SEISMIC VELOCITY MODELING OF NORTH AND NORTHEAST IRAQ USING RECEIVER FUNCTIONS

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ABSTRACT

A primary objective of this project is to estimate the local and regional seismic velocity structures of north and northeastern Iraq, including the northern extension of the Zagros collision zone, using well-established seismological techniques. This is a region where global seismic network coverage is poor and where extrapolated velocity models found in the literature lack sufficient accuracy to permit events to be located with significant precision. Installed in late 2005, ten broadband three-component stations composing the North Iraq Seismographic Network (NISN) provided the unique data that made this phase of the study possible. The results of teleseismic P-wave receiver functions (RF) analysis and velocity structure estimation are presented herein. RF is a time series computed from three-component seismograms that show the relative response of earth structure near a receiver. To date, over 4500 waveforms from about 150 events recorded by NISN stations during the period 30 November 2005 to 31 August 2006 have been scrutinized. Based on the USGS Preliminary Determination of Epicenters (PDE) bulletins, the epicenteral distances of these teleseismic events to NISN stations range from 30º to 90º, and their magnitudes equal or exceed 5.5. Additional data recorded from September 2006 through March 2007 will also be examined. It is anticipated that this will nearly double the amount of data available for reliably estimating the velocity structure of the region. Preliminary results indicate that the depth of the Moho varies considerably beneath NISN. It is relatively shallow (35–45 km) to the northwest and deeper (50–60 km) under the southeastern portion of the network area. Although these initial results correspond well with the tectonic and physiographic framework of the Arabian plate, the values will be further revised and constrained when surface wave dispersion analysis is added to the process.

OBJECTIVE

Estimating the seismic velocity structure beneath stations of the North Iraq Seismographic Network (NISN) is the focus of this paper. To fulfill this objective, the well-known RF inversion technique is first applied to the data. Other inversion and waveform modeling approaches to better constrain or improve the velocity models will follow. In other words, this is a preliminary outcome of the ongoing research to improve our understanding of the study area. In progress is the simultaneous inversion of the RF and surface wave dispersion. The latter provides valuable constraint on the RF computational process and the estimated seismic velocity structures. Evaluation of the resulting models will be performed through relocation of recorded events, synthetic waveform analysis, and correlation with available geophysical and geological information.

In August 2005 and in cooperation with the Sulaimaniyah, Erbil, Baghdad, and Mosul seismological observatories (SSO, ESO, BSO and MSO, respectively), the first two temporary stations (KSLY and ERBL) were deployed. The existing NISN was deployed in November of the same year. Stations BHD in Baghdad and MSL in Mosul, however, were installed in April 2006. The names, geographical coordinates, and elevation of the stations are given in Table 1. To date, more than 100 gigabytes of unprecedentedly high-quality, continuous, three-component broadband seismic data have been collected at a rate of 100 sps.

Table 1. Parameters of the North Iraq Seismological Network (NISN)

North Iraq Seismological Network (NISN)						
No.	Station Name	Latitude (degrees)	Longitude (degrees)	Elevation (meters)	Installation Date	Removal Date
1	KSBB	35.0415	45.7092	550	11/25/2005	
2	KSSS	35.7696	46.2362	1515	11/26/2005	
3	KSWW	36.1493	45.2624	1310	11/28/2005	
4	KSJS	35.4965	45.3452	825	11/27/2005	
5	KEHH	36.6764	45.0470	1725	11/30/2005	
6	KESM	36.9846	44.1981	1000	12/01/2005	
7	KDDA	37.2125	42.8207	750	12/02/2005	
8	KEKZ	35.9893	44.0970	450	12/03/2005	
9	MSL	36.3817	43.1483	242	04/06/2006	
10	BHD	33.2744	44.3858	32	04/11/2006	
11	KSLY	35.5559	45.4534	912	08/23/2005	04/04/2006
12	ERBL	36.3772	44.2086		08/21/2005	11/29/2005

Except for BHD all the other stations are located in the foothills and folded belts to the southwest and south of the Zagros and Taurus (Bitlis) zones, respectively. Figure 1 shows a generalized diagram of the seismotectonic framework of the Arabian plate. NISN stations (white triangles) are located along the northeast boundary of the plate where the Zagros thrust zone and the Bitlis suture zone converge. This region is characterized by a high level of seismic activity, as evidenced by the large number of local and regional events recorded by NISN (Ghalib et al., 2006) and by the teleseismically located earthquakes reported by the United Stated Geological Survey (USGS) bulletins (Figure 1).

