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14. ABSTRACT In an effort toward improving current seismic-velocity models for the Middle East, the initial step of building a high-quality database of recordings from well characterized sources is essential. This high-quality database of recordings, or broadband waveforms, encompassing the region from the Mediterranean to the eastern edge of Tibet, will be the primary measure for evaluation and improvement in the iterative, waveform-based, adjoint-inversion process. Adjoint inversions, as with any waveform-based method, require precise estimates of the location, especially depth, and the faulting parameters or moment-tensor elements of the seismic sources. Imprecise locations and/or source terms will result in real changes in the amplitude and the phase of the incoming wave train; when close to a nodal plane, these changes can occur very rapidly with incoming azimuth. These errors will directly map into the resulting velocity model as uncertainty or biased values. The initial database included about 250 well recorded, regional events in the Middle East from 1990 to 2007 with magnitudes $M_w > 5.5$. To reduce errors in the source-depth and faulting parameters, the events were evaluated using two complementary sets of data, a regional data set contained within the Middle East and a global teleseismic data set. Regional data were first utilized at long period, $\omega > 20$ s, using the waveform-based methods of Pasyanos et al. (1996) to determine the moment tensor elements. Then shorter periods, $\omega > 5$ s, were added, following Zhao and Helmberger (1994), to further assess errors in source depth and propagation effects by splitting apart the longer period surface waves from the shorter period, depth-sensitive PnI waves. Problematic, or high-error, stations and paths were further analyzed to identify systematic errors with unknown sensor responses and complex wave propagation regions. Teleseismic data were used in tandem with the regional seismic data to further assess the estimated moment tensor and place further constraints on the source depth. Synthetic seismograms were computed using a frequency wave-number integration scheme on the source and receiver sides and then time-shifted to account for direct P- and S-wave propagation. Data were then compared to synthetics, including source-side conversions, which are important to reducing error estimates of seismic-source depths.					
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**INITIAL STEPS TOWARD NEXT-GENERATION, WAVEFORM-BASED, THREE-DIMENSIONAL
MODELS AND METRICS TO IMPROVE NUCLEAR EXPLOSION MONITORING IN THE
MIDDLE EAST**

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ABSTRACT

In an effort toward improving current seismic-velocity models for the Middle East, the initial step of building a high-quality database of recordings from well characterized sources is essential. This high-quality database of recordings, or broadband waveforms, encompassing the region from the Mediterranean to the eastern edge of Tibet, will be the primary measure for evaluation and improvement in the iterative, waveform-based, adjoint-inversion process. Adjoint inversions, as with any waveform-based method, require precise estimates of the location, especially depth, and the faulting parameters or moment-tensor elements of the seismic sources. Imprecise locations and/or source terms will result in real changes in the amplitude and the phase of the incoming wave train; when close to a nodal plane, these changes can occur very rapidly with incoming azimuth. These errors will directly map into the resulting velocity model as uncertainty or biased values.

The initial database included about 250 well recorded, regional events in the Middle East from 1990 to 2007 with magnitudes $M_w > 5.5$. To reduce errors in the source-depth and faulting parameters, the events were evaluated using two complementary sets of data, a regional data set contained within the Middle East and a global teleseismic data set. Regional data were first utilized at long period, $\omega > 20$ s, using the waveform-based methods of Pasyanos et al. (1996) to determine the moment tensor elements. Then shorter periods, $\omega > 5$ s, were added, following Zhao and Helmberger (1994), to further assess errors in source depth and propagation effects by splitting apart the longer period surface waves from the shorter period, depth-sensitive *Pnl* waves. Problematic, or high-error, stations and paths were further analyzed to identify systematic errors with unknown sensor responses and complex wave propagation regions.

Teleseismic data were used in tandem with the regional seismic data to further assess the estimated moment tensor and place further constraints on the source depth. Synthetic seismograms were computed using a frequency wave-number integration scheme on the source and receiver sides and then time-shifted to account for direct *P*- and *S*-wave propagation. Data were then compared to synthetics, including source-side conversions, which are important to reducing error estimates of seismic-source depths.

