Geophys. J. Int. (1999) 136, 4'_ 1-430

The crustal and upper-mantle structure of the interior Arabian platform

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Accepted *1998* September *29.* Received *1998 July 20:* in original form *1997* August *19*

SUMMARY

The crustal and upper-mantle velocity structure of the interior Arabian platform is derived using the spectral analysis of long-period P-wave amplitude ratios. The ratio of the vertical to the horizontal component is utilized to obtain crustal transfer functions using the Thomson-Haskell matrix formulation for horizontally layered crustal models.

20 earthquakes recorded at the long-period station RYD between azimuths N20'W and ti 150¯E were selected for the analysis based on the following criteria: focal depths in the range 5 to 215 km, body-wave magnitudes greater than 5.0, and epicentral distances in the range 7' to 97'.

A careful quality check of the data left us with six events, out of 29, that had short epicentral distances (<20~) to be analysed. The selection criterion for the final model in the forward modelling process was based on the correlation coefficient between observed and theoretical transfer function. The model suggested that the crust consists of five distinct lavers. The upper crustal laver has a P-wave velocity of about 5.6 km s^{-t} and is about 3 km thick. The second layer has a velocity of about 6.3 km s^{-i} and is 10 km thick. The third laver has a velocity of 6.6 km s^{-t} and is 8 km thick. The fourth layer has a velocity of 6.9 km s^{-t} and is 15 km thick. The lower layer has a velocity of about 7.6 km s¯' and is 10 km thick. For the Mohorovicic discontinuity, a velocity of 8.3 km s^{-i} for the upper mantle and 46 km depth are indicated.

Key words: Arabian platform, Arabian shield, crustal structure, Riyadh, spectral analysis, upper mantle.

INTRODUCTION

Seismological studies have shown that the interior of the Earth can be divided into several distinct layers. For many purposes. the crust and the upper mantle may be considered as a system of horizontal layers that act as a cascaded filter in affecting the seismic energy arriving at a given station. Consequently. the motion recorded at the Earth's surface depends not only on the characteristics of the existing seismic energy and the recording instrument, but also on the elastic parameters and thicknesses of these layers.

The first attempt to investigate the structure of the whole Earth from transmission times of earthquakes was by Oldham in 1906 (Gutenberg 1953). who investigated the surface amplitudes and polarizations of incident SV vxaves and the amplitudes of the SH components from the recorded S waves. assuming that the crust and upper mantle could be represented by a simple half-space model. Sezcwa & Kanai (193[7]) attempted to calculate the theoretical response of crustal structure.

The spectral analysis of long-period data in the 1950s and 1960s was the major subject in crustal structure studies. The theoretical background of the spectral analysis method was presented by Thomson (1950) and Haskell (1953) as a matrix formulation. This formulation provides the calculations of responses of any number of horizontal layers to incident plane waves at any angle of incidence, by using products of 4 x 4 matrices. whose elements are functions of the parameters of each layer and boundary conditions. In addition, this method has been widely used in studying the parameters of the crust and in examining the erect of surface layers on amplitude.

Phinnev (1964) used Haskell's matrix method to calculate the spectral response of a layered crust to compare observed long-period P-wave spectra from distant earthquakes recorded at Albuquerque and Bermuda. Hannon (1964) used the Thomson-Haskell method to compute the synthetic surface motion due to dilatational waves striking the base of a layered system. He constructed theoretical seismograms from the transmission coefficients of crustal models.

Using the matrix method, Fernandez & Carrega (1968) determined the crustal thicknesses for the central United States and La Paz, Bolivia. They averaged several observations and obtained a crustal thickness of 4" km in the central United States. with a P-wave velocity of 6.6 km s^{-1}. For the Bolivian

Andes at La Paz, they obtained a crustal thickness of *64 km.* and a P-wave velocity of 6.7 km s`\`. Their results agreed with others determined using independent methods. They concluded that in order to use the P-wave spectra in all determinations. earthquakes of magnitude 6 and above may be 'used at epicentral distances of 2000 to 6000 km. The focal depths are not critical. and shallow-depth earthquakes may be used but deeper events are preferable. Turkelli (1984) made use of the digital P-wave data of ANTO station to determine the crustal structure in central Anatolia using the matrix formulation. His results were consistent with those determined from the traveltime data of Turkish earthquakes. More recently, AI-Amri, Necioelu & Mokhtar (1996) used the spectral analysis technique of P-wave data to investigate the crustal structure of the central Arabian Peninsula.

One of the most widely used technique to determine crustal structure on a regional scale is the receiver function (Owens & Zandt 1985). There have been many attempts at finding more robust methods of inverting receiver functions, such as fast simulated annealing (Zhao & Frohlich 1995). Sandvol *et al.* (1998) applied the receiver function deconvolution technique on nine broad-band stations in the Arabian Shield to isolate the receiver-side PS mode conversion.

Not many seismic studies have been carried out on the Arabian platform. and this study serves as a useful geographical augmentation to the 1978 seismic refraction profile. The refraction line extended a few kilometres into the platform, but not far enough to constrain the structure of the platform reliably. Consequently, the purpose of this study is to determine the crustal and upper-mantle structure of the eastern Arabian platform (interior platform) from spectral analyses of long-period P waves. To achieve our objectives, suitable earthquakes recorded between 1985 and 1993 at the seismologicalgeophysical observatory of the King Saud University, Riyadh have been utilized. The analyses are based on the matrix method of Thomson-Haskell. in which theoretical spectra obtained from horizontally layered earth models have been compared with observed spectra.

GEOLOGY AND CRUSTAL STRUCTURE OF THE ARABIAN PLATFORM

The surface geological and tectonic settings of the Arabian plate consist mainly of (1) the Arabian shield in the west and (2) the Arabian platform in the east. The platform consists of Palaeozoic and Mesozoic sedimentary rocks that unconformably overlie the shield and dip very gently and uniformly to the ENE towards the Arabian Gulf (Powers er al. 1966).

The accumulated sediments in the Arabian platform represent the southeastern part of the vast Middle East basin that extends eastwards into Iran, westwards into the eastern Mediterranean, and northwards into Jordan, Iraq and Syria (Fig. 1).

