GROUND TRUTH OF AFRICAN AND EASTERN MEDITERRANEAN SHALLOW SEISMICITY USING SAR INTERFEROMETRY AND GIBBS SAMPLING INVERSION

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ABSTRACT

Our study focuses on the further development and application of a technique to combine Synthetic Aperture Radar Interferometry (InSAR) and Gibbs Sampling (GS) inversion methods to provide ground-truth data (at GT5 or better levels) for small, shallow earthquakes in remote areas such as North Africa and the Eastern Mediterranean region. In general the analysis comprises three phases: (1) production of the interferogram, (2) inversion of the ground displacements for hypocentral location, and (3) combination with seismological data and analysis.

We are making significant progress on assembling a catalog of InSAR-based GT5 events for the region. Currently we have positively identified events in interferograms with spatial coverage in the north (Morocco), central (Zaire), and south (South Africa) of the African continent. In addition, the Bam, Iran earthquake is an excellent test-bed event for which there are both ascending and descending interferograms and numerous broadband records. Azimuth offset analysis will allow a three-dimensional (3-D) displacement field to be calculated and analyzed in conjunction with the seismic waveform data. We are also currently working on more than 15 candidate events throughout the region.

For the candidate events, interferogram production can prove to be a challenge due to temporal and geometric decorrelation effects. The short timescales of apparent temporal decorrelation has come as somewhat of a surprise, however, as many of the North African regions are desert areas where previous experience suggested that correlation should be very good. Alternative processing strategies comprising more aggressive filtering strategies show promise in retrieving usable data from some of these images.

We have collected a number of broadband waveforms for both the 2003 Bam earthquake and the 1999 South Africa seismic event and we are beginning our comparison of InSAR hypocentral locations with locations derived from seismic waveform modeling. We are actively working on a joint inversion of waveform and InSAR data. This is a highly multiparametric inversion that likely will include estimates of more than 15 parameters. Combining the Gibbs sampling method and parallel computation will likely allow this process to be accomplished with reasonable temporal latency.

OBJECTIVES

Our research focuses on delivering 5-km ground-truth (GT5) or better locations for seismic events in North and East Africa and the eastern Mediterranean region using Synthetic Aperture Radar Interferometry (InSAR) geodesy. InSAR, combined with elastic dislocation modeling, is an emerging tool for acquiring GT information in remote areas (Begnaud et al., 2000; Lohmann et al., 2002). Our work will provide much-needed GT events for a large region currently covered by a very small number of GT5 events. In addition, by applying Gibbs Sampling (GS) (Brooks and Frazer, 2005), a powerful non-linear inversion method, to the problem of inverting InSAR data for earthquake characteristics, the posterior probability distributions for our estimated source parameters will reflect accurate treatment of data variance. This will allow GT event parameters to be compared quantitatively with one another and to be used, for instance, as prior distributions for kriging-based interpolation efforts (Schultz et al., 1998). The general methodology is one that will be of use to the entire monitoring community engaged in regional calibration.

RESEARCH ACCOMPLISHED

Interferometry

To date we have identified coseismic signals in interferograms from 3 events spanning the African continent and 1 event in Iran. We are currently processing data from another 7 candidate events in the region and have ordered data for a number of other events. Below we give overviews of the interferometric results.

GT Event 1: Bam, Iran; 26 December, 2003; M_W 6.5

The Bam event is an excellent one to use as a test bed for the InSAR source parameter technique because of the large amounts of available InSAR and seismic waveform data, and because of the event's relatively clean signal. Previously (Brooks et al., 2004), we reported on our preliminary processing and analysis of the descending interferogram. Mean values from the preliminary GS results indicate that the earthquake accommodated ~2.75 meters of right-lateral strike-slip and negligible dip-slip on an ~north-south striking, 60° east-dipping fault with dimensions of ~10 x 10 km and an upper edge at ~2500 meters depth. Standard deviations of location parameters (dx, dy, the upper left corner of the dislocation) are of the order of 400 meters. These results are similar to recently published analyses (Fialko et al., 2005).

