Final Technical Report
June 2008

Toward Automated Focal Mechanism and Moment Determination for the Continental U.S. – An ANSS Product

USGS Grant 05HQGR0047

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Key words: Seismology, moment tensor, earthquakes

Abstract

This project focused on the development of software and procedures for the rapid determination of moment tensors for use by the USGS National Earthquake Information Center (NEIC) in Golden, Colorado. These procedures are currently on a test-bed at NEIC and are used by the PI and NEIC staff for routine source parameter determination.

1. Introduction

The USGS National Earthquake Information Service (NEIC) routinely reports earthquake locations in the U. S. The reporting threshold is a magnitude 2.5 to ensure that all potentially felt earthquakes are included. In addition to location the NEIC attempts to provide a consistent magnitude estimate, with a direct estimate of moment magnitude being preferred. The moment magnitude is a very important parameter, since it and source depth provide the initial model based estimate of shaking by the Prompt Assessment of Global Earthquakes for Response (PAGER) system. In order to be effective and to meet NEIC performance goals, the earthquake source parameters must be provided to the PAGER process as quickly as possible.

The issues addressed by this effort was whether rapid moment tensor inversion is possible for M > 3.5 earthquakes on the continent, whether this can be done quickly, and how to document and install the processing software at NEIC.

2. Methodology

All codes used are part of the P.I.'s Compute Programs in Seismology package:
http://www.eas.slu.edu/People/RBHerrmann/CPS330.html
which is open-source,. documented and maintained. The source inversion procedures are described by

Herrmann and Ammon (2002) and consist of two complementary techniques. Direct inversion of broadband waveforms by a grid search over strike, rake and dip, and a fit to the fundamental mode Love- and Rayleigh-wave surface-wave spectral amplitudes. The latter technique is robust but requires first motion or some waveform forward modeling to resolve the ambiguities of strike and rake resulting from working with surface wave amplitudes.

Since successful waveform inversion requires the proper velocity model for making the synthetic Green's functions, one must be careful in its application. The effect of the velocity model on surface-wave spectral amplitudes seems to be less critical. Because the number of broadband stations has increased significantly during the past decade, and because there is more confidence the ability to perform waveform inversion, the current processing routinely considers the use of broadband stations within 700 km of the earthquake for waveform inversion, while the surface-wave spectral amplitude technique uses all data with continental paths out to 5000 from the earthquake.

At present two velocity models seem to be adequate for waveforms inversion of ground velocity in the 0.02 – 0.10 Hz band and surface-wave spectral amplitudes in the 5 – 100 second period range. The Central U. S. model is used on the stable interior side of the Rocky Mountains and a Western U. S. model is used to the west. The CUS model was originally developed by the author for source studies and synthetic seismograms, while the WUS model is a modified version of a model provided by Dr. James Pechmann of the University of Utah.

The models in the Computer Programs in Seismology model96 format are

Table 1. CUS Model

```
MODEL.01
CUS Model with Q from simple gamma values
ISOTROPIC
KGS
FLAT EARTH
1-D
CONSTANT VELOCITY
LINE08
LINE09
LINE10
LINE11
  H(KM) VP(KM/S) VS(KM/S) RHO(GM/CC)    QP    QS   ETAP   ETAS   FREFP   FREFS
   1.0000  5.0000  2.8900  2.5000 0.172E-02 0.387E-02 0.00   0.00   1.00   1.00
   9.0000  6.1000  3.5200  2.7300 0.160E-02 0.363E-02 0.00   0.00   1.00   1.00
  10.0000  6.4000  3.7000  2.8200 0.149E-02 0.336E-02 0.00   0.00   1.00   1.00
  20.0000  6.7000  3.8700  2.9020 0.000E-04 0.000E-04 0.00   0.00   1.00   1.00
   0.0000  8.1500  4.7000  3.3640 0.194E-02 0.431E-02 0.00   0.00   1.00   1.00
```

and

Table 2. WUS Model

```
MODEL.01
Model after     8 iterations
ISOTROPIC
KGS
FLAT EARTH
1-D
CONSTANT VELOCITY
LINE08
LINE09
LINE10
LINE11H(KM)  VP(KM/S) VS(KM/S) HO(GM/CC)  QP      QS     ETAP  ETAS FREFP
FREFS
 1.9000 3.4065  2.0089  2.2150 0.302E-02 0.679E-02 0.00  0.00  1.00  1.00
 6.1000 5.5445  3.2953  2.6089 0.349E-02 0.784E-02 0.00  0.00  1.00  1.00
13.0000 6.2708  3.7396  2.7812 0.212E-02 0.476E-02 0.00  0.00  1.00  1.00
19.0000 6.4075  3.7680  2.8223 0.111E-02 0.249E-02 0.00  0.00  1.00  1.00
 0.0000 7.9000  4.6200  3.2760 0.164E-10 0.370E-10 0.00  0.00  1.00  1.00
```

These models work well. However they are not appropriate for parts of California where the crustal structure seems to change rapidly with distance. On the other hand the CUS model does well for msot of eastern North America for modeling in the 0.02 – 0.10 Hz velocity band.

A question often arises as to why ground velocity is modeled instead of displacement. The advantage of working with displacement, especially at even lower frequencies is that the results are even less dependent upon the earth model. However emphasis on low frequencies requires broadband instruments and instrument sites that exhibit low sensor/site noise. When nearby stations are not available and the earthquakes are small, e.g., M ~ 4, ground noise controls the useful signal band for inversion, which is typically the 0.02 – 0.10 Hz band for velocity. The other reason for working with velocity is that the response of modern broadband instruments is usually flat to velocity in the band of frequencies of interest, and hence the effect of enhancement of low frequency noise from the deconvolution to ground displacement is avoided.

