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An Assembled Western United States Dataset for Regional Seismic Analysis

W. R. Walter, K. D. Smith, J. L. O'boyle, T. F. Hauk, F. Ryall, S. D. Ruppert, S. C. Myers, R. Abbot, D. A. Dodge

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AN ASSEMBLED WESTERN UNITED STATES DATASET FOR REGIONAL SEISMIC ANALYSIS

William R. Walter[1], Kenneth D. Smith,[2] Jennifer L. O'Boyle,[1] Teresa F. Hauk,[1] Flori Ryall,[1] Stanley D. Ruppert,[1] Stephen C. Myers,[1] Robert Abbot[3] and Douglas A. Dodge[1]

Lawrence Livermore National Laboratory[1]
University of Nevada, Reno[2]
Sandia National Laboratory[3]

Introduction

Regional seismic research is largely data driven. Under the current *de facto* global moratoria on underground nuclear testing, the number of digital seismic records of nuclear explosions at regional distances is quite restricted both in number and geographical location. We believe the finite number of existing regional nuclear test records are a unique resource that has not been fully exploited, in part because of limited data availability. There have been a number of data compilations of nuclear explosions seismograms in Eurasia (e.g. Borovoye: Kim and Ekstrom, 1996; PNE lines: Morozov et al., 2004; JVE: Priestley et al., 1990). At the United States Nevada Test Site (NTS) there have been hundreds of contained underground nuclear explosions, starting with "Rainier" in September 1957, and ending with "Divider" in September 1992 (Springer et al. 2002). We collected seismograms from a number of stations in the western U.S. that had long operating histories, where we could compile a good quality dataset of some of these explosions as well as earthquakes and other events for comparison. Here we have assembled on a CD a subset of 151 regional distance events. The dataset includes 73 nuclear explosions, 61 earthquakes, 3 collapse events, 1 large chemical explosion and 13 mine-related explosions. The 3 GB dataset is in a compressed tar file on a CD and contains database table export files and waveform files. These tables include regional phase arrival picks made by Ms. Flori Ryall and an electronic version of the Springer et al (2002) table. The CD also contains a PDF copy of this report and another report by Ryall (2005) giving details of the phase arrival analysis. Copies of this CD are available from LLNL upon request.

The emphasis in this project was 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 late 1979, along with a small number of earlier events that were digitized from analog tapes. Through a partnership with Sandia National Laboratory (SNL) we have also included waveforms from their Leo Brady network stations (BMN, DWN, LDS, NEL,TON). In addition we include data from other open broadband stations in the western US 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 was to create a high-quality database that can be used in the future to analyze fundamental regional monitoring issues such as detection, location, magnitude, and discrimination.

In the first stage of the project, we 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 National Nuclear Security Administration (NNSA)-developed software to reconcile these catalogs with each other and to incorporate them into a set of larger continental scale (CNSS, see http://www.cnss.org; 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 and source properties (Springer et al. 2002). The result is a single catalog of preferred origins, source information, and station information. Concurrently, we collected continuous seismic data from open stations and recovered and reformatted old event segmented data from the LLNL and SNL managed stations for past nuclear tests and earthquakes. We then used the preferred origin catalog to extract waveforms from continuous data and associate event segmented waveforms within the database. The result is a well-organized regional western US dataset with hundreds of nuclear tests, thousands of mining explosions and hundreds of thousands of earthquakes (Walter et al., 2003).

In the second stage of the project we have chosen a subset of 151 events that are well located and cover a range of magnitudes, source types, and locations. Ms. Flori Ryall, an experienced seismic analyst reviewed this subset. She picked all clearly visible arrival onsets, which were loaded into the database ARRIVAL table. Details of her analysis are given in Ryall (2005). We believe this set of consistently picked, independently located data will provide an effective test set for regional sparse station location algorithms. Since the set includes nuclear tests, earthquakes, and mine-related events, each with related source parameters, it provides a valuable test set for regional discrimination and magnitude estimation as well.

Data Compilation

We have attempted to obtain as complete a list of catalogs in the vicinity of the NTS and the western U.S. as possible. Springer et al. (2002) have compiled the most complete listing of dates, locations and 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 exists. 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 good U. S. seismicity catalog is compiled regularly by U.C. Berkeley from most of the regional seismic network operator catalogs in the 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 (see http://neic.usgs.gov/neis/mineblast/index.html). 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 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, which can be used to extract waveforms from continuous data or to match event-segmented data. For a more complete discussion of the catalog reconciliation process see Ruppert et al., 2004.

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

Date Range	Source Types	Catalog Name	Comments and References
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
2002-2003	Earthquakes	UNR_2002present	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)
1997-2003	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 late 1979. Another set of long running stations is the Leo Brady Seismic Network (stations BMN, DAC, LDS, MVU, TPH), which is operated by Sandia National Laboratory (Lee, 2001). Through the generous cooperation of Sandia personnel we have included waveforms from these stations. Both networks have recorded many regional earthquakes, some near prior nuclear tests, making an excellent dataset for studying the physical basis of regional seismic discrimination.