Until the deployment of the NISN, most research efforts concerning the study area were conducted using distant stations. More recently Pasyanos et al. (2004) produced a generalized velocity model for the Zagros fold and thrust zones. Prior to that, Ghalib (1992) produced average velocity models derived from the dispersion of Rayleigh waves recorded at station TAB in near by northwestern Iran.

RESEARCH ACCOMPLISHED

RF is a time series computed from three-component seismograms that show the relative response of earth structure near a receiver (Ammon, 2006). The RF methodology has been extensively used by seismologists. While the overall method is straightforward to define, the computation of reliable receiver functions can be problematic due to the non-uniqueness of RF inversions and has been the subject of many papers, including Burdick and Langston (1977), Langston (1977), Ammon (1991), Cassidy (1992), Ligorría and Ammon (1999), Park and Levin (2000), and

Helffrich (2006). With these efforts, many techniques have been developed to overcome difficulties stemming from instabilities in the deconvolution process. At this early stage of research, the Ammon (2006) and Herrmann (2006) approach and computational software are used to determine the RF and invert for the seismic velocity models but without the benefit of utilizing surface waves (an invaluable step being considered next).

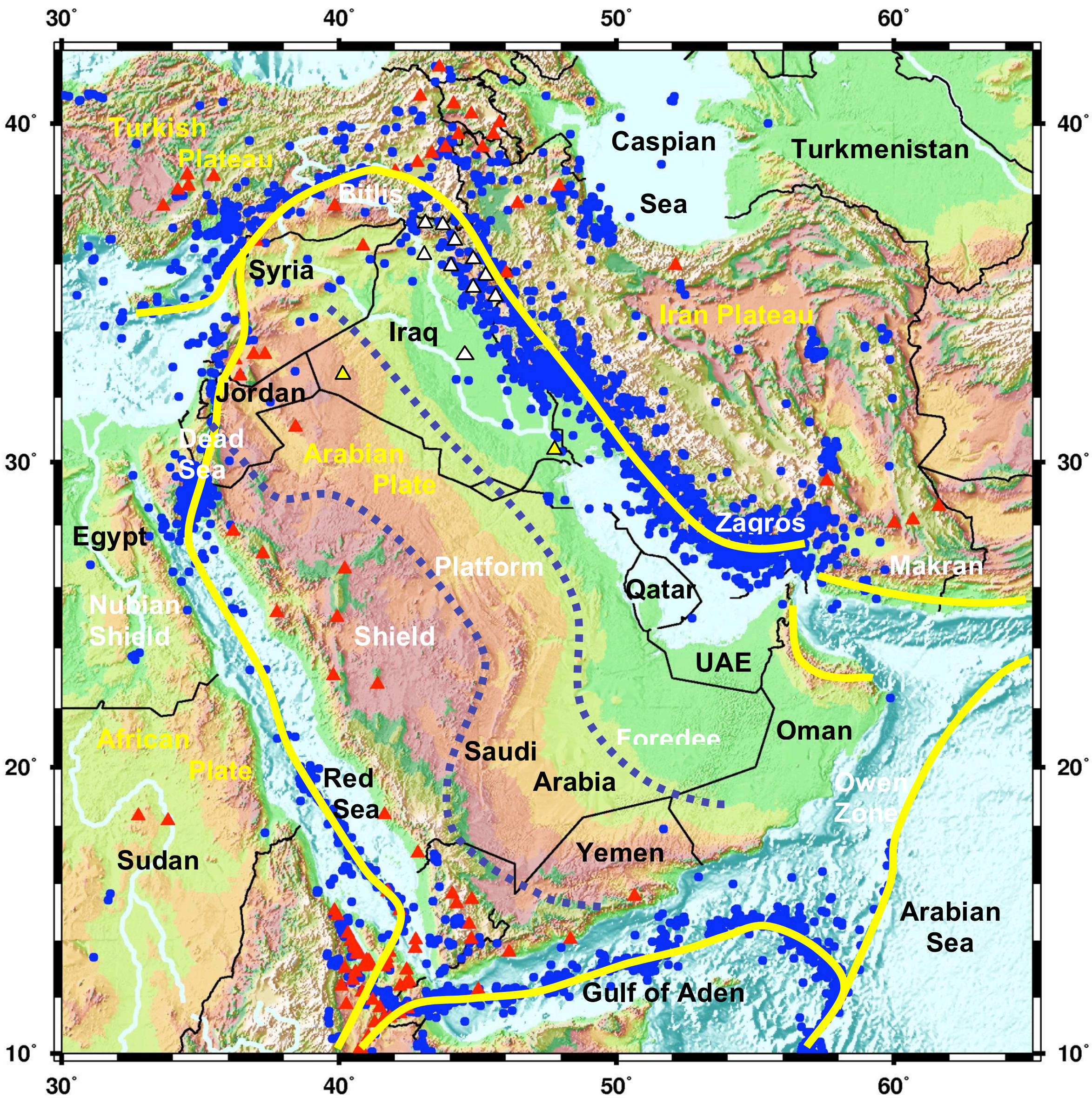

