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

USGS Grant 06HQGR0166

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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 was the implementation of regional inversion at the NEIC. Issues addressed were data access within NEIC, data quality and data presentation.

This effort is builds on the work of USGS Grant 05HQGR0047 "Toward Automated Focal Mechanism and Moment Determination for the Conbtineltal U.S. - An ANSS Product."

2. Regional data processing.

We will use the analysis if the New Mexico earthquake of June 4, 2008 as an example of the installed

processing package.

Background:

For perspective certain SHELL parameters and aliases are set in the user's environment. The SHELL variable GREENDIR points to the top level directory of Green's functions, e.g., GREENDIR=/backup/rbh/GREEN

In addition the alias M points to the processing arena,
alias M='cd /backup/rbh/MOMENT_TENSOR/MECH.NA'

The directory ${GREENDIR} has the following subdirectories, CUS.REG and WUS.REG which are the top level directories for the Green's functions for the CUS and WUS velocity models (lists in the Appendix). The contents of CUS.REG are

```
0005/  0050/  0100/  0150/  0200/  0250/  0300/  cusq.mod   SW/
0010/  0060/  0110/  0160/  0210/  0260/  0310/  dcusq.mod  SWDOIT*
0020/  0070/  0120/  0170/  0220/  0270/  0320/  DOIT*      SW.OLD/
0030/  0080/  0130/  0180/  0230/  0280/  0330/  DOIT.BIG*
0040/  0090/  0140/  0190/  0240/  0290/  0340/  Model/
```

Here the directory naming convention of 0190, for example, indicates a source depth of 19.0 km. This convention permits the specification of source depth from 0.0 to 999.9 km in 0.1 km increments. The contents of the 0190 directory have files of the type

```
028500190.ZDD  096500190.ZDS  209000190.ZEX
028500190.ZDS  096500190.ZEX  209000190.ZSS
028500190.ZEX  096500190.ZSS  W.CTL
028500190.ZSS  097000190.RDD
029000190.RDD  097000190.RDS
```

Where the naming convention is DDDDdHHHh.GRN permits the distance to be specified from 0.0 to 9999.9 km in 0.1 km increments and the depth from 0.0 to 999.9 km in 0.1 km increments. The suffix indicates the Green's function as defined in 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 file `W.CTL` has entries of the form

```
001 0.25 512 -5 8 0190 000100190
002 0.25 512 -5 8 0190 000200190
003 0.25 512 -5 8 0190 000300190
004 0.25 512 -5 8 0190 000400190
005 0.25 512 -5 8 0190 000500190
006 0.25 512 -5 8 0190 000600190
007 0.25 512 -5 8 0190 000700190
008 0.25 512 -5 8 0190 000800190
```

```
009 0.25 512 -5 8 0190 000900190
010 0.25 512 -5 8 0190 001000190
```

with columns indicating the distance in multiples of 0.1 km, the sampling interval, the number of points in the time series, the parameters for defining the initial time sample, the depth in multiples of 0.1 km, and finally the prefix for the Green's functions. This file is used in the following way: for each observed waveform in Sac format, the epicentral distance in km is extracted from the header. The `W.CTL` is searched to find the computed distance nearest the actual distance. The corresponding Green's functions are then associated with that observed trace.

The other directory structure of interest is the processing directory, e.g., MECH.NA for source studies in North America.

The contents of this directory appear as

```
00README          20080605071315/  DOQUERY*     mechna.sh*  tDO*
0XXXREG/          DO*              DOSETUP*     PROTO.CWB/
20080602175025/   DOCWBREG*        DOSOLUTION*  PROTO.I/
```

Where the 'ls -F' command indicates whether the file is a directory or an executable.

