IMPROVING THE FUNDAMENTAL UNDERSTANDING OF REGIONAL SEISMIC SIGNAL PROCESSING WITH A UNIQUE WESTERN US DATASET

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ABSTRACT

This project builds a unique historic database of regional distance nuclear explosion, earthquake, and mine-related digital broadband seismograms. The emphasis is on data from Lawrence Livermore National Laboratory (LLNL)-managed stations MNA, ELK, KNB and LAC that recorded many nuclear tests and nearby earthquakes in broadband digital form since 1980. We also include data from other open broadband stations in the western United States with long operating histories and/or ties to the International Monitoring System (IMS) (e.g. PFO, YKA, CMB, NEW, DUG, ANMO, TUC). These waveforms are associated with a reconciled catalog of events and station response information to facilitate analysis. The goal is to create a high-quality database that can be used in the future to analyze fundamental regional detection, location, magnitude, and discrimination issues.

In the initial stages of the project, we are collecting continuous data from open stations and recovering event data from the LLNL-managed stations from past nuclear tests and earthquakes that exist but have not been collected together into a coherent database. We have also collected six different regional network catalogs from the University of Nevada, Reno (UNR), to provide accurate independent location information for events on the Nevada Test Site (NTS) and in the surrounding region. We have used NNSA-developed software to reconcile these catalogs with each other and to incorporate them into a set of larger continental scale (CNSS, USGS mining catalog compiled by Jim Dewey) and global scale (PDE, REB, ISC) catalogs. Finally, we incorporate the best catalogs of NTS nuclear event locations (DOE Rev 15) and source properties (Springer *et al*. 2002). The result is a single catalog of preferred origins, source information, and station information from which regional waveforms can be extracted from continuous data and associated within the database.

Using the reconciled catalogs and databases, we are working with the UNR network data to determine a subset of about 100 events that are well located and cover a range of magnitudes, source types, and locations. An experienced analyst will then review this dataset during the summer/fall of 2002. She will pick all arrival onsets with quantitative uncertainties and make note of data problems (timing errors, glitches, dropouts) and issues. The resulting arrivals and comments will then be loaded into the database for future researcher use. It is anticipated that this set of consistently picked, independently located data will provide an effective test set for regional sparse station location algorithms. In addition because the set will include nuclear tests, earthquakes, and mine-related events, each with related source parameters, it will provide a valuable test set for regional discrimination and magnitude estimation as well.

We are concentrating on the subset of well-located events that have been picked by our analyst. A final CSS 3.0-format-compatible relational database of these approximately100 events will be put onto a CD-ROM and distributed for other researchers to use in benchmarking regional algorithms after the conclusion of the project.

OBJECTIVE

The objective of this project is to build a historic western U.S. database of regional distance nuclear explosion, earthquake, and mine-related digital broadband seismograms with their associated parameters (origins times and location, instrument response, etc.). Although the original title of the project remains unchanged, its scope has been reduced to match the level of funding. Therefore we focus on a subset of this data to undergo careful quality control, to provide independent regional network ground truth location, and to perform quantitative regional phase picking. This subset will be released as a CD-ROM at the conclusion of the project and provide source type and location ground truth data for monitoring researchers to make use of in benchmarking algorithms.

RESEARCH ACCOMPLISHED

Seismic nuclear monitoring research is data driven. The number of digital seismic records of underground nuclear tests at regional distances is quite restricted both in number and geographical location. Consequently the finite number of existing regional nuclear test records is a unique resource that needs to be thoroughly exploited to create the best verification system possible. We believe that this exploitation is incomplete for the extensive Nevada Test Site (NTS) nuclear explosion records. Therefore in this project our goal is to build the largest, most complete, and best-documented database of explosions, earthquakes, mine blasts and mine tremors in the western U.S. Once completed, this database, we believe, will provide a well-organized and highly efficient way to conduct fundamental monitoring research on regional seismic event detection, location, identification and characterization.

