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# CRUSTAL STRUCTURE BENEATH AL-REFAEI SEISMIC STATION – CENTRAL MESOPOTAMIA, IRAQ, USING RECEIVER FUNCTION TECHNIQUE

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## ABSTRACT

***Al-Refaei district is one of the largest towns in Thi-Qar, southern Iraq. Tectonically, it is located in the central Mesopotamian zone of the Arabian plate. The crustal structure of this area was estimated to understand the geological and tectonic setting. From the data of the broadband seismic station (NSR1), which is part of the Iraqi Seismic Observatory the crustal velocity model was derived using the inversion of P-wave receiver functions (RFs). Data from this station was analyzed using the Computer Programs in Seismology. The results show two distinct discontinuities; these are the basement rock at a depth of 8km (Vs 2.63 km/s) and the Moho discontinuity at an approximate depth of 46 km (Vs 3.79 km/s). The calculated velocity model can be used to locate earthquakes and build accurate Green Functions for the region in future studies.***

Keywords: Receiver functions; Crustal structure; Velocity model; Mesopotamian Zone; Al-Refaei

## INTRODUCTION

Al-Refaei district is located in the Thi-Qar, southern Iraq, about 90 km north of the Nasiriyah town and 300 km south of Baghdad. Tectonically, Al-Refaei is located at the center of the Mesopotamian zone of the Arabian plate (Fig. 1). Depending on the characteristics of the surface and subsurface structure features, the Mesopotamia Plain is divided into three subzones, these are the Euphrates Subzone in the west, the Tigris Subzone in the northeast, and the Zubair Subzone in the south. Al-Refaei district is located within the Euphrates Subzone, which is the shallowest subzone in the Mesopotamia zone having the basement rocks at a depth of about 10 km (Buday and Jassim, 1987; Jassim and Göff, 2006).

To understand the tectonic setting and the geodynamics processes of any region, the thickness of the crust must be determined. In general, geological studies indicate that the crust is variable in thickness, density, chemical composition, and velocities. The density and velocity increase with depth. The average thickness of the continental crust is 40 km which is generally divided into two main parts, the upper and the lower crust. In some regions, the continental crust is divided into three parts, upper, middle, and lower (Park, 1997; Shearer, 2009). The crust has two major discontinuities; these are the Conrad and Moho discontinuities. The Conrad discontinuity is the boundary between the upper and lower crust distinguished by a sudden increase in the seismic velocity between them. The depth of the Conrad discontinuity ranges between 15–20 km at various continental regions. Moho discontinuity is the boundary between the crust and the mantle having a sudden increase in seismic velocity at depths around 30 to 60 km beneath the continental crust (Abdulnaby, 2013).

