Crustal structure of Iraq from receiver functions and surface wave dispersion: implications for understanding the deformation history of the Arabian–Eurasian collision

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Accepted 2007 October 25. Received 2007 October 24; in original form 2007 February 7

SUMMARY
We report the crustal structure for two locations in Iraq estimated by joint inversion of P-wave receiver functions (RFs) and surface (Rayleigh) wave group velocity dispersion. RFs were computed from teleseismic recordings at two temporary broad-band seismic stations located in Mosul (MSL) in the Zagros Fold Belt and Baghdad (BHD) in the Mesopotamian Foredeep. Group velocity dispersion curves at the sites were derived from continental-scale tomography. The inversion results show that the crustal thicknesses are 39 km at MSL and 43 km at BHD. We observe a strong P sociopé Moho at BHD consistent with a sharp Moho discontinuity. However, at MSL we observe a weak P sociopé Moho suggesting a transitional Moho where crustal thickening is likely to be occurring in the deep crust. Both sites reveal low velocity surface layers consistent with sedimentary thickness of about 3 km at station MSL and 7 km at BHD and agreeing well with the previous reports. Ignoring the sediments, the crystalline crustal velocities and thicknesses are remarkably similar at both stations. The similarity of crustal structure suggests that the crust of the northeastern proto-Arabian Platform was uniform before subsidence and deposition of the sediments in the Cenozoic. If crystalline crustal structure is uniform across the northern Arabian Platform then crustal thickness variations in the Zagros Fold Belt and Thrust Zone should reveal the history of deformation and crustal shortening in the Arabian–Eurasian collision zone and not reflect pre-existing crustal thickness variations in the Arabian Plate.

Key words: Body waves; Surface waves and free oscillations; Continental tectonics: compressional; Crustal structure.

INTRODUCTION
Iraq is located in the northern Arabian Plate including the western edge of the Zagros Mountain range, where the convergent tectonic boundary between the Eurasian and Arabian plates is revealed by a fold and thrust belt. Tectonics and geology of Iraq have been influenced by the collision of Arabia with southern Eurasia (e.g. Berberian & King 1981; Adams & Barazangi 1984). The continent–continent collision of Arabian and Eurasian plates started with the closure of Neo-Tethys Ocean in mid-Miocene (Dewey et al. 1986). Therefore, the tectonics of Iraq is dominated by the collision zone related mechanisms like the folding zones and sediments. Iraq can be divided into five major geological/tectonic provinces: the Widyan Basin/Arabian platform, the Mesopotamian Foredeep, the Zagros Fold Belt and the Rutbah and Khleisha Uplifts (Fig. 1). The Widyan Basin forms the eastern part of the stable interior of the Arabian Plate and is composed of sediment deposits that dip gradually to the northeast. The Mesopotamian Foredeep was formed by subsidence and sedimentary deposition and is composed of folded sediments that reach up to 10 km depth. The Zagros Fold Belt is a zone of elevated and highly folded sediments extending from southeastern Turkey to the Oman Line (Kadinsky-Cade & Barazangi 1982). In this zone, continental collision has been accommodated by intense folding of Arabian sediments west of the Main Zagros Thrust. The folding probably started during the Upper Miocene–Lower Pliocene, and the belt is still considered to be one of the most active orogens on earth (Stocklin 1968; Kassler 1973). Sedimentary thickness (Seber et al. 1997; Bassin et al. 2000) across Iraq and the broader region defines these tectonic zones (Fig. 1). The Rutbah and Khleisha Uplifts in northwestern Iraq are divided by the Anah Graben (also called the Euphrates Depression, e.g. Sawaf et al. 1993). In Fig. 1 geological provinces and boundaries are taken from Pollastro et al. (1997a,b).

