LITHOSPHERIC MODELS OF THE MIDDLE EAST TO IMPROVE SEISMIC SOURCE PARAMETER DETERMINATION/EVENT LOCATION ACCURACY

Rengin Gök[1], Stephen Herzog[2], Keith Nakanishi[1], Michael E. Pasyanos[1], Rob J. Mellors[1], Arthur J. Rodgers[1], David B. Harris[1], and Eileen S. Vergino[1]

Lawrence Livermore National Laboratory[1] and the National Nuclear Security Administration[2]

Sponsored by the National Nuclear Security Administration and the U.S. Department of State

Award Nos. DE-AC52-07NA27344/24.2.3.2 and DOS_SIAA-11-AVC/NMA-1

ABSTRACT

The Middle East is a tectonically complex and seismically active region. The ability to accurately locate earthquakes and other seismic events in this region is complicated by tectonics, the uneven distribution of natural earthquakes, and the fact that countries run separate national seismic networks without well-developed data-sharing agreements. We report here on a variety of scientific efforts to enhance knowledge of the lithospheric velocity structure in the Middle East, making use of data from national networks in Saudi Arabia, Oman, and Kuwait to improve seismic location accuracy for events throughout the region.

Collaborative seismology engagements with research institutes in the Middle East have produced several important findings. Studies of regional seismic structure revealed that the Arabian Shield and the Arabian Platform have fundamental differences in velocity structure. The earth’s crust is relatively thicker than average in Kuwait and Iraq as a result of the Mesopotamian Foredeep, characterized by 8-10 km thick sediments. Ophiolites dominate the southeastern margin of the Arabian Peninsula, where the crust is thicker and seismic velocities are faster. In Kuwait, seismic activity is intensified near oil fields, and seismic source parameters show that this activity comes from tectonic events.

This work is informed by continuous or event-based regional seismic data obtained from 68 seismic stations from national networks, and this number is expected to grow in the future. A current effort is focused on using regional seismic data to develop better and more accurate seismic magnitude scales based on coda for stations in these national networks. Data and derived measurements from stations are integrated into lithospheric velocity and attenuation models to increase resolution, improve event location accuracy and source parameter determination, and advance tectonic understanding of the region.

Report Documentation Page		*Form Approved* *OMB No. 0704-0188*
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.		
1. REPORT DATE **SEP 2012**	2. REPORT TYPE	3. DATES COVERED **00-00-2012 to 00-00-2012**
4. TITLE AND SUBTITLE **Lithospheric Models of the Middle East to Improve Seismic Source Parameter Determination/Event Location Accuracy**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Lawrence Livermore National Laboratory,7000 East Ave,Livermore,CA,94550-9234**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES **Published in the Proceedings of the 2012 Monitoring Research Review - Ground-Based Nuclear Explosion Monitoring Technologies, 18-20 September 2012, Albuquerque, NM. Volume I. Sponsored by the Air Force Research Laboratory (AFRL) and the National Nuclear Security Administration (NNSA). U.S. Government or Federal Rights License**		
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15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

OBJECTIVES

We engage in mutually beneficial bilateral and multilateral seismology arrangements in the Middle East that provide important data coverage of the region's complex geophysical structures, thereby improving location accuracy for lithospheric velocity and attenuation models. These models can then be used to improve earthquake hazard mitigation, tsunami warning systems, and Comprehensive Nuclear-Test-Ban Treaty (CTBT) monitoring.

The Middle East is part of the Alpine-Himalayan system, where the Iranian and Turkish Plateaus meet at the Arabian Plate, and the divergent plate boundary is at the Red Sea and convergent plate boundary is at the Zagros Mountains. In addition to this geophysical complexity, seismological studies of the region typically suffer from a lack of available data. Data availability issues result from an uneven distribution of seismic stations due to logistical, financial, and even political reasons. Consequently, seismic event data distribution is highly uneven, strongly sampling from some parts of the region, while minimally sampling from others. Seismicity is also unevenly scattered throughout the region, with the highest concentration found near the eastern Zagros Mountains.

