CRUSTAL VELOCITY MODELS OF THE ZAGROS-BITLIS ZONE FROM BODY- AND SURFACE WAVE ANALYSES

Roland Gritto[1], Matthew S. Sibol[1], Pierre Caron[1], Hafidh A. A. Ghalib[1], Robert B. Herrmann[2], Ghassan I. Aleqabi[3], Bakir S. Ali[4], Ali A. Ali[5]

Array Information Technology[1], Saint Louis University[2], Washington University in Saint Louis[3], Sulaimaniyah Seismological Observatory[4], Baghdad Seismological Observatory[5]

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ABSTRACT

Results of crustal studies obtained with seismic data from the Northern Iraq Seismic Network (NISN) are presented. NISN has operated ten broadband stations in north-eastern Iraq since late 2005 and was supplemented by the five-element broadband Iraq Seismic Array (KSIRS) in 2007. In the past two years, the former Iraq Seismic Network (ISN) was reestablished with the deployment of six broadband stations throughout Iraq. The aim of the present study is to derive models of the local and regional crustal structure of the Middle East, including Eastern Turkey, Iraq and Iran. To achieve this goal, we derive crustal velocity models using surface - and body wave analyses. The velocity models will eventually be used to obtain accurate hypocenter locations and event focal mechanisms. At present we have analyzed over 3,000 surface wave dispersion curves from about 200 events throughout the Middle-East. NISN data were augmented by waveforms from IRIS including those published by the neighboring Syrian, Iranian and Turkish networks. Our Rayleigh wave velocity analysis resulted in a clear demarcation of the tectonic features in the region. The results show a thick (10-15km) sedimentary layer that overlays the crystalline basement and a Conrad and Moho discontinuities at depths of 20-25km and 45-55km, respectively. The results also show that the Arabian plate exhibits higher shear-wave velocities than found across the Turkish and Iranian plateaus; imprint of the Zagros Mountain roots extends down as deep as the Moho; and that the tectonic boundaries along the Dead Sea, Taurus and Zagros are more pronounced with depth describing a 60km or thicker Arabian plate. Current work involving body wave velocity tomography modeling is intended to improve the resolution of the obtained velocity model and extend it across the region from Iran across Iraq into Eastern and Central Turkey.

OBJECTIVES

Through collaboration with the Sulaimaniyah Seismological Observatory, Erbil Seismological Observatory, Iraqi Meteorological Organization and Seismology, and the University of Baghdad, Array Information Technology (AIT) has collected over 1 TB of continuous digital broadband seismic data as a result of the successful deployment throughout northern Iraq of ten three-component stations that comprised NISN. Since late 2005, these data have yielded over 3,000 well located events. Additional broadband data have been provided by a seismic array (KSIRS) recently installed in northeast Iraq and from the newly refurbished stations of Iraq Seismographic Network (ISN). A wealth of seismic bulletins and waveforms for over 30,000 events is also provided by the Iranian Seismological Center (IRSC) of the Institute of Geophysics at the University of Tehran, and the International Institute of Earthquake Engineering and Seismology under Iran's Ministry of Science Research and Technology. The combination of these datasets provides an unprecedented database to perform a variety of in-depth and detailed seismological studies on Iraq, Iran and neighboring countries.

The objectives of the current project include the development of high-resolution crustal and upper mantle velocity models based on a combination of the available seismic datasets. The intention is to improve the resolution of existing regional models to derive a detailed structure of the tectonics of the Middle East including the Arabian Peninsula and the Zagros Thrust Zone. In the current paper, we present results of our Rayleigh surface wave analysis and provide an outlook of our current project of 3-D P- and S-wave body-wave tomography.