For additional constraints on the earthquake solution, we are in the process of calculating offset estimates in the azimuthal (along-track) direction from comparing before and after amplitude images (Fialko et al., 2001). This technique is of lesser precision than traditional interferometry, but it should provide displacement estimates with ~5-cm precision in an orthogonal direction to the line-of-sight view of the interferogram and allow a 3-D displacement field (albeit one with a non-orthogonal basis) to be computed. Our intent is to then perform a joint InSAR-waveform inversion with the broadband data we have collected (see below).

GT Event 2: Welkom, South Africa; 23 April, 1999; M_L 4.5

For different reasons than the Bam event, the Welkom event (Doyle et al., 2001) is also an excellent test-bed example for the InSAR source parameter technique. Primarily, it was an extremely small event at least an order of magnitude smaller than previously imaged ones. In addition, the seismicity was due to a well-documented rock burst in the Matjhabeng mine that resulted in the deaths of 2 mine workers.

In Figure 1a we show an ERS-2 descending interferogram spanning the time from 4 October 1998 to 19 September 1999. Although regional coherence is poor, locally coherence is good enough to clearly identify fringes associated with the event. Our preliminary GS analysis shows the event to be well constrained, particularly the important ground-truth (GT) location parameters of x, y, z centroid location (Figure 1b). The marginal distributions for the length and width of the rectangular dislocation, however, exhibit interesting behavior (Figure 1b). They are noticeably skewed towards very small values (<100 meters) and suggest that the source may be best characterized as a point source. This may suggest that the assumption of a shear dislocation for this event is invalid and so we are currently exploring whether other parameterizations (i.e., point sources) are more appropriate for this event.

GT Event 3: N. Morocco; 24 February, 2004; M_w 6.5

For this earthquake, we have produced two differential interferograms from a descending view (baselines of 75 m and 320 m, spanning 14 months and 5 months, respectively) (Figure 2). The interferograms were quite noisy, but strong filtering has improved the spatial coherence. However, coherence in the vicinity of the epicenter is quite low, probably owing to damage and temporal decorrelation. As a result, for additional constraints we are also exploring the possibility of using azimuth amplitude offsets for this event as described above. Data in an ascending view have also been ordered for this earthquake. In addition, we will also use co-seismic displacements from 3 nearby global positioning system (GPS) sites for further control on the solutions. As part of this process, we developed a considerably more rigorous filtering scheme than we have previously used.

In some cases, iterative application of an adaptive spectral filter has helped to remove "white" noise from interferograms and improve coherence. The effectiveness of the filter depends, in part, on the size of the fast Fourier transform (FFT) window used for the spectral analysis. Larger FFT windows can be used if the topographic phase contribution is effectively removed—if it is not, severe artifacts result. Repeated application of the filter also creates coherence, although the data are significantly smoothed. We have focused on improved baseline estimates and modeling of topographic phase prior to filtering. Although a strong filter may smooth interferometric fringes and produce local errors in the unwrapped interferograms, the overall interferogram can be unwrapped sufficiently well for a very accurate baseline estimate. With this new, accurate baseline estimate, we perform another iteration of modeling and removing the topographic phase from the original interferogram, followed by filtering and phase unwrapping.

GT Event 4: E. Zaire; 11 December, 1995; M_W 5.7

Figure 3 shows a preliminary ERS-1 interferogram from the region of the Zaire event with the region containing what we believe to be the fringes associated with the event. The International Seismological Centre (ISC)-located epicenter is ~40 km to the southeast of this location along the right edge of the image. We base this preliminary assessment on the elliptical pattern of fringes representing close to 2 full cycles of phase difference. The other smaller features with semi-elliptical patterns do not exhibit similarly steep phase gradients and we believe they are likely atmospheric artifacts.

Seismic Waveform Analysis

To date, we have collected a number of broadband waveforms for both the 2003 Bam earthquake and the 1999 South Africa seismic event. We have collected only broadband waveforms in order to be able to utilize the longer period energy (greater than 10 seconds) to obtain the optimal source parameters. We have also chosen to focus on local and regional seismic waveforms for this data analysis because these stations provide the best constraints on the hypocentral location parameters. For the Bam earthquake we have found 25 three component broadband seismograms with excellent signal to noise ratios within 30 degrees of the event. For the South Africa event we have found 7 regional broadband seismograms. We show five selected broadband waveforms for the South Africa event plotted as a function of distance (Figure 4)

We are beginning our comparison of InSAR hypocentral locations of the Bam earthquake and the 1999 South Africa seismic event with locations derived from seismic waveform modeling. This comparison will allow us to assess the quality of the seismically derived hypocentral locations relative to those of the InSAR results. Ultimately, our integration of InSAR data and travel time data will also lead to more robust and reliable GT events. In order to accomplish this goal, we will utilize long period vertical and radial seismograms along with existing crustal and upper mantle lid models to find optimal location parameters. To model the observed seismograms we will use the reflectivity method of Randall (1994), which takes advantage of all possible reflections, refractions and conversions at all interfaces.