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OBJECTIVES

Robust models of 3D velocity structure within the greater Middle East, from the Turkish Plateau to the eastern edge of Tibet (Figure 1), will increase our capability to locate events, discriminate between natural and man-made events, identify source depths, and determine magnitudes, as well as make practical error estimates. Improvement of current seismic-velocity models of the Middle East (1D and 3D) will be accomplished through an adjoint-tomography method to iteratively improve the models in three dimensions. The initial step toward any constrained tomography model is a well located and well characterized set of sources. Further, the adjoint-tomography method (Tape et al., 2007) needs full seismic waveforms as a measure of the misfit of the current model iteration. As such, an associated set of recorded, quality-controlled seismic data for each event is necessary to perform the inversion. Finally, the introduction of the etree model, a seamless way to represent 1D and 3D structural velocity models, will simplify the process during each iteration of synthetic waveform creation and velocity model improvement. In future years, an improved velocity model of the Middle East will be presented and distributed, built on the foundation of the seismic-waveform data set using the new 3D model representation.

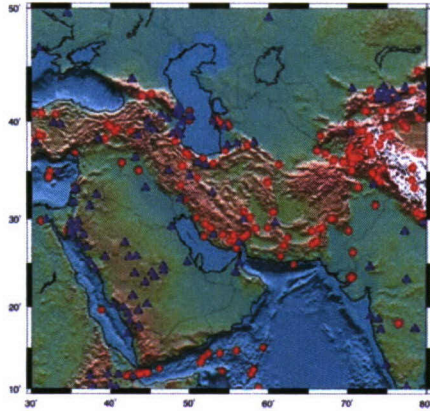


Figure 1. Map of the available sources and stations in the Middle East.

RESEARCH ACCOMPLISHED

Event Characterization

Earthquake source parameters in the Middle East, $M_w > 5$, were determined using two separate techniques: a teleseismic body-wave inversion method (Kikuchi and Kanamori, 1982) and a regional, full-waveform cut and paste (CAP) method (Zhao and Helmberger, 1994; Zhu and Helmberger, 1996). Both methods are sensitive to source-depth and faulting parameters and, to a lesser extent, to heterogeneous velocity structure, providing complementary event characterizations, including errors.

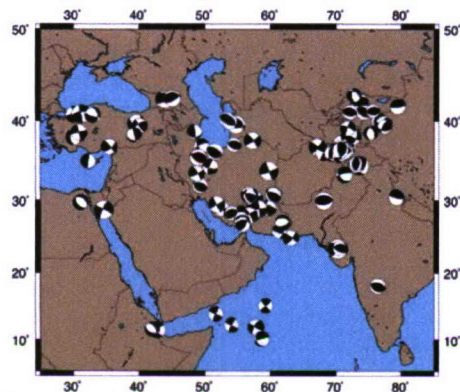


Figure 2. Teleseismically determined focal mechanisms

Initial results from the teleseismic body-wave inversion are shown in Figure 2. The teleseismic body-wave inversion uses a time-domain deconvolution to identify and solve for the faulting parameters of the largest signals in the recorded data. Depth, source duration, and, if desired, multiple subevents are solved for, using an iterative scheme to reduce misfit between the data and synthetics. A preliminary data set of 120 events for which there already existed local and regional data was analyzed for source-depth and faulting parameters, showing a good match between the data and synthetics.

A second suite of events, with smaller magnitudes and thus smaller signal-to-noise, is also being examined, but with greater care. Determined depths, faulting parameters, and magnitudes show overall close agreement with previously published reports from the Harvard Global Centroid-Moment-Tensor Project (CMT) and the U.S. Geological Survey (USGS). In Figure 3, an example of a deep event from the eastern edge of Tibet shows a good match between the data (top) and the synthetics (bottom).