RESEARCH ACCOMPLISHED

Translational and rotational interaction between the Arabian, African and Eurasian plates over time has resulted in a challenging seismotectonic framework that is least understood in the Middle East region, in particular. Sea floor spreading along the Red Sea and Gulf of Aden, transform faulting along the Dead Sea and Own fracture zone, and compressional suture zones form the seismic and tectonic boundaries between the Arabian plate and the Iranian and Turkish plateaus creating the Bitlis/Zagros fold zone along the northern boundary of Iraq and the western boundary of Iran. The geography of this region is presented in Figure 1, where major tectonic features and plate boundaries are noted for reference. Until recently, the tectonic structure of this collision was not well understood. Theories included continental subduction or delamination of the Arabian plate (Rotstein and Kafka, 1982), continental thickening of the Eurasian plate (Dewey et al., 1986), or a combination of these processes. Reilinger (2008) presented GPS measurements of the velocity field of the Arabian Peninsula. The results, comprised of measurements from 1988 through 2005 and presented in Figure 2, indicate a counter-clockwise rotation of the Arabian Peninsula, relative to the Iranian and Turkish plateaus. In order to verify plate boundaries, crustal thickness, collision zones and spreading centers associated with the plate rotation observed at the Earth surface Raleigh wave tomography was conducted throughout the Middle East.

Seismic waveform data were collected by NISN, the International Institute of Earthquake Engineering and Seismology (IIEES), Incorporated Research Institutions for Seismology (IRIS) and Observatories and Research Facilities for European Seismology (ORFEUS). The station locations and epicenters used for the surface tomography study are presented in Figure 3. The surface wave dispersion analysis was performed using the multiple filter technique (MFT) to determine group velocity dispersion curves. This analysis yields the variation of Rayleigh wave group velocities at given periods along the propagation path from the epicenter to the recording station. During our study, we calculated 4,215 dispersion curves of which 3,663 were utilized in the results presented here. The spatial distribution of the 3,663 ray paths is indicated by the light blue lines in Figure 3. It can be seen that the ray density is highest in the center of the Zagros thrust zone, where the concentration of seismicity and stations is highest. Given the density of paths, a 1°x1° grid was used to develop a detailed map of the lateral and vertical variation of shear-wave velocities in the Middle East.

The second step, after deriving dispersion curves for all ray paths, uses the grid dispersion inversion (GDI) technique to determine single dispersion curves for each 1°x1° grid cell. Once the single dispersion curves are determined, the shear velocity as a function of depth is estimated in each cell using the program SURF96 (Herrmann, 2006). An example of a dispersion curve inversion fit for a fundamental Rayleigh wave and an estimate of its associated velocity as a function of depth is presented in Figure 4. The velocity inversion as a function of depth is based on an initial starting model indicated by the dashed blue line. It can be seen that the inversion changes the velocity model only where supported by measured data. In the current case of a well fitted dispersion curve between 5 and 60 sec, the resolved depth range is limited to the crust and upper mantle to a depth of approximately 60 km (red line). Because the measured periods support velocity estimates down to the upper mantle only, it is important that the starting model reaches much deeper into the mantle. Such an approach will avoid large oscillations in the velocity estimates at depth, which may adversely affect estimates in the crust and upper mantle.

The results of the velocity inversion are presented in Figure 5. The figure shows a set of horizontal depth slices from 5 – 80 km throughout the Middle East representing the spatial distribution of the shear wave velocity. At shallow depth (5 km) the sedimentary basins in western Iraq and along the Euphrates and Tigris Rivers in central Iraq are clearly visible. Furthermore, the thick sedimentary basin below the southern Caspian Sea is apparent by its low shear wave velocities down to 20 km depth. The Arabian Shield, in the western peninsula, is demarked by higher shear wave velocities than the Foredeep (compare to Figure 1) with its thicker sediments along the eastern half of the peninsula at depths of 5–20 km. At a depth range from 20–30 km the spreading center in the Red Sea is visible by higher shear wave velocity indicating the presence of magmatic rocks. An interesting feature is the strike of the spreading center which does not follow the orientation of the Read Sea, but transects the region from Eritrea to north-western Saudi Arabia. The Zagros thrust zone is demarked by lower than average velocities along the axis of the Mountain range down to 55 km. The lower velocities are a manifestation of the tectonic forces that compress and fracture the rocks while lifting the Zagros Mountains and the Iranian Plateau. The resolution of the current study is reached at a depth of approximately 60 km, as indicated by the velocity depth profile in Figure 4. An overall velocity increase at 20 km depth may indicate the transition from crystalline to basaltic rocks (Conrad discontinuity), while the transition from crustal to mantle rocks (Moho discontinuity) is suggested by velocity increases between 45 and 50 km. In addition, the maps show that the Arabian plate exhibits higher shear-wave velocities than found across the Turkish and Iranian plateaus.

