UCRL-JC-153604

Simulation of Regional Explosion S-phases (SiRES) Project

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This paper was submitted for
Seismic Research Review
Tucson, Arizona
September 23-25, 2003

U.S. Department of Energy

Lawrence
Livermore
National
Laboratory

July 2003

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Sponsored by National Nuclear Security Administration
Office of Nonproliferation Research and Engineering
Office of Defense Nuclear Nonproliferation

Contract No. W-7405-ENG-48;[1] DE-FC03-02SF22656[2]

ABSTRACT

Seismic monitoring aims to locate and identify all events that generate elastic waves in the solid earth. Amplitudes and arrival-times of seismic phases are commonly exploited to accomplish these goals. For large events that produce strong body and surface waves out to 90°, events can be accurately located and the Ms/m_b discriminant can be used to distinguish earthquakes from explosions. As event yield/magnitude decreases, the probability of detecting signals at distant stations diminishes, and monitoring relies heavily on regional-distance stations (between about 2° and 13°). Many regional discriminant and magnitude methods make use of S-phase amplitude measurements, which are expected to diminish for explosion sources. Despite the general success of regional monitoring methods there remain instances when explosions produce anomalously large S-phases that confound regional discriminants. The 2-year Simulation of Regional Explosion S-phases (SiRES) project explores the phenomenology of regional S-phase generation through numerical simulation. In the first year of this study we construct a 3-dimensional model of the Nevada Test Site (NTS) and the surrounding region. Extensive databases of geologic information, including existing 3-dimensional models developed under past and ongoing NTS programs, are used to construct the regional model. In addition to deterministic geologic structure and topography we introduce stochastic variability within geologic units and along boundaries. The stochastic variability provides a more realistic simulation of the regional wave field, which is known to largely consist of scattered energy. Here we introduce the project and report on the first few months of progress.

OBJECTIVE

Regional monitoring relies heavily on S-phases. Discriminants commonly use P- and S-wave amplitude ratios (Pomeroy et al., 1982; Walter et al., 1995). Widely used methods of determining magnitude make use of Lg and Lg coda amplitudes (e.g. Nuttli, 1986; Mayeda and Walter, 1996; Patton, 2001), and regional S-phases often add important arrival-time observations to limited, small-magnitude datasets used for location (PNE volume, 1994, Mayeda and Walter, 1996, Myers et al. 1999).

Despite pervasive use of S-phases in seismic monitoring, generation of regional S-waves from explosive (P-wave) sources is not well understood. Most investigators agree that appreciable energy from explosion sources is converted to S-waves near the source, but the dominant P-to-S transfer mechanism is not agreed upon. Several physically reasonable transfer mechanisms are proposed, including P-to-S conversion at the free surface, spall, scattering of short-period surface waves, tectonic release, and rock-damage (e.g. Vogfjord, 1997; Day and Mclaughlin, 1991; Gupta et al., 1992; Wallace et al., 1985; Johnson and Sammis, 2001). With the exception of surface-wave scattering, each mechanism is described analytically by its supporters, and each can be used to fit a subset of observations. However, surface-wave scattering – the only mechanism without an adequate analytical representation, offers an explanation for some of the most intriguing regional S-wave observations (see below).

RESEARCH ACCOMPLISHED

The importance of Rg scattering was first proposed to explain teleseismic P-coda amplitudes (e.g. Dainty, 1990). Gupta et al. (1992) proposed Rg-to-S scattering to explain frequency-dependent variations in regional P/Lg ratios at the Kazakh and Nevada Test Sites, where the P/Lg spectra for explosions increases in the ~1-10 Hz band. The minimum in the P/Lg spectra was found to be coincident with expected spectral peaking in Rg excitation, suggesting a link between Rg and regional S-wave energy. In an in-depth analysis of NTS explosion spectra, Patton and Taylor (1995) also found evidence for Rg-to-S scattering. An expected notch in the Rg spectrum from a compensated linear vector dipole (CLVD) source, which the authors attribute to spall, matched spectral characteristics of the Lg phase. Gupta et al. (1997) confirmed these observations using an expanded data set.