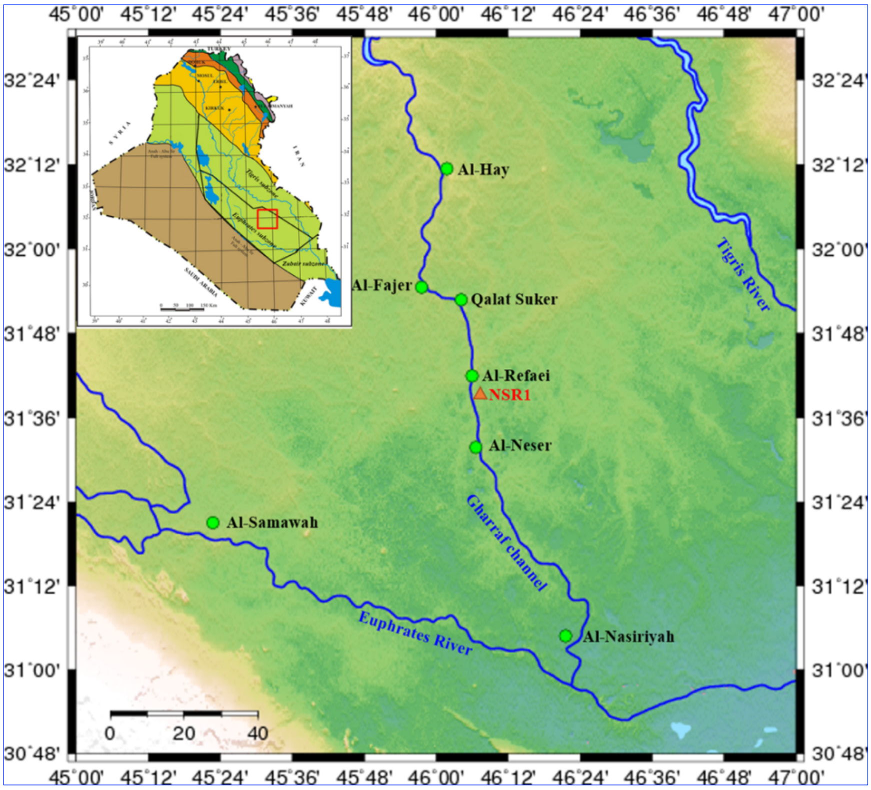


**Fig. 1. Location of the study area and site of the seismic station NSR1 represented by the red triangle. The green circles represent the locations of the main cities**

The geometrical and reflective shape of the Moho discontinuity is so diverse and may include one or more sub-horizontal or plunging reflectors (Shearer, 2009). Depending on these observations, the thickness of crust can be estimated by the changes of seismic velocities with depth. Studies that have identified the thickness of the crust in Iraq are sparse and mostly adopted the gravity method. These studies indicated that the thickness of the crust ranges from 35km in the west to 45km in the east and northeast (Alsinawi et al., 1987). Most of the Crustal structure models derived from seismological studies were carried out on a regional scale that covers the Arabian Plate. In Iraq, most studies focused on the center and the north part of the country. The study area in particular and the south of Iraq region in general, lack and fall behind any advance seismological study yet. Some important studies can be highlighted, Alsinawi and Al-Heety (1992) analyzed the teleseismic P wave to estimate the crustal structure beneath seismic stations of the Iraqi Seismological Network (ISN). The study shows that the crustal values varied in thickness, the depth in the north margin of Mesopotamian (Baghdad station) was 38 km. Mooney et al. (1998) created several velocity models of the Arabian Plate and they found that the crustal thickness varied from 39 km to 46 km with sedimentary cover ranging from 0 to 6 km. In this study, the region of Mesopotamia, for the first time received an in-depth analysis. It was found that the thickness of the crust was around 34 km with a P-wave velocity of 7.3km/s and S-wave velocity of 4.0km/s. Gök et al. (2008) relied on the joint inversion of body wave receiver functions and surface wave group velocity dispersion to estimated crustal structural in two locations of Iraq, Mosul (MSL) and Baghdad (BHD). The inversion results showed that the crustal thicknesses are 39 km at MSL and 43 km at BHD. Sedimentary thicknesses at these stations are 3 km and 7 km respectively. Therefore, in this study, the P-wave receiver function technique was used to estimate the crustal discontinuities and their depths beneath the Nasiriyah broadband seismic station (NSR1) located in Al-Refaei.