The results of the three-dimensional depth distribution of fixed shear wave velocity values are presented in Figure 6. The maps help to display the depth dependence of various terrains encountered in the Middle East. As such, the Arabian Shield is clearly distinct from the Foredeep extending to a depth of 20 km. Similarly, the root of the Zagros thrust zone can be recognized down to a depth of approximately 50 km. It is noted that this structure does not extend southward to the Makran mountain range. The strike of the Red Sea rift system is clearly visible in the maps denoting shear wave velocities of 3.8 km/s and 3.9 km/s and is oriented at an angle to the axis of the Red Sea. The deepest structures visible in the maps are indicated by the blue colored features surrounding the Arabian Peninsula at 60 – 65 km depth. The associated velocities of 4.0 km/s and 4.1 km/s suggest the presence of crustal rocks. This feature follows the tectonic boundaries along the Red Sea, the Dead Sea, the Taurus and the Zagros mountains. Therefore, it may demark the boundary of the Arabian Plate (compare to boundary indicated by yellow line in Figure 1) while indicating a thickness of about 60 km. However, these interpretations need to be viewed with caution as the limit in resolution of our study is reached at 60 km, as mentioned above.

CONCLUSIONS AND RECOMMENDATIONS

The current study generated results with significantly detailed tectonic structures of the crust in the Middle East. The main findings include a sedimentary column with a thickness of 5 – 10 km, while Conrad and Moho discontinuities were found at 20 km and 45 - 50 km depth, respectively. The thickness of the crust beneath the Arabian Peninsula is suggested to be about 60 km, which is the limit of depth resolution of the current study. Stable and well resolved features include the extent of the Zagros thrust zone down to the Moho and the Red Sea spreading center with its axis rotated counter clockwise to the axis of the Red Sea. Furthermore, the observed shear wave velocities of the Turkish Plateau to the north of the Taurus Mountains and of the Iranian Plateau to the east of the Zagros Mountains are generally lower than those of the Arabian Peninsula.

It should be noted that the presented results were obtained by combining seismic waveform data from Iraqi (NISN) and Iranian (IIEES) networks supported by IRIS and ORFEUS stations throughout the region. However, contributions from similar efforts along the various boundaries of the Arabian plate are as important to the stated objectives of better understanding the seismicity and seismotectonics of the greater Middle East region and should be pursuit in the future.

At present, efforts are under way to perform P- and S-wave tomographic studies of the crustal structure in the Middle East. These efforts will include a region including central and eastern Turkey, Iraq and Iran. Waveform analysis of NISN data from 2006 through 2008 has been completed and will be supported by data from IRIS and ORFEUS stations throughout the region. The goal is to complement the results of the surface wave analysis by increasing the resolution and detail of the imaged crustal structures.