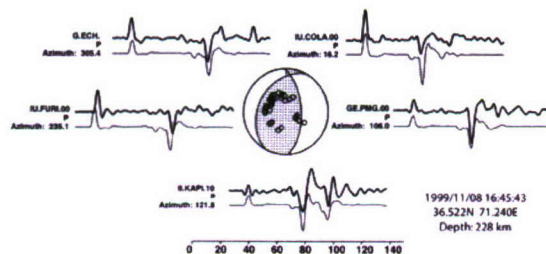


Figure 3. Event 1999/11/08

All direct and depth phases fit well in terms of timing and amplitudes. Figure 3 shows only a small subset of the data used to evaluate the faulting parameters and source depth for this event. Most events show good azimuthal coverage, with over 20 stations, on average, used in each event inversion. The results shown in Figure 3 indicate how sensitive the data and inversion are to changes in the faulting parameters when the depth phases, pP and sP, are included. P wave amplitudes for each station are all positive and about the same magnitude, but the depth phases show large variability against azimuth.

Faulting parameters were also determined using the CAP methodology (Zhao and Helmberger, 1994; Zhu and Helmberger, 1996), in which regional recordings are cut into windows around the faster, higher frequency PnI components and slower, longer period surface waves. All cut windows are fit simultaneously, allowing equal weighting of phases that may be of different absolute amplitude. By emphasizing the faster, PnI portion of the recorded data, sensitivity to source depth is substantially increased.

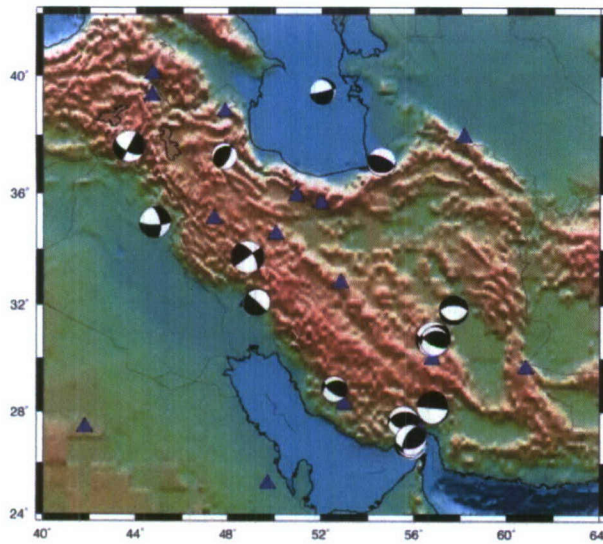
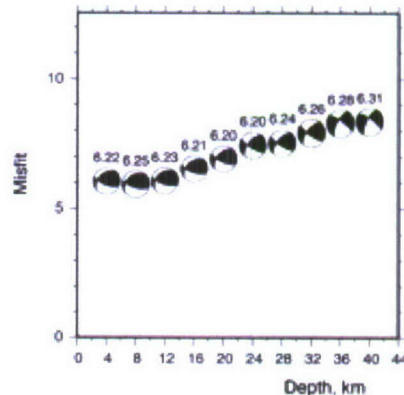
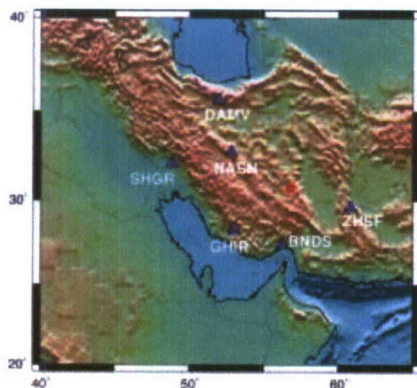


Figure 4 - CAP determined focal mechanisms

Shown in Figure 4 are preliminary results for 17 events for which faulting parameters and source depths could be determined using data solely from the Iranian National Seismic Network (INSN). Stations are plotted as blue triangles and focal mechanisms are plotted at the source. As with the teleseismic inversion, results compare well with the reported faulting parameters, including magnitude, which has a slight bias downwards of 0.16 in Mw. Depths determined for the suite of events have a much greater scatter, around 10 km, compared to those previously reported (Global CMT). This could be the result of either inadequate resolution from the long-period nature of the Global CMT or a complex velocity structure between the source and receiver. An example of the CAP method is shown in Figure 5. The first panel (A) displays the source location as a red circle and the stations used in the analysis as blue triangles. The second panel (B) presents solutions for a range of depths against the misfit, as well as any changes in focal mechanism or magnitude. The third panel (C) presents results for the best fitting solution at 8 km. Again, the PnI window of the seismogram is sensitive to the source depth, where an

increase will tend to separate the two large pulses on the PnI radial and vertical components.