Earthquake activity is intense in the Zagros Mountains, a zone of approximately 200 km width including the Zagros Fold Belt and Zagros Thrust Zone (Nowroozi 1972; Berberian 1976; Jackson & McKenzie 1984). The majority of the moderate-to-large historical
Figure 1. Base map of the study region including the locations of seismic stations BHD and MSL (triangles). Adjacent stations (RTB, MRDN, KBD, RUW, QURS and HILS, circles) have reported crustal structures. Tectonic provinces are indicated (black lines). Major features in Iraq are identified and also include the Khleisha Uplift (KU), Anah Graben (AG), Rutbah Uplift (RU) and Main Zagros Thrust (MZT), taken from Pollastro et al. (1997a,b). Sedimentary thickness across the region is plotted as yellow contours (Bassin et al. 2000). Summary of crustal and sedimentary thickness (ct and st, respectively) at stations BHD and MSL. Note that the crystalline crustal thickness (ct-st) for stations along the northeastern Arabian Platform (KBD, BHD, MSL and MRDN) is very consistent at about 36 km. Also shown are results for nearby stations referred to in the text.

Events in eastern Iraq have occurred along this belt (Alsinawi & Ghalib 1975; Alsinawi & Banno 1976; Alsinawi & A1-Shukri 1979). In general, seismicity in the Zagros Mountains is shallow with focal depths ranging not more than 20 km (e.g. Jackson & Fitch 1981; Ambroseys & Melville 1982; Maggi et al. 2000; Engdahl et al. 2006).

Estimates of crustal structure in the northern Arabian Platform are limited to a few reports, mainly due to the paucity of active and passive seismic investigations. Al-Heety (2002) reported estimates of crustal thickness at Baghdad (BHD) (38 km) and Rutbah (35 km) station using the spectral ratio method from digitized analogue records from teleseismic $P$-wave recorded by the Iraqi National Seismic Network. Sawaf et al. (1993) reported uniform crustal thickness of 37 km across the Anah Graben (Euphrates Depression) in eastern Syria. Recent receiver function (RF) analysis of broad-band data provided estimates of crustal structure in areas adjacent to Iraq. Gök et al. (2007) reported a crustal thickness of 38 km with 2 km of sediments for southeastern Turkey (station MDRN in Fig. 1). Pasyanos et al. (2007) report crustal thickness of 45 km with 8 km of sedimentary cover for station KBD (Kabd, Kuwait, Fig. 1). To the west of Rutbah, Al-Damegh et al. (2005) reported crustal thickness of 37 ± 0.2 and 32 ± 4.5 km at stations RUW and QURS, respectively. At station HILS on the Arabian Shield to the south of our study area, Al-Damegh et al. (2005) reported crustal thickness of 36.9 ± 1.0 and 35–38 km, respectively. A crustal profile from the Arabian/Persian Gulf across the central Zagros Mountains to the Iranian Plateau (southwest of Iraq) by Paul et al. (2006) found crustal thickness of 45 km west of the Main Zagros Thrust (MZT) with significant thickening (~70 km) beneath the Zagros Thrust Belt.

Studies of seismic structure in and around Iraq report faster mantle velocities beneath the Arabian Platform ($P$-wave velocities ~8.0–8.2 km s$^{-1}$) and slower velocities beneath the Turkish–Iranian Plateau ($P$-wave velocities ~7.6–7.9 km s$^{-1}$) from Pn traveltime tomography (Hearn & Ni 1994; Al-Lazki et al. 2003, 2004), surface wave group velocity dispersion (e.g. Ritzwoller & Levshin 1998; Pasyanos 2005) and partitioned waveform inversion (Maggi & Priestley 2005). Al-Damegh et al. (2004) demonstrated complexity in the short-period regional wave propagation characteristics of the region using Lg and Sn propagation efficiencies. They found that the Arabian plate had efficient Lg propagation but the seismically active regions in Iran and Turkey had Lg blockage. In particular,
there is a sharp boundary between the Sn and Lg propagation at the region between Arabian Plate and Bitlis/Zagros suture in Iran–Iraq border (Gök et al. 2003; Al-Damegh et al. 2004). Sn propagation is inefficient or not observed at the northwestern part of Iraq where Neogene and Quaternary volcanism exist (Rodgers et al. 1997; Gök et al. 2003; Al-Damegh et al. 2004). These previous seismic studies indicate that lithospheric structure changes drastically across the northern Arabian Platform and Turkish–Iranian Plateau.