`00README`	-	a readme file
`0XXXREG/`	-	directory of processing prototypes
`20080602175025/`	-	analysis directory
`20080605071315/`	-	analysis directory for the eastern Illinois earthquake
`DO*`	-	manually created startup script
`DOCWBREG*`	-	top level processing script
`DOQUERY*`	-	script to get data from NEIC Continuous Wave Buffer
`DOSETUP*`	-	script to create the event directory structure
`DOSOLUTION*`	-	script to perform the waveform inversion
`mechna.sh*`	-	curses based script to enter event information
`PROTO.CWB/`	-	scriptsfor trace processing from CWB data
`PROTO.I/`	-	scripts for processing SEED derived waveforms
`tDO*`	-	script created by `mechna.sh`

The following scripts are in PROTO.CWB in order of their use

`CWBDOEVT*`	- set event parameters and deconvolve to ground velocity in m/s
`CWBDOROT*`	- rotate traces to vertical radial and transverse
`CWBDODEC*`	- decimate traces to a sampling interval of 0.25 sec for surface-wave
`CWBDODIST*`	- select traces at distances < 600 km for examination for inversion
`CWBDOQC*`	- examine traces to select those for waveform inversion

The directory `0XXXREG` contains the following subdirectories which contain processing scripts

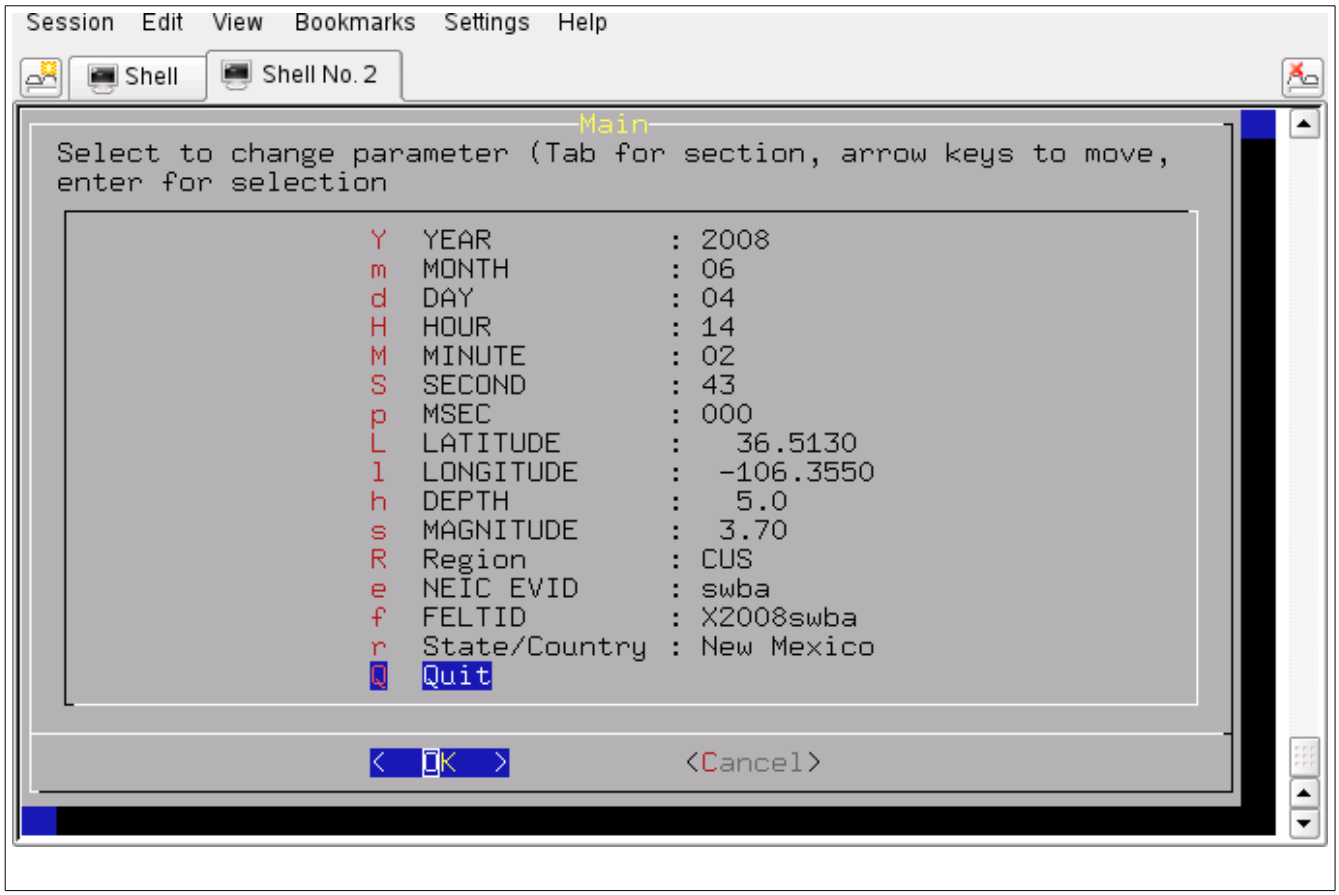
DAT.REG/ - Location of waveforms used for moment tensor inversion
GRD.REG/ - Work area for the moment tensor inversion of broadband waveforms
HTML.REG/ - Work area for creation of the final web page
MAP.REG/ - Work area for creation of the map showing stations used for surface-wave study
MT.OTHER/ - Place to store solution by other organizations
NEW2.REG/ - Work area for inversion using surface-wave spectral amplitude
SYN.REG/ - Work area for making synthetics based on the surface-wave amplitude solution