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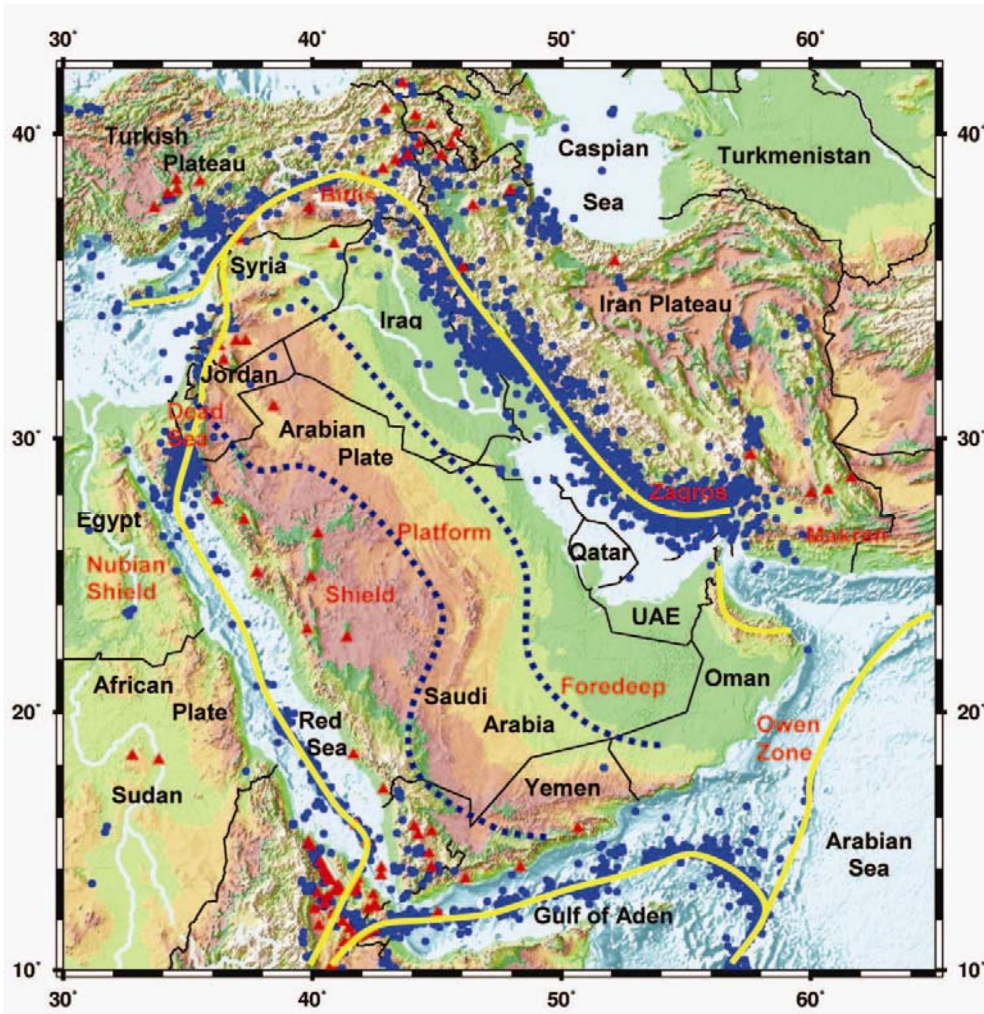

Figure 1. Map of the Arabian Peninsula and surrounding regions. The major geographic, tectonic and geologic features are labeled. The plate boundaries are marked with yellow lines. Earthquakes and volcanoes are shown as blue circles and red triangles, respectively. The depicted seismicity is for the time period between 1975 and 2001 for events of Mb ≥ 4.0.