The Arabian shield isolated the Arabian platform from the north African Tethys and played an active palaeogeographical role through the gentle subsidence of its northern and eastern sectors during the Phanerozoic. allowing almost 5000 m of continental and marine sediments to be~deposited over the platform. This accumulation of sediments represents several cycles from the Cambrian onwards; and now forms a homocline dipping very _gently away from the Arabian shield (Powers *et al.* 1966).

Several structural provinces can be identified within the Arabian platform:

(1) an interior homocline in the form of a belt about 400 km wide, in which the sedimentary rocks dip very gently away from the shield outcrops;

(2) an interior platform, up to 400 km wide, within which the sedimentary rocks continue to dip regionally *away* from the shield at low angles:

(3) intra-shelf depressions, found mainly around the interior homocline and interior platform (Powers *et al.* 1966).

Unfortunately. no locally recorded earthquake data have been used by previous authors to determine the crustal charac teristics of the Arabian platform. Most. if not all, of the crustal structure studies conducted in Saudi Arabia have been based on the 1978 Saudi Arabian seismic refraction profile. The profile was recorded by the US Geological Survey along a 1000 km line across the Arabian shield and the western margin of the Arabian platform (Mooney *et al.* 1985: Prodehl 1985). The seismic crustal structure of the Arabian peninsula has been investigated using surface signal observations and tele seismic earthquakes. Studies of shear waves on the path Addis Ababa-Shiraz (which passes through the Afar depression) have shown that the average crustal thickness for this region is about 35 km (Niazi 1968; Knopoff & Fouda 1975).

Mooney er al. (1985) applied the 2-D ray-tracing technique to analyse the crustal structure beneath the Arabian shield and platform. The general features of their results are as follows: the Arabian shield is composed, to first order, of two layers, each about 20 km thick, with average velocities of about 6.3 and 7.0 km s-', respectively.

Badri (1991) derived a crustal velocity model for central Saudi Arabia using spectral amplitude ratio (SAR) and pulse broadening method (PBAvI) techniques. His model shows that the crust consists of four distinct layers: it has a total thickness of 42 km under the Arabian platform near Riyadh (Fig. 1) and thins gradually to the southwest to about 38 km thick under the shield (250 km southwest of Riyadh). The upper layer has a P-wave velocity of about 6.1 km s-' and is about 3 km thick. The second layer has a P-wave velocity of about 6.2 km s-t and is about 14 km thick. The third crustal layer has a velocity of 6.4 km s-' and is 10 km thick. The lower crust has a velocity' and thickness of 6.85 km s-' and 15 km. respectively.

More recently, Mokhtar, Maamoun & Al-Amri (1992) used the earthquake data of a single station located inside the Arabian peninsula (RYD) and three WWSSN stations (JER. SHI. and TAB) in the surrounding areas. Their results indicate that inversions of both Love- and Rayleigh-wave group and phase velocities in the Arabian platform are comparable in their thickness to those of the shield, but with shear velocities of 3.4 km s-' and 4.0 km s-' respectively. The crustupper-mantle boundary is at a depth of about 45 km. The sedimentary sequence covering most of the Arabian platform has an average thickness of 5 km and its shear velocity is 2.31 km s-'. Its thickness increases towards the east under the interior platform and basins, where it is 7 km on average and consists of two layers-an upper 3 km with a shear velocity of 2 km s- t and a lower 4 km with a shear velocity of 3.24 km s-'.

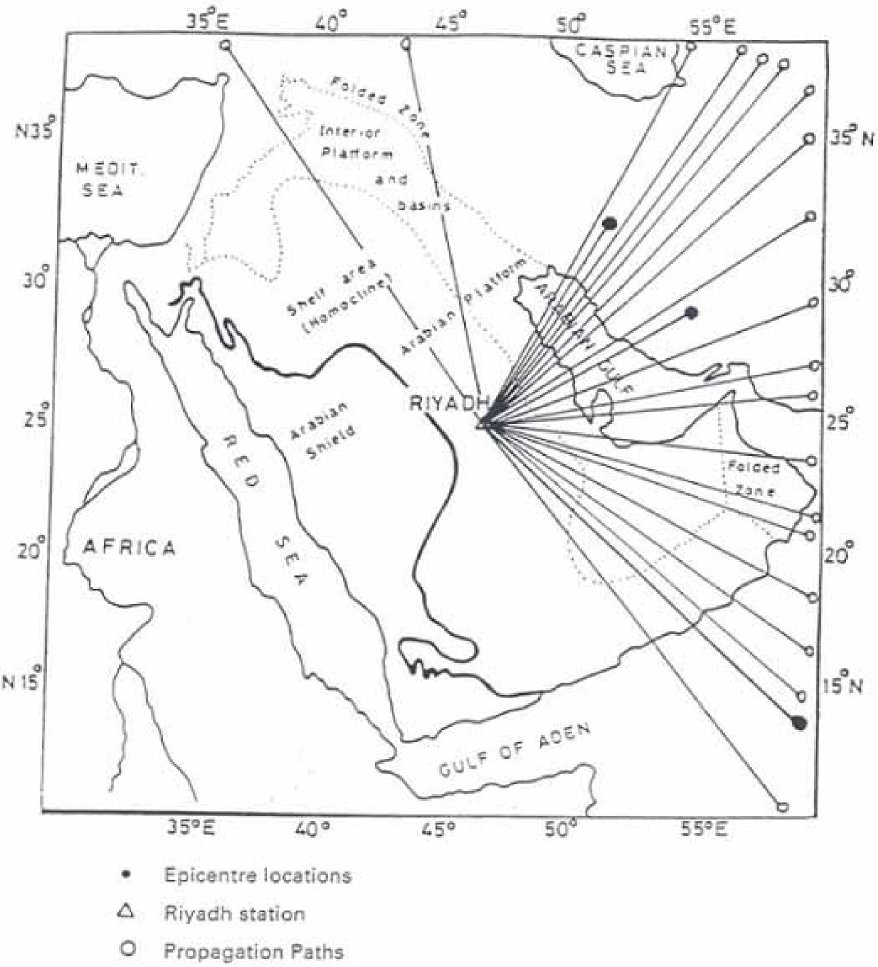

Figure 1. Location map of the Arabian Peninsula showing the propagation paths from various epicentres to RYD station.