Myers et al. (1999) found further evidence to support the importance of Rg-to-S conversion for regional seismic phases. In 1997 three, 25-ton chemical explosions where detonated at nominal depths of 50 m, 300 m and 550 m at the former Soviet test site at Balapan, Kazakhstan (Glenn and Myers, 1997). Regional distance recordings of the explosions exhibit increased S-wave excitation for the shallow shots in the 1-5 Hz band relative to P-wave amplitudes (Figure 1). Above 5 Hz, S-wave excitation scales with P-wave amplitude, and P/S ratios are relatively constant for the three shots. Likewise, regional Lg coda amplitudes for the shallow shots are peaked in the 1-5 Hz band in comparison to the deepest shot. The Kazakhstan experiment stands out because local recordings of the shots are also available, and near-source Rg amplitudes can be measured. For the 1997 Kazakh explosions Rg is 1) peaked in the 1-5 Hz band, 2) greater in amplitude for the shallow shots and 3) rapidly attenuates ($Q_{Rg}(f) \propto f$ and $Q \approx 10$ at 1 Hz) (Figure 2). The extreme attenuation and frequency dependence is interpreted to result from scattering. In summary, Rg rapidly looses energy in the 1-5 Hz band and regional S-waves correspondingly gains energy in the 1-5 Hz band. Also, both Rg and regional S-phase amplitudes increase for the shallow shots. Taken as a whole, these observations point towards Rg-to-S scattering as an important mechanism for generation of regional S-energy.

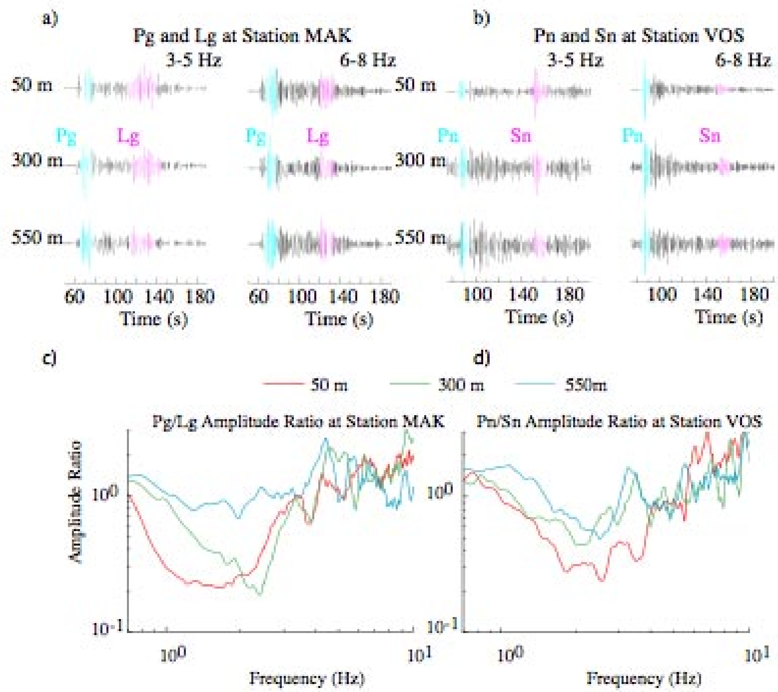

Figure 1. Observations of the 1997 Depth Of Burial (DOB) experiment (Myers et al., 1999). a) Bandpass seismograms (3-5 Hz and 6-8 Hz) at station MAK. Highlighted Pg and Lg phases show enhanced Lg amplitude for the shallower shot in the 3-5 Hz band pass. b) The same band passes as a) but with Pn and Sn phases highlighted at station VOS. Again, the S-phase (Sn) amplitude is enhanced in the 3-5 Hz pass band for the shallow shots. Spectral ratios for Pg/Lg c) and Pn/Sn d) show the frequency dependence of the P/S energy partitioning. The frequency band with lower P/S ratios is coincident with the peaking of the Rg phase.

Currently the Rg-to-S mechanism is represented by an empirical transfer function (e.g. Gupta et al., 1992; Patton, 2001). Because analytical representation of the Rg-to-S mechanism is, at best, cumbersome for complex geologic structure, a transfer function is a practical representation. Although Jih (1995) used numerical simulation and simple 2-dimensional models to show the plausibility of Rg scattering into regional phases, application of the transfer function would be bolstered by a more detailed understanding of the physical mechanism in more realistic geology. In particular, a better understanding of the effects that geologic and source emplacement conditions have on transfer function parameters is needed
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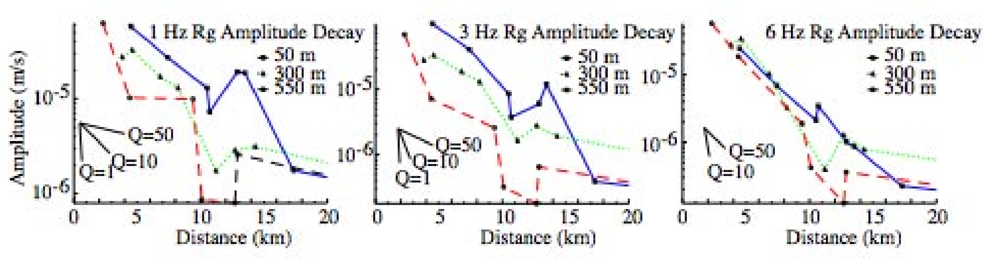

Figure 2. DOB Rg amplitude as a function of distance is shown in 3 frequency bands. These observations suggest rapid, frequency-dependent attenuation of Rg.

