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Travel Time Residuals in the Iranian Plateau

B. Akasheh

Institute of Geophysics, Tehran University

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Abstract. Travel time residuals with respect to the Herrin 1968 tables have been calculated for about 120 events ($45° < \Delta < 100°$), recorded at 5 Iranian Stations (Shiraz, Tehran, Tabriz, Kermanshah and Meshed). The residuals do not show a significant variation with respect to epicentral distance, azimuth (except Shiraz), magnitude of events, but show a variation with depth of events. To minimize source effects, residuals relative to Tehran have also been computed. The residuals are positive and suggest crustal and/or upper mantle velocity anisotropy. The crustal and/or upper mantle velocity anisotropy is different under stations on the Iranian Plateau. The stations are underlain by an unusual low velocity material or different crustal thickness. The residual at the Shiraz Station is +0.3 s in NE direction but + 1.7 s in the SE direction. This phenomenon can be explained by the existence of a high velocity zone under the Zagros Mountains which dips towards NE. The Bouguer gravity anomalies and crustal thickness contour are calculated for about 70 points and they have been compared with P wave travel time residuals.

The absolute anomalies are expressed in terms of variations of the thickness of the crust, difference in velocity in the low velocity channel, and the velocity variations in the crust under the stations.

Key words: Travel Time — Residual — Iranian Plateau — Crust — Upper Mantle — Low-Velocity Channel.

1. Introduction

Travel time of seismic P waves from earthquakes and nuclear explosions determined at many stations indicate certain deviations from Jeffreys-Bullen and Herrin Tables. Part of the deviation is systematic, varying as a function of epicentral distance, part is station dependent. Seismic travel times and their residuals (observed travel time minus theoretical travel time) have been extensively analyzed statistically by Herrin (1968) and Herrin and Taggart (1968), who have determined residuals at many stations and by Lomnitz (1969). The P travel time residuals, with respect to the 1968 Herrin tables have been calculated for about 120 events ($45° < \Delta < 100°$), recorded at 5 Iranian Stations to determine the anomalies in the crust and in the upper mantle and to estimate the crustal thickness variation under the stations on the Iranian Plateau. The next attempt is to correlate the travel time anomalies with the Bouguer gravity anomalies and to make some models. Values of the Bouguer anomaly in the Iranian Plateau are used to deduce some regional thickness.

2. Seismicity and Tectonics of the Region

The Iranian Plateau is made primarily of sediments accumulated over geological time in the Tethys. The main folding of this sea area into the Zagros and Elburz

Mountains began during the passage from the Cretaceous to the Eocene periods. The Zagros thrust zone extends about 1400 km and has a straight alignment, extending westward, where it joins the Taurus ranges in Turkey. At its southern extension it goes toward Pakistan and Oman. Southwest of the Zagros thrust zone lie the foothills and the foreland. The foreland extends from the Red Sea to the Persian Gulf. The folded zone is characterized by a long parallel pattern of asymetric synclines with axes, generally parallel to the Zagros trend, indicating a northeast-southwest compression, (Stöcklin, 1968; Pilger, 1971). The width of the Zagros seismic zone extends from the northern shore of the Persian Gulf to the southern boundary of the Zagros thrust. This zone is the most active seismic zone in Iran. The focal depths increase with a dip about 15° toward the northeast (Niazi and Basford, 1968; Gansser, 1969; Akasheh 1971, 1972a, 1973; Nowroozi, 1971). The Elburz Mountain Range extends from north-west to the nort-east and appears to be linked with the Hindu-Kush ranges. This range is geologically a continuation of Central Iran but with a decrease of folding.

3. Data, Method, Results and Discussion

For about 120 events the epicentral distance and azimuth have been computed. The epicentral location, depth, origin time and magnitude of events published in the Bulletins of the USCGS and their *P* wave arrival times are given in the Bulletin of the Institute of Geophysics, Tehran University.

The location of the 5 stations used in this study are:

Shiraz	29° 48′ 39″ N	52° 51′ 34″ E	Height 1595 m
Tehran	35° 44′ 16″ N	51° 23′ 09″ E	Height 1360 m
Kermanshah	34° 21′ 08″ N	47° 06′ 21″ E	Height 1310 m
Tabriz	38° 04′ 03″ N	46° 19′ 36″ E	Height 1430 m
Mesheh	36° 18′ 40″ N	59° 35′ 16″ E	Height 830 m