CALCULATION OF THE THEORETICAL AND OBSERVED SPECTRA

Calculation of the spectra

The digitized data were analysed using the PITSA program of the IASPEI package (1992). The three seismogram components (Z. N-S, and E-W) for each earthquake were treated identically. The frequency range of 0.0006 to 0.2 Hz is consistent with the RYD long-period components (narrow band), and 0.0166 to 2.0 Hz is consistent with intermediate-period components (wide band). The total system response of RYD is broad band (0.01 to 33 Hz). The traces were filtered with a bandpass filter whose corner frequencies matched the instrument response curves. This eliminated the effect of signal components outside the pass band of the systems. The two horizontal components were then rotated along radial and transverse directions. Hamming window was applied to minimize the later arrivals after the P wave.

The effect of different model parameters on the theoretical spectra was tested by first keeping the thickness of the first layers and angle of emergence constant and varying the velocities. Next the velocities and angle of emergence were kept constant, but the thicknesses varied: finally, thicknesses and velocities were kept constant and the angle of emergence varied. Variations of theoretical transfer function ratios with angle of emergence. velocity and thickness are discussed in later sections.

This initial model was derived by allowing both layer velocities and thicknesses to vary until a theoretical model was reached which fitted the observed data. Minor changes had to be made to the parameters to obtain the best correlation coefficients. However, these variations were constrained by lithological conditions. The addition of a thin layer up to 2 km thick with a P-wave velocity of 5.7 km s^{-1} at the top of the model gives a better correlation. Only layers with a thickness greater than 3 km have an effect (Al-Amri 1998). Near-surface layers are not affected by long-period spectral ratios (Phinney 1964).

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Theoretical assumptions and errors

The technique used in this study requires theoretical assumptions, as do many other geophysical methods. If the assumptions regarding the vertical velocity gradient and lateral velocity variations should be considered, then the solution of the elastodynamic equation becomes very difficult to solve if not impossible. The vertical velocity gradient is taken into account by constructing a model with many layers with constant velocities. It is generally assumed in earth models that the layers are horizontal. homogeneous and isotropic. In reality, though. dipping layers are present and may influence the crustal transfer functions. Some of the discrepancies between the observational and theoretical curves may be due to this effect.

The purpose of the transfer function is to derive the amplitude and phase of ground motion from the recorded signal or to predict the characteristics of a recorded signal that will result from a given input of ground motion. This transfer function is a function of the angle of emergence of the P waves at the bottom of the crust and the characteristics of the propagation path. The assumptions made regarding the theoretical properties of the transfer ratio are as follows.

(1) A thin low-velocity surface layer has no effect on the crustal peaks. Only layers with a thickness greater than 3 km have an effect. Phinney (1964) states that long-period spectral ratios are insensitive to near-surface crustal layering.

(2) The effects of intermediate and deep crustal structure can be isolated in the behaviour of the crustal peaks in the transfer ratio. The upper frequency limit of 0-2 Hz is sufficient to include all frequencies that can reasonably be investigated using standard lon,g-period recordings. The frequency range of 0.006 to 0.2 Hz is consistent with the RYD long-period recordings (narrow band).

Another possible source of error is introduced by the procedure to digitize the analogue seismogram. Owing to the incoherent flow of the ink, the trace width in the analogue recording may vary over time, so the digitizer could produce unwanted steps in the digitized seismogram. Second, because of the non-linear behaviour of the pen the seismic signals are often distorted, especially if the amplitude of the signal is large. Finally, the recording speed may not be constant with time. as a result of drifts in the driving motor of the recording drum. This could cause an apparent change in frequency of the seismic signal. Superposition of the inter-reflection in the source crust of the P-wave motion may have an influence on the computed P-wave spectra. This effect can be minimized by working with earthquakes whose foci are beneath the crust. In this study, reverberations of this kind riding over the P phase have not been observed.

The variations in the thickness of the trace can introduce errors both in amplitude and time. This effect was minimized by adding the traces after digitization. There is an unknown distortion introduced into the records during recording and digitization. This distortion can be written as

$$_{Pt)} = g(t) + e(r).$$

Table 1. List of earthquakes recorded between azimuths N20'W and N150'E.

LOC			DATE O.T.				COORD.			DEP MAG DIST			B AZ T-OFF EMER		
	D	M	Y	H	M	S	LAT	LON	KM	MB	MS	DEG	DEG	DEG	DEG
IRAQ	25	07	88	07	58	42.2	42.2 0	35.94	99	5.0	5.2	11.2	357	55	4
ARME	7	12	88	7	41	242	40.99	44.19	5	6.2	6.8	16.3	353	51	40
ARAB	14	12	85	18	13	31.5	14.71	58.00	10	5.5	5.0	15.0	130	39	4.
BONI	8	11	85	18	40	24.8	27.96	140.61	42	5.8	6.1	82.1	62	18	15
MOLL'	14	8	86	19	39	13.6	1.79	126.52	33	6.6	7.2	80.1	92	18	15
FOX	5	1	87	12	11	55.7	52.45	169.38	33	6.1	6.7	97.0	21	16	13
KAMC	19	1	87	6	47	4.3	54.74	163.28	42	5.4	5.2	84.1	31	17	14
HONS	6	2	87	12	23	4.8	36.99	141.79	36	5.9	6.1	79.4	54	19	15
HONS	7	4	87	0	40	43.4	37.36	141.80	29	6.4	6.6	79.3	53	19	1:
CHIN	30	4	87	5	17	3.7	39.76	74.57	8	5.7	5.6	27.9	50	33	27
BURM	18	5	87	01	53	05.1	25.27	94.20	50	5.7	5.9	43.0	78	29	24
KAZA	17	7	87	01	17	07.0	49.80	78.11	10	5.8	0.0	35.0	36	28	17
PAK1	10	8	87	10	52	19.9	29.87	63.84	165	5.6	0.0	16.1	67	51	40
KAMC	6	10	87	20	11	35.1	52.96	159.97	34	6.1	6.3	83.5	33	18	14
IRAN	30	3	88	2	12	42.8	30.89	50.19	33	5.4	5.7	6.9	26	58	45
AFGH	26	9	88	7	17	0._	36.29	71.37	107	5.6		24.2	55	35	29
KURL	9	1	89	13	42	36.4	49.99	153.48	14	6.0	6.4	83.0	41	18	15
MOLL	10	2	89	11	15	24.6	2.31	126.76	44	6.2	6.8	80.1	92	i8	I5
KLRL	II	4	89	3	56	36.9	49.49	159.15	16	6.3	6.6	85.0	37	17	14
XING	17	4	90	1	59	33.4	39.4	74.90	33	6.0	6.2	28.0	51	33	27
SAKH	12	5	90	4	50	8.0	49.04	141.85	600	6.5		75.0	42	20	16
IRAN	6	11	90	13	45	512	28.25	55.46	1 1	6.2	6.7	8.7	64	57	44
KUSH	31	1	91	23	3	33.6	35.99	70.42	142	6.4	0.0	23.4	55	36	29
MINA	20	6	91	5	13	52.5	1.20	122.79	31	6.2	7.0	76.9	94	20	16
TIMO	04	7	91	11	43	10.4	-8.10	124.68	29	6.2	7.0	82.6	102	18	15
AFGH	14	7	91	9	9	11.9	36.33	71.12	213	6.4	0.0	24.0	55	35	29
KL'RL	22	12	91	8	43	13.4	45.53	151.0²_	25	6.3	7.4	82.1	43	i8	15
MIND	17	5	92	9	49	19.1	7.24	126.64	33	6.2	7.1	78.0	87	19	16
KUSH	09	8	93	12	42	48.1	36.38	70.86	215	6.2	0.0	23.3	55	25	29