NPE Case Study

We fashion the seismic simulations around the 1993 Non-Proliferation Experiment (NPE) (see reference in Denny and Stull, 1994). The NPE was a chemical explosion with nominal yield of 1 kiloton. Knowledge of the source location, origin time, emplacement conditions, and near source geology are unparalleled, providing an excellent data set for modeling.

The NPE was well instrumented both locally and regionally (Figure 3), including two temporary deployments extending to regional distance. One deployment forms a line to the northwest and the other forms a line to east, where the shot was well recorded with high signal to noise ratio. Each of these deployments is anchored by a permanent station (Elko and Kanab, respectively) with historic recordings of nuclear tests. Perhaps most importantly, regional NPE seismograms are near replicas of nearby nuclear explosions (Walter et al, 1994), so our simulations are directly applicable nuclear test monitoring. Local stations surround the NPE out to about 20 km (Figure 3). Local recordings provide crucial validation of the near-source model and propagation effects.

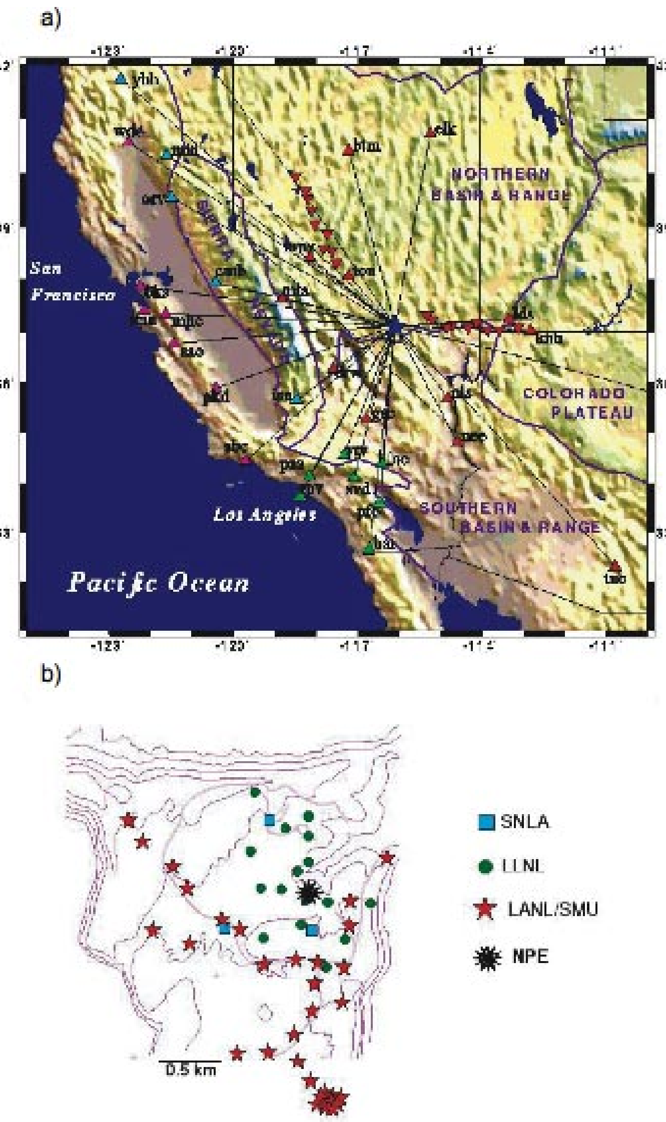

Figure 3. a) Regional and b) local networks recording the NPE shot. The local and regional recordings of the NPE provide validation data for simulations.

Seismic Simulation

E3D Finite-Difference computer code

Computational simulations in this study are performed with E3D, a state-of-the-art finite-difference seismic wave propagation code developed at LLNL (e.g., Larsen and Schultz,1995; Larsen and Grieger, 1998). E3D is based on the elastodynamic formulation of the full wave equation on a staggered grid [e.g., Levander,1988]. It is 4th-order accurate in space and 2nd-order accurate in time. E3D can be used to simulate the propagation of elastic waves (compressional and shear energy) in a complex and fully heterogeneous 3-D geologic environment (Figure 4).