Observed travel time and theoretical travel time according to 1968 Herrin tables have been calculated. Fig. 1a is a plot of the travel time residuals at 5 stations. The residuals are corrected with regard to station elevation. Each data point is the average of a 10° azimuth sector. The circle around each station shows zero residual. Fig. 1b is a plot of the travel time residual versus epicentral distance. Each data point is the average for 10° distance interval. The average residual for all data is about +0.5 s at the Shiraz Station, +1.6 s at the Tehran and Kermanshah Stations, +2.1 s at the Tabriz Station and +2.8 s at the Meshed Station. The residuals do not show a significant variation with azimuth (except Shiraz) and epicentral distance. The residuals at the Shiraz Station are +0.3 s in the N and NE direction but are +1.7 s in the SE direction. This phenomenon can be explained by the existence of a high velocity zone under the Zagros Mountains which dips toward NE. Nowroozi (1972) discussed independentely the existence of a slab under the Zagros Mountains. To minimize the source region effects, residuals relative to Tehran Station have also calculated. The residual relative to Tehran is at the Shiraz Station about —0.9 s, at the Kermanshah Station —0.1 s, at the Tabriz Station +0.4 s and at the Meshed Station about +1.4 s.

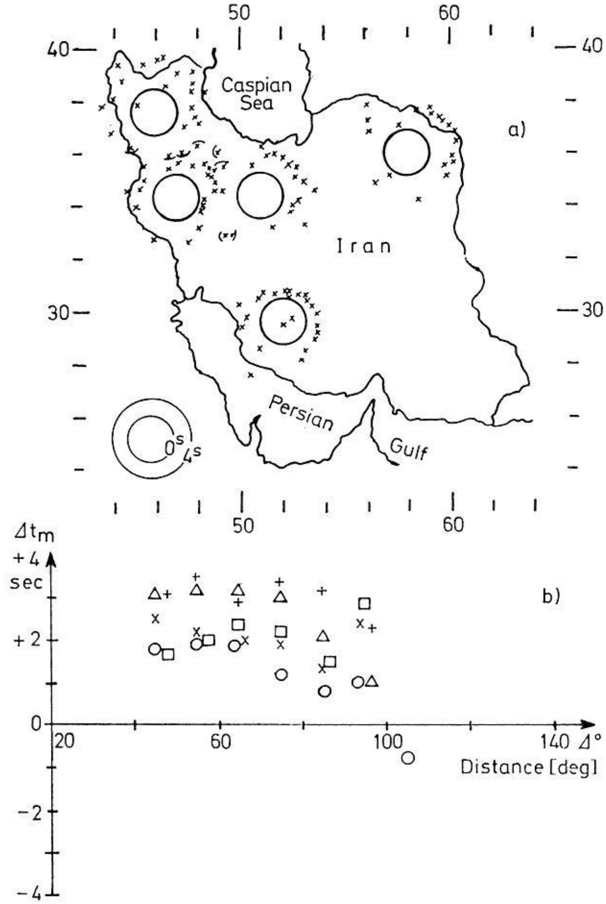

Fig. 1. Travel time residuals at 5 Iranian Stations. The circle around each station means the zero residual. Each data point is the average residual a) for a 10° sector, b) for 10° epicentral distance interval. O: Shiraz Station, □: Tehran Station, Δ : Tabriz Station, x: Kermanshah Station, +: Meshed Station

The residuals do not show regular variation according to the angle of incidence i_0 at the station, the angle of incidence i_d in the focus and the magnitude of events but show a regular variation according to the depth of events. Fig. 2 shows the travel time residuals at the Tehran Station according to d, depth of events. The circles represent the averages for 10, 20, and 100 km depth intervals. It is to seen from Fig. 2 that the residuals vary with depth of event. Residuals of events deeper than about 140 km are about one second less than the mean.

The residuals are positive and suggest crustal and/or upper mantle velocity difference and anisotropy. The crustal and/or upper mantle velocity variation and anisotropy may be different under station on Iranian Plateau. The stations on Iranian Plateau may be underlain by different crustal thickness or an unusual low-velocity material. If we assume that the anomalies (Δt) are caused by the variations in the crustal thickness (ΔH_0) we can calculate (for the mean angle of incidence at the station