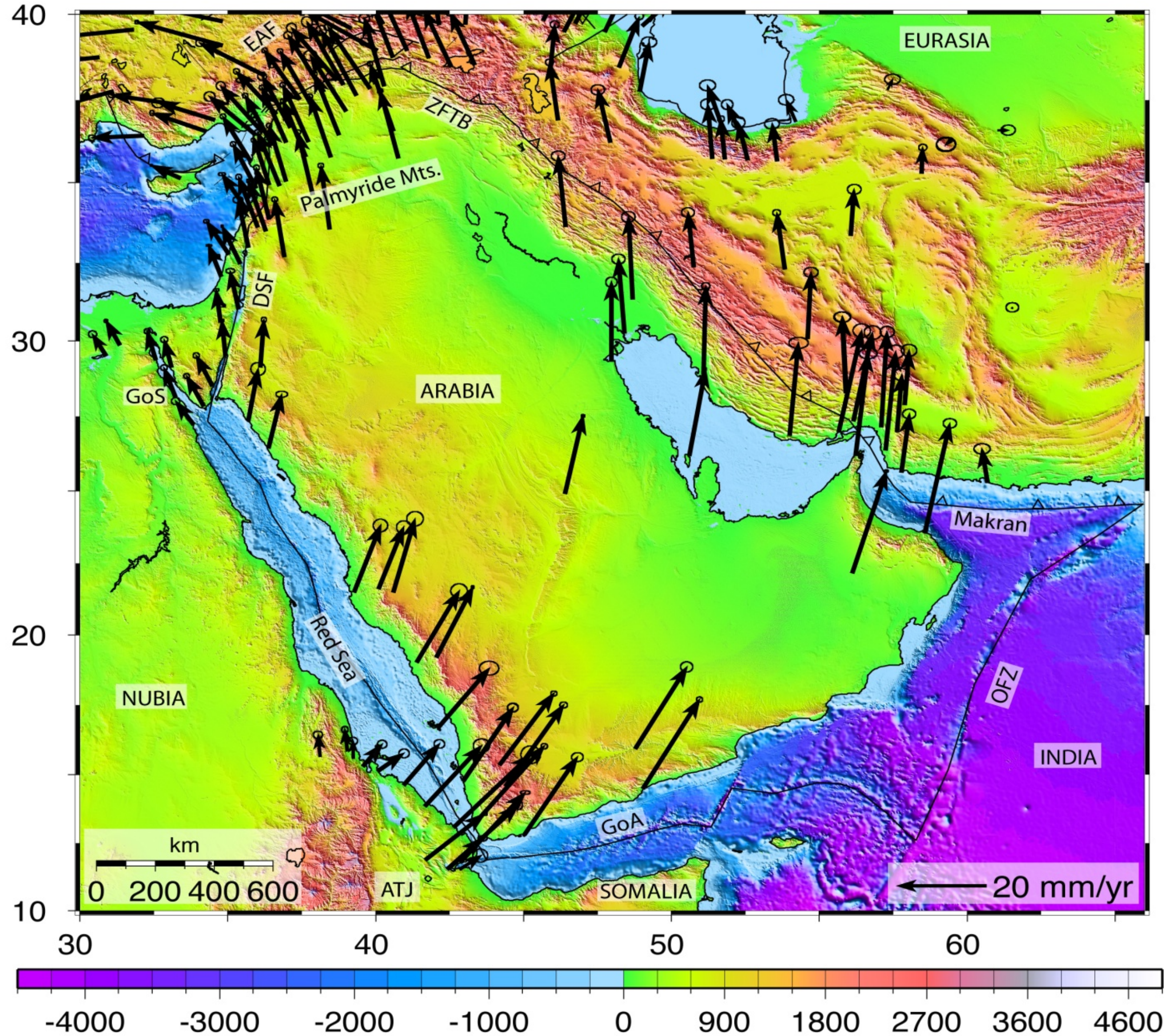

Figure 2. GPS-derived velocity field of the Arabian, African and Eurasian plates, showing counter-clockwise rotation of the Arabian Peninsula with a velocity of 20 – 30 mm/yr (Reilinger et al., 2008).