Figures 5A (left) and 5B (right). Event Kerman, Iran

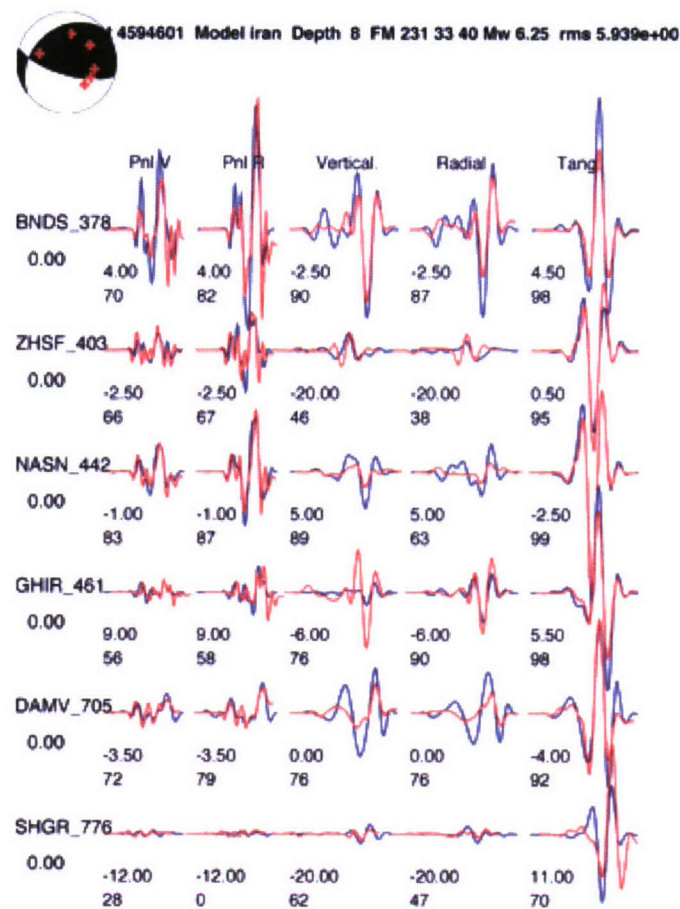


Figure 5C. Event Kerman, Iran

3D Velocity Model Representation

Models used in the adjoint tomographic inversion will be stored and accessed through the etree framework (Tu et al., 2004). This framework is currently being incorporated into the SPECFEM3D waveform simulation code (Komatitsch and Tromp, 1999), the numerical solver for the adjoint tomography. An etree is a compact representation of a 3D space allowing rapid access and variable resolution throughout the model. Figure 6 shows how quick access to elements within an etree is accomplished. The model on the left is divided into regions of variable resolution by powers of 2. The largest regions (h, m, and the regions containing i through l) are near the initial node of the etree, and regions of greater resolution are subdivided from there. The locations of the regions are encoded in compact notation for rapid access to material parameters, metadata such as units, and/or references from which the model is derived. Important motivations for using etree model representation are to build a framework within which models from a variety of references can be utilized to create synthetic seismograms and to improve these models within the adjoint framework.