where $f(t)$ is the digitized record, $g(t)$ is the true ground motion, and $e(t)$ is the error introduced during recording and digitizing.

EARTHQUAKE DATA TREATMENT

The seismographic station in Riyadh (RYD), at King Saud University is a 12-channel station that has been operating since January 1985. The sensors, which consist of three Teledyne Geotech S-13 short-period and three SL-200 long-period seismometers, are located on Jurassic limestone at 3 m depth (Sinno *et al.* 1986). The total system response is broad band, extending from around 0.03 to 100 s period.

The local bulletins of King Saud University's observatory and monthly listings of the Preliminary Determination of Epicenters (PDE) of the US Geological Survey were used for the preliminary selection of earthquakes. The earthquake source parameters, hypocentral coordinates, origin times, magnitudes, and depths were taken from the PDE and observatory monthly listings. These source parameters, together with the station coordinates, were used as input for the computer program of Herrmann (1978) to calculate the epicentral distance, azimuth, backazimuth, *P*-wave arrival time and angles of incidence of *P* waves.

Earthquake selection started by reviewing the available microfilm cassettes to determine if the selected events had been recorded by RYD and what the quality was of these records. The second step was to view the seismograms. Only 70 out of the 420 events were clearly recorded at RYD during the period 1985 to 1993. Owing to the low signal-to-noise ratio of RYD at times, as well as to clipping of the traces due to large amplitudes and a malfunctioning component, the number of selected events was reduced to only 18. Therefore, in order to increase the number of selected events, the epicentral distance range was enlarged to be from 7° to 97° (from Iran, Fox and Kurl islands) and the focal depth allowed to be as shallow as 5 km (from Armenia) as long as the *P*-wave onset was very clear and there was no interference from other phases. During the reviewing process, a few near events which fulfilled the requirements of our study were added, resulting in 29 very good events. The list of the earthquakes is given in Table 1.

Digitization of seismograms

Long-period three-component (Z, N–S, and E–W) seismograms from RYD were digitized by hand using a high-resolution 0.0005" Numonics AccuGrid digitizer. A Sigma Scan PC program (IASPEI 1992) was used for hand digitization, channel by channel. With application of this program, there is no need to do any seismogram coordinate corrections. The digitization includes several steps: seismogram preparation and manipulation; calibration of the seismogram for time and amplitude scales; and digitization of the traces and related time marks. The length of the digitization window is not less than two minutes with three time marks, and is the same for all three components. Several tens of points per wave were digitized to minimize the folding effect (to increase the Nyquist frequency $Nq = 1/2t$, where 't' is the digitizing interval). The sampling rate of 4.26 s^{-1} (512 points × 1/20 s) of real time gives a Nyquist frequency of 2.14 Hz, which is above the frequency range for long-period spectral ratio studies. This means that the Nyquist frequency cannot cause aliasing.

Digitization usually started at the first minute mark prior to *P* onset (at least 30 s earlier than the first *P*-wave arrival time) and continued until the third minute mark after the *P*-wave portion of the signal. Fig. 2 shows RYD long-period analogue seismograms before the digitization procedure. Digitized long-period seismograms from RYD are given in Fig. 3.

RESULTS AND INTERPRETATION

The generation of the theoretical spectra requires an earth model. The cross-correlation method has been utilized to develop theoretical models to compare with the observed crustal transfer functions of the analysed events. The previously determined models (Mooney *et al.* 1985; Badri 1991; Mokhtar *et al.* 1992) have been used as a preliminary model to test the correlation between the theoretical and observed spectra. It is assumed that there are no lateral variations in the velocity structure. The initial model, modified from previous models, assumes that the crusts consists of five layers with a total thickness of 42 km. Standard deviations of upper and lower layer thicknesses vary between ±2 km and ±3 km, respectively. Al-Amri (1998) has indicated that the layer thickness and velocity for the western Arabian platform can be resolved within 3 km and 1 km s^{-1}, respectively.

