Crustal Velocity Structure of Western Iraq from Inversion of Receiver Functions at Anbar Seismic Station

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Abstract
The inversion of the teleseismic P-wave receiver functions was employed to determine the structure of the crust under Anbar broadband seismic station. Some of the computer programs in seismology were used to analyze the receiver functions of nine teleseismic earthquakes. Results of inversion show that the crustal structure (Moho depth) beneath the ANB1 station is 44 km. The sedimentary cover thickness (basement depth) at the ANB1 station is 12 km. In general, the obtained sedimentary cover and crustal thicknesses are consistent with the results of some previous studies in the Mesopotamian plain. As well as the inversion results show that the crustal velocity model beneath the ANB1 station has four distinct discontinuities; the first at 6 km with Vs of 2.83 km/s, the second one at 12 km with Vs of 3.63, the third one at 36 km with Vs of 4.21 km/s, and the fourth one at 44 km with Vs of 4.37 km/s. The obtained velocity model may be employed to locate and relocate the local and teleseismic earthquakes and in moment tensor solutions.

Keywords: Receiver function; Body waves; Crustal structure; Velocity model; Moho

1. Introduction
The crust has a record of the Earth's evolution dating back over 3.4 billion years (Mooney, 2007). The physical state and evolution of the planet are all influenced by the Earth's crust. The structures of the crustal and upper mantle are studied using different geophysical methods, such as seismic refraction and reflection techniques, gravity and magnetotelluric methods. Because the above-mentioned methods are expensive require logistic support and detailed modeling of crustal body wave travel times and amplitudes, the receiver functions (RF) analysis and the surface wave dispersion analysis overcomes most of these difficulties (Saikia et al., 2017). The crustal transfer function ratio method was introduced by Phinny (1964) and used by Hasegawa (1971) to determine the crustal structure beneath Yellowknife, USA. It has evolved into the receiver function analysis technique (Langston, 1979; Ammon, 1991; Dugda and Moazzami, 2020). This technique has based on high-quality broadband and short-period seismograms. The teleseismic P–waveform receiver function analysis has been used to determine the crustal and upper mantle structure beneath different regions around the world, Canada (Vervaet and Darbyshire, 2022), China (Zhou et al., 2009; Chen et al., 2010; Zhang et al., 2021), Egypt (Badawy et al., 2018), Hungary (Kalmár et al., 2019), India (Mitra et al., 2008; Saikia et al., 2017), Iran (Taghizadeh-Farahmand et al., 2010; Afsari et al., 2011), Southern Korea (Chang and Baag, 2005),

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Malaysia (Kieling et al., 2011), Myanmar (New et al., 2021), Norway (Ottemöller and Midzi, 2003), Spain (Ortega and D’Auria, 2021), and Turkey (Alkan et al., 2019). In Iraq, the crustal thickness beneath was estimated for the first time based on gravitational data by utilizing a trial- and- error method (Alsinawi et al., 1987; Al-Banna and Al-Heety, 1996). The crustal structure in different regions in Iraq was determined using the surface wave dispersion technique (Dahham and Mohammed, 1993; Abdulnaby et al., 2012). Many authors employed the receiver function analysis to investigate the crustal velocity model under seismic monitoring stations in Iraq (Alsinawi and Al-Heety, 1994; Al-Heety, 2002; Gök et al., 2008; Abdulla and Abdulnaby, 2020; Abdulnaby et al., 2020; Ramthan et al., 2020). The present study intends to evaluate the crustal velocity structure of western Iraq using inversion of the P-waveform receiver functions.

2. Materials and Methods

2.1. ANB1 Seismic Station

ANB1 seismic station was launched in November 2018 as part of Mesopotamian Network (MP), at University of Anbar campus. With three component digitizers, the ANB1 seismic station is providing with CMG40T/DM24 broadband seismometers. The ANB1 seismic station is located at latitude 33.4018°N and longitude 43.2576°E, (Fig. 1).

![Fig.1](image1.png)

Fig.1. Location of the ANB1 seismic station represented by a red triangle. The yellow squares represent the locations of the major cities (Compiled by authors)

2.2. Tectonic and Geological Setting of Study Area
Tectonically, the area of study is located in the Stable Shelf. The Stable Shelf is a tectonically stable monocline that has been mostly undamaged by Late Cretaceous and Tertiary deformation. The geometry of the underlying basement blocks and faults, Paleozoic epirogenic processes, and Mesozoic arching all influenced the orientations of the structures in this tectonic unit. From west to east, the shelf is presently divided into three major tectonic zones: The Rutba-Jezira, Salman, and Mesopotamian Zones. The study area is located on the stable continental shelf area's western edge of the Mesopotamian zone (Jassim and Goff, 2006). The Mesopotamian zone is divided into three longitudinal units: The Zubair zone, Euphrates zone, and Tigris zone. The Euphrates subzone, where the study area is located, is the shallowest unit in Mesopotamia, but the Quaternary sediments are thicker than those in the Tigris subzone. The sediments and geologic sequence of the study area, from oldest to youngest units (Hussein, 2012): Fatha Formation (Middle Miocene), Dibdibba Formation (Middle Miocene), Injana Formation (Late Miocene), and Quaternary Deposits.