Since the determination of the surface-wave spectral amplitudes uses the multiple filter analysis technique to determine the model spectra, ground velocity dispersion values are obtained for each source-receiver path. At present we have a data base of about 600,000 Love and Rayleigh wave dispersion points in the 4 – 200 second period range for paths in North America. Using a tomography program developed by Dr. Charles Ammon of the Penn State University, we are now able to able to test the *a priori* choice of velocity model for a region against actual dispersion measurements. Consider first a location in north-central Colorado (Figure 2.1). The WUS model predictions fit all dispersion estimates well. The quality of fit between 8 and 40 seconds is crucial since this period range controls the surface-wave signal which is dominant on the seismogram. For a site in northeastern-Arizona (Fig 2.2), the comparison is not as good, indicating that a different set of values for the upper-crust shear-wave velocities is required. This was noted in the processing of the Arizona earthquake of 20080327010714 (YearMoDyHrMnSc) which showed some simple pulselike surface wave arrivals along some paths.

It is hoped that the dispersion studies will lead the a better set of regionalized velocity models for source parameter inversion.

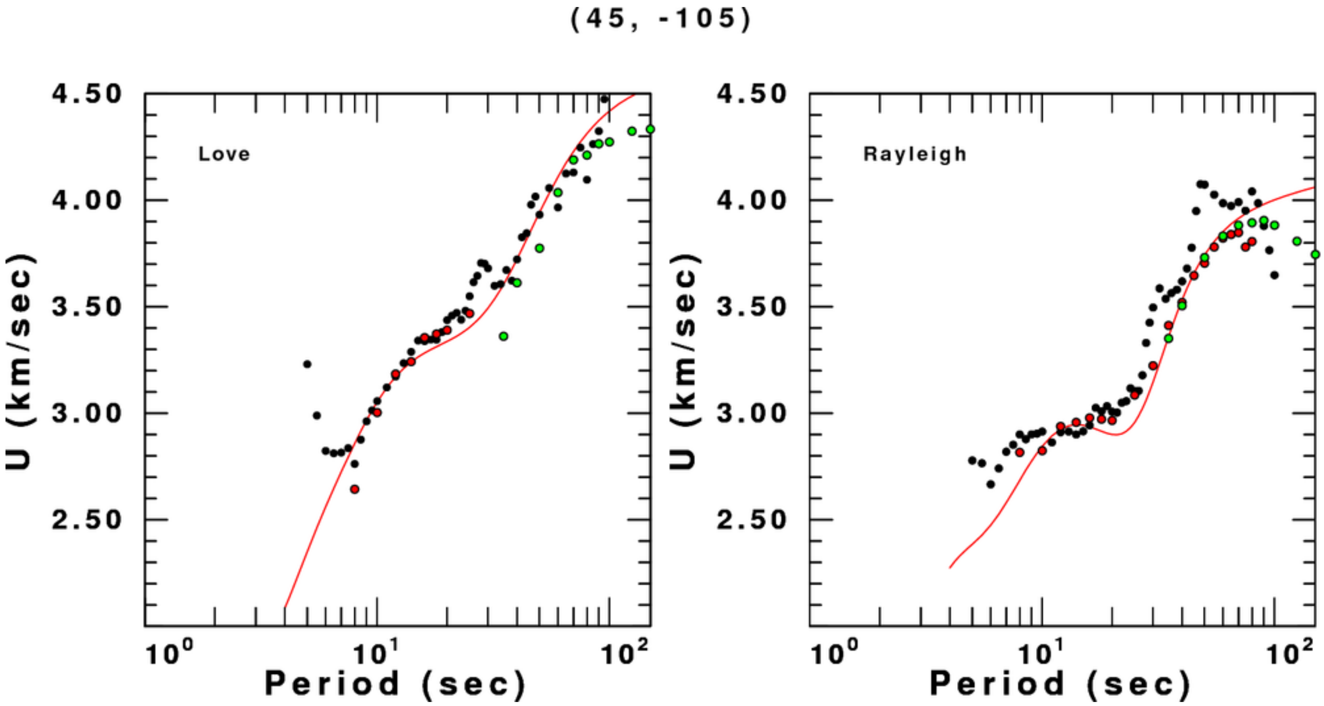

Fig. 2.1. Comparison of WUS model predicted (red curves) Love and Rayleigh wave group velocities to observed values for a site in north-central Colorado. Black dots – Herrmann, Ammon and Benz tomography using the data set generated int his report; red dots – University of Colorado tomography based of ground noise inter-station empirical Green's functions; green dots – Harvard global tomography.