This will be done using well-developed double-couple grid search methods (Walter, 1992). Three-component long-period (from 20 up to 50–100 seconds) waveforms are fit to synthetics for an appropriate velocity model by systematically searching over depth, strike, dip and rake. The seismic moment is solved for each parameter combination. The optimal solution provides the minimum misfit to the observed waveforms. We will also compare our regional waveform modeling with the locations from the Harvard Centroid Moment Tensor (CMT) studies. An example of the approach we will use is shown in Figure 5.

CONCLUSIONS AND RECOMMENDATIONS

We are making progress on realizing a significant catalog of InSAR-located GT events for the African continent and the Eastern Mediterranean region. Our analyses further demonstrate the utility of InSAR for GT efforts. The combination of the InSAR data with seismic waveform data in joint inversions will certainly allow for even tighter GT constraint for the events.

A practical issue stems from the uncertainty in reported epicenter locations. In some of these regions, this uncertainty is large enough that the events could be outside of the initially ordered SAR scenes. If data from the sensing platforms were more freely available, then the temporal bottleneck involved in ordering data and evaluating whether they contain the seismic event would be alleviated.

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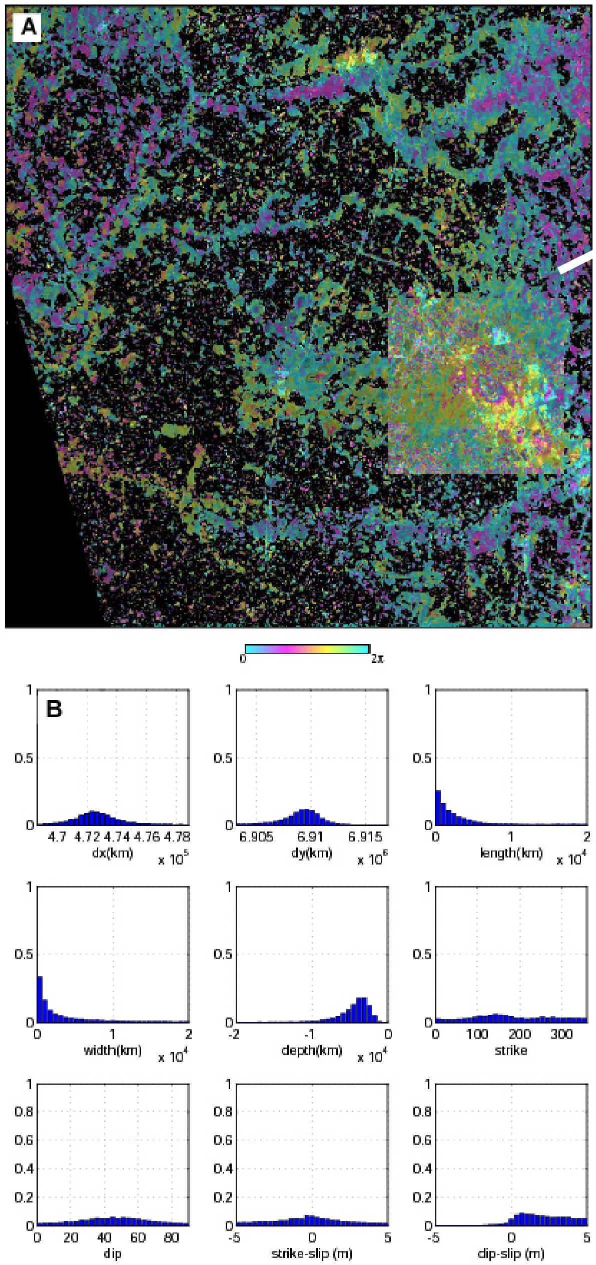

Figure 1. A) ERS-2 descending interferogram spanning the time from 4 October, 1998-19 September, 1999. The arrow demonstrates fringes associated with the 23 April 1999 earthquake. B) Results of Gibbs Sampling inversion for earthquake source parameters presented as marginal probability distributions.