Step 1:

Interactively create the 'tDO' script by executing the program 'mechna.sh'. This is done by looking at the NEIC posted solution at

http://earthquake.usgs.gov/eqcenter/recenteqsww/Quakes/quakes_all.html

and clicking on the page to get the NEIC 4 character NEIC event ID, swba, and then the "did you feel it?" link to get the felt ID, X2008swba. After entering the information the user sees the screen



Upon quitting the strongly annotated file 'tDO' is created which has the following content:

```
#!/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" "04" "14" "02" "43" "000" " 36.5130" " -106.3550" " 5.0" \
    " 3.70" "CUS" "swba" "X2008swba" "New Mexico"
```

Step 2:

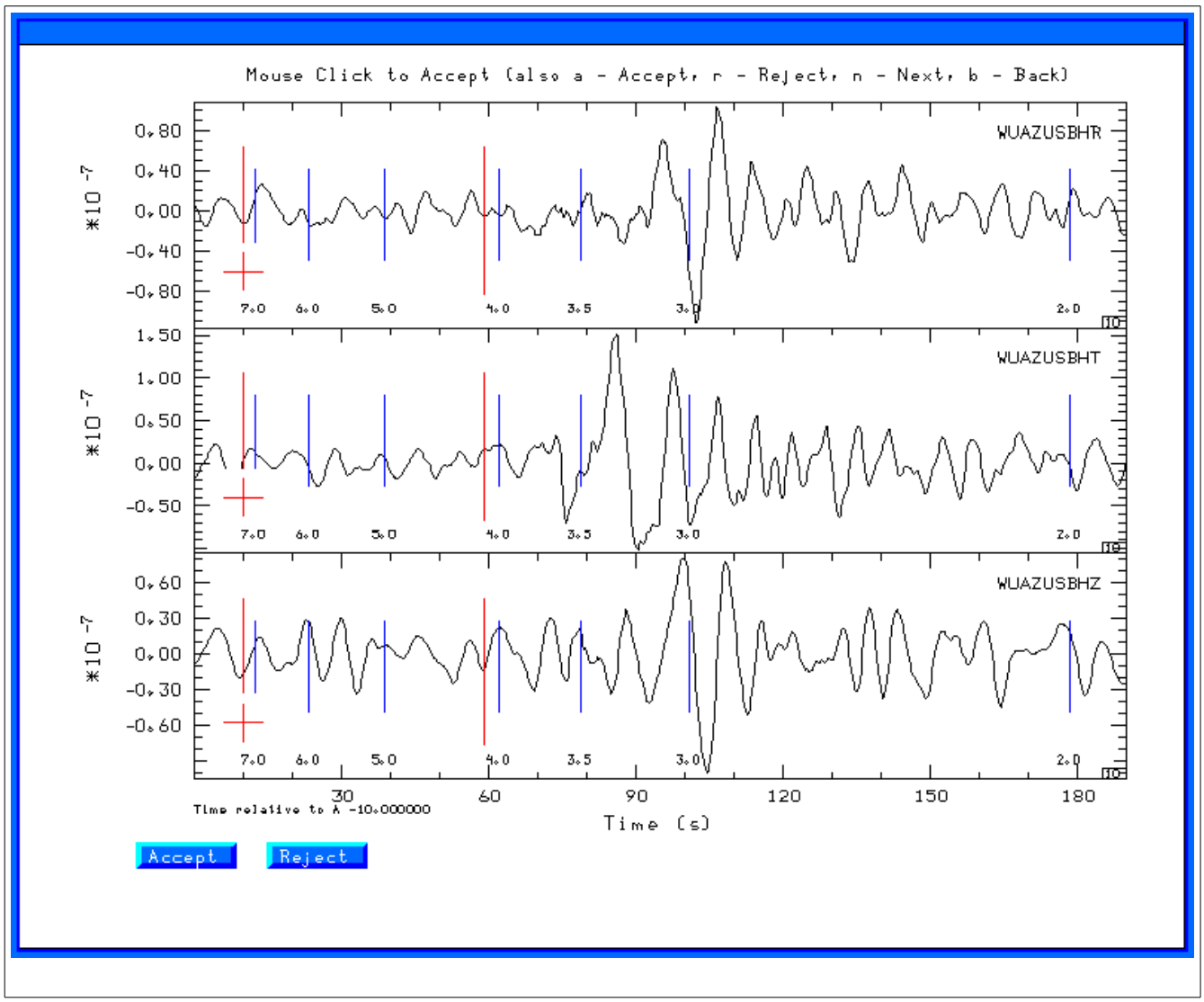
Start the process by entering the command 'tDO'. The script DOCWBREG in turn runs the scripts DOSETUP, DOQUERY, and DOSOLUTION.