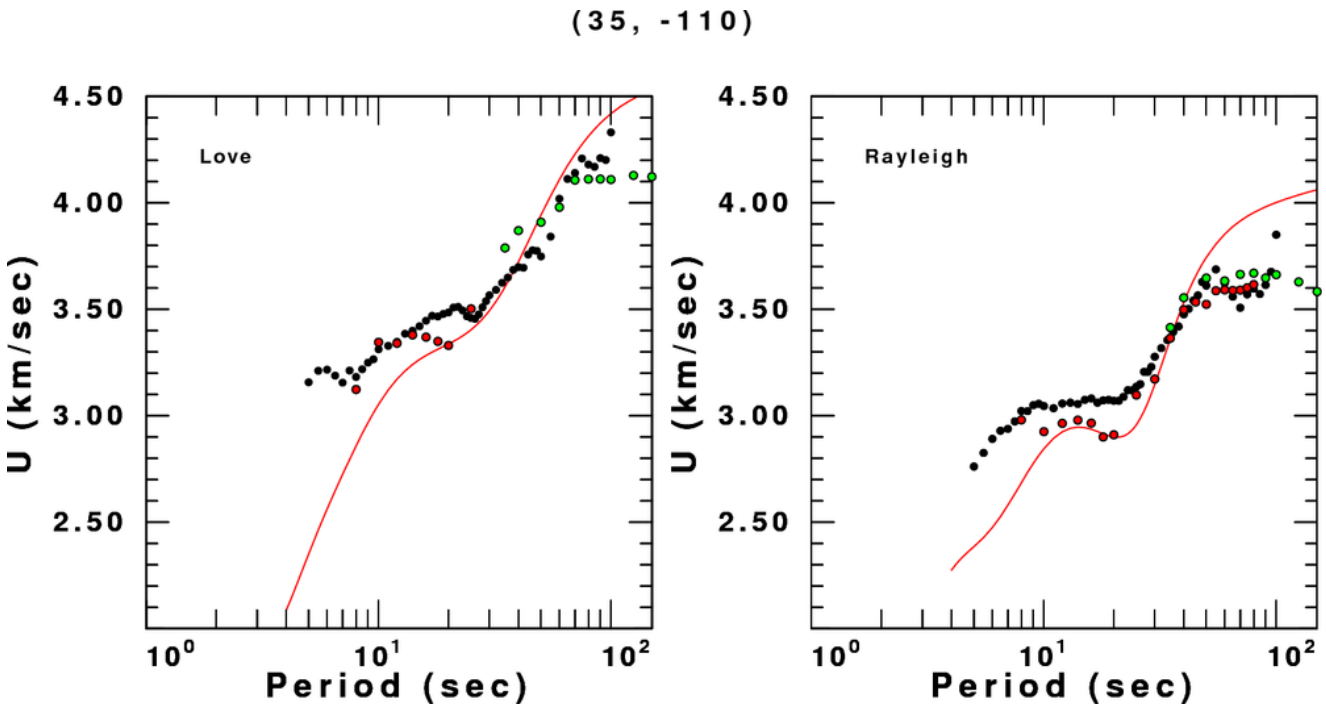

Fig. 2.2. Comparison of WUS model predicted (red curves) Love and Rayleigh wave group velocities to observed values for a site in north-eastern Arizona. Black dots – Herrmann, Ammon and Benz tomography using the data set generated int his report; red dots – University of Colorado tomography based of ground noise inter-station empirical Green's functions; green dots – Harvard global tomography.

3. Processing

Processing will be described as part of the final report on the successor effort "Focal Mechanism and Moment Determination for the Continental U.S. - An ANSS Product" USGS Grant 06HQGR0166.

The processing has evolved as more was learned about inversion, the applicability of regional velocity models, and data access. "We currently use the NEIC 'CWBquery.jar' problem internally and externally. All processing is driven by at command that reads, for example, as

```
#!/bin/sh
#####
# valid regions
# REG    Region              FELTID  VELOCITY_MODEL
# HI     Hawaii              hi        [Not implemented June 23, 2007]
# AK     Alaska              ak        CUS  (in continent from Rockies -no deep)
# CA     California          ca        WUS
# PNW    Pacific Northwestrn pnw       WUS
# IMW    Intermountain west  imw       WUS
# CUS    Central US          cus       CUS
# NE     Northeastern US     ne        CUS
# ECAN   Eastern Canada      ous       CUS (in continent from Rockies)
# WCAN   Western Canada      ous       [Not implemented June 23, 2007]
#####
# Command syntax:
#DOCWBREG YEAR MO DY HR MN SC MSC  LAT     LON     DEP  MAG REG  NEIC FELTID STATE/COUNTRY
#####
DOCWBREG "2008" "06" "05" "07" "13" "15" "467" " 38.4469" " -87.8673" "17.5" " 3.60" "CUS" "sxba" \
                "X2008sxba" "Illinois"
```

This script sets up the directory structure for the event, acquires the waveforms data, deconvolves and rotates the traces, starts an interactive QC of the waveforms for inversion, performs the source inversion, and prepares the web page documentation.

4. Results

The results of all source inversions are available at the link

http://www.eas.slu.edu/Earthquake_Center/MECH.NA/

This page provide links to detailed analysis of each earthquake as well as summary figures. As of June 5, 2008, source parameter information is provided for more than 259 earthquakes in North America. The catalog is based on recent efforts by the PI, for the years 1996-2008, publications based on broadband waveform studies by students and researchers at Saint Louis University, and studies for some eastern and north-eastern U. S. earthquakes by Du *et al.* (2003) and Kim and Chapman (2005). The tabulation on the page

http://www.eas.slu.edu/Earthquake_Center/MECH.NA/MECHFIG/mech.html

provides a complete list of references for the solutions.

The source mechanisms in the tabulation are are presented in Figures 4.1 and 4.2. Figure 4.1 shows the focal mechanisms in the context of M > 3.0 seismicity for North America. Recalling that this effort did not attempt to duplicate the routine source determination in California and coastal Alaska by the California Integrated Seismic Network and the Alaska Earthquake Information Center, respectively, interesting spatial patterns are apparent. First most of North America is relatively aseismic. Second the larger earthquakes, e.g., those for which it is possible to determine moment tensor solutions from broadband waveforms, seems to occur where the M > 3 earthquakes occur. This is especially true in Utah, Wyoming and Montana. There are exception, but this spatial coincidence argues for upgraded monitoring in those regions so that the completeness level for source inversion can be lowered.

Another perspective is shown in Figure 4.2, which plots the orientation of the maximum compressive stress axis (Zoback, 1992) with bar colors indicating the mode of faulting. The impressive features of this figure are the spatially coherent patterns - thrust faulting in the northeastern U.S. and southeastern Canada, strike-slip faulting in much of the central U.S., normal faulting in the Great Plains, strike-slip faulting in the southern Great Basin, and normal faulting in the eastern and northern Great Basin. The regionally uniform orientation of the axes argues for a common causative process in the regions. Exceptions warrant extra study. For the two thrust events in central Virginia are from a study by Kim and Chapman (2005) of two M=4.1 earthquakes separated by 12 seconds in origin time. The effect of the equal size and delay causes a spectral hole at 24 seconds, which forced them to use high frequencies in the inversion.