## MATERIALS AND METHODS

NSR1 seismic station was installed in May 2014, as part of the Iraqi Seismic Observatory (ISO), by Thi-Qar, Sumer, and Basra universities in collaboration with the Lawrence Livermore National Laboratory (LLNL) and the University of Arkansas at Little Rock (UALR). The seismic station NSR1 equipped with CMG40T/DM24 broadband seismometers at three components digitizers. The location of the station is marked by the red triangle in Fig. 1. Inversion of P-wave receiver functions technique was used to derive the crustal discontinuities and their depths beneath NSR1 station. For this purpose, the Computer Programs in Seismology (CPS) prepared by Herrmann and Ammon (2002) was used. The CPS is a package of more than 155 programs that can be run interactively or by shell scripts (Herrmann and Ammon, 2002). The basic concept of the receiver function technique depends on the teleseismic P-wave, where these waves carry the information of the crustal structures beneath a single station. When body waves propagate in the interior of the earth, they encounter many interfaces. In this case, the energy of waves will be transmitted, reflected, or converted depending on the nature of the interface and the incident angle of the wave. Therefore, the receiver functions technique can be considered as a time series recorded by seismometer's three components which give the Earth's response to changes in the crustal structure beneath a seismic station (Torsvik, 2015). The Moho discontinuity is one of the interfaces that body waves encounter. It represents the boundary between the mantle and the crust where seismic velocity for both P and S waves exhibit a sharp variation in values across this boundary. When an earthquake occurs, the teleseismic waves travel spherically in all directions. The body wave, especially P-wave, will strike the Moho discontinuity and travel upward through the crust and recorded as P-wave at the seismometer. Some part of this wave will be converted and traveled as an S-wave, therefore, this seismic wave will reach the station as responses of the direct P wave and Ps (P-to-S converted waves that reverberate in the structure beneath the seismic station between the Moho and the free-air surface). These reflected waves are used in the receiver functions technique are the P-wave and its multiples (PpPs, PsPs, PpPs) (Ammon, 1991).

From the above, its shown that the basic concept of receiver functions analysis depends on (1) the difference in the velocities of seismic P and S waves across the Moho discontinuity, (2) the conversion of P-wave to S-wave at the crustal-mantle boundary, and (3) the multiples of the converted P-to-S waves reverberations in the crust that are recorded at the seismic station.

**Data Preparation**

The receiver function technique is based on some criteria that must be met to accurately imaging the interior of the Earth. These criteria include high magnitude to ensure high signal-to-noise ratio for long distances and also the earthquake location must be within the distance between 30°–90° from the seismic station to ensure that usable propagation paths arrive (Rondenay, 2009). Accordingly, the events with a magnitude higher than 6 Mw, and the epicentral distances of 30° to 90° were selected from the NSR1 station are considered suitable events for this analysis. The European-Mediterranean Seismological Centre (EMSC) offers free metadata for all and full access to the events information that happened in the world through its search option. The information includes the date, time, coordinates, depth and magnitude of all events that were analyzed. It also provides a custom search for a specific region within the database. The time period of the search was set to the start date of operation for NSR1 station. More than 20 teleseismic events were selected for the period from June 2014 to July 2017, which is the period of operation of the NSR1 station. Before processing, the data must be converted from GCF to SAC format and then GSAC formats. This step can be performed by the scream program version 4.4 to be ready for analysis. Additionally, the header file of the data must be edited to add the event parameters information, such as magnitude and epicentral distance (latitude and longitude of the event). Not all events were usable. Many of the events that have high noise or those where it was difficult to determine the beginning of the direct P-wave arrival were removed from the data list. Therefore, after removing the poor events from the data list, 9 events were finalized for processing by the receiver functions analysis technique. Table 2 shows the seismic events that were used in this study for the inversion of receiver functions.

**Table 2. Teleseismic events that were used in the inversion of receiver functions (RFs) taken from the EMSC site**

| No. | Date | Time (UTC) | Latitude | Longitude | Depth (km) | Mag. | Mag.Type. |
|---|---|---|---|---|---|---|---|
| 1 | 2017-07-17 | 23:34:16.4 | 45.55 | 168.84 | 30 | 7.7 | MW |
| 2 | 2017-01-22 | 04:30:23.8 | 6.20 | 155.10 | 150 | 7.9 | MW |
| 3 | 2016-07-29 | 21:18:30.2 | 18.58 | 145.51 | 267 | 7.7 | MW |
| 4 | 2016-04-15 | 16:25:06.5 | 32.78 | 130.68 | 10 | 7.0 | MW |
| 5 | 2016-01-30 | 03:25:09.8 | 54.03 | 158.54 | 159 | 7.2 | MW |
| 6 | 2015-11-18 | 18:31:05.0 | 8.96 | 158.41 | 20 | 7.0 | MW |
| 7 | 2015-04-25 | 06:11:26.9 | 28.24 | 84.74 | 15 | 7.8 | MW |
| 8 | 2016-08-29 | 04:29:59.6 | 0.05 | 17.82 | 20 | 7.1 | MW |
| 9 | 2016-01-25 | 04:22:02.6 | 35.70 | 3.710 | 10 | 6.3 | MW |