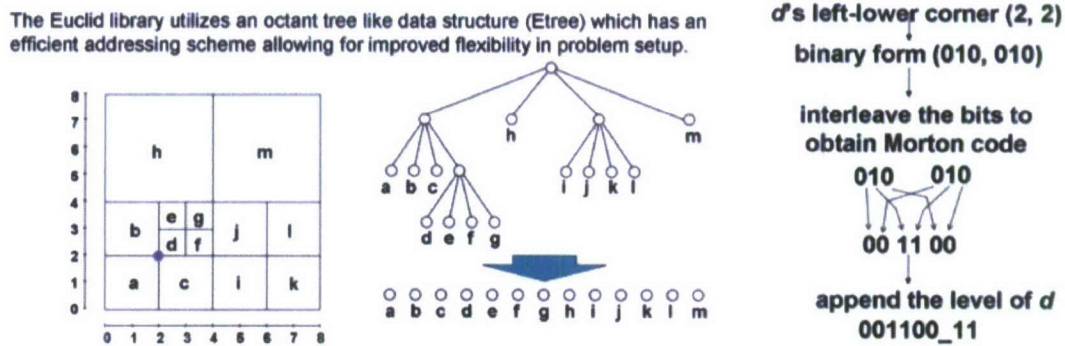


Figure 6. Etree model representation

Initial tests using a priori 3D models have shown dramatic improvements in fitting seismograms in the Middle East. An initial model to be evaluated is the Unified/WENA (Western Eurasia/North Africa) model (Pasyanos et al., 2004). Figure 7A shows sediment and crustal thickness within the model and how it affects the propagating wavefield. Crustal thickness in the Middle East varies between 30 and 40 km on land, with the exception of the eastern edge of Tibet, while it is less than 10 km in the Red Sea and oceanic environments. Conversely, there is little to no sediment throughout much of the Middle East but large basins of sediment in the Mediterranean, Black, and Caspian Seas, as well as in a large basin extending north from the Persian Gulf to the deltas of the Tigris and Euphrates Rivers. These rapid changes in crustal and sediment thickness can dramatically extend and twist the propagating wavefield.

Use of the Unified/WENA model against an 1D reference model in the Middle East is shown in Figure 7B. For the 1D model and an explosion source (left panel), a simple pulse of coherent energy travels radially outward from the source, with lighter colors indicating larger amplitudes. The Unified/WENA 3D model (right panel) for the same source produces a radically different wavefield. In regions of large basins and deep sedimentation, e.g., the Persian Gulf, the wavefield becomes extended in space and shows greater dispersion than in other regions, e.g., paths that propagate directly north and south into the Indian Ocean.

Effects of the 3D velocity structure can easily be seen by comparing data to 1D and 3D synthetics, as in Figure 7C. The data seismogram (black, top) has an extended, complex surface wave in comparison to the much simpler 1D reference synthetic (green, bottom). By using a 3D model—here, the Colorado University Boulder (CUB) global model (Shapiro and Ritzwoller, 2002)—the duration of the surface wave is now represented more fully, although there are still mismatches at high frequencies and overall amplitudes.