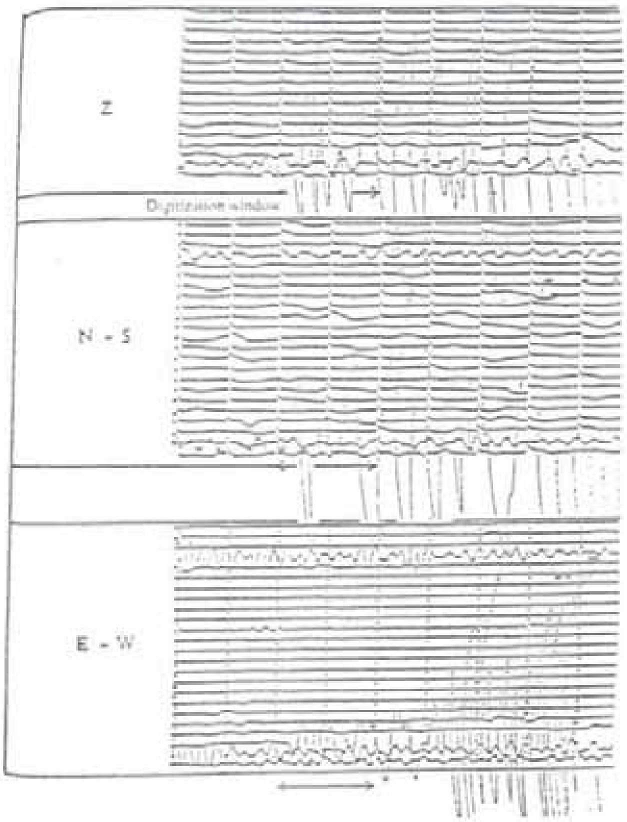

Figure 2. RYD long-period analogue seismograms for the 1988 December 7 Armenian earthquake.

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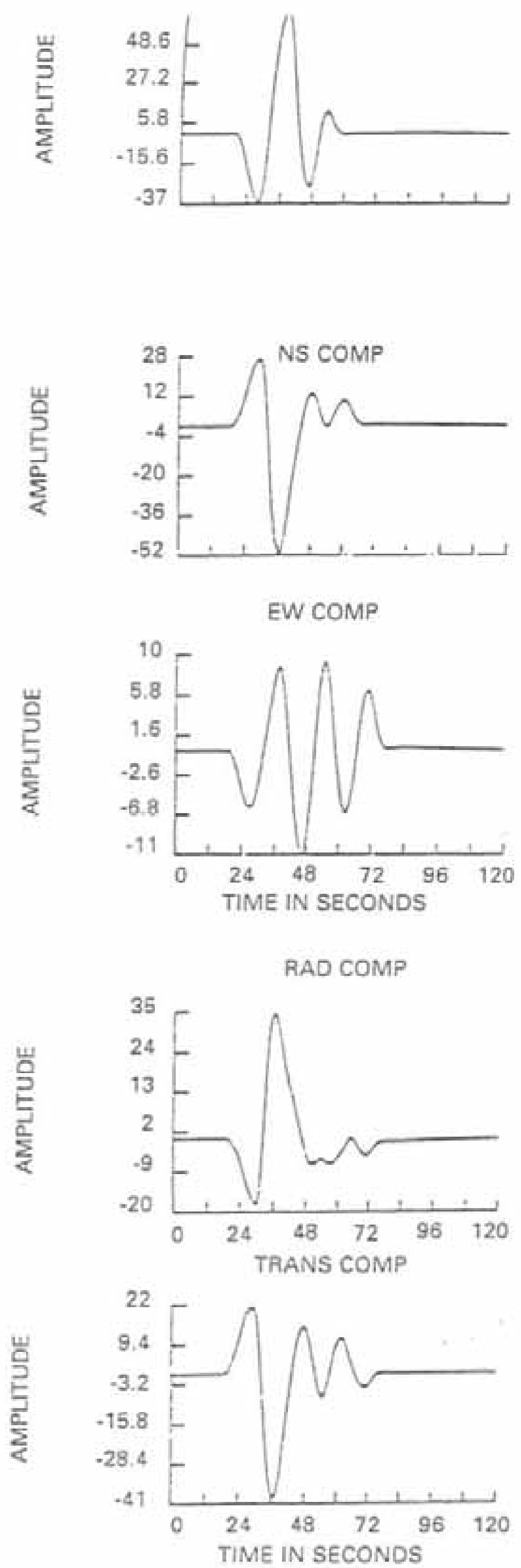


Figure 3. Re-plot of the digitized RYD long-period seismograms for the 1988 December 7 Armenian earthquake.

The input model in Figs 4, 5 and 6 assumes a crustal thickness of 30 km, a *P*-wave velocity of 6.5 km s^{-1} and an angle of emergence of 24°. By decreasing the *P* wave velocity from 6.5 to 5.5 km s^{-1} and keeping the other two parameters constant (Fig. 5), the frequency peak stays at 0.14 Hz. Low angles of emergence (12°) in Fig. 4 move the frequency peak from 0.14 to 0.13 Hz, and there is a slight shift in the case of high angles of emergence (34°). On the other hand, increasing the thickness from 30 to 40 km results in two more peaks and shifts the frequency peak appreciably from 0.14 to 0.1 Hz, or from 0.14 to 0.19 Hz when the thickness is decreased from 30 to 20 km. Figs 4, 5 and 6 show an appreciable decrease of the spectral amplitude ratios in the case of higher velocities (7.5 km s^{-1}) and thicker crust (40 km). This decrease reaches up to 50 or 30 per cent in the case of high (34°) or low (12°) angles of emergence, respectively.

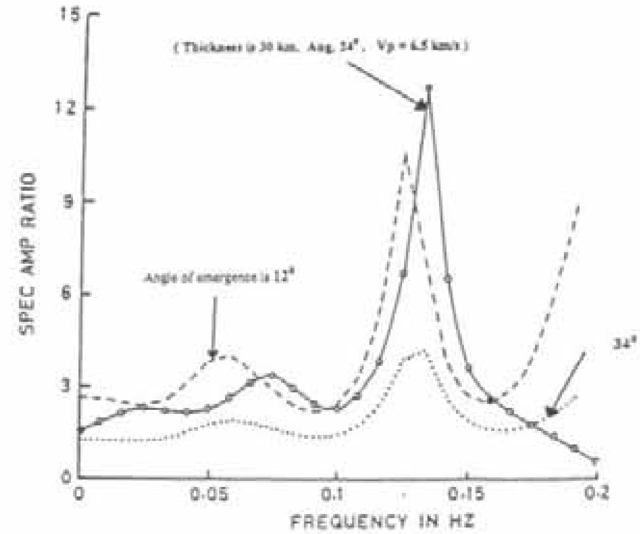


Figure 4. The theoretical transfer function ratio variations with respect to the angle of emergence.