In this study, we report crustal structure for two sites in Iraq from the joint inversion of P-wave receiver functions and surface wave group velocities. Results provide new constraints on structure of the northern Arabian Platform and can be used to constrain tectonic models of shortening across the Zagros Fold and Thrust belt, as well as to improve seismic data analysis in the region, such as event location, moment tensor estimation and ground motion prediction.

DATA AND ANALYSIS

Receiver functions (RFs) isolate the response of near vertically propagating plane-waves to seismic velocity discontinuities underneath a broad-band seismic station (Langston 1979; Owens et al. 1984; Cassidy & Ellis 1993). Teleseismic P-wave RFs emphasize \( P \) to S-wave conversions and are widely analysed for crustal and upper-mantle discontinuities. The P-to-S converted waves are isolated by deconvolving the vertical component from the radial component to eliminate the source and the instrument response effects from the waveforms.

Two temporary broad-band stations were deployed in BHD and Mosul (MSL) in early 2005. The stations were equipped with Guralp CMG-3ESPD digital broad-band seismometer. Unfortunately the sites were noisy due to their location near major cities. Recording was intermittent reflecting of the difficult conditions in Iraq. However, we managed to identify a few large teleseismic events that could be used for RF analysis. In this study we employed the iterative time domain deconvolution method (Ligorria & Ammon 1999) to isolate the crustal response. In order to reduce the noise and improve the signal coherence we used a Gaussian filter with the bandwidth of 1.5 (~1 Hz). After eliminating the noisy events we stacked seven individual RFs for MSL and two for BHD, accounted for differences in slowness. Fig. 2 shows a map of the event locations along with the individual and stacked RFs for each station. Note that the RFs are different with the amplitudes of the individual and stacked RFs for each station. The RFs to S-wave velocity structure.

First, we tried to estimate the crustal thickness for both stations using the \( H-k \) stacking technique of Zhu and Kanamori (2000), where \( H \) is the Moho depth and \( k \) is the \( V_p/V_S \) ratio, related to the Poisson’s ratio. This technique is excellent for obtaining estimates of average crustal properties (e.g. Al-Damegh et al. 2005). The method compares the observed amplitudes and arrival times of the RF crustal multiples (shifted and summed to form a stack) with predictions from ranges of crustal thickness \( H \) and \( V_p/V_S \) ratios. The best estimates of crustal thickness and \( V_p/V_S \) ratio are found when the main observed Moho phases (Ps, Pps, PpSs + PsP) result in a high amplitude stack. However, there are limitations and cases where this technique may fail, for example when reverberations from sedimentary and/or mid-crustal discontinuities interfere with main Moho phases, or when the \( V_p/V_S \) ratio varies in the crust, such as in the presence of sedimentary structures. We applied the technique by searching over broad ranges of crustal thickness (25–60 km) and \( V_p/V_S \) (1.5–2.3). The average \( V_p \) value in the crust was estimated as \( V_p = 6.0 \) km s\(^{-1}\) by Rodgers et al. 1999 (using waveform modelling of regional waves in the Arabian Platform). If the average \( V_p \) value is not known the Moho might be underestimated or overestimated. As we fixed \( V_p \) to 6.0 km s\(^{-1}\) we found that the Moho depth at station BHD is 44.8 ± 6.2 km and \( V_p/V_S \) is 1.83 ± 0.12. The average crustal thickness and \( V_p/V_S \) ratio at MSL is shown in Fig. 3. The Moho depth at station MSL is 38.1 ± 2.5 km and \( V_p/V_S \) is 1.85 ± 0.09. The errors in stacking were estimated using the bootstrapping resampling with 100 samples.