In addition to the National Laboratory run networks, we have collected data from other broadband open seismic stations that are archived by the IRIS DMC and the University of California at Berkeley Seismological Laboratory. We have selected particular stations with emphasis on those with 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 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	Corvalis, 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	Topapah Springs, Nevada
Continuous 1997-2001	NEW	Newport, Washington (IMS Auxiliary station)
Continuous 1992-2002 Event segments 1968-1992	ELK	Elko, Nevada (IMS Auxiliary station)
Continuous 1992-2002 Event segments 1968-1992	KNB	Kanab, Utah
Continuous 1992-2002 Event segments 1968-1992	MNV	Mina, Nevada (IMS Primary array element)
Continuous 1992-1998 Event segments 1968-1992	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
Event segments	NLS	Nelson, Nevada

Finally through the generous cooperation of the University of Nevada, Reno (UNR) Seismological Laboratory we were able to include some local data from the digital stations of the Southern Great Basin Network (SGBN) for a number of the earthquakes. This local data provides addition waveforms and phase picks for examining research issues involving mixed local and regional data.

In Figure 1 we show a map of the events and regional distance stations included in the assembled data. The data emphasis was on the most recent nuclear tests and earthquakes on or near NTS. The dataset includes 73 nuclear explosions, 61 earthquakes, 3 collapse events, 1 large chemical explosion and 13 mine-related explosions.

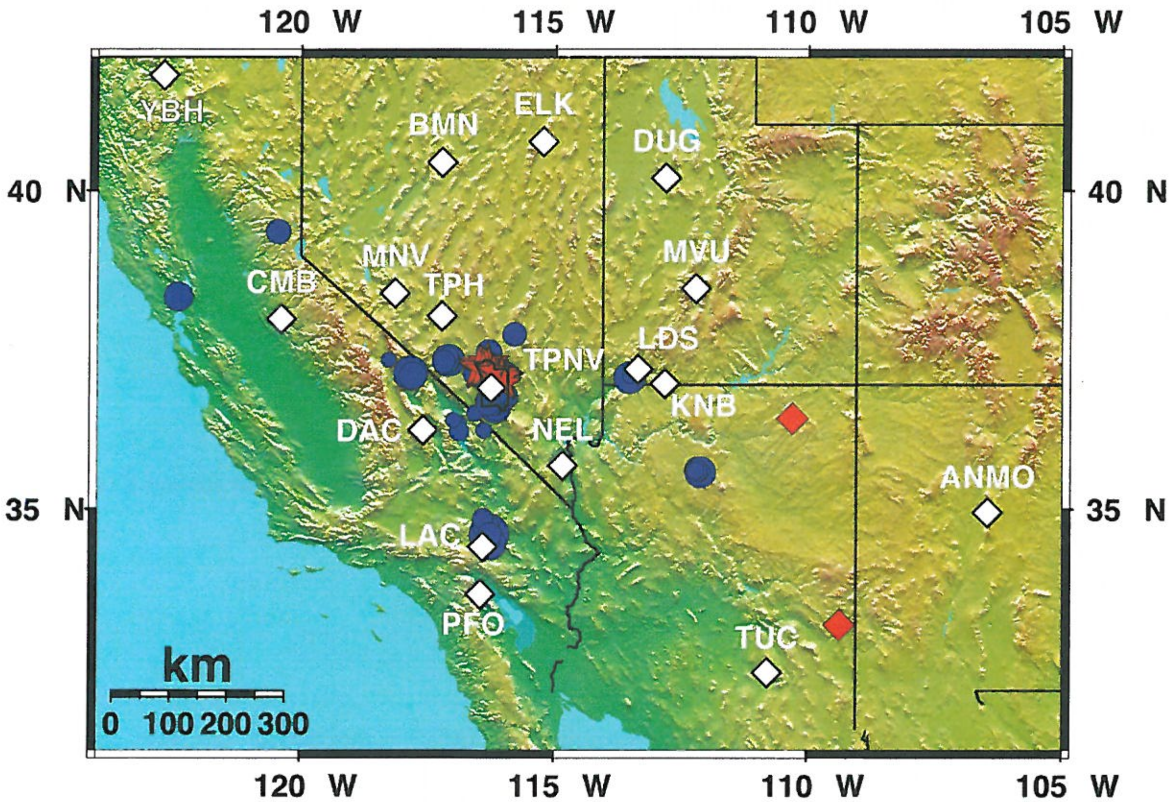

Figure 1. A shaded relief map showing the locations of seismic stations and events in this dataset. Stations are listed in Table 2 and the events are drawn from a reconciled composite catalog created from the catalogs listed in Table 1. with an emphasis on the nuclear tests and earthquakes near NTS. An outline of NTS is shown in black. Seismic stations are labeled by name. Earthquakes are plotted as blue circles, nuclear explosions as red stars and mine seismicity as red diamonds. Seismic event symbols are scaled by magnitude. Station NEW and the SGBN and secondary stations in the site table are not shown.

For each of the seismic events Ms. Flori Ryall, an experienced LLNL seismic analyst reviewed the waveforms using the software code GEOTOOL. She picked all clearly visible arrival onsets, which were loaded into the database ARRIVAL table. An example of some of her picks using GEOTOOL for an explosion recorded at the LNN stations is shown in Figure 2.