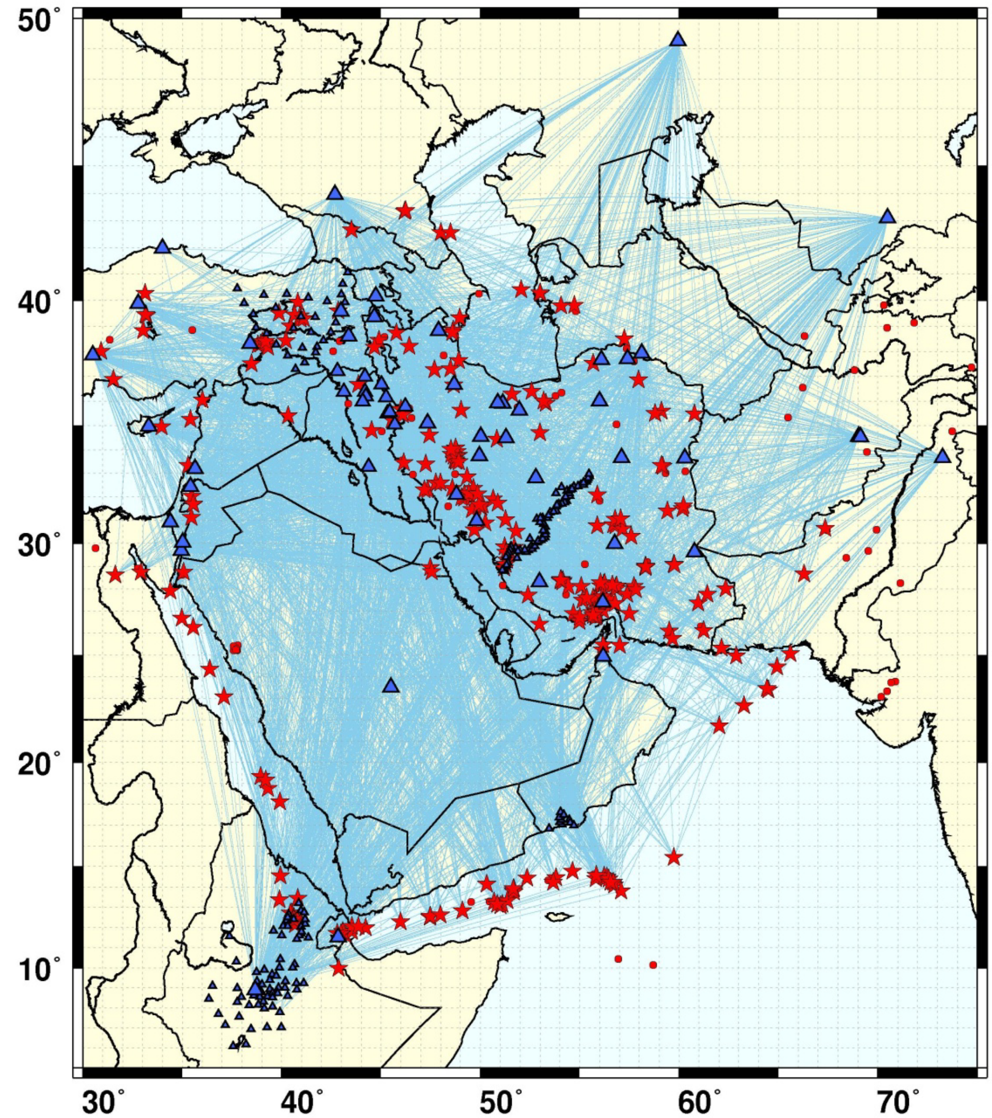

Figure 3. Mixed path dispersion curve coverage of the study area. A total of 262 earthquakes, denoted by red stars, were used for the surface wave analysis. The large blue triangles indicate the locations of the NISN, IRIS, ORFEUS, and IIEES seismic stations where the analyzed waveforms were recorded.