2.3. Receiver Function Method

The crustal structure beneath the ANB1 station was determined using the method of inverting P-wave receiver functions. Herrmann and Ammon's (2002) Computer Programs in Seismology (CPS) were employed for estimating the crustal structure beneath the ANB1 station. The CPS is a collection of more than 155 interactive and shell scriptable software (Herrmann and Ammon, 2002). The main idea of receiver function technique is based on teleseismic P-waves, which provide information about the structure of crust underneath a seismic station (Fig. 1). When body waves travel into the earth's interior, they come into contact with a variety of interfaces. The transmission, reflection and conversions of the body waves at these interfaces depend on the wave's incidence angle and nature of the contact. Moho discontinuity is one of the boundaries at which body waves interact. It marks the mantle-crust border, where the velocities of the P and S waves alter considerably. The waves of teleseismic earthquake propagate in all directions spherically when it occurs. When the body waves hit the Moho discontinuity, they bounce back to the top of the crust where, it will be detected by a seismometer as a P-wave. The P, PpPs, PsPs and PpPs are the reflected waves utilized in the receiver functions technique (Ammon, 1991).

2.4. Data Preparation

The receiver function method was dependent on a set of constraints that must be completed to accurately picture the Earth's interior. High magnitude is one of these characteristics, as it ensures a high signal-to-noise ratio across long distances, and the earthquake must be located between 30° and 90° from the seismic station to ensure that appropriate propagation routes arrive (Rondenay, 2009). As a result, the events from the ANB1 station with magnitudes more than 7 Mw and epicentral distances of 30° to 90° were chosen as appropriate events for this study. The events information (date, origin time, latitude, longitude, magnitude and focal depth) was extracted by the open access to metadata of the European-Mediterranean Seismological Centre (EMSC). It also allows performing customized searching within the database for a certain region. The search was limited to the ANB1 station's operational start date. The ANB1 station was operational from November 2018 to August 2021. The selected earthquakes information is listed in Table 1. The selected teleseismic events distribution is shown in Fig. 2. Many of the earthquakes recorded by the ANB1 station were eliminated from the data set due to the high ambient noise and the difficulty of picking the first break of P-wave (Fig. 3), therefore not all of them could be used. The receiver functions analysis method was used to process nine teleseismic events that satisfied the criteria specified above.
Table 1. Teleseismic events that were used in the inversion of receiver functions of the ANB1 station that are taken from the EMSC site

| Date       | Time (UTC)   | Latitude  | Longitude | Depth (km) | Mw |
|------------|--------------|-----------|-----------|------------|----|
| 20181229   | 03:39:09.740 | 5.89830   | 126.9209  | 60.21      | 7  |
| 20191114   | 16:17:40.582 | 1.61990   | 126.414   | 33         | 7.1|
| 20200213   | 10:33:44.492 | 45.6313   | 148.9293  | 144        | 7  |
| 20200325   | 02:49:20.896 | 48.9688   | 157.6914  | 55.39      | 7.5|
| 20210121   | 12:23:04.237 | 5.00540   | 127.5185  | 80         | 7  |
| 20210213   | 14:07:50.838 | 37.7602   | 141.7196  | 51.89      | 7.1|
| 20210320   | 09:09:44.002 | 38.4754   | 141.6328  | 43         | 7  |
| 20210521   | 18:04:13.557 | 34.5884   | 98.2402   | 10         | 7.3|
| 20211229   | 18:25:51.877 | -7.5924   | 127.5808  | 166.92     | 7.3|

3. Calculating of Receiver Functions

The teleseismic waves that arrive to the broadband seismic station provide information about the source of the event, its course across the mantle, and the localized structure underneath the station. The receiver function method aims to extract the structure of the crust at the receiver by isolating it from the influence of source time functions and near-source structure. The influence of source structure and source and remote structure impacts (Shearer, 2009). The influence of source time functions and near-source structure are removed by the deconvolution technique (Ligorria and Ammon, 1999).

![Fig. 2. Teleseismic events distribution map for the ANB1 seismic station. The yellow stars represent the locations of the events and the red triangle is the location of the ANB1 station](image)
Fig. 3. P-wave receiver function of the 2020/02/13 earthquake (Table 1). R and T represent the radial and transverse components filtered with three values 0.5, 1.0, and 2.5.

The receiver functions for the nine selected events, extending from 30° to 90°, are shown as a function of the back azimuth in Fig. 4. The back-azimuth number assists in identifying the skewness or alignment of events.

Fig. 4. Receiver functions plotted as a function of back azimuth for 9 events recorded by the ANB1 station ranges from 30° to 90°. Overlapping one event with the four events shown.