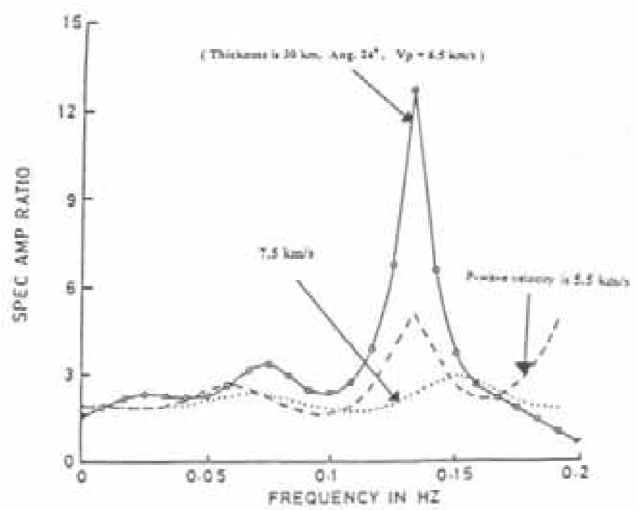


Figure 5. The theoretical transfer function ratio variations with respect to the *P*-wave velocity.

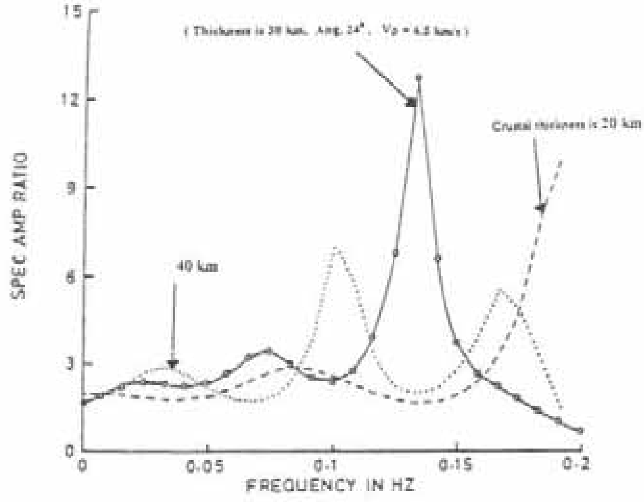
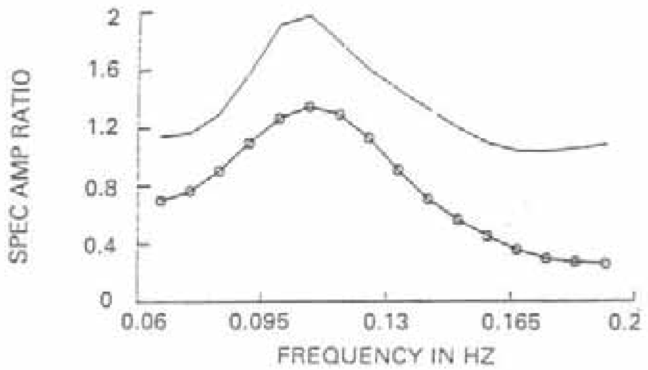


Figure 6. The theoretical transfer function ratio variations with respect to the crustal thickness.

Generally, by comparing the peak positions of the observed and theoretical spectral curves, we can resolve the crustal thickness and velocity within 3 km and 1 km s^{-1} respectively of the observed values. The sensitivity of the transfer functions to the changes of model parameters indicates that the peak at the lowest frequency is directly related to the total thickness of the crust. Thicker crust shifts the position of the peak to lower frequencies. A peak response at 0.1 Hz is shifted towards higher frequencies (Fig. 6). This may indicate a thinner crust under the shield. However, there is another peak for some events with less than 60 per cent cross-correlation coefficients between the theoretical and observed spectra. This could be due to the contamination of *P* waves when the epicentre is at a large distance or to complications from the nearby earthquake *pP* phases. The model parameters were perturbed within the constraints imposed by different tectonics and the geological difference between the Arabian shield and Arabian platform.

There were 29 events from Romania, Armenia, Turkey, Iraq, Iran, Pakistan, Afghanistan, China, Indonesia, Japan, Philippine Islands and the Arabian Sea within the azimuth range of N20°W–N150°E. The epicentral distances varied in the range 7° to 97°, as shown in Table 1. Only six events were selected, from among those with the highest correlation coefficients (above 0.85). The models and spectral plots of these six events are illustrated in Figs 7 to 12. Spectral analysis

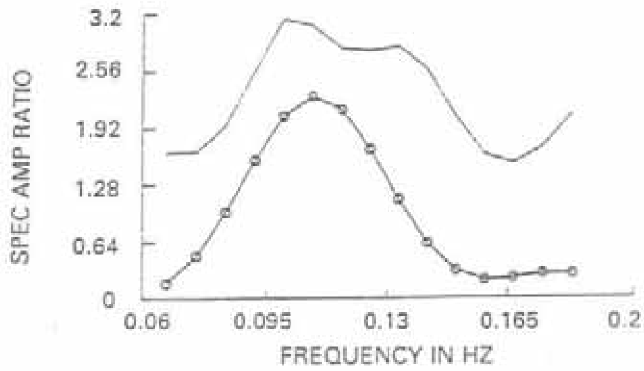


EPI COORDINATES	25.24 N, 55.37 E
DISTANCE	8.6°
BACK AZIMUTH	64°
DEPTH	18 KM
MAGNITUDE(m_b)	5.4
ANGLE OF EMERGENCE	44°

THICKNESS (KM)	P VELOCITY (KM/S)	DENSITY (GM/CM^3)
2	5.6	2.1
8	6.6	2.3
7	6.7	2.5
17	7.05	2.7
11	7.6	2.90
999.00	8.30	3.08

CORRELATION COEFF= .93

Figure 7. Plots of theoretical and observed spectral ratios for the earthquake of 1990 November 6 (Iran) and relevant information, together with the crustal model obtained. Open circles and solid lines represent observed and theoretical curves, respectively.