On the basis of independent high frequency ground motion simulations, this P.I. believes that there may be regional variations in high frequency ground motion scaling at short epicentral distances because of the regionally specific mechanism parameters.

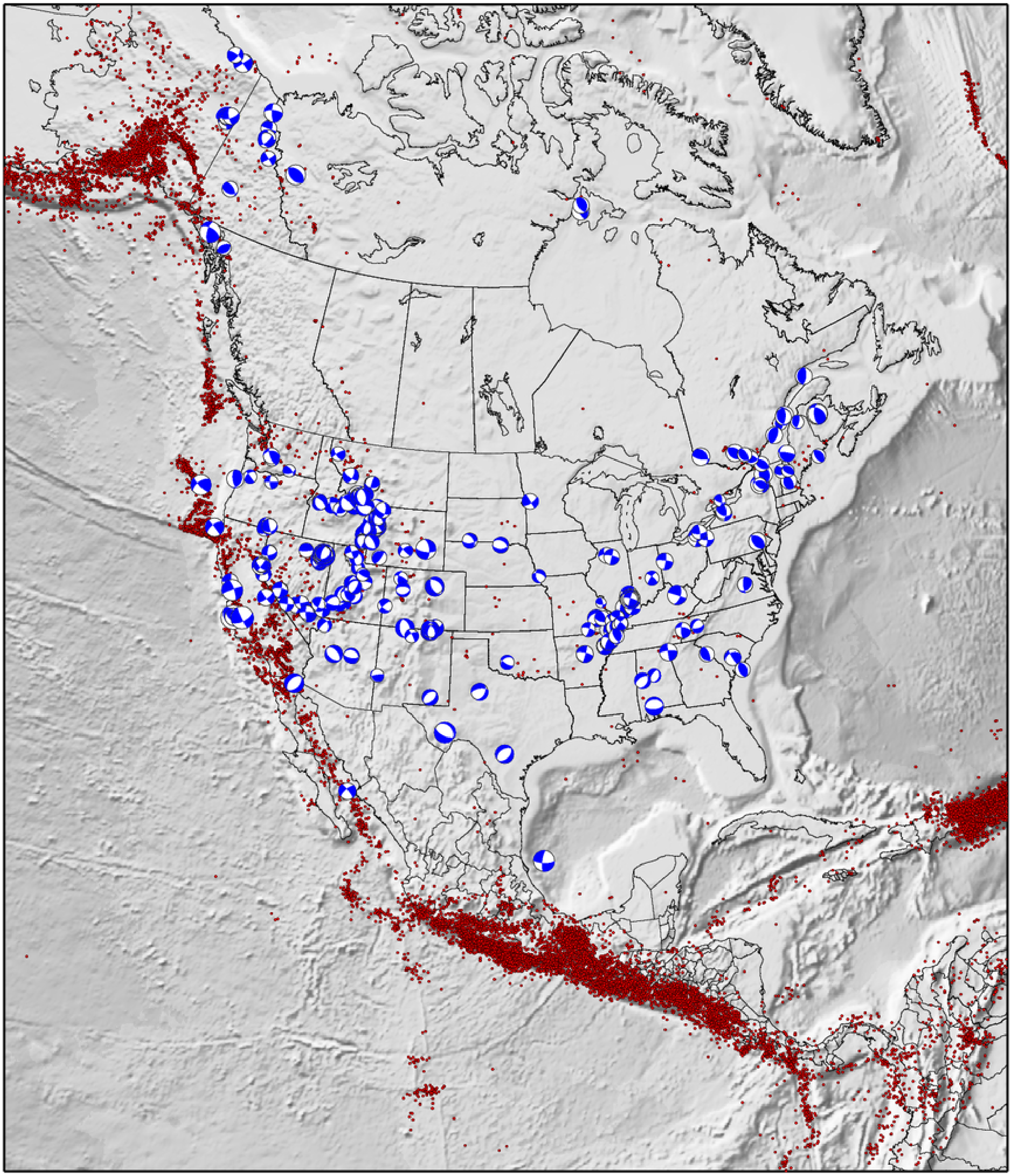

Fig. 4.1. North American focal mechanisms. The location of all earthquakes with M < 3.0 in the 1999-2006 time period from the ANSS and Geological Survey of Canada catalogs. The source parameters of all but 17 earthquakes were determined at SLU.