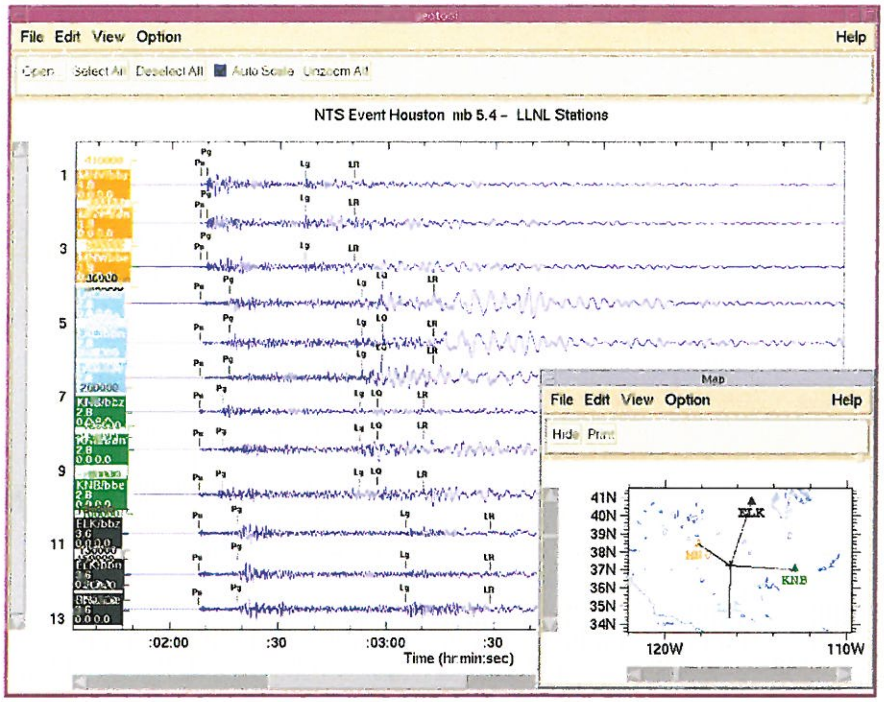

Figure 2. Analyst Flori Ryall's regional phase arrivals for the NTS explosion Houston at stations ELK, KNB, LAC, and MNV as displayed in GEOTOOL.

Research Potential

Travel times, velocity model and location

As an example of the utility of the analyst phase picks included in this dataset we show the Pn, Pg and Lg picks with a high quality designation from the 73 NTS explosions in Figure 3. These events have very precise location and timing (GT0 in the nomenclature of Bondar et al. 2004) giving an excellent set of travel time curves for the Basin and Range. In the lower part of this figure we focus on the reduced Pn travel times for each station. First we note that none of the stations have good picks for all 73 events, due to station down time. Because nuclear testing at NTS ended in 1992, many of the open station networks (shown in red) have a very limited number of picks. In contrast the two regional networks maintained by LLNL and SNL have a very large number of picks for the nuclear tests making them quite valuable for regional research. Looking at quality control, we note that a number of NTS events at the LLNL stations in the 1982-1983 time frame (Atrisco, Borrego) appear to have network clock problems of a couple of seconds. In addition there appear to be both some network and individual station clock errors ranging from a couple seconds to tenths of seconds. Clock errors that are less than one second are very difficult to distinguish from picking errors. Despite these events with clock errors, the dataset is large enough that after removing outliers we are able to obtain a very tight fit to linear travel time curves.