Figure 1. **Map of the Arabian Peninsula and surrounding regions. The major geographic, tectonic, and geologic features (Arabian Shield, Platform, and Foredeep) are labeled. The plate boundaries (Gulf of Aden, the Red Sea, the transform fault along the Dead Sea and East Anatolia of the Turkish plateau, the Bitlis Suture in eastern Turkey, the northwest-southeast trending Zagros thrust zone, the Makran east-west trending continental margin and subduction zone, and the Owen fracture zone in the Arabian Sea) are marked with yellow lines. Earthquakes and volcanoes are shown as blue circles and red triangles, respectively. White triangles represent the 10 stations that compose the NISN. The yellow triangles reflect the location of some of Iraq Seismological Network (ISN), but those are currently not operational.**

A search of the PDE bulletins for the period from 30 November 2005 to 31 August 2006 resulted in a long list of teleseismic events at various azimuths and epicenteral distances in the range of 30–90 degrees from NISN. Corresponding searches of NISN records resulted in about 150 events with magnitudes equal to or exceedng 5.5 and over 4500 waveforms available for scrutiny and analysis. Figure 2 is an example of well-recorded teleseismic P waveforms at stations KSBB, KSSS, and KSWW. The event occurred in the Kuril Islands on 22 June 2006, and its magnitude (Mw) was 6.0. The quality of observed P waves was assigned a subjective grading scale (A, good, through D, poor) to reflect the quality of recorded signal-to-noise levels (i.e., acceptable level of signal-to-noise ratio to produce stable and reliable receiver functions). This exercise helped with the waveform selection process and with understanding of the impact of lower-grade signals on the RF and resulting models. In the final data processing, only good-quality waveforms (grade A and B) were used.