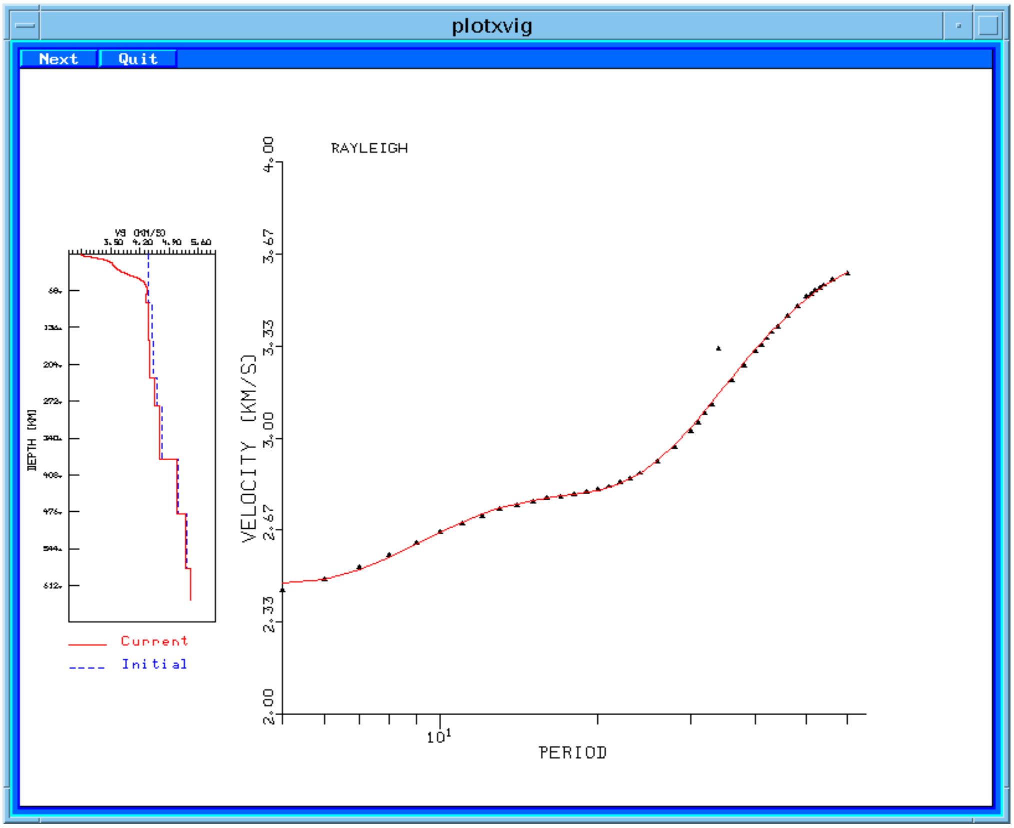

Figure 4. Example of dispersion curve inversion (right) and estimation of corresponding velocity model (left) along a ray path from epicenter to recording station. The black triangles (right) depict the observed dispersion curve data resulting from MFT, while the red line represents is the best dispersion curve fit. The velocity depth model (left) is characterized by its starting model, shown by the blue dashed line, and the resulting velocity profile given by the solid red line.