Building a Comprehensive Western U.S. Database

The process of building this new database involves a series of steps, which include:

1. Collecting local, regional and global seismicity catalogs around NTS and the western U.S.
2. Reconciling catalogs into a single table of events with preferred origin information
3. Compiling event parameter information (e.g. yield, material properties, focal mechanisms, etc.)
4. Collecting continuous data from selected stations
5. Compiling station site and instrument response information
6. Extracting event waveforms from continuous data and loading into database with ties to the reconciled catalog
7. Selecting a high quality data subset to analyze
8. Quantitatively analyzing the data subset and loading timing picks and uncertainties into database
9. Distributing data subset and maintaining a database for use in nuclear explosion monitoring research

At the time of this writing, we have completed steps 1-5 and are working on steps 6-9. Here we briefly describe the research accomplished on this project so far.

We have attempted to obtain as complete a list of catalogs in the vicinity of the NTS and the western U.S. as possible. A full list of the dates and locations of all U.S. nuclear explosions is available from DOE (US DOE 2000). Some of these events have announced yields. In addition Springer *et al*. (2002) have compiled the most complete listing of working point parameters (e.g. depth, working point density, velocity, gas porosity) for U.S. underground nuclear tests. These parameters affect seismic frequency content and discriminants (e.g. Walter *et al*., 1995). The University of Nevada Reno (UNR) runs regional seismic networks in southern and northern Nevada that provide the most complete and accurate lists of earthquakes for this region. We have worked with UNR to obtain as complete a set of catalogs for the state of Nevada as possible. We believe these local networks can be used to obtain independent high-quality ground truth location and depth information.

In addition to Nevada and NTS catalogs, we have also collected a number of regional and global scale catalogs. A very nice U. S. regional seismicity catalog is compiled regularly by the University of California at Berkeley from most of the regional seismic network operator's catalogs in this country as part of the Council of National Seismic Stations (see http://www.cnss.org). Although this catalog contains a very large number of events, it does not capture all the events in the local UNR catalogs listed above. We have also collected the USGS mine explosion listing that is compiled by Jim Dewey. Finally, we include the standard global catalogs from the USGS Preliminary Determination of Epicenters (PDE), the International Seismological Commission (ISC) and the International Monitoring System (IMS) Reviewed Event Bulletin (REB).

We have gained much experience in building large reconciled databases over the past several years (see O'Boyle *et al*, this volume) and we make full use of these tools and procedures in this project. We assign each of these catalogs a rank order for reconciliation. The catalogs are then parsed and locations and origin times are compared. Events in common are assigned to one unique event identification number and the highest ranking catalog's origin information then becomes the preferred one. The other origin information is retained as well. In this way we build up a single listing of events that can be used to extract waveforms from continuous data or tie to event segmented data. For a more complete discussion of the catalog reconciliation process see O'Boyle *et al*. (this volume).

Table 1. Seismicity Catalogs Collected, Parsed and Reconciled for this Project

Date Range	Source Types	Catalog Name	Comments and References
1945-1992	Nuclear tests	DOE U.S. Announced List	Revision 15 (USDOE, 2002)
1946-1992	Nuclear tests	Springer catalog	Below surface tests, Springer *et al* (2002)
1978-2000	Earthquakes	UNR_SGB_merged	Covers Southern Great Basin (SGB) only
1992-2000	Earthquakes	UNR_SGB_relocated	Covers Southern Great Basin (SGB) only. Smith *et al*. (2002)
1868-2000	Earthquakes	YMP_PSHA	Yucca Mountain Project (YMP) Probability of Seismic Hazard Assessment (contains a composite of many catalogs within 300 km of YM)
1978-1999	Earthquakes	UNR_NN_consolidated	Covers northern Nevada (NN) area only
2000-2001	Earthquakes	UNR_2000-2001	University of Nevada Reno networks catalog
1850-1998	Earthquakes	Nevada historic catalog	Compiled by Depolo and Depolo (1999)
1898-2002	Earthquakes	CNSS	Council of National Seismic Stations - a partially reconciled catalog of western US seismicity compiled by UC Berkeley
1920-2002	Earthquakes, explosion and mine tremors	USGS Monthly PDE	Preliminary Determination of Epicenters (PDE)
1964-1999	Earthquakes	ISC	International Seismological Commission (ISC)
1995-2000	Earthquakes	IMS REB	Comprehensive Nuclear-Test-Ban Treaty International Monitoring System (IMS) Reviewed Event Bulletin (REB)
1997-2002	Mine Blasts	USGS Dewey catalog	A catalog of mining explosions compiled by Jim Dewey at the U.S. Geological Survey