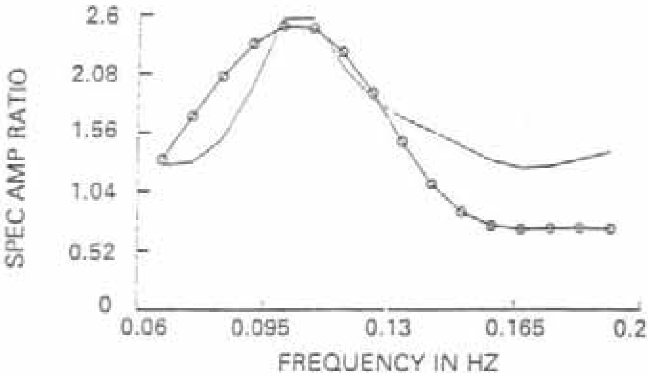


EPI. COORDINATES	36.33° N, 71.12° E
DISTANCE	24.0°
BACK AZIMUTH	55°
DEPTH	213 KM
MAGNITUDE(m_b)	6.4
ANGLE OF EMERGENCE	29.°

THICKNESS (KM)	P VELOCITY (KM/S)	DENSITY (GM/CM^3)
1	5.7	2.1
9	6.5	2.3
8	6.6	2.5
14	6.85	2.7
11	7.35	2.90
999.00	8.2	3.08

CORRELATION COEFF= .90

Figure 8. Plots of theoretical and observed spectral ratios for the earthquake of 1991 July 14 (Afghanistan) and relevant information, together with the crustal model obtained. Open circles and solid lines represent observed and theoretical curves, respectively.

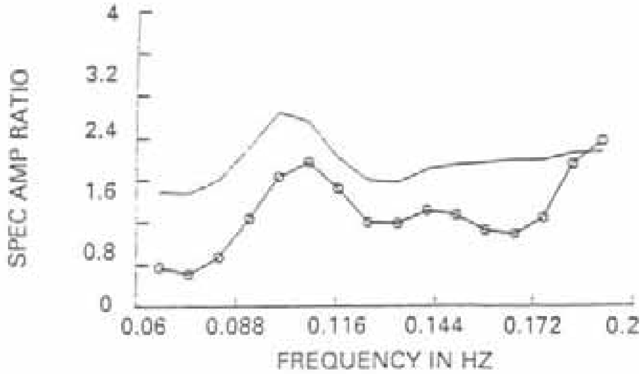


EPI. COORDINATES	39.71° N 39.60° E
DISTANCE	16.1°
BACK AZIMUTH	340°
DEPTH	27 KM
MAGNITUDE(m_b)	6.2
ANGLE OF EMERGENCE	40°

THICKNESS (KM)	P VELOCITY (KM/S)	DENSITY (GM/CM^3)
2	5.6	2.1
10	6.2	2.3
6	6.7	2.5
15	6.9	2.7
10	7.45	2.90
999.00	8.2	3.08

CORRELATION COEFF= .87

Figure 9. Plots of theoretical and observed spectral ratios of the earthquake of 1992 March 13 (Turkey) and relevant information, together with the crustal model obtained. Open circles and solid lines represent observed and theoretical curves, respectively.



EPI.COORDINATES	35.99°N 70.42°E
DISTANCE	23.4°
BACK AZIMUTH	55°
DEPTH	142KM
MAGNITUDE(m_b)	6.4
ANGLE OF EMERGENCE	29°

THICKNESS (KM)	P VELOCITY (KM/S)	DENSITY (GM/CM^3)
1	5.7	2.1
9	6.1	2.3
9	6.55	2.5
12	6.8	2.7
11	7.55	2.90
999.00	8.30	3.08

CORRELATION COEFF= 0.96

Figure 10. Plots of theoretical and observed spectral ratios for the earthquake of 1991 January 31 (Kush) and relevant information, together with the observed crustal model. Open circles and solid lines represent observed and theoretical curves, respectively.

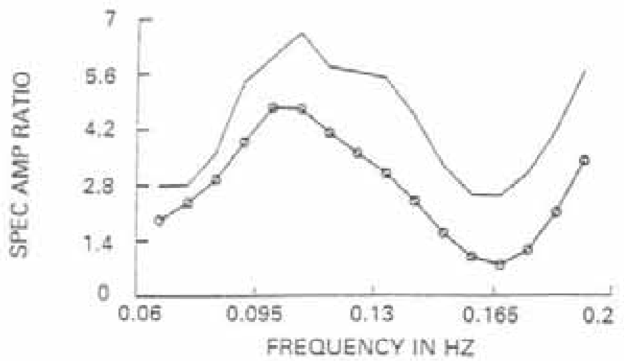
of the selected earthquakes shows a range of P velocity from 5.35 to 5.85 km s^{-1} for the first 3 km depth. This velocity range represents unconsolidated sedimentary material underlain by a thicker layer with higher P velocity. The thickness of the second layer ranges from 7 to 11 km, with the P velocity ranging from 6.10 to 6.50 km s^{-1}, which represents the upper basement rocks. The third layer has a velocity range from 6.35 to 6.70 km s^{-1}, with the thickness varying between 5 and 8 km. The fourth layer has a velocity range from 6.8 to 6.95 km s^{-1}, with the thickness varying between 12 and 17 km. The lower crustal velocity has a range from 7.40 to 7.55 km s^{-1}, with the thickness varying between 10 and 11 km. Most models indicate a transition zone between the lower crust and upper mantle at a depth of about 46 km with a P-wave velocity of 8.30 km s^{-1}. The difference in crustal structure is reasonable for the study area of about 250 km radius centred in Riyadh.

Comparison of the seismically defined features with surface geology and other geophysical data shows good correlation and a consistent model of the crust. Compared with previous crustal models (Mooney *et al.* 1985; Prodehl 1985; Badri 1991; Mokhtar *et al.* 1992; Al-Amri 1998), this study suggests a 4 km increase in the total crustal thickness towards the north-east between the interior (46 km) and homocline (42 km) of the Arabian platform. A slight increase of 0.1 km s^{-1} in the upper-mantle velocity was found in the interior Arabian platform (8.3 km s^{-1}).