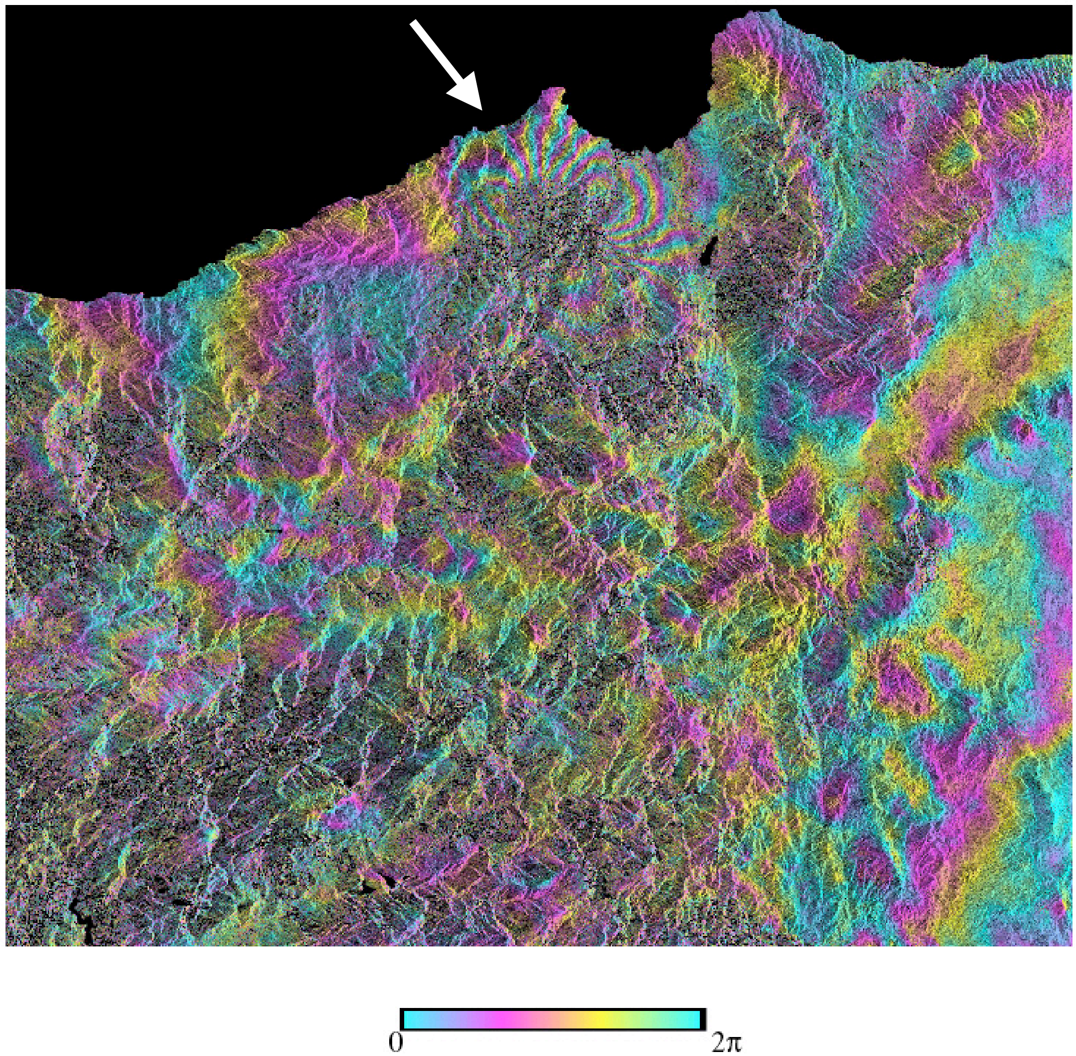

Figure 2. Envisat descending interferogram in flipped radar coordinates with a 14-month temporal baseline and a 75-m perpendicular baseline. The arrow demonstrates fringes associated with the 24 February 2004 earthquake.