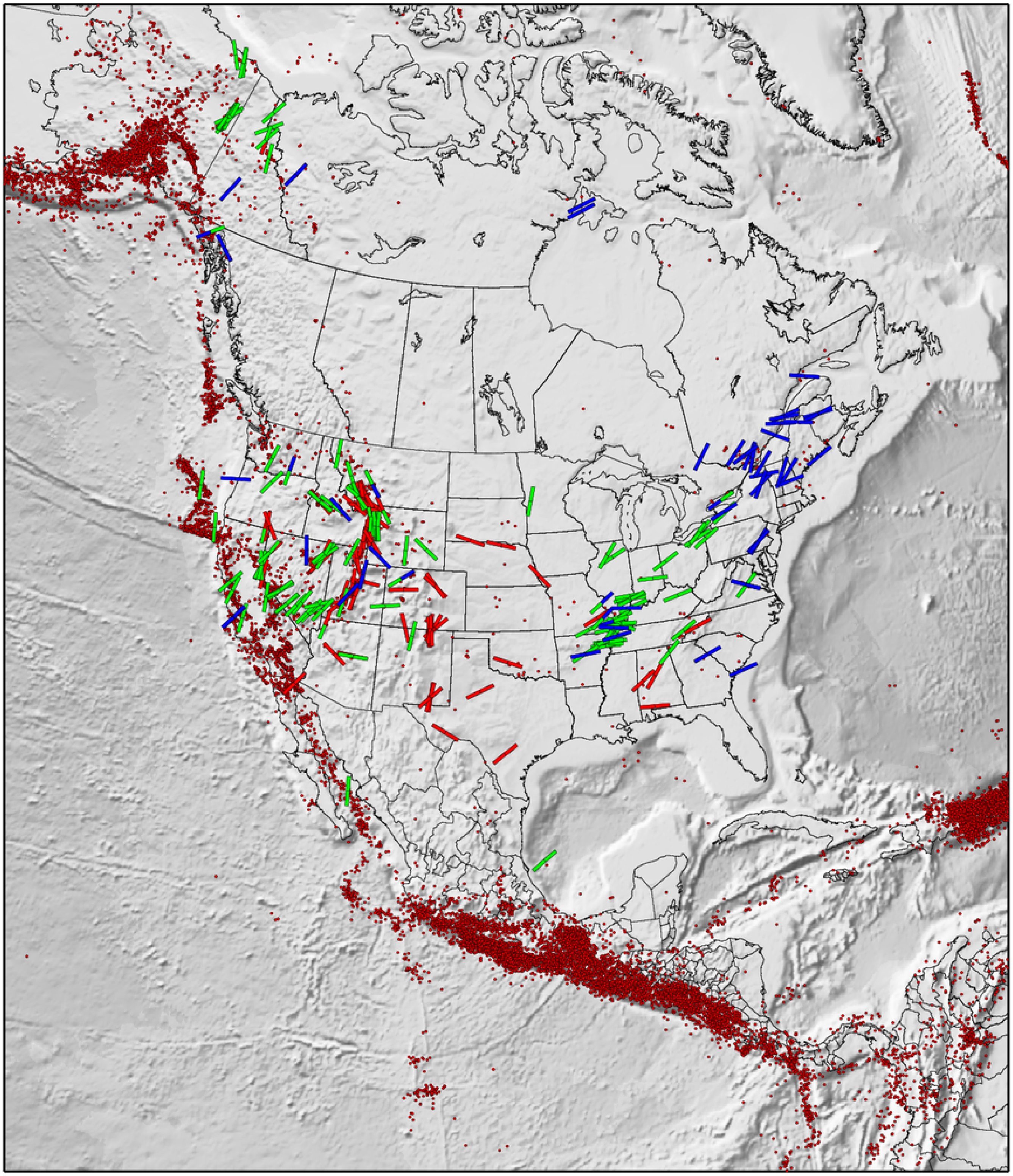

Fig. 4.2. Orientation of the direction of maximum compressive stress following the convention of Zoback (1992). The bar colors indicate the type of faulting: red normal, blue thrust and green strike-slip. The M > 3.0 earthquake locations from 1999-2006 are plotted

5. Case Study

A magnitude **M**=5.3 occurred in southeastern Illinois on April 18, 2008 at 09:37 UT (04:37 CDT). This was the largest earthquake since 1987 in the area and is interesting because of the number of aftershocks. Moment tensor solutions were obtained for the **M**=5.3 (20080418093700), **M**=4.6 (20080418151416), **M**=4.0 (20080421053830) and **M**=3.7 (20080425173100) earthquakes of the sequence. Because I wave traveling, these moment tensors for the first two events were determined at the NEIC using the installed processing procedures. The official solution for the **M=**4.6 earthquake is shown below. Note the attribution to SLU.

```
USGS/SLU Regional Moment Tensor Solution

          08/04/18 15:14:16
    ILLINOIS
      Epicenter:  38.539  -87.865
                MW 4.6

    USGS/SLU REGIONAL MOMENT TENSOR
    Depth  15         No. of sta: 12
    Moment Tensor;   Scale 10**15 Nm
        Mrr= 0.00       Mtt= 9.74
        Mpp=-9.74       Mrt=-1.21
        Mrp= 1.21       Mtp= 0.00
             Principal axes:
      T  Val=  9.89  Plg= 7  Azm=180
      N        0.00      80      314
      P       -9.89       7       89

    Best Double Couple:Mo=9.9*10**15
     NP1:Strike=315 Dip=90 Slip=  10
     NP2:       225     80       180

              #######
          #################
        #####################
      -######################--
    -----#################-------
   --------#############----------
   ----------#########------------
  -------------#####---------------
  ---------------#---------------
  --------------##--------------- P
  ------------######-------------
  -----------#########-------------
   --------#############----------
   -------################--------
    ----####################-----
      -#######################-
        #########   #########
          ####### T #######
              ##   ##
```

The inversion of waveforms was not difficult because of the depth of the earthquake, the simplicity of the crustal structure and the large number of broadband stations in the region (Fig. 5.1). Note the plot does not show the University of Memphis stations since they were not available in the NEIC Continuous Wave Buffer. Figure 5.2 compares the observed and predicted waveforms.