Crustal RFs are primarily sensitive to the depth of velocity contrasts and have poor sensitivity to absolute velocities (e.g. Ammon et al. 1990). Surface wave dispersion is primarily sensitive to depth averages of the \( S \)-wave velocity structure with poor sensitivity to velocity discontinuities or fine structure. Julia et al. (2000, 2003) developed a method for estimating structure from the joint inversion of RFs and surface wave group velocity dispersion curves. This method exploits the independent sensitivity of each data type to result in more reliable velocity models. Combining surface wave dispersion with RF can reduce the non-uniqueness of each individual dataset (Julia et al. 2000). Using broad-band waveform data from the Eastern Turkey Seismic Experiment (ETSE) Gök et al. (2007) showed that shear wave velocities can be overestimated up to 0.5 km s\(^{-1}\) (~10 per cent) if only RF modelling is used. More reliable results for crustal velocity models are expected from the joint inversion of RFs and surface wave group velocity dispersion. Two recent studies in adjacent regions (Tkalcic et al. 2006; Gök et al. 2007) were able to fit Love and Rayleigh dispersion curves and RF data simultaneously with an anisotropic mantle lid. Anisotropy is generally required to resolve the Love-Rayleigh discrepancy for long period (>50 s) dispersion curves. In this study we inverted Rayleigh wave dispersion curves taken from Pasyanos (2005) with RFs to estimate vertically polarized S-wave (SV) velocity structure.

Pasyanos & Walter (2002) performed a study of surface wave group velocity dispersion across Western Eurasia and North Africa and a larger-scale across Eurasia, North Africa and surrounding regions (Pasyanos 2005) using 30 000 Rayleigh and 20 000 Love paths. A conjugate gradient method was used to perform a group velocity tomography between 7 and 100 s. Due to large seismicity along the Zagros belt the surface wave tomography path coverage in the region is quite dense (Pasyanos 2005). The Rayleigh wave dispersion at MSL and BHD are extracted from those global tomography maps. The uncertainties of group velocity estimates vary from 0.01 to 0.08 km s\(^{-1}\) (Figs 4b and 5b).

We used the computer codes developed by Julia et al. (2000) to simultaneously invert the RF and Rayleigh wave group velocity curves for plane-layered structure at each site. The system of equations relating the observed RF and dispersion data to depth varying shear velocity structure is inverted using the partial derivative matrices in a damped least-square sense. The models were parametrized with a series of layers to a depth of 100 km, 2 km thick from 0 to 10 km and 3 km thick below. The inversion method uses an influence parameter (\( p \)) to adjust the relative weight of RF and dispersion data in the inversion. If \( p = 0 \) the inversion only considers the RF and \( p = 1 \) only considers the group velocities. We performed inversions using various values of \( p = 0.3, 0.5 \) and 0.7 in order to explore the sensitivity of the resulting inversion to the data weighting. For the final model, we choose to take average of those three inversion results (Figs 4c and 5c). Generally, RF inversions are known to be non-unique and dependent on the starting model (Ammon et al. 1990). In our experiments, the group velocity dispersion data

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stabilizes the inversions (discussed below). We found the optimal damping parameter by considering the trade-off between stability and resolution.

RESULTS

The results of the joint inversion of $P$ wave RF and Rayleigh wave surface group velocity dispersion for stations MSL and BHD are shown in Figs 4 and 5, respectively. The observed and predicted RFs at MSL and BHD are shown in Figs 4(a) and 5(a), respectively. The observed (with 2σ uncertainties) and predicted Rayleigh wave group velocities at MSL and BHD are shown in Figs 4(b) and 5(b), respectively. Fig. 5(c) shows the starting model for both MSL and BHD. Figs 4(c) and 5(c) show the resulting velocity models for MSL and BHD, respectively, using two different starting models. Figs 4(c) and 5(c) show the resulting models using two very different starting models. One is a homogeneous earth model (where $V_S = 4$ km s$^{-1}$ down to 110 km shown in dotted blue) and the other is an average continental crust model (shown in dotted red, Fig. 5c). There are no significant differences seen between the fits to the data for the two different input models or the resulting models. We tried other starting models (not shown) and they too converged to the same final models. These tests demonstrate the robustness of the joint inversion.