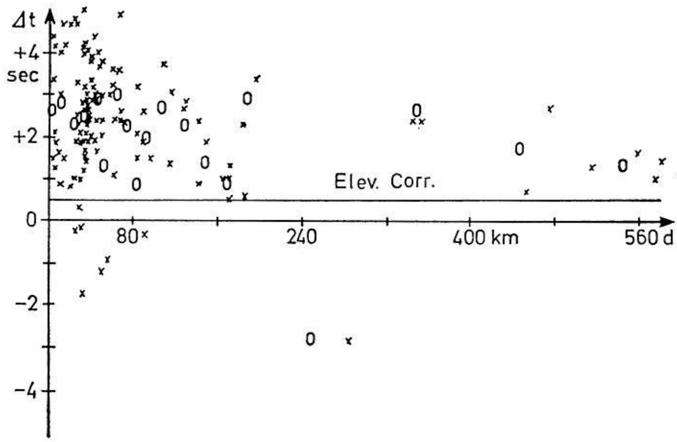

Fig. 2. Plot of the travel time residuals at the Tehran Station versus the angle of incidence in the focus. The station correction is shown with line parallel with d axis. The circles are the mean values

i_0 about 20°, mean crustal velocity $v_0 = 6.37$ km/s, velocity in the upper mantle $v_1 = 8.05$ km/s (Herrin *et al.*, 1968) the rate of change of crustal thickness H_0 for corresponding change in t by the relation $\Delta H_0 = \dfrac{v_0 \cdot v_1 \cos i_0}{v_1 - v_0} \Delta t$. To explain the absolute anomalies (+0.5 s at the Shiraz Station, +1.6 s at the Tehran and Kermanshah Stations, +2.1 s at the Tabriz Station and +2.8 s at the Meshed Station) we have to assume crustal thickness under Shiraz to be about 14 km thicker than the Herrin *et al.* model 1968 (40 km), under Tehran and Kermanshah about 46 km thicker, under Tabriz about 60 km thicker and under Meshed about 80 km thicker than the value of H_0 in the model.

Deep refraction seismic work in the region has not been done, but attempts have been made from body wave studies of earthquakes to determine the crustal structure and the thickness of the crust in Iran. From these studies it is quoted that the southern regions have a crustal thickness of 49 ± 6 km, whereas crustal thickness in the western and central regions is 55 ± 6 km (Akasheh, 1972b; Akasheh and Nasseri, 1972). Goudarzi *et al.* (1970) give a thickness of 39 ± 5 km for the crust in the Shiraz region. Eslami (1972) gives a thickness of 48 ± 4 km for region Shiraz, 42 ± 4 km for the south and south east region of Shiraz, 48 ± 6 km for the region Kermanshah and 53 ± 3 km for the region north and north west of Kermanshah and 57 ± 6 km for the south and south east region of Kermanshah.

We know that crustal thickness varies with respect to the Bouguer anomaly and surface elevation. For a continental type of crustal structure Heiskanen and Vening Meinesz (1958) have given a linear relationship between the surface elevation and the depth to the Mohorovicic discontinuity. Demenitskaja (1958) and Woollard (1959) have shown empirically in their works that the thickness of the crust varies with respect to Bouguer anomaly and elevation.

Gravity measurements are made since 1960 by the Institute of Geophysics, Tehran University (1960, 1962, 1970) and by Zomorrodian (1971, 1972). For about 70 points the Bouguer gravity anomaly is calculated for a simple model, using a

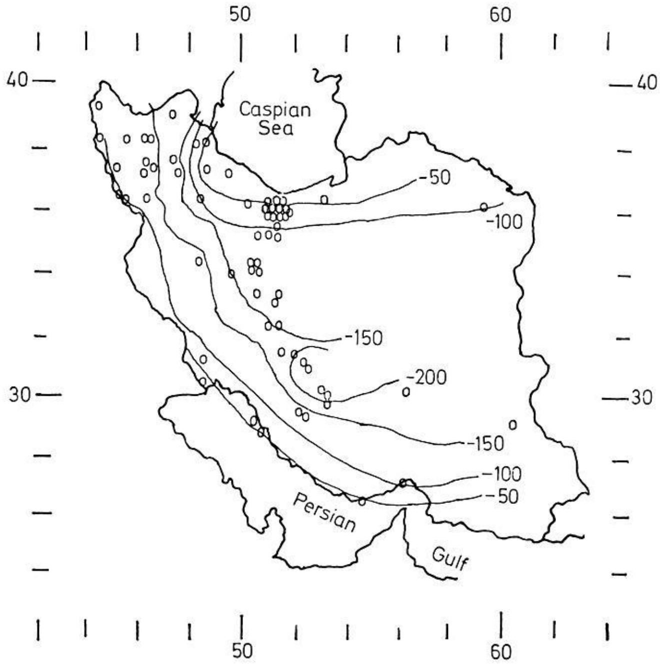

Fig. 3. Simple Bouguer gravity map of Iran (in mgal)

density of 2.67 g cm^{-3} (Schick and Schneider, 1973), Fig. 3. The gravity anomaly values display trends that are related to the major relief. The axis of regional Bouguer gravity anomalies is parallel with the Zagros chains. The gravity fields in the Iranian Plateau are characterized by large negative Bouguer anomalies (about —200 mgal) in the Zagros zone and about —150 mgal in the Elburz zone, but it seems that the Bouguer gravity anomalies are about zero in the Caspian Sea and Persian Gulf. That means that the Zagros and Elburz zones are associated with a large mass deficiency, a mechanism involving underthrusting of light continental crust into higher density mantle in the Zagros and Elburz zones. This mechanism is consistent with regional seismicity, focal mechanism, depth of the foci and crustal thickness variation.