Mooney *et al.* (1985) mapped the basement surface beneath the sediments of the western Arabian platform (beneath shot-point 1) and indicated that the thickness of the accumulated sediments was about 1.75 km. This study suggests a 3 km thickness of surficial sediments, which is in good agreement with the result obtained by Sandvol *et al.* (1998). This depth is also in good agreement with the depth to basement found from oil exploration wells in the Riyadh region (Peterson & Wilson 1986), which also found the basement to be at 3 km.

The results of this study are, however, slightly different from those obtained by Mokhtar *et al.* (1992). They indicate that the P-wave velocity of the uppermost layers along the path from southern Iran to RYD reaches 5.27 km s^{-1} at 3 km depth and 5.9 km s^{-1} at 17 km depth, and the average thicknesses of the upper and lower crust of the platform are both about 20 km. The upper-mantle velocity ranges between 7.4 and 7.49 km s^{-1}.

The derived crustal model is calculated using six events from 29 with an epicentral distance of less than 20° from different azimuth ranges. Three of them show 88 per cent correlation coefficient and the other three show correlation coefficient

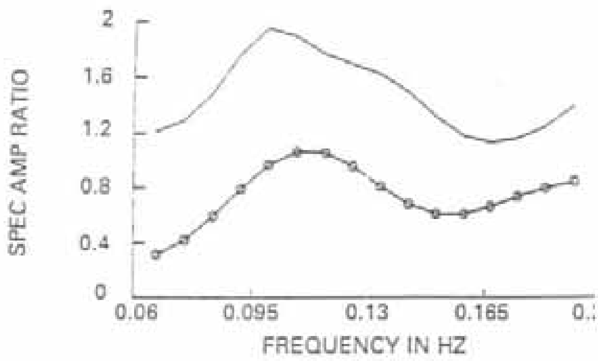


EPI. COORDINATES	52.96° N 159.97° E
DISTANCE	83.3°
BACK AZIMUTH	33°
DEPTH	34 KM
MAGNITUDE(m_b)	6.1
ANGLE OF EMERGENCE	14°

THICKNESS (KM)	P VELOCITY (KM/S)	DENSITY (GM/CM³)
2	5.7	2.1
9	6.1	2.3
5	6.35	2.5
15.00	6.8	2.7
11	7.5	2.90
999.00	8.30	3.08

CORRELATION COEFF= .93

Figure 11. Plots of theoretical and observed spectral ratios for the earthquake of 1987 October 6 (Kamchatka) and relevant information, together with the crustal model obtained. Open circles and solid lines represent observed and theoretical curves, respectively.



EPI. COORDINATES	30.89 N, 50.19 E
DISTANCE	6.9°
BACK AZIMUTH	26°
DEPTH	33 KM
MAGNITUDE(m_b)	5.4
ANGLE OF EMERGENCE	45°

THICKNESS (KM)	P VELOCITY (KM/S)	DENSITY (GM/CM³)
1	5.5	2.1
9	6.1	2.3
8	6.55	2.5
14	6.8	2.7
14	7.80	2.90
999.00	8.2	3.08

CORRELATION COEFF= .88

Figure 12. Plots of theoretical and observed spectral ratios for the earthquake of 1988 March 30 (Iran) and relevant information, together with crustal model obtained. Open circles and solid lines represent observed and theoretical curves, respectively.

between 52 and 78 per cent. The crustal model for the interior platform is shown in Table 2.

CONCLUSIONS

29 distant earthquakes recorded at the long-period station RYD were selected for spectral analysis. Spectral analysis calculations were based on comparing the observed spectral ratios with those computed from theoretical *P*-wave motion obtained using the Thomson–Haskell matrix formulation for horizontally layered crustal models.

The effects of different model parameters on the theoretical spectra were tested. By comparing the peak positions of the observed and theoretical spectral curves, the crustal thickness

Table 2. The crustal structure model for the interior Arabian platform.

Thickness (km)	*P* velocity (km s^{-1})
3.0	5.6
10.0	6.3
8.0	6.6
15.0	6.9
10.0	7.6
999.0	8.3

and velocity can be resolved within 3 km and 1 km s^{-1} respectively of the observed values.

Generally, the resulting model is not unique, due to the theoretical assumption (horizontal layering, constant velocity and density in each layer) in this method and to the complexity of the crustal structure of the earth. The method is easy to apply and requires seismograms from just a single station. The accuracy of this method is based primarily on the quality and frequency band of seismic data and the parameters pertaining to the layered crustal model. The selection of the most suitable model is based on the identification of a theoretical model that exhibits the highest cross-correlation coefficient with the observed transfer function ratio.

The derived model suggests that the crust consists of five distinct layers. The upper crustal layer has a *P*-wave velocity of 5.6 km s^{-1} and it is about 3 km thick. The second layer has a velocity of about 6.30 km s^{-1} and is 10 km thick. The third layer has a velocity of 6.6 km s^{-1} and is 8 km thick. The fourth layer has a velocity of 6.9 km s^{-1} and is 15 km thick. The lower layer has a velocity of about 7.6 km s^{-1} and is 10 km thick. For the Mohorovicic discontinuity beneath the interior Arabian Platform, a velocity and depth of 8.3 km s^{-1} and 46 km respectively are indicated. A strong velocity gradient of about 0.06 km s^{-}` km^{-t} was found in the upper crust and 0.03 km s^{-}' km^{-}t in the lower crust.

ACKNOWLEDGMENTS

I would like to express my thanks and gratitude *to* King .Abdulaziz City for Science and Technology *(KACST)* for funding this project (grant no. 13-46). This work would not have been possible without the generous assistance *of KACST* and KSL'. I am also indebted to Dr Ali A. Gharib and Dr .Altan Necioglu *of* the Seismological Observatory. King Saud University for their tremendous help and for carrying out data processing during the project phases. Grateful acknowledgment *is* also extended to the project referees. Professors M. Barazangi and Zuhair Issa. for their helpful suggestions and criticism.~I owe the project consultant Dr N. Turkelli a deep debt of gratitude and a great deal of thanks for his guidance and continuing advice.

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