At station MSL, in the northernmost part of Iraq, the joint RF and Rayleigh wave inversion resulted in a crustal thickness of about 39 km with average shear velocities of 3.1 km s$^{-1}$. Low velocities near the surface are interpreted as sedimentary layers with a thickness of 2–4 km. The Moho is not a sharp discontinuity in our model and is apparently spread across 2–3 layers (6–9 km). This is consistent with the absence of a strong $P_{sMoho}$ phase on the RF stack. The crustal thickness obtained from the joint inversion is very similar to what we obtained with $H$–$k$ stacking technique (41.3 km, shown in Fig. 3). The mantle directly below the Moho at station

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Figure 3. The receiver function $H-k$ stacking (Zhu & Kanamori 2000) at station MSL. Mean values and standard deviations are obtained by a bootstrap technique. Individual receiver functions are shown with theoretical onset of multiples (red lines with phase names) at $H = 41.3$ km and $k = V_P/V_S = 1.8$.

MSL has velocities of 4.2–4.4 km s$^{-1}$ with a positive gradient. The comparison between the observed and predicted RFs and surface wave dispersion curve for both starting models is quite good (Fig. 4). This estimate of crustal structure is very similar to one of the ETSE stations, MRDN, also shown in Fig. 4(c) taken from Gök et al. (2007). This station was located south of the Bitlis suture on the Arabian Platform in the southernmost part of Turkey (crustal thickness of 38 km). We observe a strong $P_{s\text{Moho}}$ at MRDN RFs (Fig. 4a). The mid-crust at MSL reveals constant velocities in the range 15–38 km similar to station MRDN.

The data available at station BHD were limited, only two individual RFs were judged appropriate for modelling. Note that the individual RFs for BHD (Fig. 2) are very consistent except for the energy arriving after about 16 s. We tried to invert each individual BHD RF, thinking that the different ray parameters for each event could bias the modelling. However, we obtained similar fits for each inversion as those obtained from the inversion of the stacked RF. We concluded that the individual RFs are consistent with the stack and we preferred to use the stacked RFs (Fig. 2).

At station BHD we infer a crustal thickness of 43 km with a 6–8 km thick layer of sediments (Fig. 5c). Similar to MSL, the inversion results are not strongly sensitive to the starting model as indicated by the inversion results for two different models shown in Fig. 5(c). Low near surface velocities are required to fit the lower short-period (7–15 s) Rayleigh wave group velocities (Fig. 5b). We infer a larger, more abrupt velocity increase across the Moho for station BHD, required to fit the strong $P_{s\text{Moho}}$ phase at about 4 seconds (Fig. 5a). The middle to lower crustal velocities are broadly consistent at both stations MSL and BHD, with average values of about 3.6 km s$^{-1}$. Uppermost mantle velocities are 4.4–4.5 km s$^{-1}$, slightly higher than those at station MSL. The inferred crustal structure at station BHD can be compared with a recent study at station KBD (Kabd) in Kuwait by Pasyanos et al. (2007), also located on a thick layer of Mesopotamian Foredeep sediments. The

$$\text{vp} = 6.0 \text{ km/s} \quad h = 38.1 +/−2.5 \text{ km} \quad \text{vp}/\text{vs} = 1.85 +/−0.09$$
reported crustal thickness at KBD is 45 km and sedimentary layer is 8 km.

**DISCUSSION**

Inversion of RF and Rayleigh wave dispersion data at two sites in Iraq reveals new constraints on the crustal structure of the northern Arabian Platform. The results for crustal structure in Iraq are summarized in Fig. 1 along with results for other stations located in the region and discussed above. The crustal models for these stations are consistent with the sediment depth model report by Bassin et al. (2000). Interestingly the crystalline crustal thickness, that is, crustal thickness minus sediment thickness, at these stations is remarkably similar, about 36 km, at the four stations along the eastern Arabian Platform (KBD, BHD, MSL and MRDN). Similarly, the average velocities of the crystalline crust (about 3.5 km s$^{-1}$) are consistent between these four stations sampling a broad area of the northern Arabian Platform. Fig. 6 compares the inferred shear velocity profiles at BHD and MSL. Note that the shear velocities in the range of about 10–35 km are very similar.