Location accuracies and lithospheric models are greatly influenced and oftentimes limited by these geophysical and data availability factors. Specifically, small event detection and identification for seismic hazard mitigation and CTBT monitoring poses a significant challenge in the region due to the complicated tectonic regime and uneven distribution of both seismic sources and seismic stations. Openly available regional data through the CTBT International Monitoring System (IMS) and other sources like the Global Seismographic Network (GSN), operated by Incorporated Research Institutions for Seismology (IRIS), is fairly limited (Figure 1a). However, national seismic networks run by governments, universities, and non-governmental organizations and research institutes enhance the quality of potential data and increase the number of seismic stations in the region (Figure 1b). These stations are used for various purposes such as seismic hazard mitigation, tsunami warning systems, and studies of oil field-related seismicity. Seismic source, attenuation, and 3-D velocity models can be improved by incorporating national network data from the greater Middle East region. Incorporating data from these stations—which is usually absent from but essential for higher quality lithospheric models—will greatly improve scientific knowledge of event locations and source characteristics in the Middle East.

To improve lithospheric models of the Middle East and build regional seismological capacity, the U.S. Department of Energy (DOE) began sponsoring Lawrence Livermore National Laboratory (LLNL) in cooperation with research institutes in the Middle East in 1996. Since 2006, this work has been pursued by the National Nuclear Security Administration's (NNSA) Confidence-Building Measures (CBM) Program and includes seismic data-sharing, joint data analysis, technical training, and seismic station installation (Figure 1b). In 1998, LLNL began collaborating with the Jordan Seismological Observatory (JSO), which involved the deployment of two broadband seismometers, exchange visits of seismologists, and joint research projects. And in 1999, with LLNL technical support, DOE initiated seismic cooperation with King Saud University in Riyadh, Saudi Arabia. The longstanding LLNL relationship with King Saud University has resulted in temporary deployments of seismic stations, as well as ongoing technical cooperation in seismological research. This scope of work continued through relationships with the Kuwait Institute for Scientific Research and the Earthquake Monitoring Center at Sultan Qaboos University in Muscat, Oman. Further, CBM worked with the University of Sharjah in the United Arab Emirates to begin a regional seismology meeting called the Gulf Seismic Forum (GSF), which completed its seventh iteration in Jeddah, Saudi Arabia in January 2012. CBM also provides assistance to the Reducing Earthquake Losses in the Extended Mediterranean Region (RELEMR) workshops run by the United Nations Educational, Scientific, and Cultural Organization (UNESCO) and the U.S. Geological Survey (USGS).