DOSETUP creates the event processing structure by using the prototypes in 0XXXREG. All processing scripts are modified to use the specific event parameters about the event from the DOCWBREG command line so that processing will use the correct velocity model and that final documentation will require no manual intervention. As a result of DOSETUP running, the following event directory structure is created with indicated command files:

```
20080604140243/
|-- DAT.REG
|    `-- NOUSE
|-- GRD.REG
|    |-- DOGRD
|    |-- DOPLTSAC
|    `-- DOSTA
|-- HTML.REG
|    |-- DOHTML
|    |-- QUALITY
|    |-- SHWP
|    `-- html.tmp
|-- MAP.REG
|    |-- DOCOORD
|    `-- na.gmt
|-- MT.OTHER
|    `-- 00README
|-- NEW2.REG
|    |-- DOGRID
|    `-- DOPLTRAD
`-- SYN.REG
```

```
|-- DOMCH
|-- DOPLTSAC
`-- DOSTA
```

Next the script DOQUERY is run. This script copies the data preparation scripts from the PROTO.CWB, gets the waveforms from the CWB, deconvolves, rotates and then permits a QC to select waveforms for inversion. Success of the inversion requires the selection of relatively noise and problem free traces. Using the 'ppk qc' command of 'gsac', the following screen appears.



A simple mouse click on a good trace creates the red '+' sign at the lower left of the trace frame marking the trace for use by setting a trace header of the sac file. Qc consists of selecting traces for which there is a good signal-to-noise, traces for which the Love wave on the transverse component appears earleir than the Rayleigh wave on the vertical and radial components, traces for which the Rayleigh wave particle motion in the vertical and radial components indicates retrograde elliptical motion for the dominant fundamental mode, traces for which the P-wave particle motion is either up and away form the source or down toward the source and for which the P-wave amplitude on the

transverse component is negligible. At the same time, anomalous amplitudes are flagged which indicate an incorrect instrument response. Such steps are required since instrumentation and network operation is not perfect.

Finally the DOSOLUTION script runs the moment tensor inversion and creates the final documentation for the Web. Sufficient graphics are created to permit an evaluation of the processing. It may be possible to augment the data set from other sources, e.g., from the Transportable Array of USArray and from the Natural Resources Canada broadband stations. For completeness the much more labor intensive surface-wave spectral amplitude radiation pattern search can be performed.

This processing procedure has slowly evolved during the past 4 years as the PI has learned to handle different data sets. The implementation of the CWBQuery mechanism by NEIC has greatly simplified the task of NEIC performing the same processing.

The result of procesing these data augmented by waveforms from the Transportable Array are given at the link

http://www.eas.slu.edu/Earthquake_Center/MECH.NA/20080604140242/index.html

The emphasis on the scripting was consistency of event processing. The prefixes '.REG' were introduced recognizing that some events may also be large enough to have teleseismic data sets for inversion. The teleseismic processing would use different Green's functions and scripts and would appear in directories with prefixes of '.TEL'.

The scripting is stable now. The next step will be to train NEIC analysts on the inversion procedure and to document the different ways to obtain and use data from the Canadiam autodrm and the IRIS DMC.

3. 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.

Figure 3.1 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.