A major emphasis of this project is on regional seismic waveforms from the four seismic stations of the Lawrence Livermore National Laboratory (LLNL) operated Livermore NTS Network (LNN). These stations have been all digital since about 1980 and have recorded more than 120 underground nuclear tests in that time. In addition there are a number of waveforms that were digitized from analog records that are of more uncertain quality. We have identified LNN waveforms from approximately 320 nuclear tests to review for quality control and include in the database. Another large database of regional nuclear seismic waveforms was recorded on the Leo Brady Seismic Network (stations BMN, DAC, LDS, MVU, TPH), which is operated by Sandia National Laboratory (Lee, 2001). We are actively working with Sandia personnel to include this data set in the database as well. Both of these

networks have recorded hundreds of regional earthquakes, many in close proximity to prior nuclear tests, which make an excellent dataset for studying the physical basis of regional seismic discrimination.

In addition to the National Laboratory run networks, we have also collected data from other broadband open seismic stations that are archived by the IRIS DMC. We have selected just a subset of these stations with emphasis on stations that have long operating histories, stations that are part of the IMS network and stations that are spread throughout the western U.S. Table 2 below gives a list of the stations for which we have collected data to be included in the database.

Table 2. Seismic Station Data Retrieved for Event Waveform Extraction to Database

Data Type and Period	Station code	Location and comments
Continuous 1988-2001	PFO	Pinion Flat, California (IMS auxiliary station)
Continuous 1989-2001	COR	Corvallis, Oregon
Continuous 1989-2001	ANMO	Albuquerque, New Mexico (IMS auxiliary station)
Continuous 1992-2001	CMB	Columbia, California
Continuous 1992-2001	TUC	Tucson, Arizona
Continuous 1993-2001	YBH	Yreka, California (IMS auxiliary station)
Continuous 1997-2001	DUG	Dugway, Utah
Continuous 1997-2001	TPNV	Tonopah Springs, Nevada
Continuous 1997-2001	NEW	Newport, Washington (IMS auxiliary station)
Event segments	ELK	Elko, Nevada (IMS auxiliary station)
Event segments	KNB	Kanab, Utah
Event segments	MNV	Mina, Nevada (IMS primary array element)
Event segments	LAC	Landers, California (closed in 1999)
Event segments	BMN	Battle Mountain, Nevada
Event segments	DAC	Darwin, California
Event segments	LDS	Leeds, Utah
Event segments	TPH	Tonopah, Nevada
Event segments	MVU	Marysvale, Utah

In Figure 1 we show a map of the region covered by this project, with the locations of stations (Table 2) for which we are archiving seismic data and the locations of the reconciled events for the time period from 1997-present (July 2002). We have chosen 1997 as the starting point for this plot since that is when the Dewey catalog of mine seismicity starts. The reconciled catalog as a whole goes back to 1852. Figure 1 shows the more than 8000 earthquakes and 1600 mining events (mainly explosions) in our reconciled catalog with magnitudes (mb, Mw or ML) greater than or equal to 2.5. The catalog does include events of all magnitudes, and in some locations where the UNR network is dense; there are magnitudes of -1 or less. At the time this map was produced, the reconciliation was not quite finished and the final map shown at the meeting will include even more earthquakes.