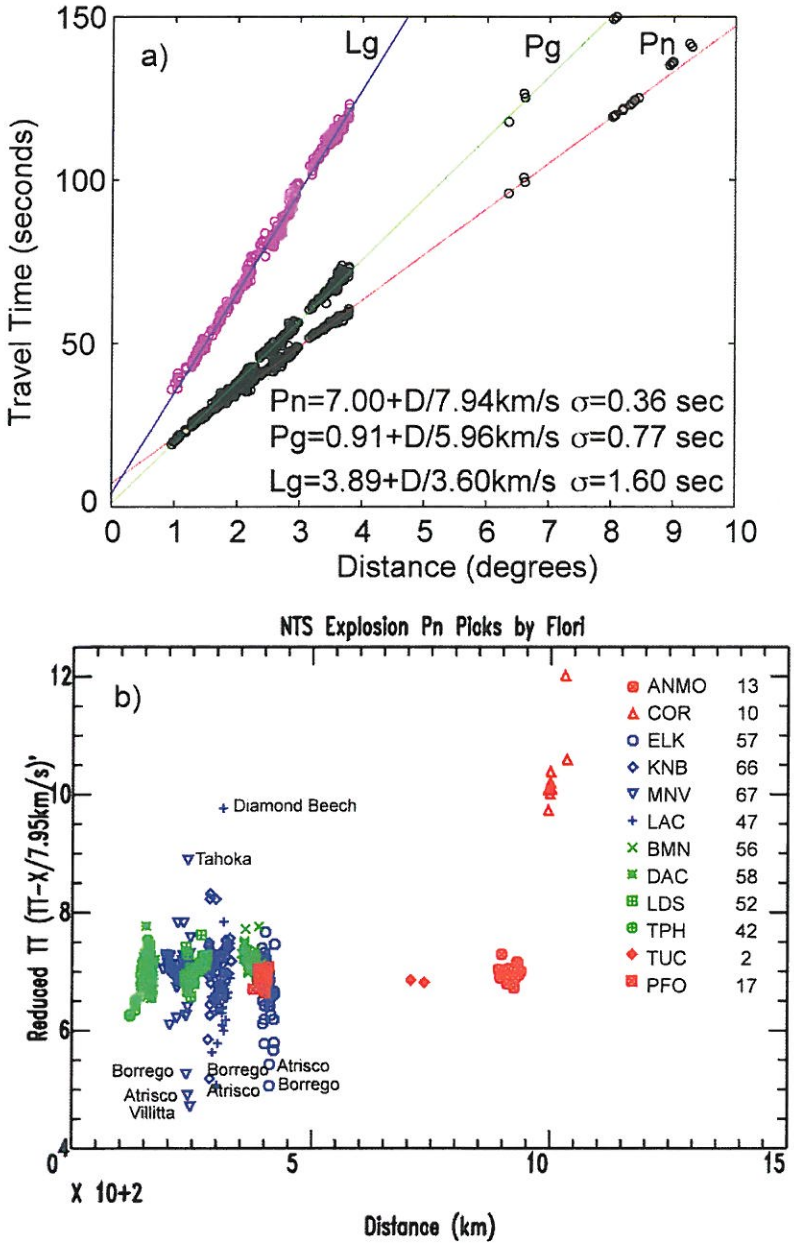

Figure 3. Travel time picks from 74 NTS nuclear tests recorded at regional stations and analyzed by Ms. Flori Ryall are shown. Top plot (a) shows picks and linear travel time fits after removing three sigma outliers. Bottom plot (b) shows an expanded view of the reduced Pn picks listed by station along with the total number of Pn picks available. Some obvious outliers due to clock problems are labeled by the event names.

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. The NTS explosions are clearly the best dataset for this purpose. These data and their picks are currently being used in relative regional relocation research (see location paper by Myers et al., 2003) and to test new location algorithms (e.g. Rodi et al., 2003; Myers et al., 2005). For the earthquakes on or near NTS we obtained the local UNR network data and re-picked these to allow high-quality local network locations to provide ground truth independent of that based on the regional stations. We believe the high quality 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.

Event Identification

We have also selected the high quality data set with an eye towards discrimination research. Therefore in addition to excellent ground truth locations, we also chose 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 have selected explosions that span a wide range of these properties. We include a small number of explosions with announced yields to help facilitate yield estimation research. Finally we try to span the full range of magnitudes and depths and therefore include a few of the larger explosions that were conducted prior to the 150 kt Threshold Test Ban Treaty of 1974. For earthquakes we selected events that cover a range of magnitudes, depths and locations in the western U.S. For this reason we have picked events with a range of magnitude from some aftershock sequences (e.g. 1992 Little Skull Mountain, 1999 Scotty's Junction, 1999 Hector Mine, 1993 Eureka Valley, 1993 Cataract Creek). We also wanted focal mechanism information for as many of the earthquakes as possible. The impact of variations in focal mechanism and depth on regional discriminants is the subject of current research (e.g. Zhang et al., 2002).

In Figure 4 we show 50 of the events around the Nevada Test Site. 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 which investigate the details of this seismicity (e.g. Smith et al, 2003; Ichinose, 2003). These studies provide additional ground truth about these events such as focal mechanisms and depth.