The original coordinate system is ZNE (vertical, north-south, and east-west). In order to align the data along the axis between the station and the epicenter of the event, and to better isolate of the energy from different waves, rotation of three components is applied to the three components seismograms. The GSAC program was used to convert all the data from ZNE to ZRT system, where the vertical component (Z) stays the same and the horizontal components rotated to radial (R) and transverse (T) (Fig. 2).

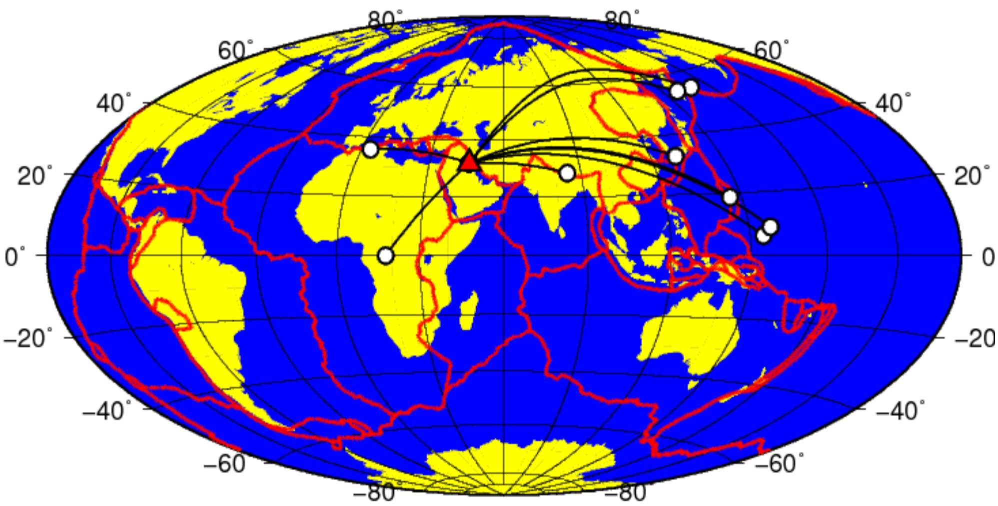


**Fig. 2. Teleseismic events distribution map for NSR1 seismic station. The white circles represent the locations of events and the red triangle is the site of NSR1 station**

**Calculating of Receiver Functions**

The teleseismic waves arriving at the broadband seismic station include information about the source of the event and the propagation path which they traveled across the mantle as well as the local structure below the station. Thus, the main objective of the receiver function technique is to isolate the near-receiver structure from the source and distant structure effects (Shearer, 2009).

Ligorria and Ammon (1999) developed a method to eliminate the effects of near-source structure and source time functions called deconvolution. The CPS package provides a set of programs to calculate the receiver functions. These are gsac, saciterd, saclhdr, and udtdd. The saclhdr program checks the header of the SAC file to restore a particular header value and allows its transport to SHELL. Saciterd program performs a time-domain deconvolution of 9 teleseismic events to obtain the receiver function. Fig. 3 shows the receiver function results for one of the selected events which are event number 3 in Table 2. The first three panels represent the radial component that filtered with three values of the Gaussian filter (0.5, 1.0, and 2.5 Hz) respectively. The other three panels represent the transverse component of the same filter for the same values.