4. Results and Discussion

The nine receiver functions were inverted to estimate a crustal structure beneath the ANB1 seismic station. Gaussian filter parameters equal to 0.5, 1 and 2.5 were employed in the inversion of receiver functions. The best matching between the observed and the theoretical receiver functions identifies the final velocity model. The velocity model fit to the receiver function is shown in Fig. 5. Results of the nine receiver functions inversion are shown in Figs. 6 and 7 and listed in Table 2.
4.1. Sedimentary Cover Thickness (Basement Depth)

The current study showed that the sedimentary cover thickness beneath the ANB1 seismic station is about 12km. In other words, the basement depth is 12km. The thickness of sedimentary cover under the Karbala (KAR2) seismic station, near the ANB1 seismic station, is 11km (Abdulnaby et al. 2020). The sedimentary cover thickness (basement depth) at ANB1 station is in good agreement with a value of basement depth (12km) carried out by Compagigne General de Geophysique (C.G.G., 1974) using aeromagnetic data, and inconsistent with that estimated by Alsinawi (2006) -7km. This difference may be interpreted in terms of the resolution of the technique used in estimating the basement depth.

![Fig. 5. Model matching to the receiver functions of nine earthquakes recorded by ANB1. The blue curve shows the observed data and the red curve shows the model prediction. Each receiver functions are annotated at the left of each trace with the station name, the Alpha (Gaussian filter parameter), the percentage of fit, and the ray parameter (sec/km); and with year/month/hour/minute at the upper right of each trace. A time scale is also provided.](image)

4.2. Crustal Thickness (Moho Depth)

The obtained results showed that the crust beneath the ANB1 seismic station has 44km-thick. The ANB1 station locates in the margin of the inner unstable platform, the Mesopotamian zone. The average crustal thickness beneath the northern Arabian platform including the study area ranges from 35km at Rutba to 38 km at Baghdad (Al-Heety, 2002). The crust beneath the Baghdad seismic station (BHD) has 43km-thick (Gök et al., 2008). The crustal thickness beneath the Mesopotamian plain was estimated using the receiver functions technique and the ambient seismic noise cross-correlation technique (Abdollah and Abdulnaby, 2020). They reported that crustal thickness beneath Amara, Basrah and Nasiriya seismic stations is 41km. The crust beneath Al-Refaei seismic station has an approximately of 46km-thick (Ramthan et al., 2020). The crustal thickness beneath a number of seismic stations distributed in the Mesopotamian plain, East of Iraq, ranges from 44km beneath the KAR2 station at the western margin of the Mesopotamian plain to about 52km under the AMR2 seismic station at the eastern part of the plain (Abdulnaby et al., 2020). The crustal thickness beneath the ANB1 station estimated by
receiver functions analysis is in agreement with the results of some previous studies (Gök et al., 2008; Abdulnaby et al., 2020). The crustal thickness value under the ANB1 station is consistent with the global average of crustal thickness in the platform regions which is equal to 38.96 ± 7.03km (Mooney et al., 1998).

4.3. Crustal Velocity Model

The crustal velocity model beneath the ANB1 seismic station derived by the receiver functions analysis is listed in Table 2 (Figs. 6 and 7). The crustal velocity model beneath the ANB1 station consists of four layers: The first two layers represent the sedimentary cover; the third layer is the upper crust and the fourth layer is the lower crust. The velocity model shows four seismic discontinuities, the first between the two sedimentary layers, the second one between the sedimentary cover and upper crust, the third one between the upper crust and lower crust, and the fourth is Moho discontinuity. The depths of the first, second, third, and Moho discontinuities are 6, 12, 36, and 44km, respectively. The obtained crustal velocity model may be employed to locate and relocate the earthquakes and in moment tensor solutions in the future investigations of the study area.

| Crustal    | Depth (km) | Thickness (km) | P-wave (km/sec.) | S-wave (km/sec.) | Density (gm/cm3) |
|------------|------------|----------------|-----------------|-----------------|-----------------|
| Sediment 1 | 00 – 06    | 06             | 2.8578          | 1.5939          | 2.2408          |
| Sediment 2 | 07 – 12    | 06             | 5.0813          | 2.8342          | 2.5144          |
| Upper crust| 13 – 36    | 24             | 6.5158          | 3.6344          | 2.8483          |
| Lower crust| 37 – 44    | 8              | 7.5524          | 4.2125          | 3.1626          |
| Moho       | 44 – 46    | 44             | 7.8519          | 4.3795          | 3.2530          |

Fig. 6. Crustal velocity model beneath ANB1 station. The red line is the starting velocity model. The blue line is the final Vs model.
Fig. 7. Average crustal velocity model beneath the ANB1 seismic station

5. Conclusions

From the analysis of the P-wave receiver functions for the ANB1 seismic station, the following conclusions have been drawn:

- The depth of Moho discontinuity beneath the ANB1 station is 44km with Vp and Vs of the upper mantle equal to 7.85km/s and 4.37km/s, respectively.
- The basement depth, or sedimentary cover thickness, under the ANB1 seismic station is 12km, which is compatible with the conclusions of some prior studies but not with those of others.
- The crustal thickness under ANB1 station is consistent with that beneath several of the Mesopotamian plain's seismic stations.
- The crustal velocity model shows four discontinuities, the first one is about 6km with Vs of 2.83km/s, the second one is at 12km with Vs of 3.63km/s, the third one is at 36km with Vs of 4.21km/s, and the fourth one is at depth of 44km with Vs of 4.37km/s.

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