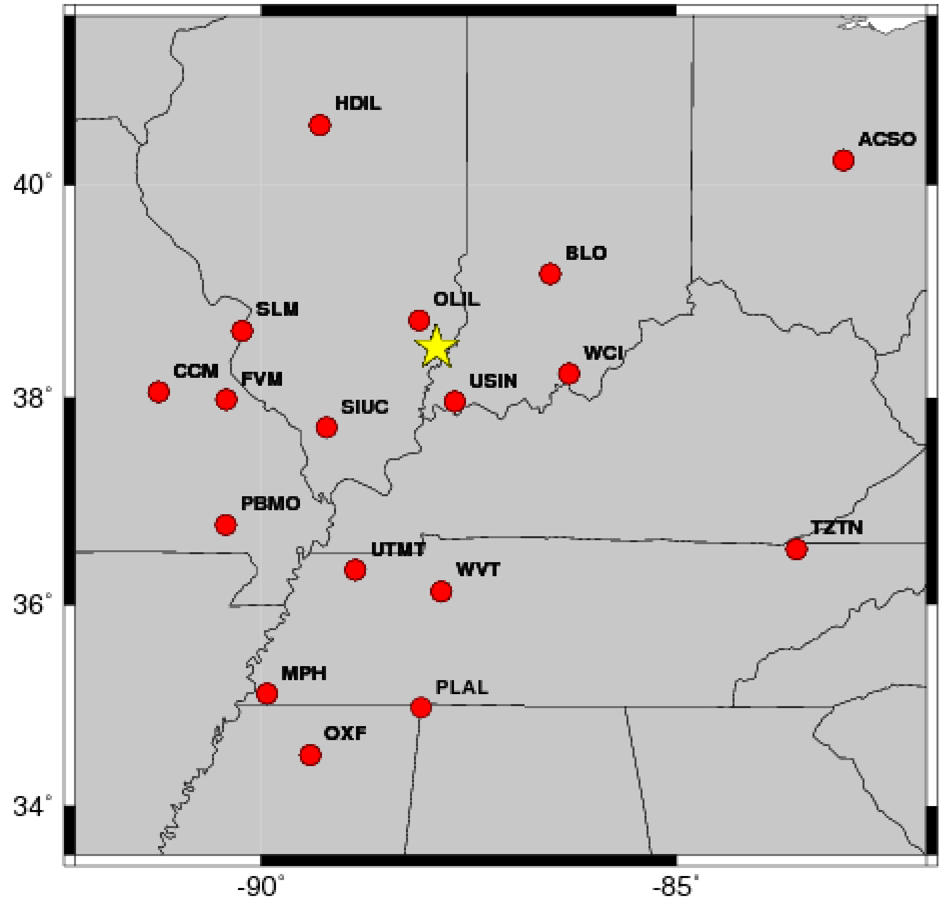

Fig. 5.1 Broadband stations used for direct inversion of broadband waveforms for source inversion.

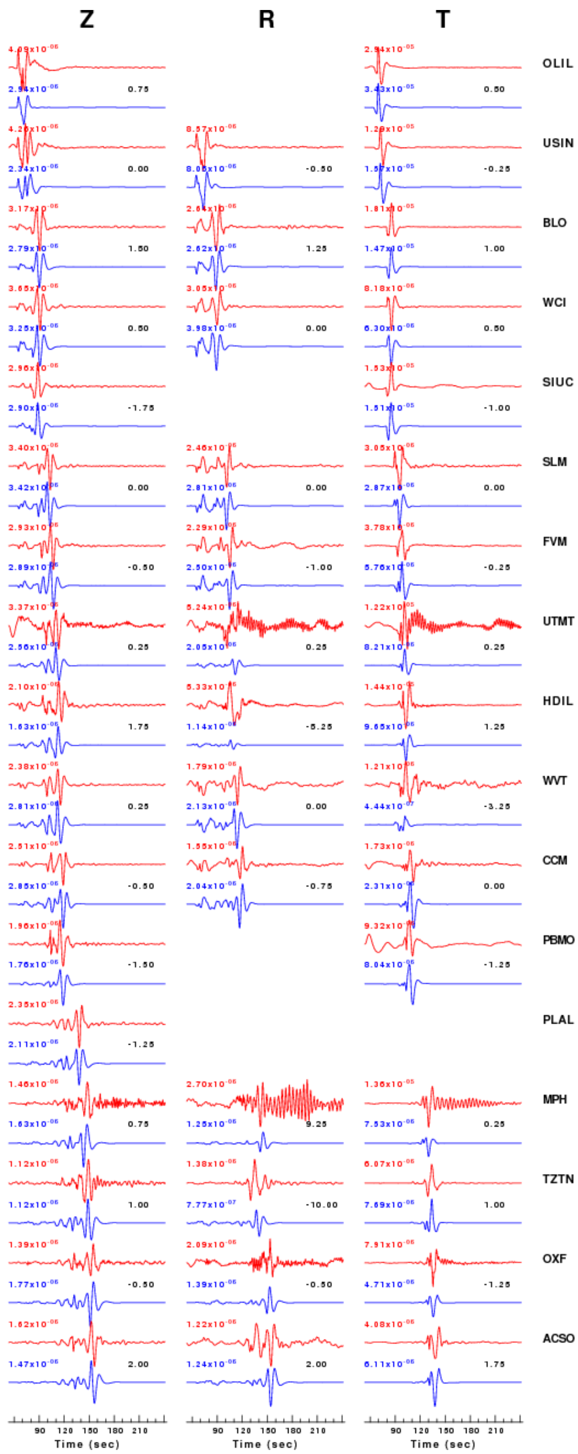

Fig. 5.2 Comparison of observed and predicted waveforms for the moment tensor given above. Ground velocity (m/s) is displayed in the 0.02 – 0.10 Hz band. Each pair of observed (red) and predicted(blue) traces is plotted to the same scale. Different scales are used for other pairs. The comparison indicates that the velocity model used (CUS) is adequate for modeling these waveforms. In addition the effect of deep Mississippi Embayment sediments on the transverse components at UTMT, PVMO and MPH is quite apparent.

Surface-wave spectral amplitude data were obtained using data available within the NEIC Continuous Wave Buffer and from the Geological Survey of Canada/Natural Resources Canada. Waveforms from the Transportable Array of EarthScope were not include since their addition would add little to the solution or to the tomogrpahy study. The TA data was included for the analysis of the main event. Figure 5.3 shows the locations of the stations used for the surface-wave study, and Figures 5.4 and 5.5 show selected radiation pattern fits for Love and Rayleigh waves, respectively.