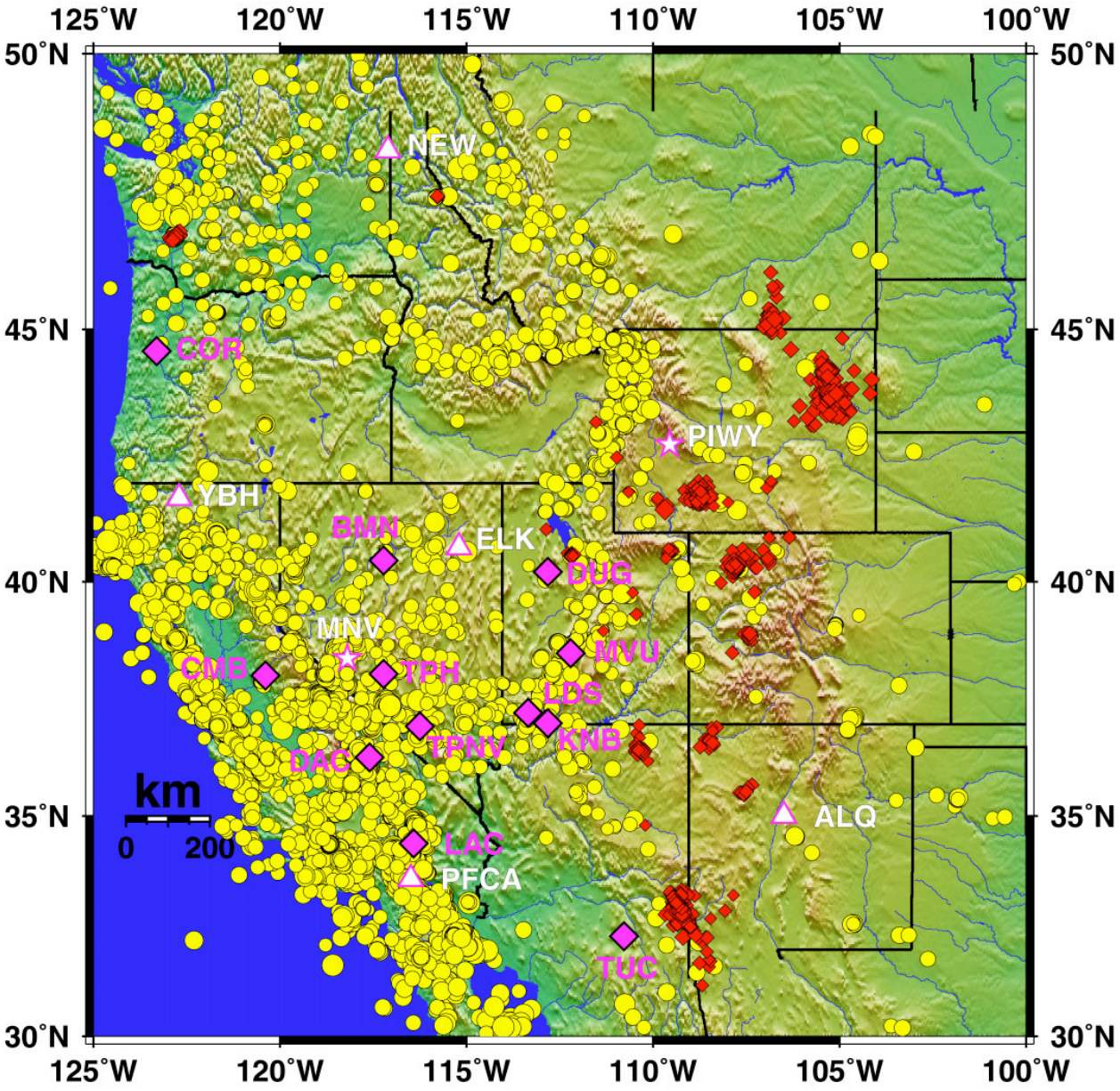

Figure 1. A shaded relief map showing the locations of seismic stations and select events in this project. Stations are listed in Table 2, and the events are drawn from a reconciled composite catalog created from the catalogs listed in Table 1. IMS primary stations are plotted as white stars. IMS auxiliary stations are plotted as white triangles, and other broadband stations are plotted as pink diamonds. Seismic stations are labeled by name. Earthquakes are plotted as yellow circles and mine seismicity as small red diamonds. Seismic event symbols are scaled by magnitude.

High-Quality Data Subset

Once we have completed the reconciled catalog of seismicity, extracted the available seismic waveforms for each event and organized the results into the western U.S. database, we want to select a high-quality subset for detailed analysis. We plan to comb through the thousands of events in the database with magnitudes greater than about 2 to find events recorded at many stations with good quality waveforms and well document locations and source properties.

One goal for this high-quality subset is to choose events with excellent ground truth hypocenters from the regional networks for use in location research. We will work with the UNR network locations and picks to determine the level of accuracy of the locations and will relocate some events to improve them. Once we have selected the high-quality subset, an experienced seismic analyst, will examine the data. She will pick all arrival onsets with quantitative uncertainties and make note of data problems (timing errors, glitches, dropouts) and other issues. Her arrivals and comments will then be loaded into the database for future researcher use. We believe her picks at local, near and far regional distances when combined with the independent ground truth will be useful in testing and benchmarking sparse station location algorithms.