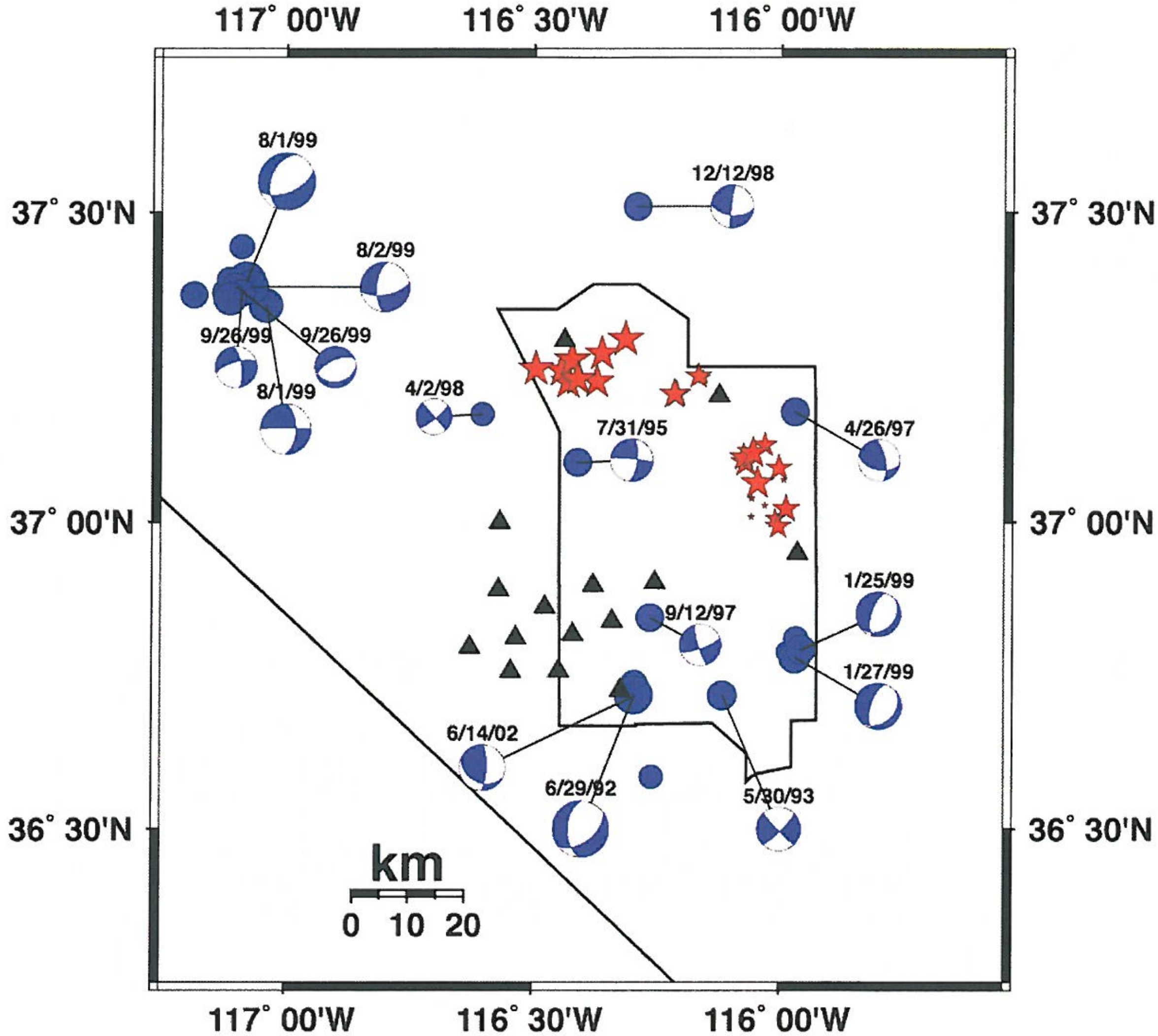

Figure 4. A map showing 25 earthquakes (blue circles) and 25 explosions (red stars) from 1989-2002 near NTS that are included in the high quality data subset. The map shows the boundaries of NTS and the locations of some of the UNR run Southern Great Basin network which can provide excellent ground truth 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 cover 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.

In Figure 5 we show some 6-8 Hz Pg/Lg ratios at station KNB for this dataset. We have limited the points to those with signal above pre-event noise greater than 2 and the ratios are raw values, no distance or amplitude corrections have been applied. The plot shows the same data in two different formats, versus distance and versus magnitude. It is clear from the earthquakes in the distance plot that differential apparent attenuation is causing the ratios to increase with increasing distance. In general the explosions have higher P/S values than the earthquakes as shown previously for some of this same data by Walter et al. (1995). The few mine blasts and collapse points also have higher values than the average earthquakes. This dataset is being used along with other datasets to look at a number of issues related to event identification using regional body-waves including, source and path corrections; depth, focal mechanism and containment effects; relations of mine explosions to nuclear explosions; and optimal combinations of measures (e.g. Ledig et al, 2004; Walter et al., 2004; Walter et al., 2005)

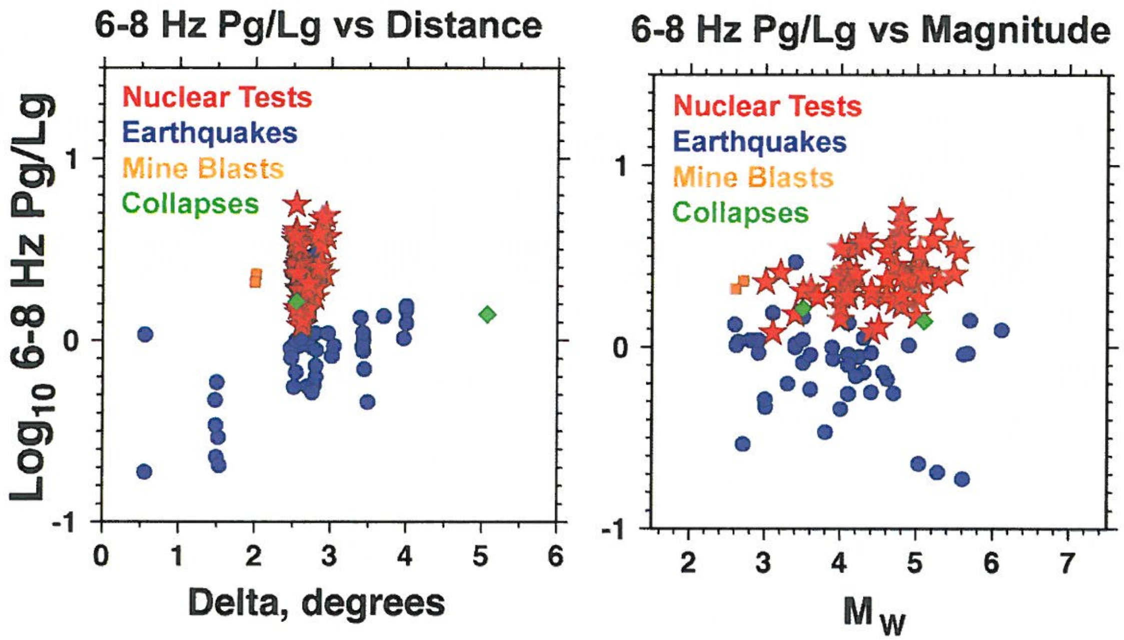

Figure 5. Plot of uncorrected 6-8 Hz Pg/Lg values versus distance (left) and magnitude (right). Amplitudes are root mean square measures on band pass filtered time-domain traces using had picked windows based on group velocities appropriate for the Basin and Range, with a signal-to pre-event noise value of two or more.