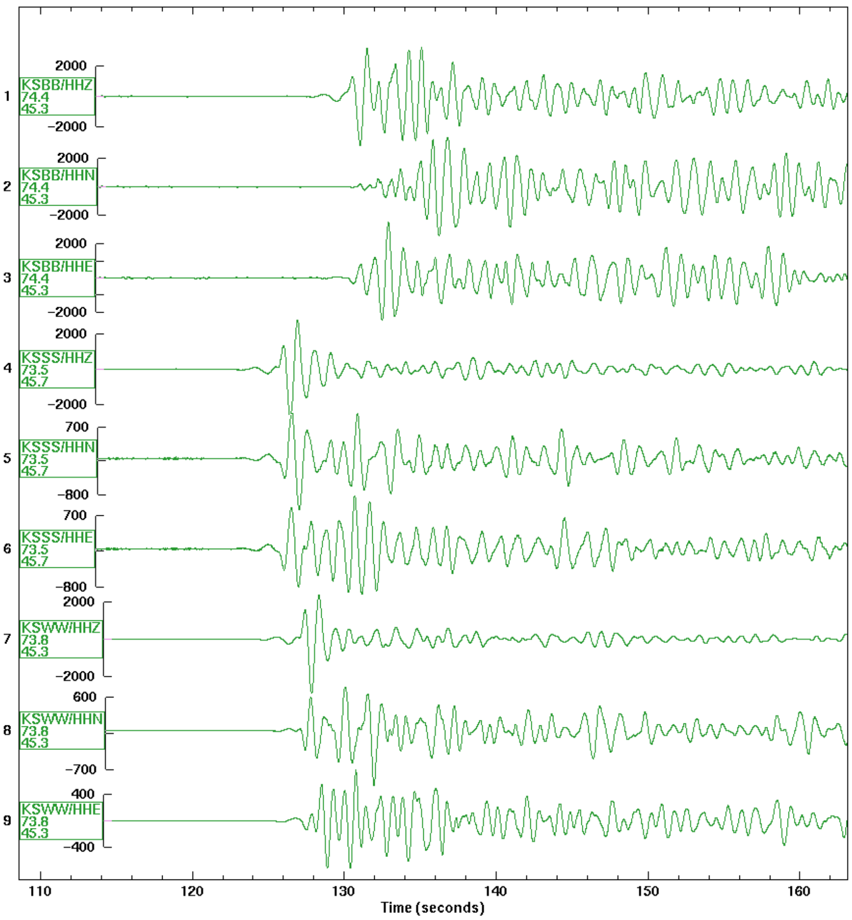

Figure 2. Sample teleseismic P waveforms of a Kuril Islands event recorded at three of NISN stations (KSBB, KSSS, and KSWW) and used in the RF inversion. The event occurred on 22 June 2006, and according to the USGS PDE, its magnitude (Mw) was 6.0.

After the data were reformatted to include the required event location (latitude, longitude, and depth) and P-wave arrival time in the SAC header, the receiver functions were estimated for each high-quality station seismogram. Also in preparation for the inversion process, a simple multi-layered initial shear velocity model was created to follow the general characteristics of the models derived by Ghalib (1992), using the group velocity dispersion curves of observed Rayleigh waves traversing the study area. The S-velocity of the crustal layers was set to 4.0 km/s and the upper mantle layers (below 90 km) to 4.5 km/s to reflect the lower-than-average velocity structure previously observed throughout the region. The thicknesses of the layers vary from 0.5 km at the top and to a maximum of 10 km at the bottom of the crust (a gradual increase with depth). In the upper mantle, the layer thicknesses range from 10 to 100 km.

The RF inversion process is iterative and requires a certain measure of damping administration to control the problem of finding a reasonable model. Figure 3 is an example of the observed (blue) and estimated (red) RF for 39 events recorded at station KSWW. The best fit of these receiver functions ranges from 60% to 93%, and the back-azimuth to these events ranges from 20 to 120 degrees.

The resulting preliminary one-dimensional seismic velocity models for stations KESM, KEHH, KSWW, KSSS, KDDA, KEKZ, KSJS, and KSBB are presented in Figure 4. No models were estimated for stations MSL and BHD due to the scarcity of data available at the time and to the generally low signal-to-noise ratios that disqualified most of the available waveforms recorded at these two stations. Common among the eight models is the relatively lower-than-average shear velocities of the layers when compared with other regions of the Earth and the presence of a significant discontinuity at about 15 km depth. The depth of the Moho seems to vary from about 45 to 55 km. These results may not be final, but they are certainly consistent with previous observations made by, among others, Aleqabi et al. (2007), Pasyanos et al. (2004) and Ghalib (1992). Also noticeable is the diminishing data resolution at depths exceeding about 80 km. The observed change in shear velocity values below that depth is simply a perturbation in response to the better-estimated velocities of the crustal layers where the data resolution is highest.