We also want to select the high-quality data set with an eye towards discrimination research. Therefore, in addition to excellent ground truth locations, we also want to choose events that have well documented source properties. For explosions this means working point source medium properties such as density, P-velocity, and gas porosity. We plan to select explosions that span the full range of these properties. We want to include some of a small number of explosions with announced yields to facilitate yield estimation research. Finally, we want to span the full range of magnitudes and depths and will therefore include a few of the larger explosions that were conducted prior to the limit of 150-kT imposed by the Threshold Test Ban Treaty of 1974. For earthquakes we want to select events that cover a range of magnitudes, depths, and locations through the western U.S. We also want to provide focal mechanism information for as many of the events as possible. The impact of variations in focal mechanism and depth on regional discriminants are the subjects of current research (e.g. Zhang *et al*., 2002).

In Figure 2, we show an example of some candidate events we are examining around NTS for inclusion in the high-quality data subset. The high level of natural earthquake activity since the 1992 Landers earthquake provides a nice dataset to contrast with the nuclear tests that ended in 1992. Recently a number of studies have been done that investigate the details of this seismicity (e.g. Smith *et al*, 2002; Ichinose, 2002). We plan to review these studies and use them to provide additional ground truth about these events.

At the conclusion of this project, we plan to put the high-quality subset of approximately 100 events, along with associated parameters (time picks, focal mechanisms, source media properties, etc.) on a CD-ROM in CSS 3.0 compatible database format for release to interested monitoring researchers. We hope this well organized and compact set of data will prove useful in both researching and benchmarking seismic monitoring algorithms in detection, location, identification and magnitude yield estimation.