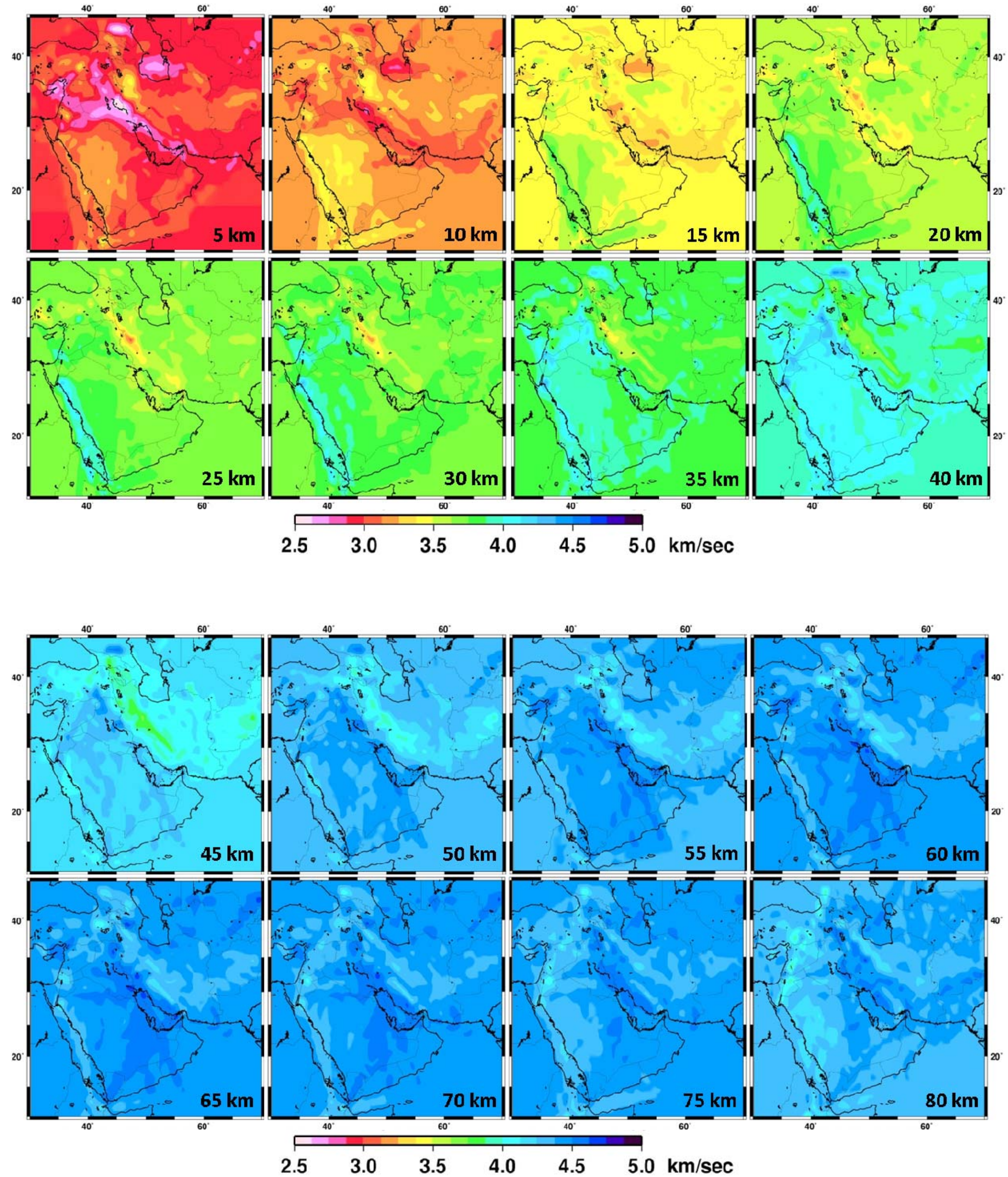

Figure 5. Maps showing the three-dimensional shear wave velocity variations in the Middle East for selected depths (5-80 km) derived from Rayleigh surface wave dispersion curves.

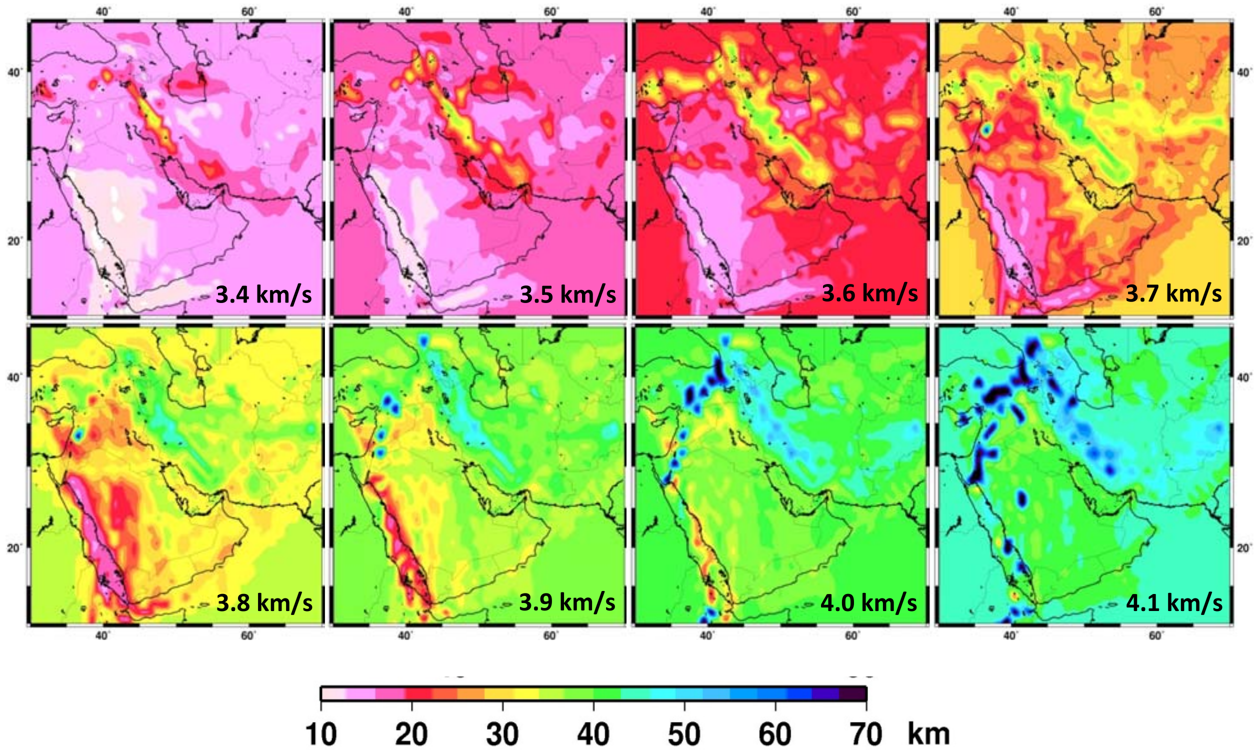

Figure 6 Maps showing the three-dimensional depth distribution of fixed shear wave velocity values (3.4 – 4.1 km/s) in the Middle East. A depth color scale is shown at the bottom.