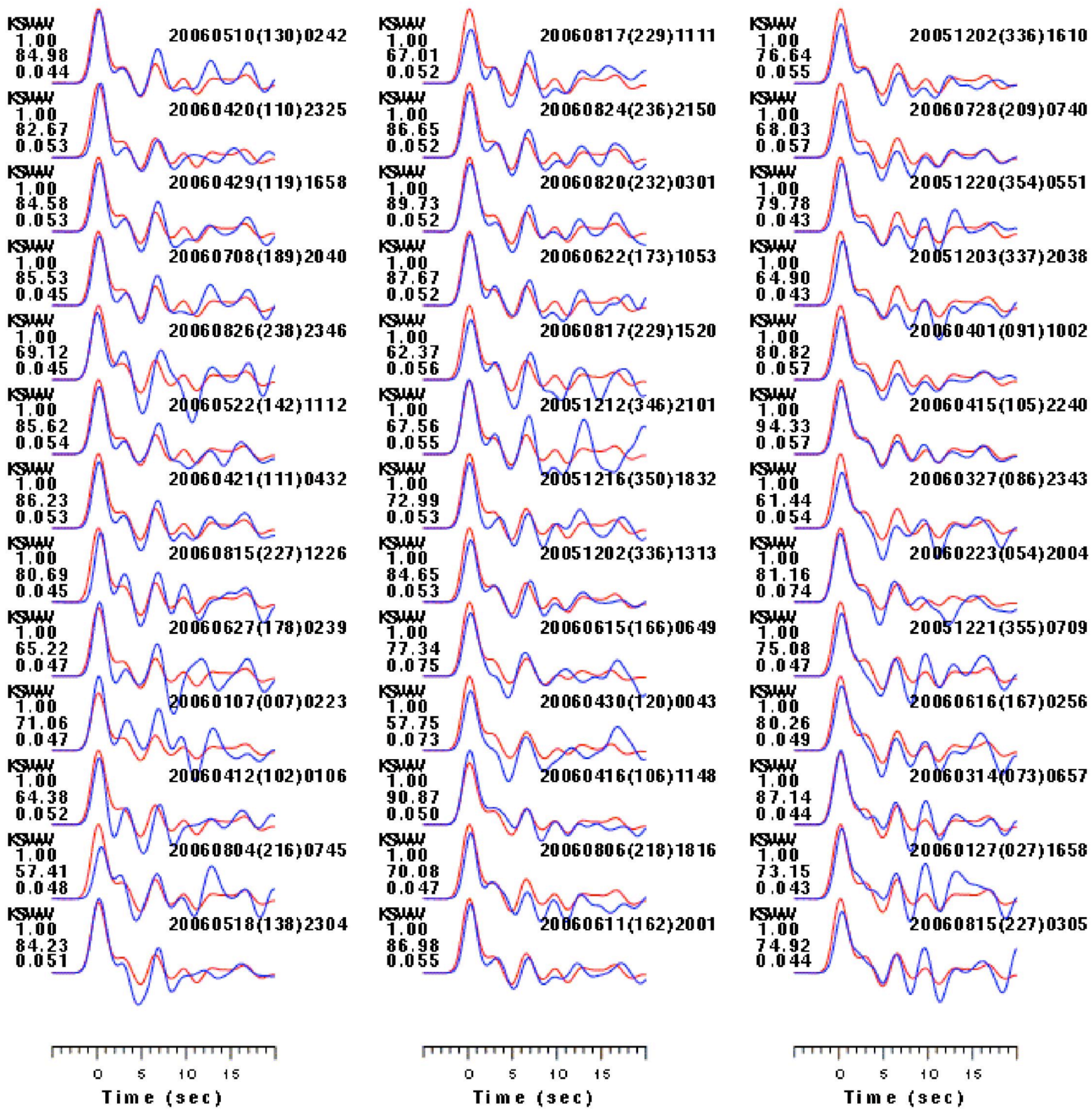

Figure 3. Sample receiver functions for 29 teleseismic events recorded at station KSWW. The observed RF are shown in blue and estimated from the inversion process in red. The best fit for these RF range from 60% to 95%.