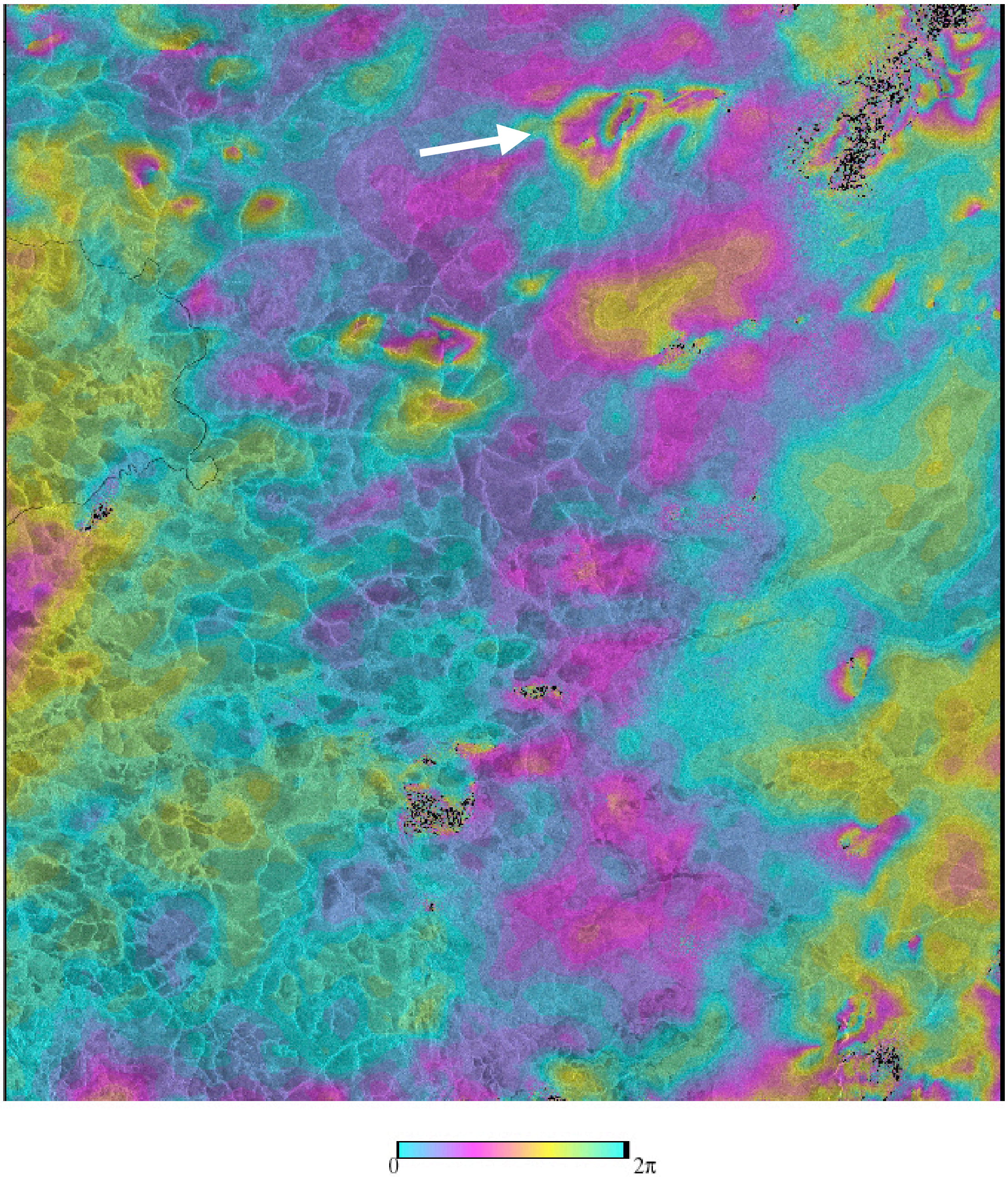

Figure 3. ERS-1 descending interferogram in flipped radar coordinates with a 35-day temporal baseline and a 235-m perpendicular baseline. The arrow demonstrates fringes likely associated with the 11 December 1995 earthquake.