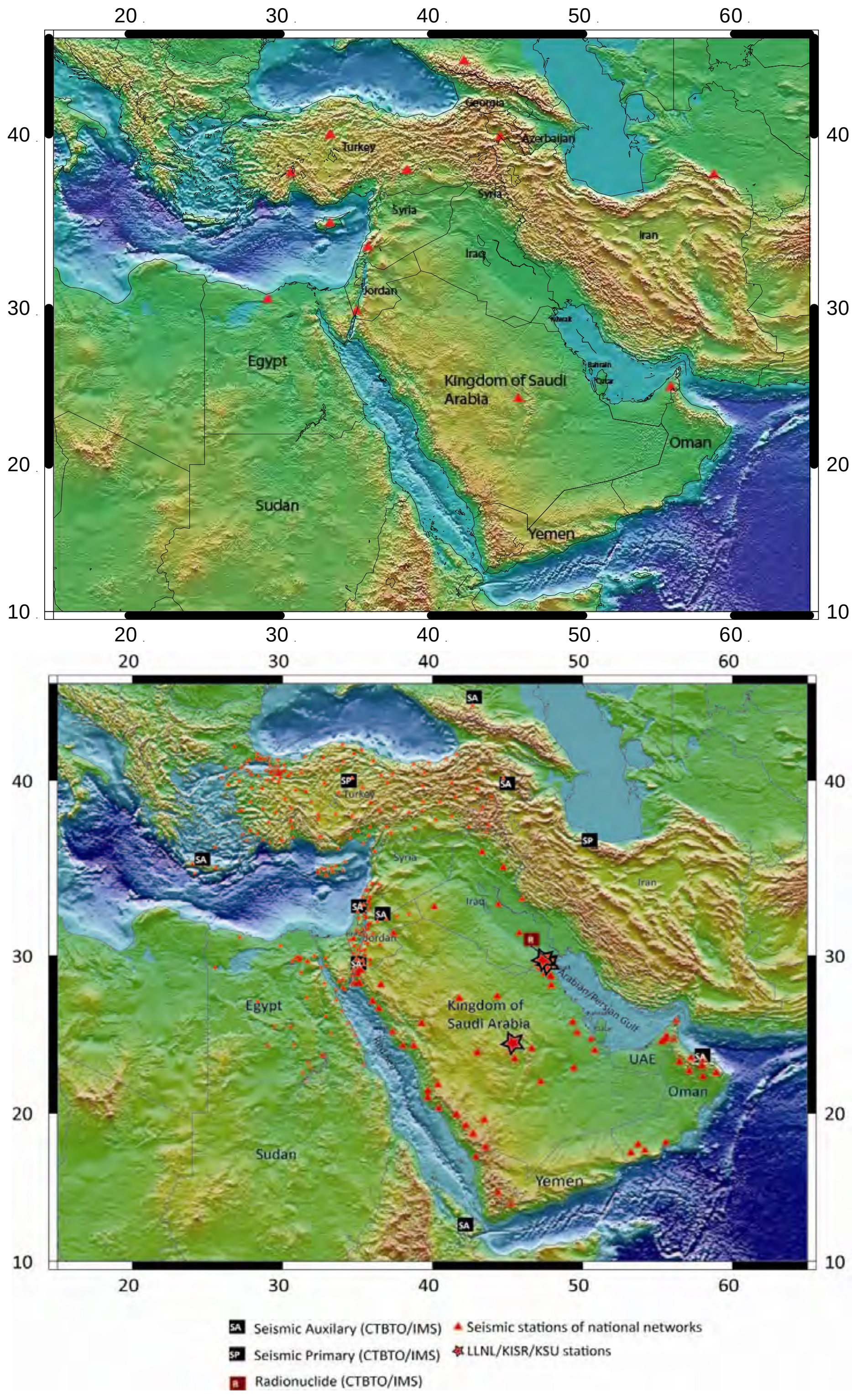

Figure 1. (Top) Operational International Monitoring System (IMS) Seismic Stations and Global Seismographic Network (GSN) Stations. (Bottom) National network stations, IMS Seismic Stations, and stations collaboratively operated by Lawrence Livermore National Laboratory (LLNL) with the Kuwait Institute for Scientific Research (KISR) and King Saud University (KSU).

RESEARCH ACCOMPLISHED

We perform data analysis that increases scientific understanding of regional seismicity in the Middle East. In doing so, we use several techniques for estimating the velocity models in the crust and upper mantle. One key technique that we use is to jointly invert receiver functions with surface waves (Gök et al., 2006; Tkalčić et al., 2006), which is a technique that has wide applicability in various parts of the world. The new velocity models from our data analysis are used for improving seismic network location accuracy and/or informing seismic hazard studies. Seismic waveform modeling studies for source parameter estimates also benefit from these new velocity models that help to calculate Green's function.

Joint work in Saudi Arabia includes data analysis and collaboration that has resulted in a number of papers in leading, peer-reviewed seismological journals (e.g. Rodgers et al., 2006; Tkalčić et al., 2006; Hansen et al., 2008; Park et al., 2007; Al-Damegh et al., 2009). Data analyzed through these efforts samples various tectonic environments on the Arabian Peninsula, including both active continental rifting and more stable environments. The resultant velocity models confirm rapid crustal thinning of the Arabian Shield toward the Red Sea (Tkalčić et al., 2006). Lithospheric thickness on the Arabian Peninsula varies considerably, with thin lithosphere centered on the rift axis, thickening toward the Arabian interior (Hansen et al., 2008). A nine-element seismic array is jointly sponsored by LLNL and King Saud University (KSU) for small event detection and joint data analysis purposes. The array was originally installed at Ar-Rayn, Saudi Arabia in 2010 (Figure 2) but was moved to Al-Quwaiyah in 2012 to strengthen data collection efforts. Initial beam-forming results demonstrate that the Al-Quwaiyah array will provide improved estimates of P-wave arrival times and waveforms for small events in the region (Al-Amri et al., 2011). We currently have seismic attenuation and ambient noise correlation data analysis projects with KSU to study the crust and upper mantle structure of Saudi Arabia through data collection from broadband stations.

