	
72	01.11.1986	03:18:10.3	41.24	40.21	29	4.7	4,13,14	18			
73	22.02.1987	06:51:42.3	38.42	40.50	10	5.0		18-20	12,22		
74	01.05.1987	21:15:09.7	36.07	27.34	39	4.7				5,13	
75	14.05.1987	22:24:00.4	39.95	40.16	10	4.8	2,5,7,9,13		22		7&5
76	24.06.1987	06:53:24.0	38.32	39.35	30	4.7	2,4,9,13-15		12,22		
77	30.10.1987	10:28:30.5	37.64	37.56	10	4.7	2,4,13,14,17				
78	07.12.1987	00:07:32.3	37.95	42.95	33	4.8			22		
79	21.12.1987	19:34:36.7	35.26	26.20	29	4.8				3,4,6	
80	30.12.1987	16:17:09.7	36.88	27.72	30	4.8				2-6,8,9	
81	16.02.1988	11:20:17.0	35.19	27.15	37	5.0				4,5,13,16,17	
82	10.03.1989	08:00:50.3	40.26	41.96	10	4.7	15	21	12,22		
83	20.05.1989	20:44:02.2	39.59	40.18	34	5.0	2-7,9,15-17	19-21	12,22		
84	24.06.1989	03:09:58.3	36.71	35.93	35	4.9	14-17	19,21	12		13&6,14&17

1* Profiles approximately in E-W direction for stations in west. 2* Profiles approximately in E-W direction for stations in east.
3* Profiles approximately in N-S direction for stations in east. 4* Profiles approximately in N-S direction for stations in west.
5* Station pairs that construct the profiles approximately in E-W direction for two-station travel-time method (Osmansahin and Sayil, 1996).
! Six great earthquakes used in two- station travel-time method for all the possible station pairs method (Osmansahin and Sayil, 1996).

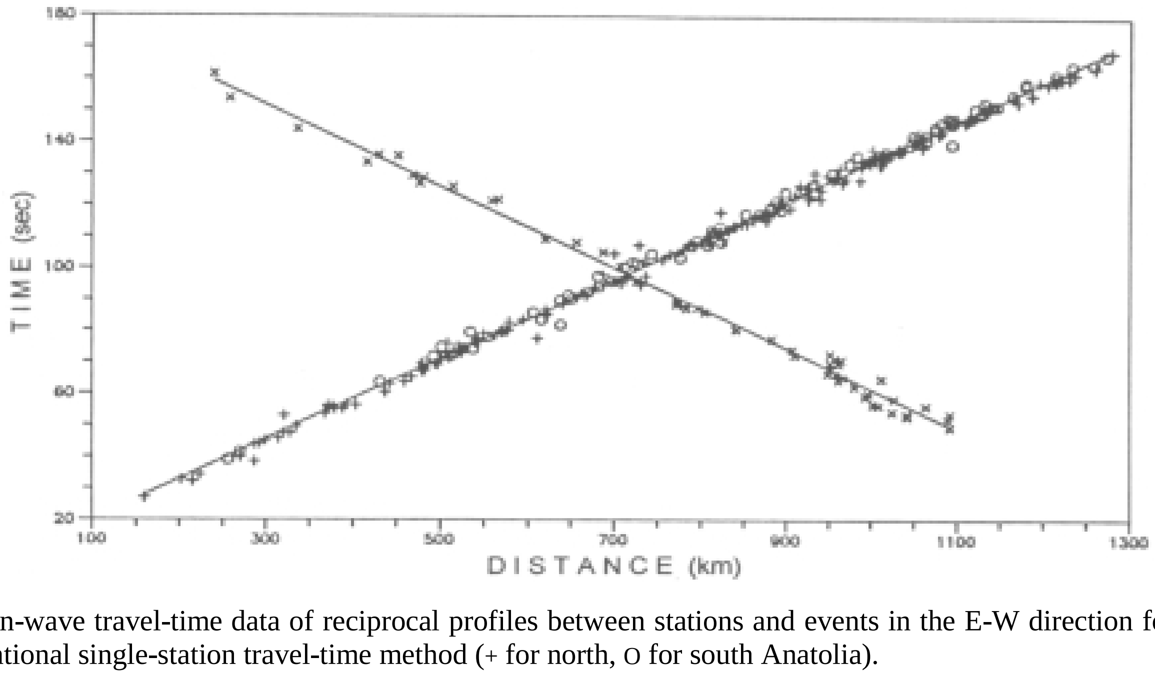

FIG. 2. Pn-wave travel-time data of reciprocal profiles between stations and events in the E-W direction for the conventional single-station travel-time method (+ for north, O for south Anatolia).