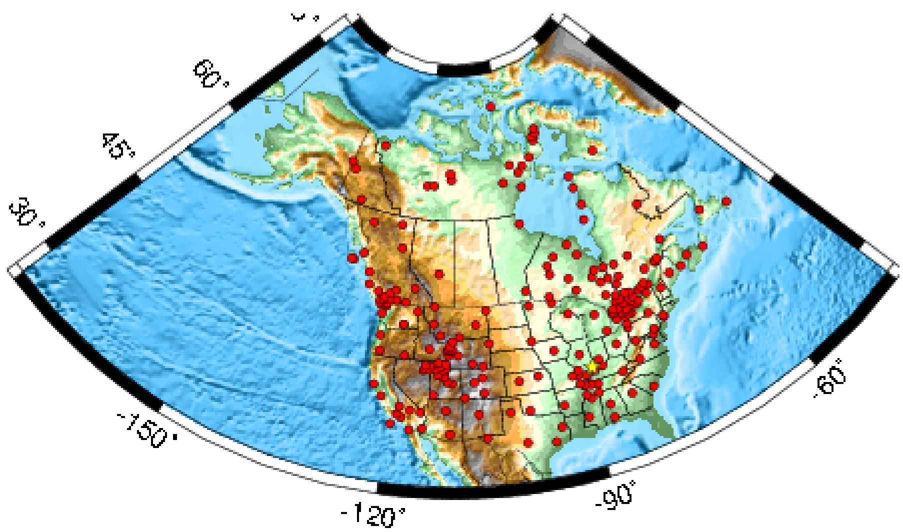

Fig. 5.3. Location of stations used for surface-wave radiation pattern study.

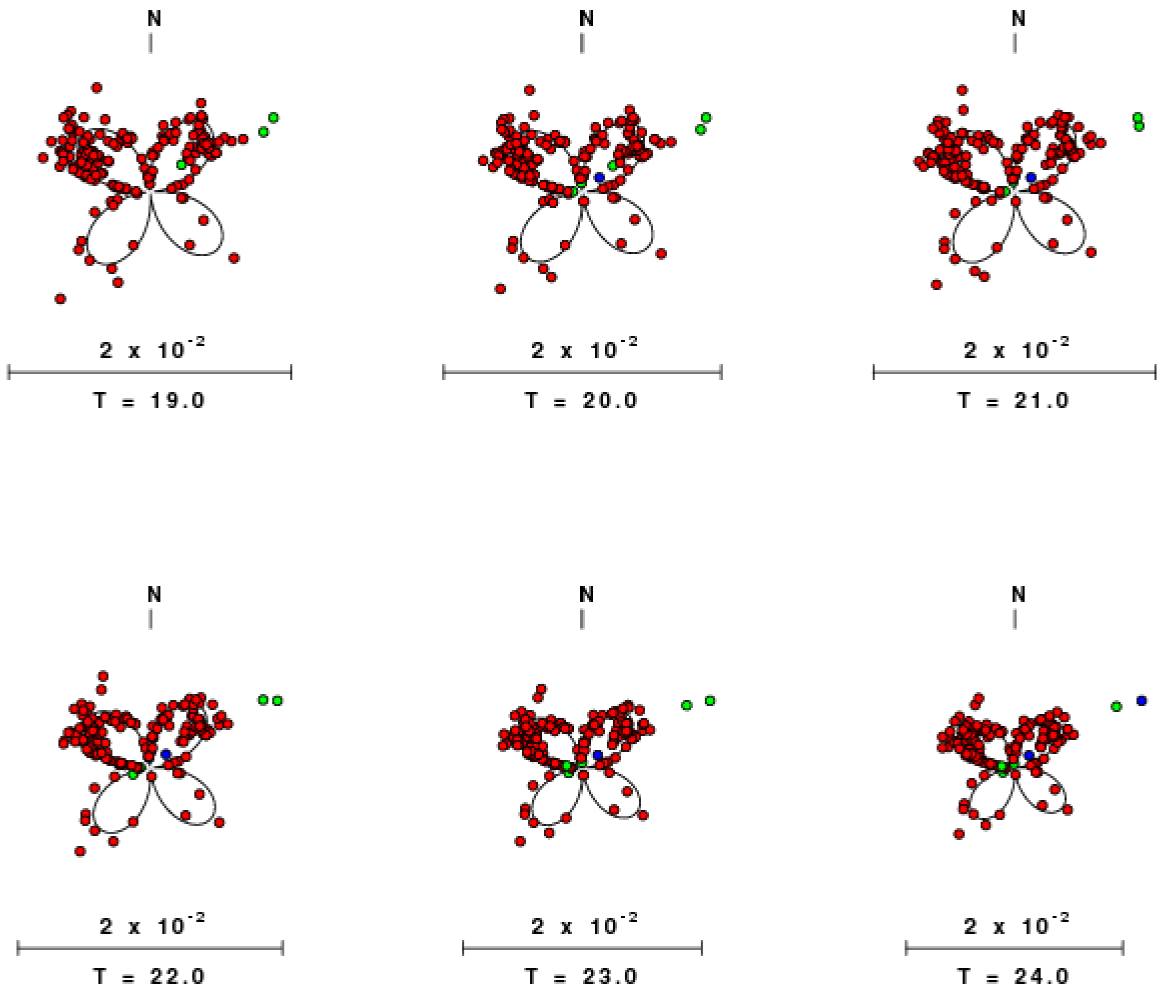

Fig. 5.4. Love wave spectral amplitude radiation patterns. The observe points have been corrected for anelastic attenuation back to the source and corrected for geometrical spreading to an epicentral distance of 1000 km. The scaling units are spectral amplitude in cm-sec. The underlying black curves are the model predicted radiation pattern. The green and blue dots for the observed values indicate significant outliers in the relation between predicted and observed amplitudes.