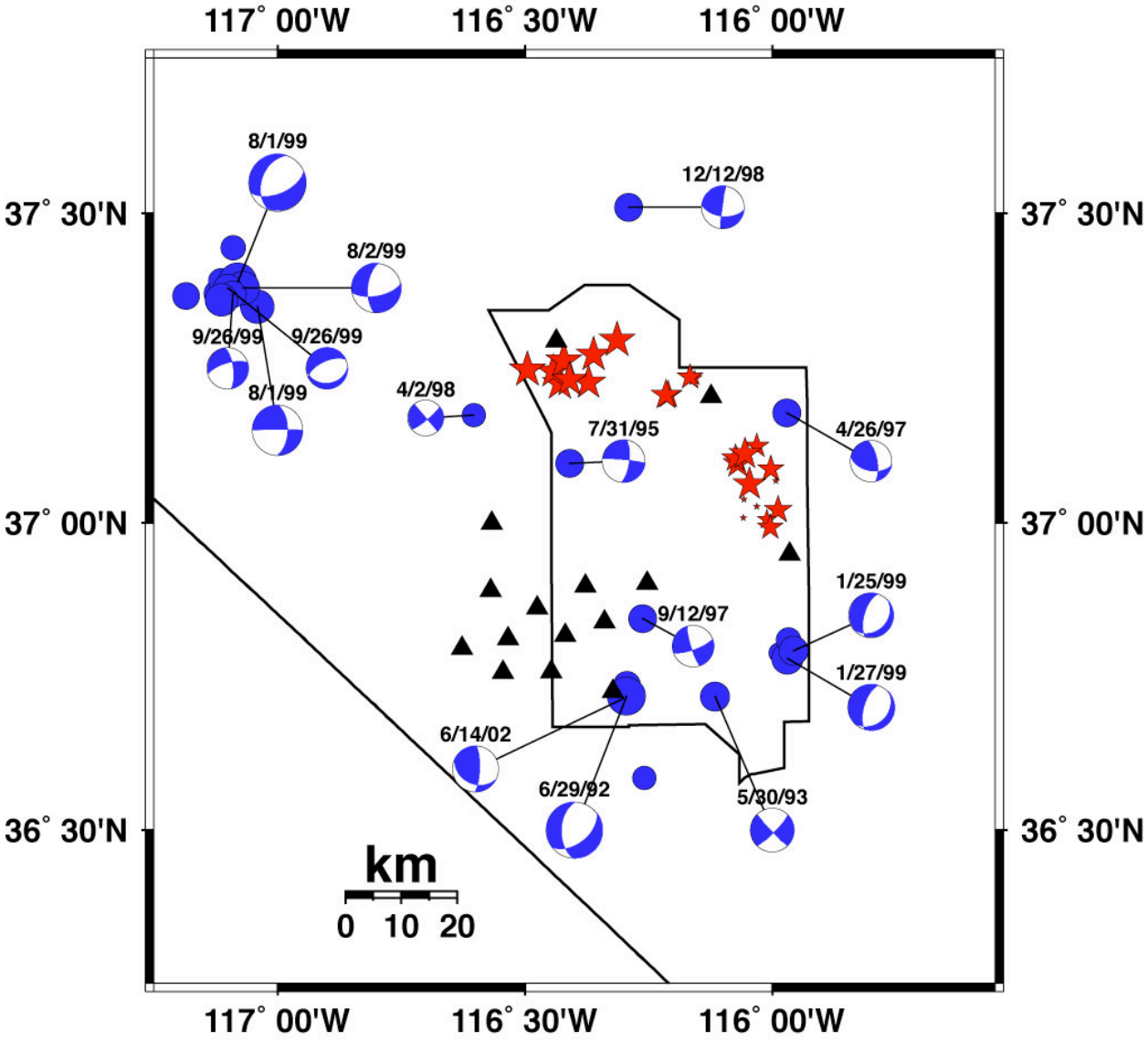

Figure 2. A map showing 25 earthquakes (blue circles) and 25 explosions (red stars) from 1989-2002 near NTS that are under consideration for inclusion in the high-quality data subset. The map shows the boundaries of NTS and the locations of some of the UNR-run Southern Great Basin network that can provide excellent ground truth hypocenter information for many of these events. Also shown are focal mechanisms for about 15 of these earthquakes drawn from regional studies by Smith *et al* (2002), Ichinose *et al* (2002) and the U. C. Berkeley moment tensor catalog. These earthquakes cover most of the seismicity in this region with magnitudes greater than about 3.5. The nuclear explosions cover the most recent 25 events when seismic network coverage is most complete and include all three main testing areas at NTS (Pahute Mesa, Rainier Mesa and Yucca Flat). The explosions also cover a fairly full range of magnitude, depths, and source material properties.

CONCLUSIONS AND RECOMMENDATIONS

We continue our project to build the most complete and best-documented database of regional distance nuclear explosion, earthquake, and mine-related digital broadband seismograms in the western U.S. We plan to select and mark phase onset times for a high-quality subset of these data, which will be distributed at the conclusion of this project. We believe this set of consistently picked, independently located data will provide an effective test set for regional sparse station location algorithms. In addition because the set will include nuclear tests, earthquakes, and mine-related events, each with related source parameters, it will provide a valuable test set for regional discrimination and magnitude/yield estimation as well.

REFERENCES

DePolo, D. M and C. M. DePolo, (1999). Earthquakes in Nevada, Nevada Bureau of Mines and Geology, Map 119.

Ichinose, G. A., J. G. Anderson, and K. D. Smith (2002). Source parameters of Eastern California and Western Nevada Earthquakes from regional moment tensor inversion, *Bull. Seism. Soc. Am*. (submitted) 2002.

Lee, J. W., (2001). A new seismic data system for determining nuclear test yields at the Nevada Test Site, Sandia National Laboratory Report, SAND2001-3373.

Smith, K. D., D. von Seggern, D. Depolo, (2002). Seismicity in the vicinity of Yucca Mountain 1992-2000 and regional tectonic process, *Bull. Seism. Soc. Am*. (submitted) 2002.

Springer, D. L., G. A. Pawloski, J. L. Ricca, R. F. Rohrer and D. K. Smith, (2002). Seismic source summary for all U. S. below surface nuclear explosions, *Bull. Seism. Soc. Am*. (in press) 2002.

United States Department of Energy, (2000). United States Nuclear Tests, July 1945 through September 1992, Technical Report DOE/NV-209-REV15.

Walter, W. R., K. Mayeda, and H. J. Patton (1995). Phase and spectral ratio discrimination between NTS earthquakes and explosions Part 1: Empirical observations, *Bull. Seism. Soc. Am.,* **85**., 1050-1067.

Zhang, J., T. Lay, J. Zaslow and W. R. Walter, Source effects on regional seismic discriminant measurements, *Bull. Seism. Soc. Am*. (in press) 2002.