Dataset CD Contents

The CD contains a compressed (GZIP) tar file of database export tables and waveform files. Waveforms include all the available components, vertical and horizontal that have sample rates over 1 Hz. We follow the CSS3.0 relational database schema where possible but supplemented it with some custom tables. There are 153 events (151 with two precursors to double events) from up to 147 selected LLNL, Sandia and IRIS regional and UNR local stations. Available waveforms from the selected stations are provided. There are 11,176 waveforms, which use up 3 GB of space. We also include arrivals and site info for ISC picks with 90 degrees of NTS for location research purposes. Tables:

ARRIVAL	- Flori Ryall's phase arrivals picked for this project
ARRIVAL_ISC	- phase arrivals within 90 degrees of NTS from ISC catalog
ASSOC	- Associates Flori's arrivals with origin
ASSOC_ISC	- Associates ISC arrivals with origin
ETYPE	- LLNL GT Event type (overrides origin entry)
EVENT	- gives preferred origin (PREFOR)
EXPLOSION	- custom table with Springer et al. (2002) source info
INSTRUMENT	- instrument info
ORIGIN	- single or multiple origins for each event
REMARK	- comments
SEARCH_LINK	- a custom pre-joined table for searching events or stations
SENSOR	- more instrument info
SITE	- station location info for waveforms and picks
SITE_ISC	- station location info for ISC picks
SITECHAN	- channel info for waveforms
WFDISC	- pointers to waveforms
WFTAG	- another pointer to waveforms

A note about quality control – Older seismic data has many problems. We have done some work to correct or note these within the limited funding and time scale of this project. See the separate report by Flori Ryall (2005) for additional detailed problems. However, PROBLEMS REMAIN. Users are strongly encouraged to do their own checking – CAVEAT EMPTOR! – We would appreciate it if users would please report found or suspected problems not previously documented.

A complete list of events with the number of picks and some event specific information is provided in Appendix A.

Conclusions

We hope this well-organized and compact set of data will prove useful for regional seismic research and for benchmarking seismic monitoring algorithms in detection, location, identification and magnitude/yield estimation.

Acknowledgements. We thank the many LLNL, Sandia and UNR employees who have worked on seismic data over the years. They built and ran the LNN, Leo Brady and UNR seismic networks, collecting and maintaining much of seismic data we have used here. We thank IRIS and U. C. Berkeley for also maintaining outstanding data archives that we have used in this project. We thank Megan L. Anderson for dataset comments and testing during her location research project at LLNL in the summer of 2003. We thank Paul Richards, Marie Renwald and Mark Fisk for helpful comments on an earlier version of this report and dataset. This is LLNL contribution UCRL-TR-206630. This work was supported by the NNSA, particularly under ROA01-40-LLNL. This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

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Western US ROA List of High Quality Subset Events for CD-ROM Release

Event Types	Etype	Count
Nuclear Explosions	EN	73
Chemical Explosions	EC	14
Collapses	MC	04
Earthquakes	QT	62
Total -		153

FS=Stations with Flori picks

Nuclear Explosions (73)

Last six years of nuclear tests at NTS (50)

EVID	Year	JDAY	ML	Name	FS	Comments
653332	1992	267	4.4	Divider	11	last-nuclear-test
653134	1992	262	4.4	Hunters_Trophy	12	
648423	1992	175	3.9	Galena	11	3-simultaneous-tests
648221	1992	171	3.0	Victoria	10	
643767	1992	086	5.5	Junction	11	
638595	1991	330	4.6	Bristol	10	
636899	1991	291	5.2	Lubbock	10	
635695	1991	262	4.0	Distant_Zenith	10	
635527	1991	257	5.5	Hoya	11	
634291	1991	227	4.2	Floydada	9	
628994	1991	094	5.6	Bexar	11	
627879	1991	067	4.3	Coso	10	3-simultaneous-tests
623055	1990	318	5.4	Houston	10	
618780	1990	206	4.7	Mineral_Quarry/Randsburg	10	2-tests
617078	1990	172	4.0	Austin	11	
616762	1990	164	5.7	Bullion	11	
612817	1990	069	5.0	Metropolis	11	
609251	1989	342	5.5	Barnwell	12	
608389	1989	319	3.47	Muleshoe	10	