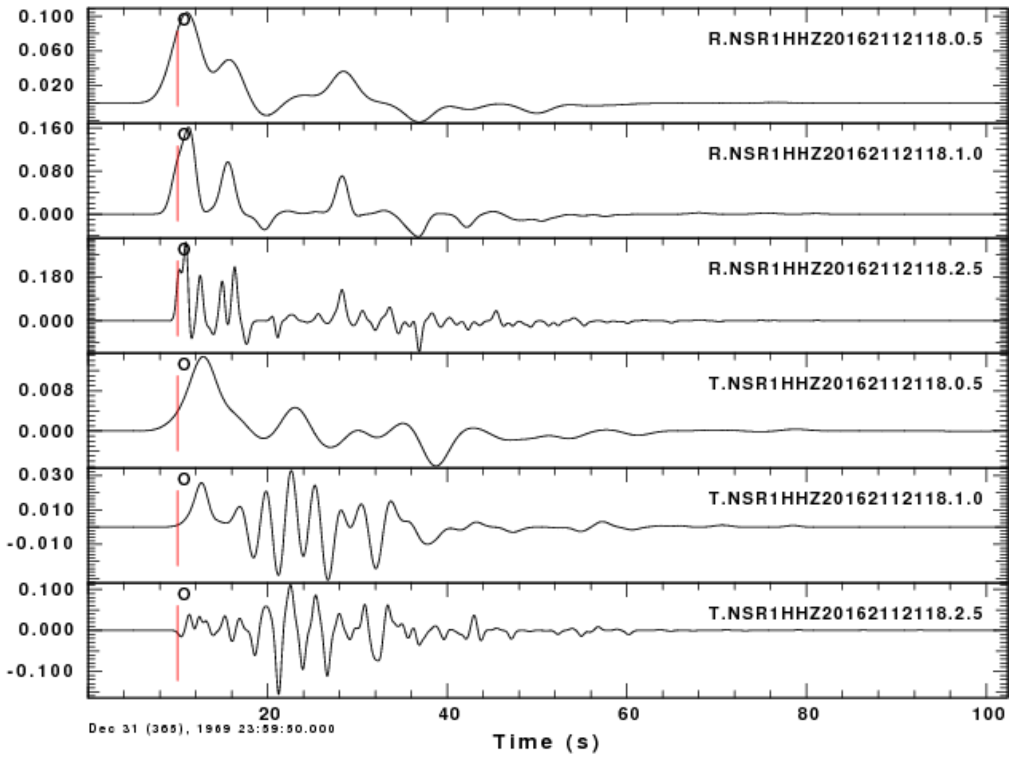


**Fig. 3. P-wave receiver function of the event that occurred in the Northern Mariana Islands, which is number 3 in Table 2. The epicentral distance is about 80°. R and T represent the radial and transverse components filtered with three values 0.5, 1.0, and 2.5**

Fig. 4 shows the receiver functions plotted as a function of back azimuths for the 9 events that selected, which range from 30º to 90º. The back azimuth figure helps to determine the extent of the match or deviation of events. The teleseismic earthquakes that were used for receiver function analyses in this study are situated mainly along the Asian side of the Pacific Rim, which determining mostly eastern back azimuths with NSR1. Two earthquakes are located in the continent of Africa, thus forming the western back azimuths with NSR1. Accordingly, there was good coverage of the seismic station. The travel of P-waves from the earthquake epicenter to the seismic station varies from one event to another, meaning that the deconvolution will give individual solutions. So by stacking the events we reduce the noise and enhance the coherent main signals.