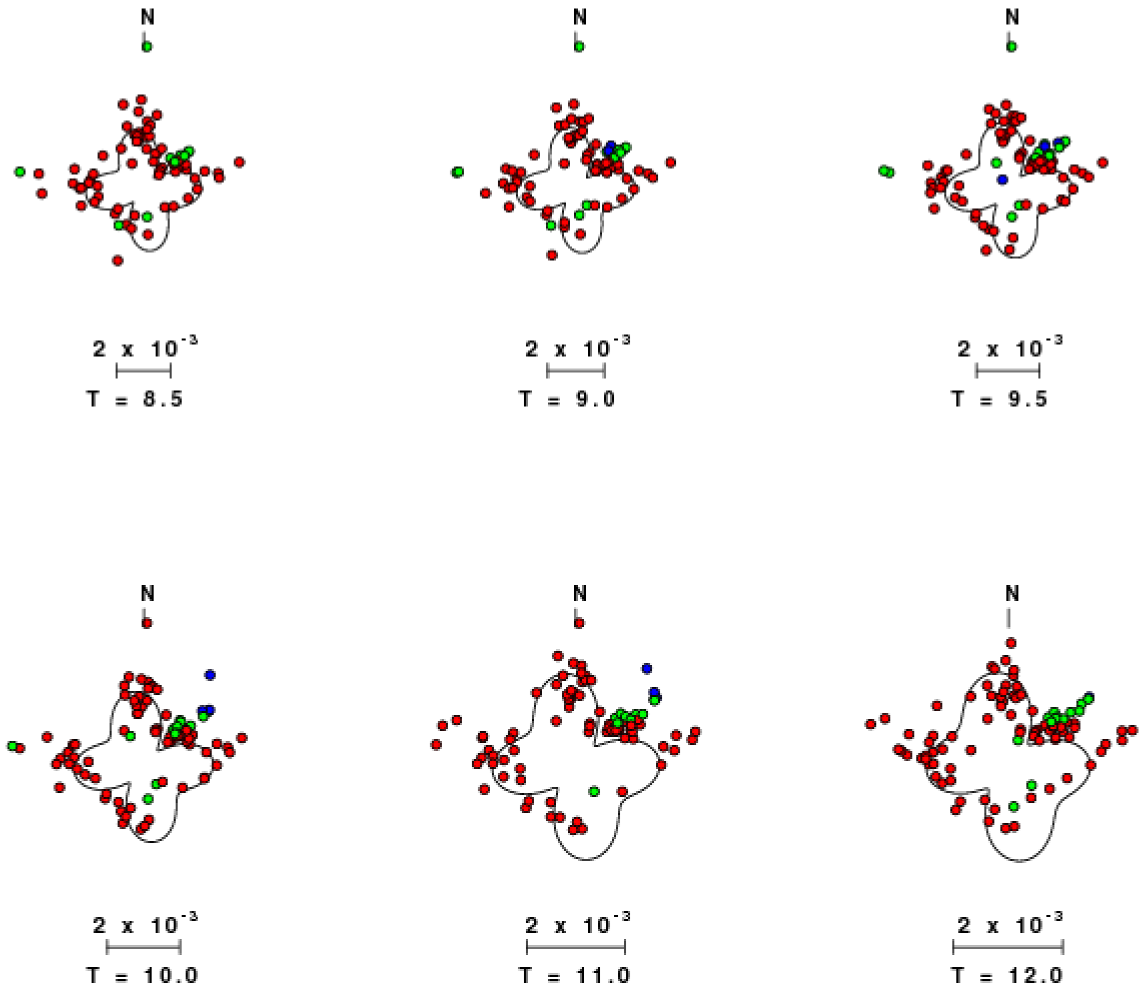

Fig. 5.5. Rayleigh-wave spectral amplitude radiation patterns. The observe points have been corrected for anelastic attenuation back to the source and corrected for geometrical spreading to an epicentral distance of 1000 km. The scaling units are spectral amplitude in cm-sec. The underlying black curves are the model predicted radiation pattern. The green and blue dots for the observed values indicate significant outliers in the relation between predicted and observed amplitudes.

6. References

Du, Wen-xuan; Kim, Won-Young; Sykes, Lynn R. (2003). Earthquake Source Parameters and State of Stress for the Northeastern United States and Southeastern Canada from Analysis of Regional Seismograms, *Bull. Seism. Soc. Am.* **93,** 1633 – 1648.

Herrmann, R. B., and C. J. Ammon (2002). Source inversion, ftp://ftp.eas.slu.edu/pub/rbh/TUTORIAL.330/cps330s.pdf, 98pp.

Kim, W.-Y., and M. Chapman (2005). The 9 December 2003 Central Virginia earthquake sequence: a compound earthquake in the central Virginia seismic zone, *Bull. Seism. Soc. Am.* **95,** 2428-2445.

Zoback, M. L. (1992). First- and second-order patterns of stress in the lithosphere – The World Stress Map project, J. Geophys. Res. **97,** 11,703-11,728.

7. Summary

Procedures have been established for routine moment tensor inversion of North American earthquakes, especially for use outside of California. It should be possible for NEIC to have the solution within 30 minutes maximum from the occurrence of the earthquake. This timing is based on the scenario that NEIC officially releases the reviewed event coordinates within 10 minutes, the source inversion processing be immediately initiated and that the next 20 minutes are spend downloading, deconvolving, and inverting the waveforms.

8. Reports/papers Published

None: All software and results are available on the web links cited above.