607806	1989	304	5.27	Hornitos	12	
605660	1989	257	3.99	Disko Elm	11	
602554	1989	178	4.72	Amarillo	8	
602360	1989	173	5.09	Contact	8	
601434	1989	146	3.74	Tulia	9	
600991	1989	135	4.39	Palisade	8	3-tests
598292	1989	068	4.78	Ingot	8	
597777	1989	055	4.17	Kawich Black/Red	9	2-tests
597197	1989	041	5.09	Texarkana	7	
595016	1988	345	4.77	Misty Echo	6	
592897	1988	287	5.39	Dahlhart	9	
591528	1988	243	4.83	Bullfrog	9	
591069	1988	230	xxx	Kearsarge	9	(JVE-announced-yield=100-150)
589522	1988	189	5.29	Alamo	8	
589000	1988	174	3.11	Rhyolite	8	
588391	1988	154	5.6&	Comstock	8	mbLg
587931	1988	142	4.6&	Laredo	9	mbLg
587630	1988	134	4.64	Schellbourne	8	
586371	1988	098	3.88	Abilene	9	
584497	1988	046	5.7&	Kernville	8	mbLg
582123	1987	336	3.86	Mission_Cyber	8	
582065	1987	335	2.9&	Waco	4	mbLg
579732	1987	267	5.9&	Lockney	8	mbLg
578449	1987	225	6.2&	Tahoka	7	mbLg
577064	1987	181	4.8&	Panchuela	7	mbLg
576762	1987	171	3.27	Mission Ghost	8	
576701	1987	169	3.95	Brie	8	
575300	1987	120	5.22	Hardin	7	
574939	1987	108	5.23	Delamar	8	
574020	1987	077	4.00	Middle_Note	8	
572906	1987	042	4.11	Tornero	8	

NTS nuclear tests since 1979 with announced yields (Springer et al, 2002) (6)

566078	1986	198	5.31	Cybar	8	(announced-yield=119)
561697	1986	081	4.94	Glencoe	8	(announced-yield=29)
532302	1983	244	5.12	Chancellor	7	(announced-yield=143)
522227	1982	217	5.43	Atrisco	4	(announced-yield=138)
518434	1982	028	5.41	Jornada	4	(announced-yield=139)
501491	1979	249	5.43	Hearts	4	(announced-yield=140)

selected older NTS nuclear tests (e.g. overburied, small magnitude, etc.) (13)

555746	1985	282	3.99	Diamond_Beech	8
536206	1984	031	4.23	Gorbea	8
544116	1984	315	4.30	Villeta	9
532799	1983	265	4.05	Techado	8
532764	1983	264	3.89	Tomme/Midnight_Zephir	8
526700	1983	042	3.69	Coalora	9
523362	1982	272	3.71	Borrego	4
522359	1982	223	3.18	Queso	3
511553	1981	036	2.83	Clairette	4
511204	1981	015	5.23	Baseball	4
503353	1979	348	3.65	Azul	3
501525	1979	251	3.50	Pera	4
494770	1978	256	4.39	Diablo Hawk	3

selected NTS nuclear test historic digitized traces (4)

444278	1968	354	Benham	3	(announced yield 1150 kt)
450458	1970	085	Handley	4	(announced yield > 1000 kt)
451341	1970	146	Flask Green	4	(3 simultaneous announced yields 105, 0.035 and 0.09 kt)
475350	1975	170	Mast	4	(announced yield range 200-1000 kt)

Chemical/Minning Explosions (14)

Single chemical explosion (1)

EVID	Year	JDAY	H:M	Mag	Type	FS	Name/Comments
672993	1993	265		4.06	ML	8	NPE (announced 1 kt chemical yield)

Mine blasts (ripple fired) from Dewey USGS Catalog(13)

2021889	1999	083	21:07	2.7	ML	6	Black Mesa Arizona (GT0 event - Bonner et al. 2003)
2021892	1999	084	21:10	2.6	ML	7	Black Mesa Arizona (GT0 event - Bonner et al. 2003)
2021879	1999	069	20:41	3.1	ML	7	Black Mesa AZ
2022075	1999	340	21:08	3.1	ML	10	Black Mesa AZ
2022467	2000	210	20:13	2.8	ML	7	Black Mesa AZ
2022671	2001	025	21:31	2.9	ML	10	Black Mesa AZ
2021841	1999	020	18:50	2.8	ML	5	Morenci AZ
2021861	1999	049	18:47	2.8	ML	4	Morenci AZ
2021995	1999	293	22:51	3.0	ML	3	Morenci AZ
2022048	1999	327	21:05	3.0	ML	5	Morenci AZ
2022110	1999	354	22:00	3.0	ML	6	Morenci AZ
2022300	2000	088	21:54	3.1	ML	7	Morenci AZ
2022378	2000	157	21:37	3.3	ML	8	Morenci AZ

Cavity Collapses (4)

1324942	2000	030	14:46	4.4	mb	17	Wyoming mine collapse
697661	1995	034	15:26	5.2	mb	10	Wyoming mine collapse (Pechmann et al., 1995)
4361929	1982	217	14:21	3.5	Ms	4	Atrisco hole collapse
4361928	1982	217	14:21	small		3	Atrisco collapses initiation ~5s earlier

Earthquakes (62)

EVID	Year	JDY	H:M	Mag	Type	FS	Comment
Earthquakes on or near NTS, some with local data (38)							
4240981	2002	275	14:36	2.6	ML	43	NTS region quake
3996284	2002	205	15:15	2.8	ML	44	NTS region quake
1592802	2002	165	12:40	4.56	Mw	43	Little Skull Mtn aftershock?
3687630	2002	038	13:58	2.6	ML	58	NTS region quake
1581601	2002	033	23:07	2.9	ML	50	NTS region quake
4240983	2002	019	15:06	2.6	ML	38	NTS region quake
4240982	2002	016	17:32	2.6	ML	42	NTS region quake
1579698	2002	003	23:08	2.7	ML	53	NTS region quake