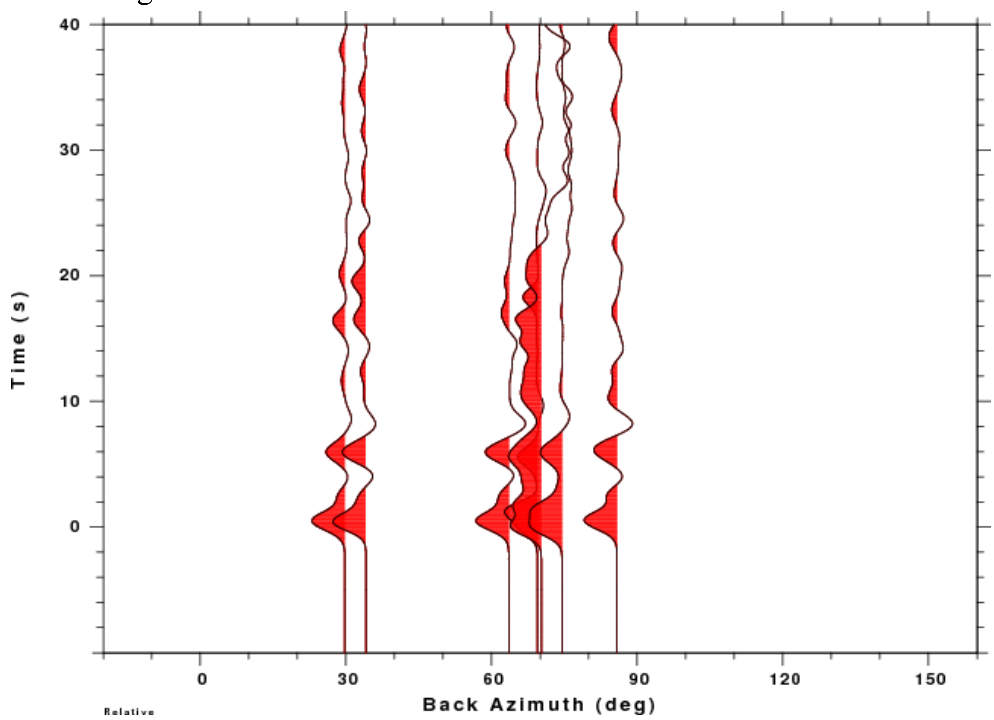


**Fig. 4. Receiver functions plotted as a function of back azimuth for 9 events recorded by the NSR1 station ranges from 30º to 90º. Two of the events overlapped with the seven shown**

## RESULTS AND DISCUSSION

The receiver function technique is a time series created from surface registrations of seismic station in a manner focused on layers' difference in their velocities. The inversion of receiver functions is conducted by converting the arrival times of converted phases at a discontinuity, such as the Moho, to depths. The inversion can be done by the iterative technique that requires knowledge of seismic Earth velocities to convert their phases to depths. Receiver functions depend mainly on the S-wave velocity variance and discontinuities (Abdulnaby, 2013). A homogeneous earth structure model called half-space starting with S-wave velocity (Vs) of 4.48

km/sec was used for inverting the results for the receiver function. The half-space represents starting velocity model consists of 65 layers for 400 km depth. The 65 layers subdivided into three parts. Part one consists of 25 layers in the upper 50 km depth with each layer 2km thickness and has a constant velocity. Part two consists of 10 layers in middle 50 km depth each with 5km thickness. Part three consists of 30 layers in the lower 300 km depth each having 10 km thickness. This type of models is unbiased and detect any sharp velocity discontinuity during the inversion. For the inversion procedure, the rftn96 program in the CPS package was used. This program depends on linearized-iterative inversion by reducing the misfit between the observed and predicted receiver functions (Herrmann and Ammon, 2007). Twelve iterations were run of each event to produce the receiver functions.