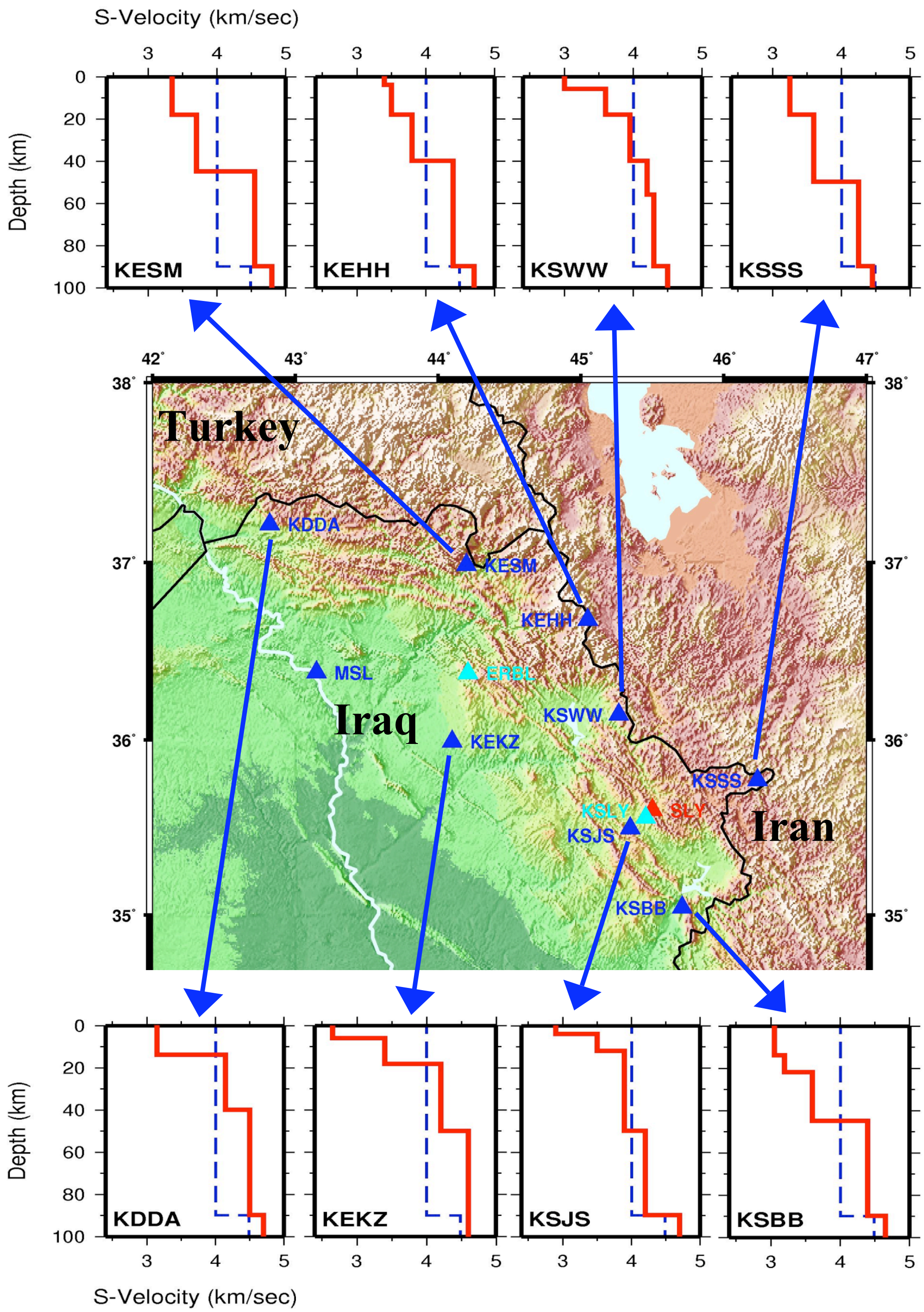

Figure 4. A map showing the location of NISN (marked with blue triangles) and the preliminary shear-velocity models obtained from RF inversion. Station ERBL and KSLY (aqua triangles) are the temporary stations. Station SLY (red triangle) belongs to the ISN.