least squares best fit to the travel-time distribution. Profiles in the direction of E-W have been investigated separately for north and south Anatolia as in the study of Osmansahin and Sayil (1996). They have found about the same velocity values for both north and south, and interpreted that the similar structure is talked about these regions. Expanded data set here support this result, but there is a difference between velocity values computed for reciprocal profiles (Fig. 2). These are 7.92±0.03 and 7.76±0.03 km/s for stations in the west and east, respectively. This situation can be interpreted as thickness of crust is increasing toward east, that is convenient with the definitions in previous studies about crust and upper-mantle structure of the region (Kenar and Toksöz, 1989; Mindevalli and Mitchell, 1989; Osmansahin and Alptekin, 1990 and Sayil *et al.*, 1992). Profiles in N-S direction could be constructed of single side for west (for stations in northwest) and reciprocally for east (for station in northeast and southeast). Pn-wave velocity computed from the data set concerning west Anatolia (Fig. 3) is 7.93±0.03 km/s. Kalafat *et al*. (1992) have defined that Pn-wave velocity is changing between 7.70-7.90 km/s in west Anatolia. Pn-wave velocities computed from reciprocal profiles in N-S direction for east Anatolia are about the same. For that reason, these data sets have been evaluated together (Fig. 4), and Pn-wave velocity of 7.99±0.03 km/s has been detected. In the recent studies referred above, thickness of crust has given as about 40 km. According to our results, it is about 38 km for an

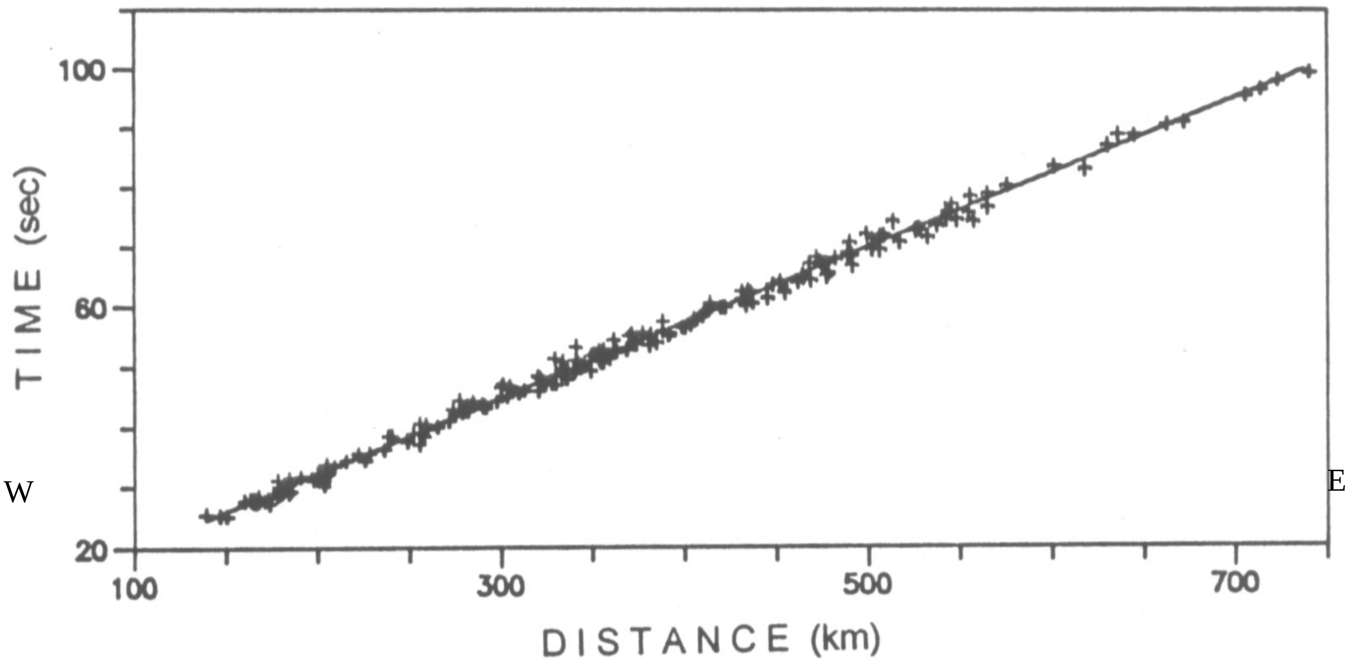

FIG. 3. Pn-wave travel-time data of profiles in the N-S direction for west Anatolia from single-station travel-time method.

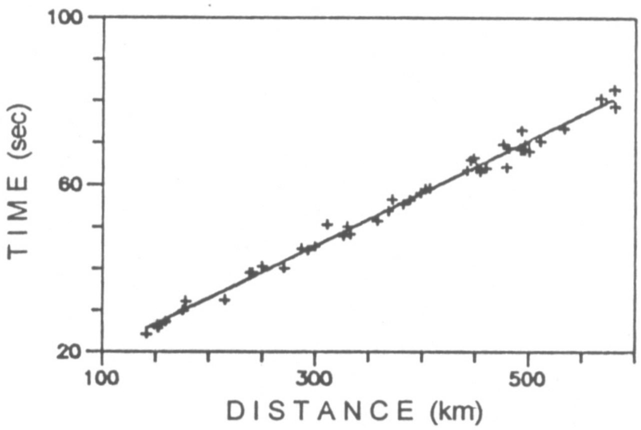

FIG. 4. Pn-wave travel-time data of profiles in the N-S direction for east Anatolia from single-station travel-time method.