An estimate of the crustal thickness is made from Demenitskaja's formula. Fig. 4 shows the contours of crustal thickness based on the Bouguer anomaly. The crustal thickness in Fig. 4 delineate the Zagros and Elburz zones, which seem to have an average depth to the Moho of the order of 50 km. The crustal model used in travel time studies by Herrin *et al.*, 1968, has a thickness of 40 km for the crust. That is of the order of crustal Thickness under the 5 Iranian Stations.

We assume now that the travel time absolute anomalies at the stations are caused within a depth of 300 km, we can calculate the velocity in the low-velocity channel. On the basis of a reference model:

Crustal thickness $H_0 = 35$ km, crustal velocity $v_0 = 6.1$ km/s. Thickness Moho-Low Velocity Upper Interface $H_1 = 85$ km with a velocity $v_1 = 8.2$ km/s.

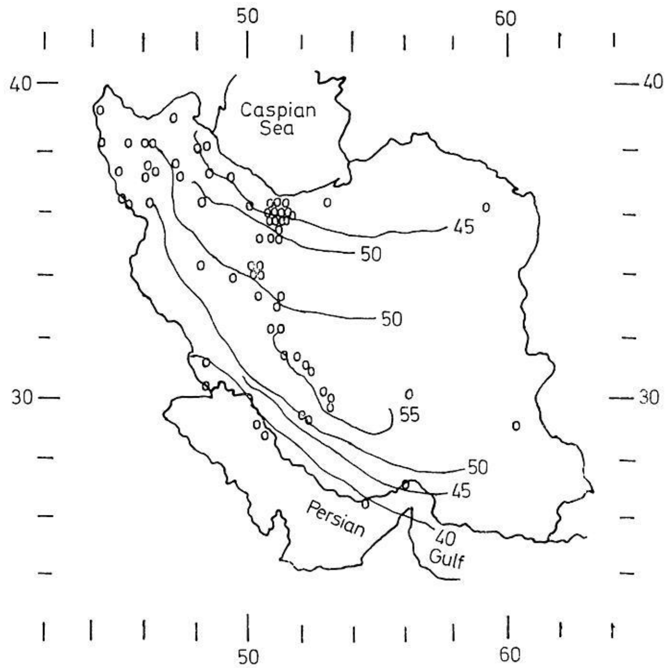

Fig. 4. Contours of crustal thickness (in km) based on the Bouguer anomaly

Thickness Low Velocity Upper Interface and 300 km depth, $H_2 = 180$ km with a velocity $v_2 = 8.13$ km/s.

Which is consistent with results from Jacob, 1971, we have calculated several models to explain the travel time anomalies at the stations. For $v_0 = 6.1$ km/s $H_0 = 45$ km, $H_1 = 75$ km and $v_1 = 8.2$ km/s under all stations, we can express the anomalies in terms of low-velocity channel. We find that:

$v_2 = 8.10$ km/s for the Shiraz Station
$v_2 = 7.75$ km/s for the Tehran and Kermanshah Stations
$v_2 = 7.56$ km/s for the Tabriz Station
$v_2 = 7.34$ km/s for the Meshed Station

We assume but now that the travel time absolute anomalies are caused within the crust and we calculate the velocity in the crust under the stations. On the basis of the same reference model and for $H_0 = 45$ km, $v_1 = 8.2$ km/s, $v_2 = 8.13$ km/s beneath all stations, we can explain the anomalies at the stations in terms of different crustal velocity v_0 as:

$v_0 = 6.03$ km/s for the Shiraz Station
$v_0 = 5.26$ km/s for the Tehran and Kermanshah Stations
$v_0 = 4.97$ km/s for the Tabriz Station
$v_0 = 4.61$ km/s for the Meshed Station

The $+0.7$ to $+1.9$ s smaller travel time residual at Shiraz Station means that the reason of smaller residual at Shiraz Station can be the different crustal velocity or the different upper mantle velocity under stations. The Shiraz Station indicates higher velocity with respect to other stations.

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Dr. B. Akasheh
Institute of Geophysics
Tehran University
Amir-Abad-Bala
Tehran/Iran