1582262	2002	056	19:48	3.4	ML	46	NTS region quake from PDE-M	
1496312	2001	018	15:12	4.0	ML	55	Scotty's Junction aftershock	
1471866	2000	359	20:52	3.5	ML	64	Scotty's Junction after	
1466973	2000	294	14:02	3.5	ML	25	from UNR_SGB_reloc X	
1466542	2000	288	04:53	4.2	ML	52	Scotty's Junction after	
2746251	2000	150	23:21	3.6	ML	6	Scotty's Junction after	no local data
1319983	1999	293	10:15	4.8	ML	46	Scotty's Junction after	
1318646	1999	269	16:15	4.12	Mw	48	Scotty's Juncton after	
1315833	1999	214	05:40	4.1	ML	44	Scotty's Junction after	
4361917	1999	213	16:06	5.62	Mw	47	Scotty's Junction main	
1315772	1999	213	16:06	4.8	ML	22	SJ foreshock 2.5s earlier	
768593	1998	346	01:41	4.24	Mw	10	Kawich Range main	no local data
754694	1998	092	19:20	3.5	Mw	21	Thirsty Canyon main	
770911	1999	028	12:39	3.0	ML	37	Frenchman flat	
770868	1999	027	10:44	4.61	Mw	37	Frenchman Flat	
770782	1999	025	19:51	3.6	Mw	36	Frenchman flat	
770778	1999	025	18:52	4.40	Mw	38	Frenchman Flat	
770646	1999	023	03:00	3.9	Mw	39	Frenchman flat	
743984	1997	255	13:36	4.1	Mw	11	Calico Fan main .	no local data
737983	1997	116	01:49	4.1	Mw	32	Groom Pass main	
706312	1995	212	12:34	4.2	Mw	4	Timber Mountain main	no local data
665710	1993	150	15:21	4.3	Mw	7	Rock Valley main (shallow)	no local data
655407	1992	311	20:23	3.3	Mw	5	Little Skull Mtn after	no local data
1795785	1992	283	00:16	3.0	Mw	4	Little Skull Mtn after	no local data
1795721	1992	282	12:23	3.4	Mw	6	Little Skull Mtn after	no local data
652888	1992	257	11:46	4.3	Mw	6	Little Skull Mtn. After	no local data
649220	1992	187	06:54	4.4	Mw	8	Little Skull Mtn after	no local data
1778048	1992	186	05:57	2.8	Mw	4	Little Skull Mtn after	no local data
648768	1992	181	10:31	4.7	Mw	8	Little Skull Mtn. After	no local data
648766	1992	181	10:14	5.7	Mw	6	Little Skull Mtn main	no local data

Selected earthquakes from sequences in the Southwestern U. S. (24)

1470540	2000	337	15:34	4.4	ML	14	Sierra Nevada, CA

1384177	2000	247	08:36	5.2	ML	19	Napa, CA
1384076	2000	245	19:03	4.1	ML	17	Central NV
1323158	1999	357	14:30	4.1	ML	10	Hector Mine aftershock
1321310	1999	317	06:33	3.0	ML	9	Hector Mine aftershock
1320235	1999	297	12:13	3.5	ML	9	Hector Mine aftershock
1320090	1999	295	03:49	4.0	ML	9	Hector Mine aftershock
1319917	1999	292	12:20	4.0	Mw	10	Hector Mine aftershock
1319912	1999	292	10:39	4.1	ML	9	Hector Mine aftershock
1319654	1999	289	21:10	4.0	ML	8	Hector Mine aftershock
1319565	1999	289	12:57	5.3	Mw	9	Hector Mine aftershock
1319532	1999	289	09:46	7.1	Mw	8	Hector Mine mainshock
665055	1993	139	14:13	5.0	ML	9	Eureka Valley, CA
665028	1993	139	04:42	3.2	ML	8	Eureka Valley CA
664948	1993	138	05:10	3.8	ML	8	Eureka Valley CA
664907	1993	137	23:20	6.1	ML	9	Eureka Valley CA
664866	1993	137	09:50	3.0	ML	7	Cataract Creek, AZ
664299	1993	127	15:34	3.8	ML	7	Cataract Creek, AZ
663991	1993	121	19:32	2.7	ML	3	Cataract Creek, AZ
663896	1993	119	21:08	3.6	ML	6	Cataract Creek, AZ
663871	1993	119	08:21	5.5	ML	8	Cataract Creek, AZ
663680	1993	115	09:29	5.0	ML	7	Cataract Creek, AZ
2903943	1992	254	06:42	2.7	ML	3	St. George, UT
652419	1992	246	10:26	5.8	ML	9	St. George UT

Appendix Notes

Earthquake, collapse and mine blast information reconciled from multiple catalogs as described in the text. Nuclear explosion information from Springer et al., (2002).

&Mb and ML magnitudes for explosions from PDE, except for mblg which are based on Patton (1988). Mw magnitudes from coda (Mayeda and Walter, 1996 and K. Mayeda, pers. Comm.) or waveform modeling.