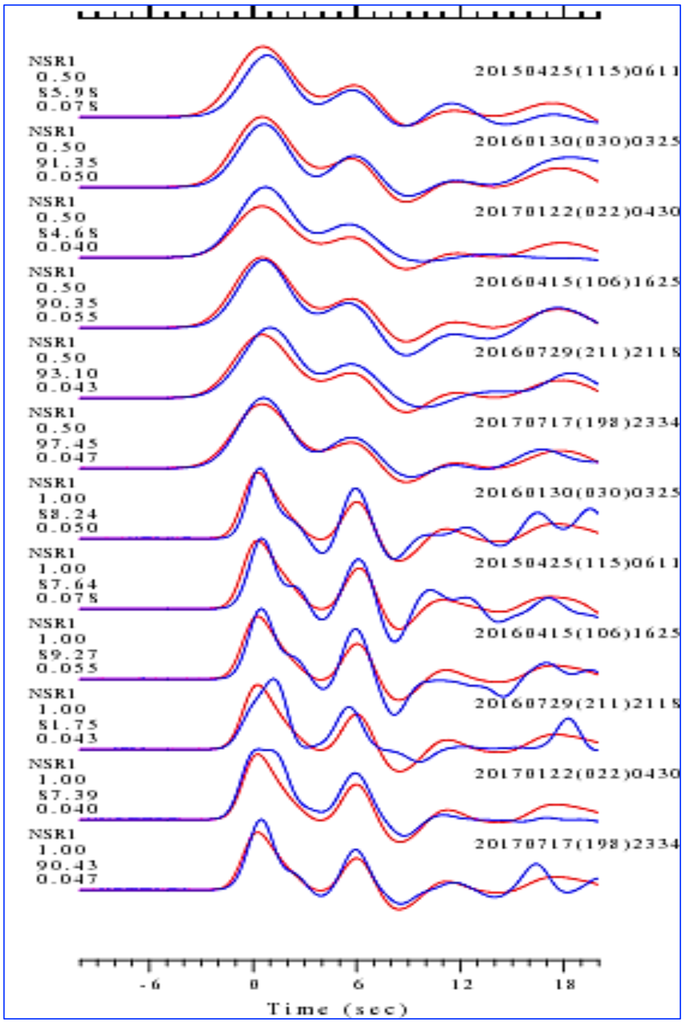


**Fig. 5. Model fit to the receiver functions of nine earthquakes recorded by NSR1. The blue curve shows the data and the red curve shows the model prediction. Each receiver function is annotated at the left of each trace with the station name, the Alpha (Gaussian filter parameter), the percentage of fit, and the ray parameter (sec/km); and with the year/ month/ day/ hour/ minute at the upper right of each trace. A time scale is also provided**

The rftn96 program saves the final crustal structure model after each iteration and put them in one plot. The final velocity model beneath NSR1 seismic station that results from the inversion of receiver functions is shown in Figs 5 and 6 and Tables 3 and 4. (Fig. 5) displays the fit between the data of 9 observed receiver functions (in blue) and the model prediction (in red) that have 0.5 and 1 Alpha (Gaussian filter parameter). The percentage of fit between the observed and predicted ranges between 84% to 97%. Fig. 6 demonstrates the velocity model of the crustal structure beneath NSR1 station. Two main discontinuities can be identified; these are the upper sedimentary sequence, which is about 8 km thickness, and the Moho at 46 km depth.