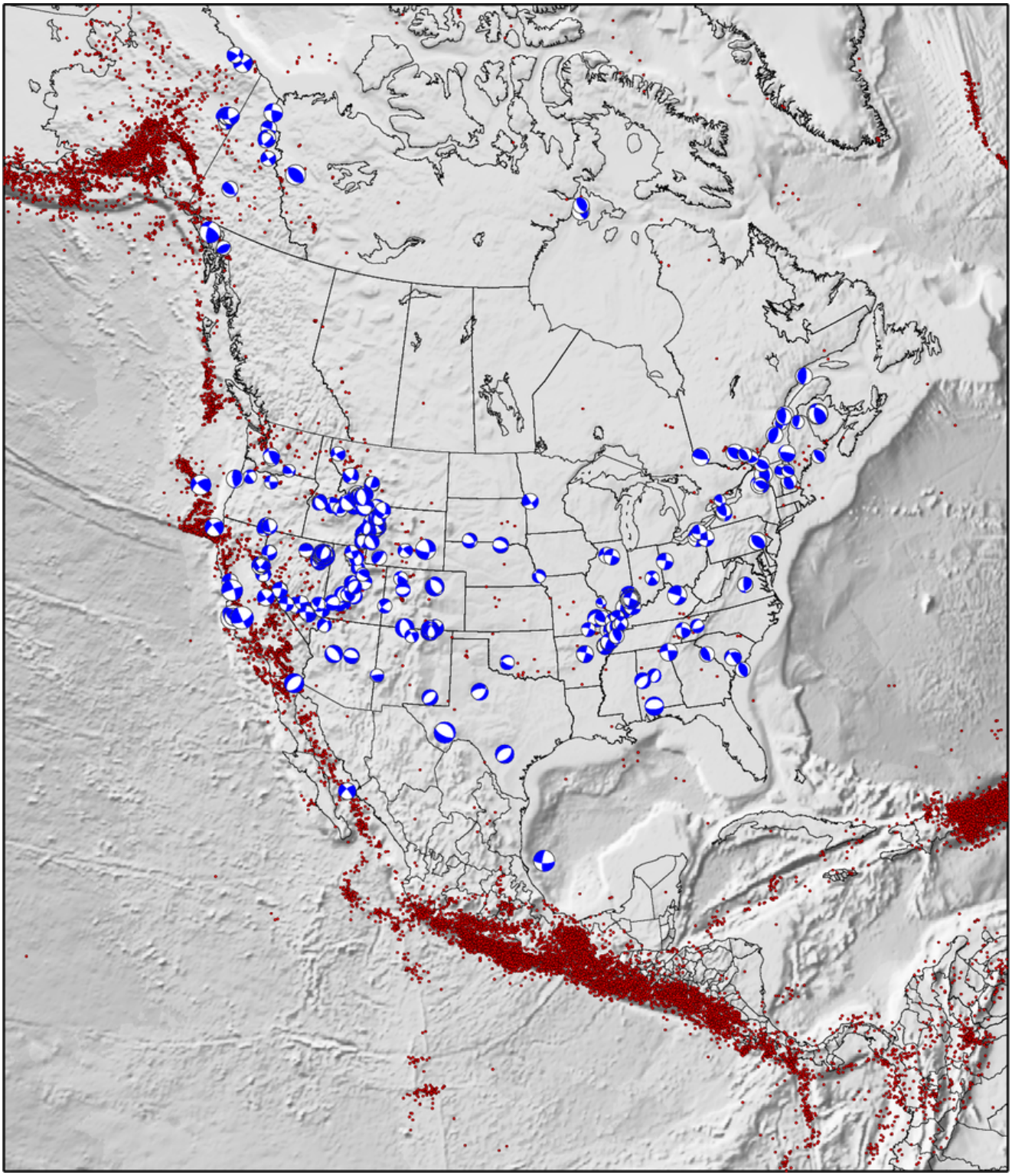


Fig. 3.1. North American focal mechanisms. The location of all earthquakes with M < 3.0 in the 1999-2006 time period from the ANSS and Geological Survey of Canada catalogs. The source parameters of all but 17 earthquakes were determined at SLU.

4. 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.

5. Summary

Procedures have been established for routine moment tensor inversion of North American earthquakes, especially for use outside of California.

6. Reports/papers Published

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

Appendix – Velocity Models

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.