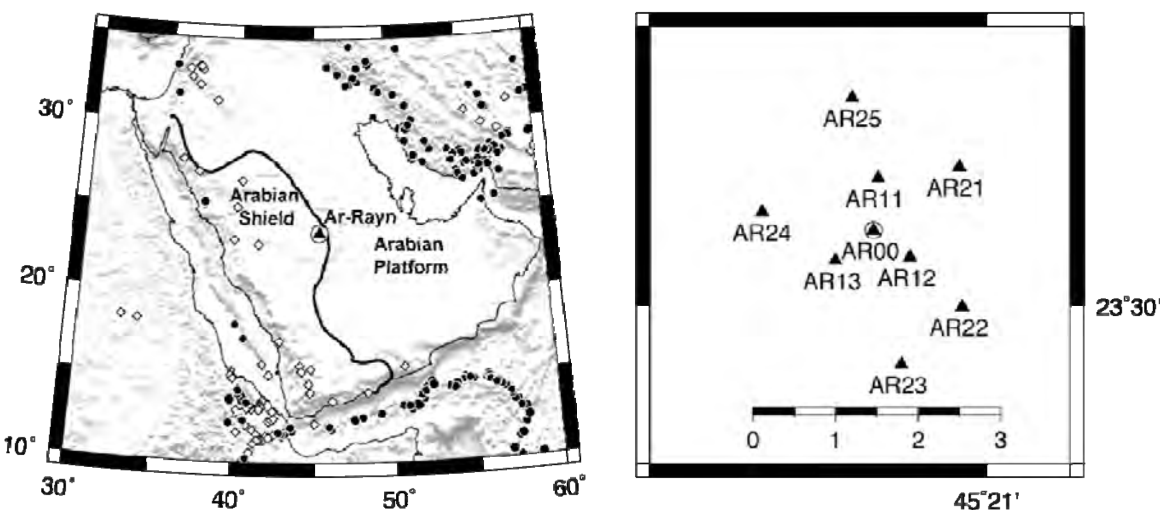

Figure 2. (Left) Map of Arabian Plate showing major tectonic elements of Arabian Shield and Arabian Platform and position of Ar-Rayn seismic array (triangle): earthquakes greater than magnitude 5 for period 2000-2010 and volcanic centers (black circles and white diamonds, respectively). (Right) Array geometry: broadband sensor (STS-2) at center (triangle with circle), surrounded by two rings of short-period sensors (triangles).

Collaboration with the Kuwait Institute for Scientific Research (KISR) began in 1999 when the Kuwait National Seismic Network (KNSN) had few stations and difficulties with network operations. Two jointly written, peer-reviewed papers were published on the seismic structure and the source characteristics of earthquakes in the Persian Gulf region (Pasyanos et al., 2007; Rodgers et al., 2006). Seismic source studies demonstrated that the location of earthquakes is predominantly confined to the upper crust, and they also showed the features of tectonic events

(Figure 3). Due to Kuwaiti concerns about seismicity and whether oil field activities were triggering earthquakes, a cooperative project between KISR and LLNL began in May 2010. Two broadband, three-component seismic stations were successfully deployed in the existing vaults for KNSN sites MIB (Mutribah) and UMR (Umm ar Rimam). The average crustal thickness in the sampled area is 43-45 km.