CONCLUSIONS AND RECOMMENDATIONS

This report signifies the initial outcome of an ongoing effort to estimate the seismic velocity structure beneath eight of the NISN three-component broadband stations. At this early stage of the research, the models are exclusively estimated from the inversion of the receiver functions of teleseismic P wave seismograms. Most significant about these models is that they consistently reflect lower-than-average velocities, as has been previously observed, and seem to characterize the seismic structure of this region.

Evaluation of the presented models is premature since more teleseismic P- and surface-wave data are being scrutinized for processing and simultaneous inversion. The amount of available data is expected to double, and more than one RF inversion approach is being considered. These data will help generate more-reliable models that can withstand the test of relocating events with higher precision and synthetic waveform modeling that matches well with the observed seismograms.

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REFERENCE

Aleqabi, G., M. Wysession, H. A. A. Ghalib, M. Sibol, B. Saeed Ali, B. Saleh, A. Mahmood, S. Abdullah, L. Omar, N. Aziz, N. Ahmed, D. Mahmood, N. Alridaha, T. Alnasiry, O. Shaswar, A. Ali, A. Taqi, S. Khalaf, and F. Ibrahim (2007). Seismic velocity structure of Iraq and surrounding regions from surface-waves waveform inversion, (Abstract) *Seism. Res. Lett.* 78: 310.

Ammon, C. J. (1991). The isolation of receiver effects from teleseismic P waveforms, *Bull. Seism. Soc. Am.* 81: 2504–2510.

Ammon, C. J. (2006). Receiver-Function Analysis, Pennsylvania State University, Web page: http://eqseis.geosc.psu.edu/~cammon/HTML/RftnDocs/rftn01.html

Burdick, L. J. and C. A. Langston, (1977). Modeling crustal structure through the use of converted phases in teleseismic body-wave forms, *Bull. Seism. Soc. Am.* 67: 677–691.

Cassidy, J. F. (1992). Numerical experiments in broadband receiver function analysis, *Bull. Seism. Soc. Am.* 82: 1453–1474.

Ghalib, H. A. A., G. I. Aleqabi, B. S. Ali, B. I. Saleh, D. S. Mahmood, I. N. Gupta. R. A. Wagner, P. J. Shore, A. Mahmood, S. Abdullah, O. K. Shaswar, F. Ibrahim, B. Ali, L. Omar, N. I. Aziz, N. H. Ahmed, A. A. Ali, A.-K. A. Taqi, and S. R. Khalaf (2006). Seismic characteristics of northern Iraq and surrounding regions, in *Proceedings of the 28th Seismic Research Review: Ground-Based Nuclear Explosion Monitoring Technologies*, LA-UR-06-5471, Vol. 1, pp. 40–48.

Ghalib, H. A. A. (1992). Seismic velocity and attenuation of the Arabian plate, Ph.D. dissertation, Saint Louis University, p. 314.

Helffrich, G. (2006). Extended-time multitaper frequency domain cross-correlation receiver-function estimation, *Bull. Seism. Soc. Am.* 96: 344–34.

Herrmann, R. B. (2006). Surface waves, receiver functions and crustal structure, in *Computer Programs in Seismology*, Version. 3.30, Saint Louis University, St. Louis, MO. Web page: http://www.eas.slu.edu/People/RBHerrmann/CPS330.html.

Langston, C. A. (1977). The effect of planar dipping structure on source and receiver responses for constant ray parameter, *Bull. Seism. Soc. Am.* 67: 1029–1050.

Ligorría, J. P. and C. J. Ammon (1999). Iterative deconvolution and receiver-function estimation, *Bull. Seism. Soc. Am.* 89: 1395–1400.

Park, J. and V. Levin (2000). Receiver functions from multiple-taper spectral correlation estimates, *Bull. Seism. Soc. Am*. 90: 1507–1520.

Pasyanos, M. E., W. R. Walter, M. Flanagan, P. Goldstein, and J. Bhattacharyya (2004). Building and testing a priori geophysical model for western Eurasia and North Africa, *Pure Appl. Geophys*. 166: 47.

Wessel, P. and W. H. F. Smith (1998). New, improved version of Generic Mapping Tools released, *EOS, Trans. AGU* 79: 579.