These observations suggest that the crustal structure of the northern Arabian Platform may have been largely uniform before subsidence and emplacement of the sedimentary structure in Palaeozoic to late Tertiary times. Studies of crustal thickening along the northern section of the Zagros Fold and Thrust Belt (e.g. Snyder & Barazangi 1986; Paul et al. 2006) reveal heterogeneity that is likely to have been formed by dynamic processes, rather than differences pre-existing crustal thickness or strength under uniform loading. Indeed the gravity profiles reported by Snyder & Barazangi (1986) reveal slight but resolvable differences in crustal deformation along three transects across the northern and central Zagros Mountains and were successfully modelled with different Moho geometries. Generally two-stage crustal thickening has been inferred, where low amplitude long wavelength thickening of the crust changes abruptly to more pronounced thickening near the Main Zagros Thrust.

Differences in mantle shear wave velocities (4.2–4.4 km s$^{-1}$ at MSL and 4.4–4.5 km s$^{-1}$ at BHD) may indicate the differences at upper–mantle velocity structure under MSL and BHD. The lithospheric mantle might be expected to be shallower close to Bitlis-Zagros suture zone at MSL whereas BHD having higher velocities at the more stable part of the Arabian Platform. If so, the lithospheric mantle is probably thinner at MSL than BHD station.

**CONCLUSION**

Newly available broad-band seismic waveform data from seismic stations in MSL and BHD Iraq provide a unique opportunity to
estimate the crustal velocity structure in poorly sampled regions of the northern Arabian plate. In spite of limited data, we were able to infer reliable crustal velocity structures through the joint inversion of stacked RFs and Rayleigh wave dispersion. The inversion results were tested for their sensitivity to the starting models and we obtained very consistent velocity models down to about 100 km, indicating that the joint inversion is quite robust.

Our results show that the crustal and sedimentary thicknesses are 39 and 3 km at MSL and 43 and 7 km at BHD, respectively. The inferred sedimentary thicknesses agree well with the existing models (e.g. Seber et al. 1997; Bassin et al. 2000). In fact the main difference between our results at MSL and BHD and those at nearby stations MRDN (southern Turkey) and KBD (Kuwait) are in the sedimentary structures. The crystalline crustal structures are remarkably similar between these stations (well within estimated errors) separated by over 1000 km. While the crystalline crustal structures are similar between MSL and BHD, the P-wave RFs require very different Moho structures. The large amplitude $P_{S\text{Moho}}$ phase at station BHD requires an abrupt crust–mantle transition, while the weak $P_{S\text{Moho}}$ at MSL requires a gradual crust–mantle transition occurring over 6–9 km. The transitional Moho at MSL, located in the Zagros Fold Belt, may reflect compositional processes related to crustal thickening. Indeed crustal thickening is required by gravity data modelled by Snyder and Barazangi (1986) in the Zagros Fold Belt in southern Iraq.

The uniformity of crystalline crustal structure in the northern Arabian Platform suggests that before subsidence and emplacement of sediments the proto-Arabian Platform was very uniform. This observation can be used as a constraint on crustal deformation of the Arabian–Eurasian collision. While the crystalline crustal structure in northern Arabia is uniform, crustal structure of the Zagros Fold and Thrust Belt is quite complex along strike based on inferred structure from crossing transects (Snyder & Barazangi 1986; Paul et al. 2006). This suggests that the crust has deformed differently in response to pre-existing plate boundary geometry or heterogeneous stress along the strike of the Zagros Fold and Thrust Belt. Our observation of relatively uniform crystalline crust in the northern Arabian Platform suggest inferred crustal thickness variations along the Zagros Mountains may reveal differences in the geometry of the plate boundary and/or the magnitude and orientation of convergence between Arabia and Eurasia. Future broadband and active source seismic investigations coupled with other field geophysical and geological will be needed to bring light to this issue.

ACKNOWLEDGMENTS

We thank Charles Ammon for providing his time-domain deconvolution code and Jordi Julia for joint inversion codes. Mike Pasyanos provided group velocity dispersion curves and comments that improved the original manuscript. The helpful suggestions of
Christel Tiberi and other anonymous reviewer helped us to improve this manuscript. This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344, UCRL-TR-224124.

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