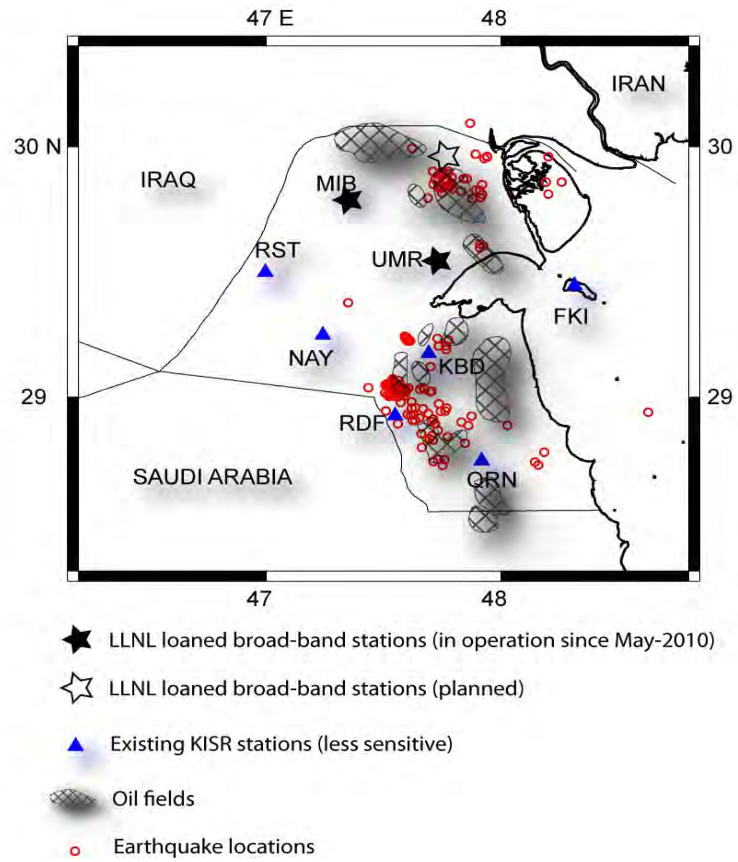

Figure 3. Seismicity and seismic station locations in Kuwait: notice proximity of earthquakes to oil fields.

Additionally, two temporary broadband stations were deployed in Bagdad (BHD) and Mosul (MSL) in early 2005. The stations were equipped with Guralp CMG-3ESPD digital broadband seismometers. Despite the fact that the sites were prone to background noise due to their location near major Iraqi cities, we were able to estimate the crustal thickness under stations BHD and MSL (Gök et al., 2007) (Figure 4). Our results indicated that crustal thicknesses increase toward the south correlated with increasing sedimentary thickness due to the Mesopotamian Foredeep. Ignoring the sediments of the Mesopotamian Foredeep, crustal velocities and thicknesses are remarkably similar between northern and southern Iraq near Kuwait, suggesting that the crustal structure of the proto-Arabian Platform in northern Iraq was uniform before subsidence and deposition of the sediments in the Cenozoic.

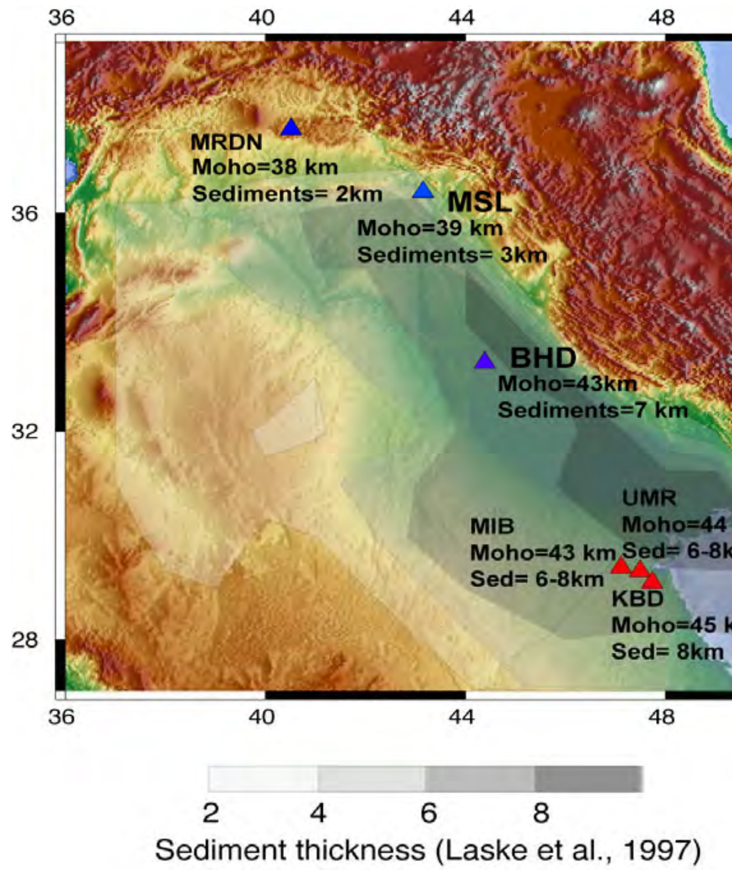

Figure 4. Estimated crustal thicknesses overlaid on sediment thickness model.