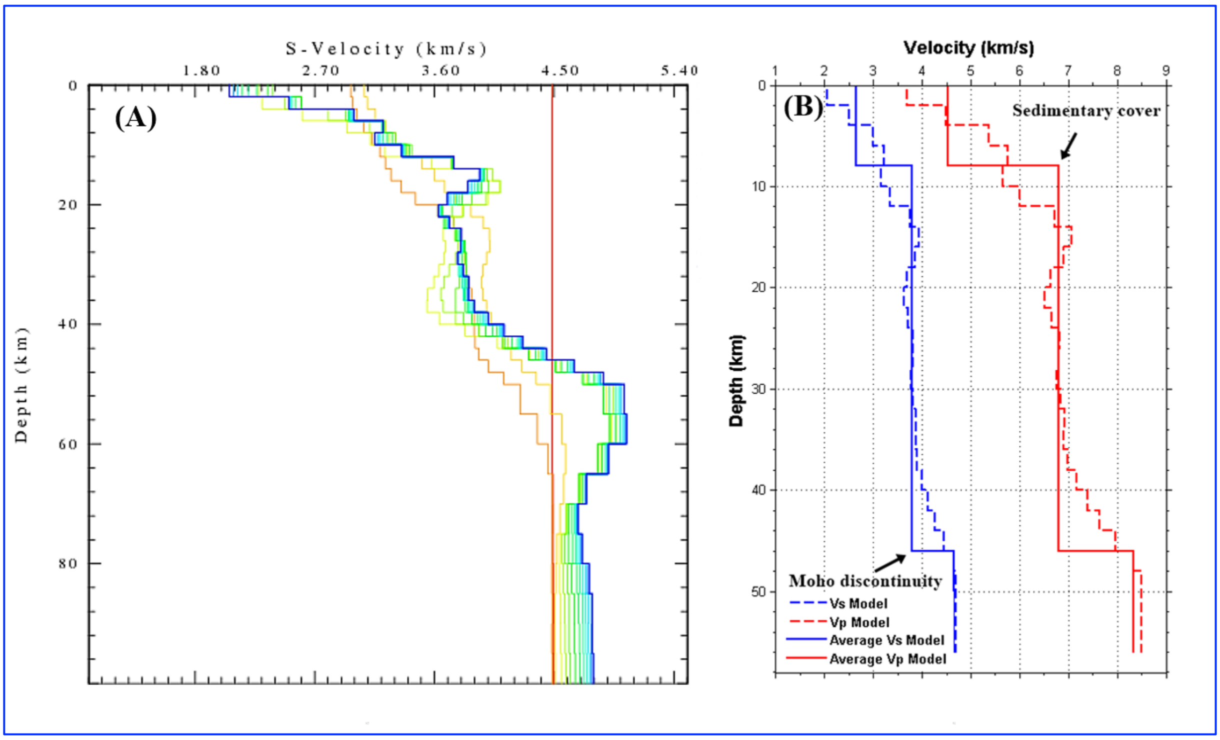


**Fig. 6. Final velocity model of the crustal structure beneath the NSR1 seismic station obtained from the inversion of P-wave receiver functions. (A) The outputs of the rftn96 program in the CPS package. (B) The weighted final velocity model that shows two major discontinuities at depths 8 and 46**

**Table 3. Final velocity model beneath NSR1 derived from the inversion of P-wave receiver functions**

| Layers | Depth (km) | P-wave velocity (km/s) | S-wave velocity (km/s) | Density (gm/cm$^3$) |
|---|---|---|---|---|
| Sedimentary cover | 0.0-8.0 | 4.53 | 2.63 | 2.46 |
| Continental crust | 8.0-46 | 6.80 | 3.79 | 2.96 |
| Moho discontinuity | 46 | 7.96 | 4.44 | 3.29 |

**Table 4. Velocity model beneath NSR1 derived from the inversion of receiver functions**

| Depth (km) | P-wave velocity (km/s) | S-wave velocity (km/s) | Density (gm/cm$^3$) |
|---|---|---|---|
| 4 | 4.4917 | 2.5055 | 2.3896 |
| 8 | 5.7655 | 3.2158 | 2.6524 |
| 12 | 6.0099 | 3.3520 | 2.7053 |
| 16 | 7.0620 | 3.9389 | 3.0036 |
| 20 | 6.6305 | 3.6984 | 2.8878 |
| 24 | 6.6609 | 3.7153 | 2.8874 |
| 28 | 6.8045 | 3.7955 | 2.9310 |
| 32 | 6.8475 | 3.8194 | 2.9360 |
| 36 | 6.9110 | 3.8546 | 2.9533 |
| 40 | 7.1779 | 4.0036 | 3.0298 |
| 44 | 7.6428 | 4.2631 | 3.1818 |
| 48 | 8.344 | 4.6540 | 3.4238 |

## CONCLUSIONS

A seismic velocity structure model was derived for the AL-Refaei District - central Mesopotamia based on the inversion of receiver functions. This model provides new information about the geology and seismic velocity structure of the study area in particular and the Mesopotamian zone in general. The final results of the crustal structure show two distinct discontinuities. The first is around 8 km discontinuity (Vs 2.63km/s) that represents the depth of basement rocks (thickness of sedimentary column). The second is around 46 km (Vs 3.79 km/s) that represents the depth of Moho discontinuity. The results of the sedimentary column were comparable with the Arabian platform profiles which shows that the sedimentary thickness in the Mesopotamian zone is 7.3 km (Pasyanos et al., 2007). The comparison was also made locally depending on Gök et al. (2008) which confirm the sedimentary thickness beneath Baghdad seismic station is 7 km (Vs 2.5 km) and the Moho depth is 43 km (Vs 3.9 km/s). The calculated velocity model can be used to locate earthquakes and build accurate Green Functions for the region in future studies.

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