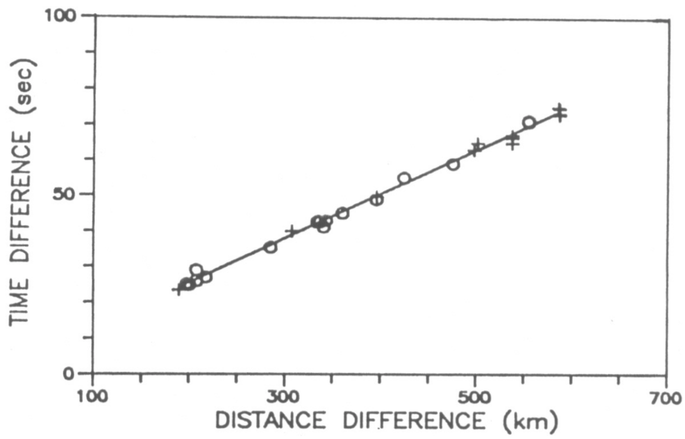

FIG. 5. Pn-wave travel-time data of profiles in the E-W direction for west (+) and north (O) Anatolia from two-station travel-time method (Osmansahin and Sayil, 1996).

intercept time of 8 s and crust and upper-mantle velocities of 6.1 and 8.0 km/s, respectively.

Osmansahin and Sayil (1996) have applied two-station travel-time method to the profiles in the E-W direction in west and north Anatolia, and to the profiles between all the possible station pairs for six large magnitude earthquakes pointed out in Table 2. Since Pn-wave velocities for west and north are about identical (8.00±0.02 km/s), these data have been evaluated together (Fig. 5). The data of the profiles between all the possible station pairs for six large magnitude earthquakes are shown in Fig. 6. Pn-wave velocity obtained from these data is 7.98±0.02 km/s.

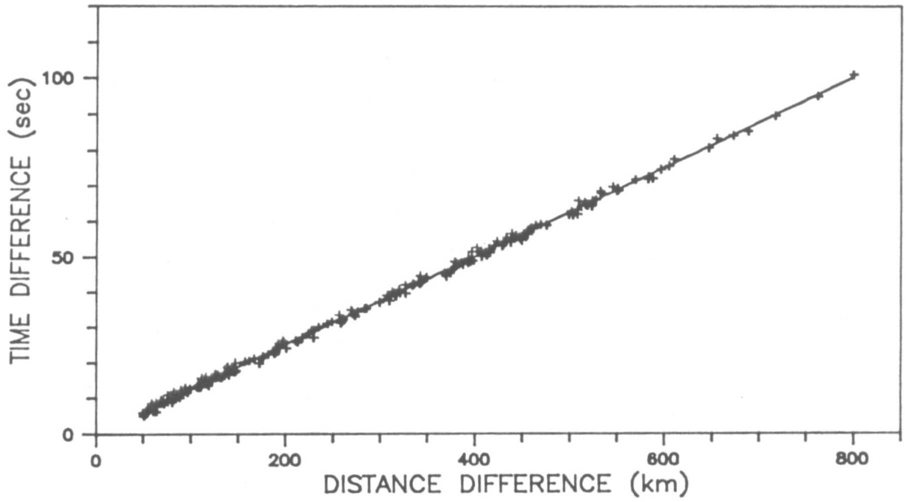

FIG. 6. Pn-wave travel-time data of profiles between all the possible station pairs for six large magnitude earthquakes given in Table 2 from two-station travel-time method (Osmansahin and Sayil, 1996).

CONCLUSION

Pn-wave velocity beneath Anatolia have been computed by using single-station travel-time method for a various profiles with an expanded data set, and broad structure of crust has been tried to interpret with the results of this and previous studies.

In the applications of single-station travel-time method, reciprocal profiles in E-W direction for north and south Anatolia and in N-S direction for east Anatolia and single side profile in N-S direction for west Anatolia have been analyzed separately. In spite of computed Pn-wave velocities are about identical for profiles in E-W direction for north and south, there is a velocity difference between reciprocal profiles which are 7.92±0.03 km/s for stations in west and 7.76±0.03 km/s for stations in east. This situation points out that crustal structure is about the same in north and south, and thickness of crust is getting thicker toward east. Pn-wave velocities obtained from reciprocal profiles in N-S direction for east Anatolia are also identical (7.99±0.03 km/s). It has been computed as 7.93±0.03 km/s from the 7.93±0.03 km/s single side profile in N-S direction for west.

Profiles that could be constructed for two-station travel-time method are in the direction of E-W and locate in west and north. Pn-wave velocities computed for these profiles are about identical (7.98±0.02 km/s). Finally, taking account the proximity of velocities computed for different profiles, Pn-wave velocity has been computed as 8.00±0.02 km/s for all the possible station pairs from six large magnitude earthquakes (Osmansahin and Sayil, 1996). Thickness of crust for Anatolia has been determined roughly as 38 km. All the solutions seems to be appropriate with the results of previous seismological investigations. In order to obtain more detailed information, it is necessary to perform a crust and upper-mantle project.

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