Another productive scientific collaboration is between LLNL and the Earthquake Monitoring Center (EMC) of Sultan Qaboos University (SQU) in Oman to study the lithospheric structure of the southeastern Arabian Peninsula by analyzing teleseismic P-receiver functions recorded at broadband and short-period seismic stations of the Oman Seismological Network (Al-Hashmi et al., 2011). Lithospheric structure is obtained by jointly inverting receiver functions and Rayleigh wave group velocities derived from continental-scale surface tomography. We observed relatively thick crust (40-48 km) within the ophiolite-formed mountains in northern Oman. The crustal thickness is about 35 km within the passive continental margin of the southern Dhofar region (Figure 5). Uppermost (<5 km) crustal shear wave velocities are faster in the northern ophiolite regions compared to the southern Dhofar region, while shear velocities in the middle crust are faster in the Dhofar region compared to the ophiolite region. This observation coincides well with Cretaceous to Eocene marine platform sequences overlying the Precambrian to Cambrian basement of the southern region. Joint inversion analysis shows that the Moho depth within the southeastern Arabian Peninsula varies from 34 km in the southern region to 48 km in the northern part. Currently, studies are underway to supplement this effort with ambient noise cross-correlation for Green's function and coda-magnitude calibration. Our goal is to calibrate the magnitudes of smaller events in the country to meet Omani operational needs.

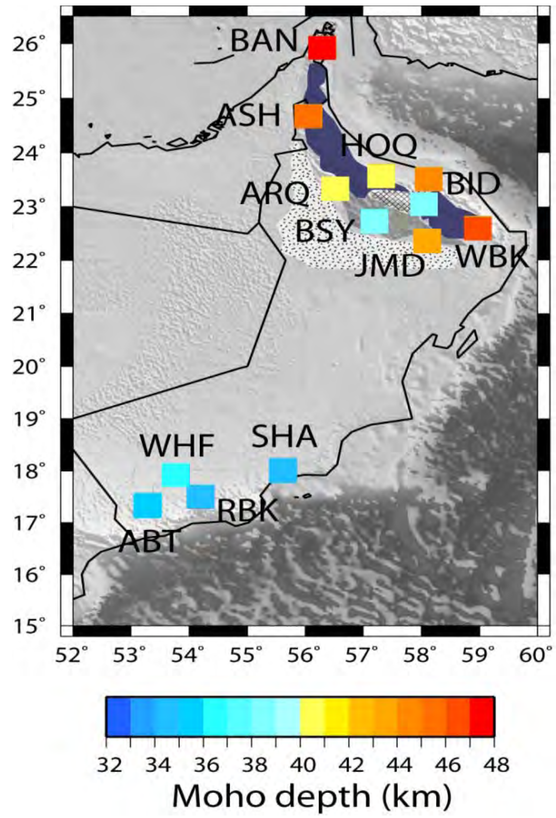

Figure 5. Moho depths color-coded at each Oman Seismological Network Station.

CONCLUSIONS AND RECOMMENDATIONS

Our research results demonstrate that, as expected, significant tectonic and seismic complexity is observed in the geophysical structure of the Middle East. These large variations in structural complexity—combined with limited event data availability—provide the dominant reason for seismic source and event location inaccuracies that constrain current lithospheric models. Open source seismological data-sharing mechanisms are highly useful for scientists and other researchers interested in studying the lithospheric structure of the Middle East and regional seismic wave propagation patterns. However, both national investments in seismic instrumentation and formal data-sharing agreements between states in this region of high seismicity are limited. LLNL collaboration with research institutes in the Middle East has enhanced the ability of partner countries to operate national seismic networks and strengthened regional seismic expertise. These scientific and technical relationships have improved lithospheric velocity and attenuation models of the Middle East by revealing information about the complexity of the crustal and upper mantle structure in the region.

Further scientific and technical cooperation in seismic monitoring with research institutes and universities in the Middle East can help to build upon these models, increasing station coverage and event data availability. In turn, new data and velocity models will increase our lithospheric knowledge of the Arabian Peninsula and other structures, enhancing seismic source parameter determination and event location accuracy. This will benefit geophysical studies, city planning and development efforts, civilian and military disaster responses, mining and oil drilling activities, and CTBT monitoring.

ACKNOWLEDGEMENTS

The authors would like to thank several individuals for their programmatic contributions to this research:

Preparatory Committee of the Comprehensive Nuclear-Test-Ban Treaty Organization: John Coyne, Belkacem Djermouni, and Lassina Zerbo. Sultan Qaboos University: Issa El-Hussain. King Saud University: Abdullah Al-Amri. Kuwait Institute for Scientific Research: Abdullah Al-Enezi. Lawrence Livermore National Laboratory: William Walter and Jay Zucca. National Nuclear Security Administration: Paula Alfonso, Leslie Casey, Michele Dash-Pauls, Tim Evans, Edward Fei, Wayne Mei, Mike Newman, and Anne Phillips. United States Department of State: John Godfrey and Terrill Ray.

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