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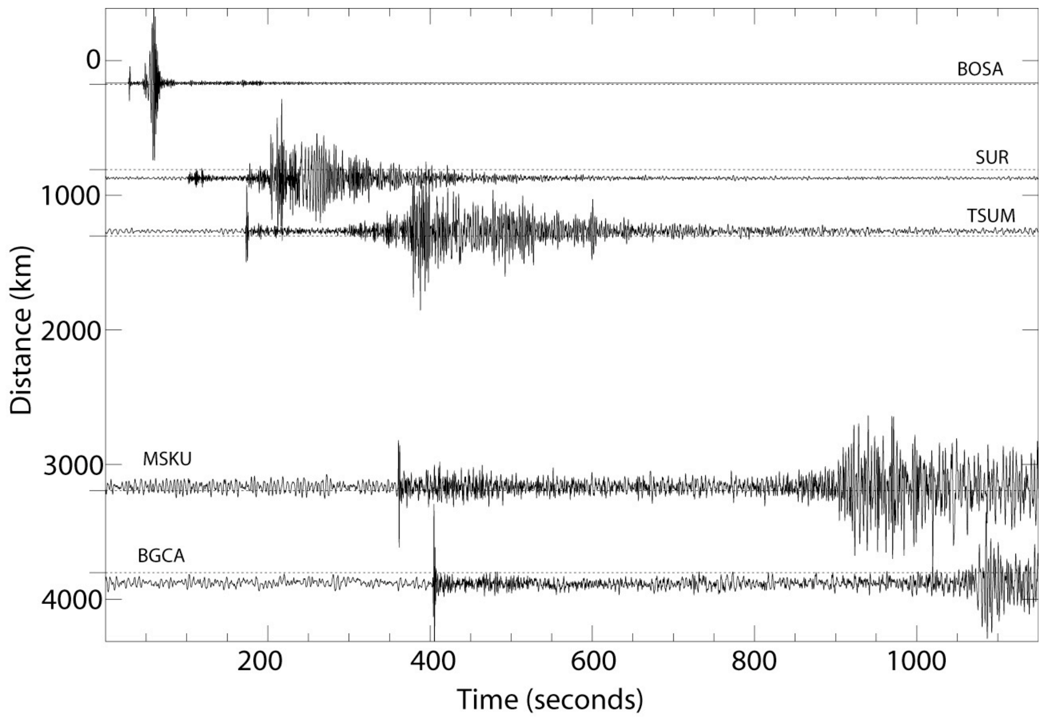

Figure 4. A record section plot of the 22 April 1999 seismic event in South Africa.

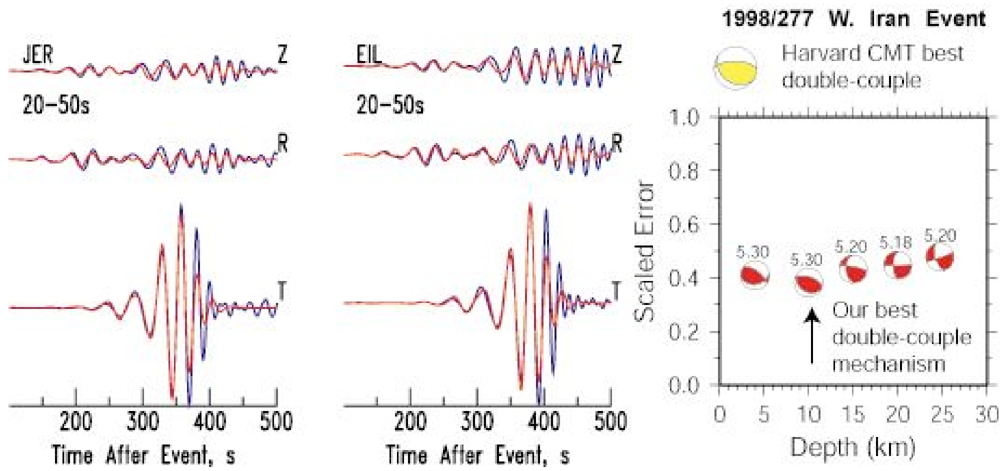

Figure 5. An example of the waveform fit for source parameters of the 1998/277 western Iran event. We used the multiple station grid search (based on Walter, 1992) for optimal double couple mechanism, depth and seismic moment. Observed and synthetic three-component waveforms were filtered 20–50 s. Good agreement with the Harvard CMT gives us confidence to apply these methods to other events with good signal-to-noise ratios in this pass band. (Courtesy Arthur Rodgers)