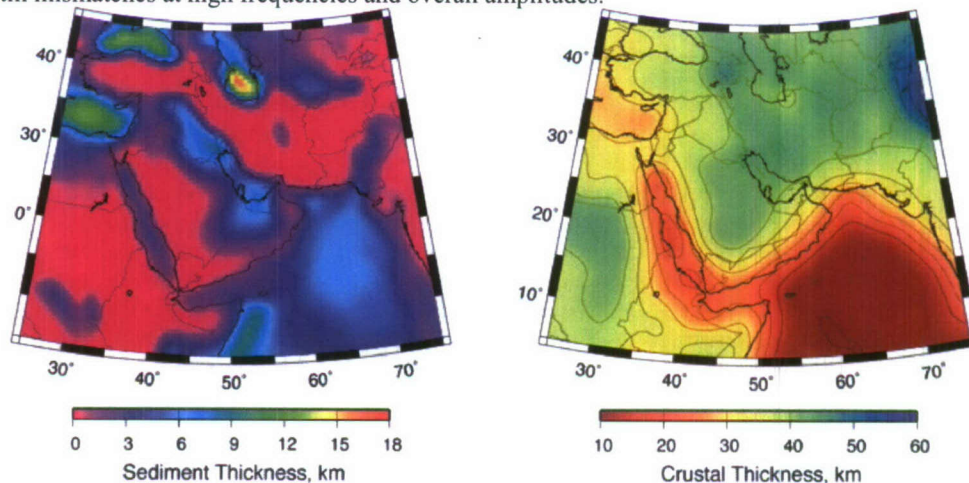


Figure 7A. Unified/WENA Model

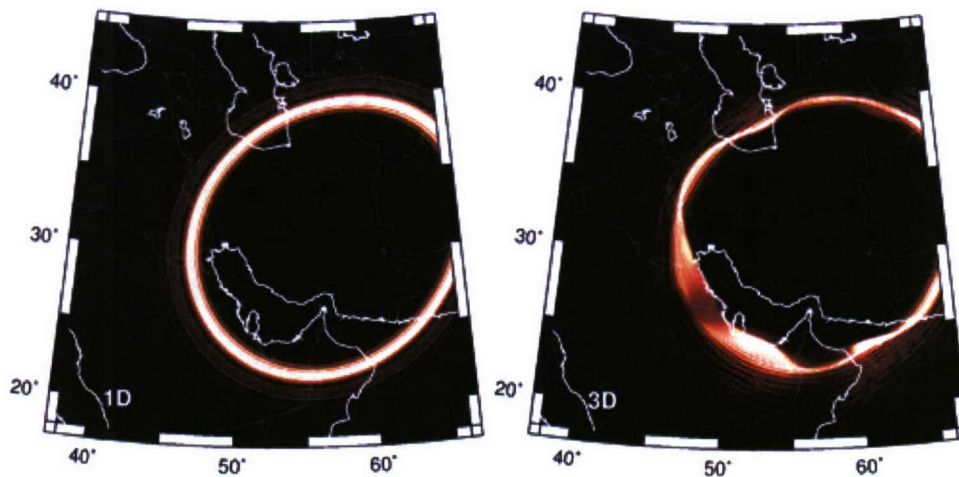


Figure 7B. Wavefield distortion from 1D vs. 3D models

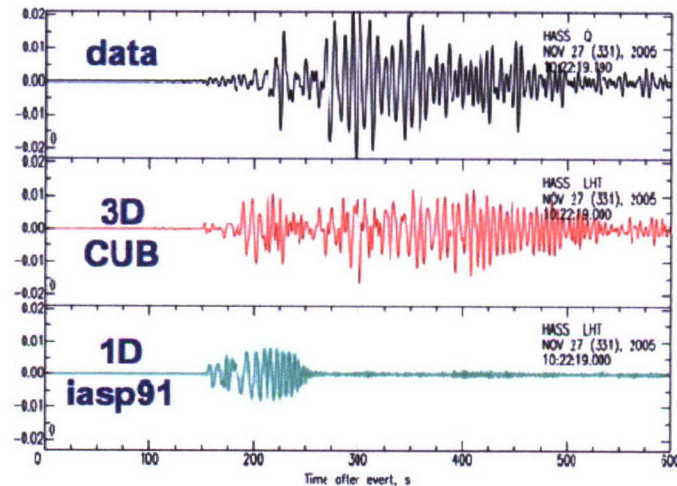


Figure 7C. 3D velocity structure effects

CONCLUSIONS AND RECOMMENDATIONS

Foundations of a seismic-waveform database of the Middle East have been created. Initial work to characterize events in and around the Middle East has produced a large (> 100) and growing data set, constrained by teleseismic and regional waveform inversions. Both inversion methods provide robust estimates of source-depth and faulting parameters. When used jointly, each offers important verification of the other's result. Event characterization results from both inversions agree well with previously reported, routine determinations. Parallel work has also been undertaken to introduce the etree 3D model representation framework into the spectral-element, adjoint-tomography calculations. This new approach to 3D model representation will allow for more streamlined model handling and model updating during the inversion process. Initial testing of these 3D models has shown that they too meet the requirement to accurately depict recorded seismic data in the Middle East. For the best possible 3D velocity model results in the greater Middle East, we recommend that data from a wide range of sources be collected, quality checked, and added to the new waveform database, particularly seismic data from remote and/or sparsely instrumented areas.

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