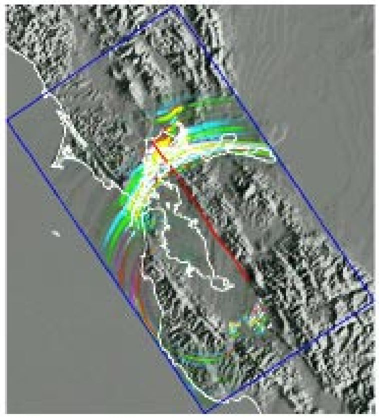

Figure 4. Example of full elastic simulation using the e3d finite difference code. The e3d code can accommodate topography and 3-dimensional geology to produce a more realistic simulation of seismic wave propagation.

E3D contains several advanced features that make it particularly well suited to our study. Physics-based enhancements include fully 3-D elastic wave propagation, 3-D viscoelastic propagation (attenuation, Q), 3-D topography, and multiple source representations, including explosions. Computational enhancements include propagating grids, and parallelization. Of particular interest to this study is the advanced-graphic run-time visualization, which can be used to visually evaluate wave propagation phenomenology.

Our simulations require world-class computational facilities, like those available at LLNL. A 3-D elastic simulation at a source frequency of 4 Hz propagated through typical regional geology out to 300 km will require approximately 12 hours of run time using 1 Terabyte of computer memory and 1000 CPU's in a parallel computing environment. Simulations in the presence of topography or viscoelastic attenuation will be more intensive.

Geological Simulation

Explosions are detonated and Rg propagates in the top few kilometers of the crust, which is typified by fault-bounded geologic units that comprise a highly heterogeneous medium. This patchwork of complex, non-stationary units may not be adequately represented by either homogeneous, fault-bounded units or by continuous stochastic models. Hybrid models may be necessary. From the 1997 Kazahk experiment (described above) we know that near-source Rg attenuation is strong and highly frequency dependant. Although narrow-band scattering attenuation may be simulated with any number geologic realizations, frequency-dependent broadband scattering attenuation requires realistic geologic structure. To better simulate the close-in NPE wave field, we have collected geologic information near the NPE shot and constructed a deterministic model. We are also working to characterize the stochastic properties of the geologic media to create a realistic model that extends for local to regional distance.

Deterministic structure

Geologic structure close to the NPE source is likely to control Rg scattering. Numerous studies of geologic structure at the NTS allow construction of a detailed model that will enable us to credibly evaluate whether Rg scattering contributes appreciably to regional S-phases. Geologic mapping at fine scales, ten of thousands of borings, and geophysical imaging have all been conducted in and around NTS. We have compiled this information to construct of a detailed deterministic model near the NPE shot (Figure 5). The detailed model extends 20 km from the NPE shot and to a depth of 6 km. A 10-meter digital elevation model forms the topographic surface, and the following stratigraphic units are specified: Quaternary alluvium, Tertiary volcanics, Mesozoic intrusive granites, Paleozoic sedimentary and metasedimentary rocks, and upper-crustal crystalline rocks.

The surfaces of these units are defined primarily by geologic mapping and borehole data. As an example, we show the top of the Paleozoic (Figure 6a,b), which is constrained by numerous borehole data points. Two other examples are the intrusive granites (Gold Meadows stock and Climax stock; green in Figure 5), which are locally exposed at the surface, penetrated by several boreholes and further constrained by gravity modeling (Healey and Miller, 1963; USGS OFR, 1983).

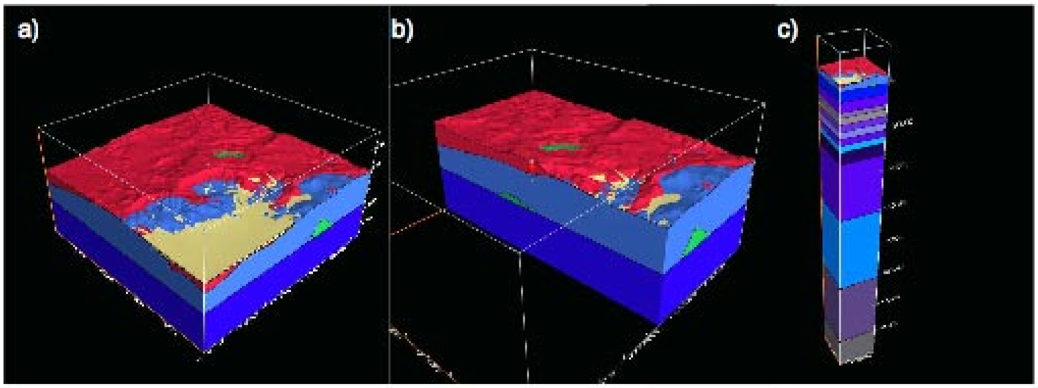

Figure 5. Local model around NPE shot determined from detailed geologic and geophysical studies. a) The entire local model. b) Cross section through the NPE shot. c) Local model merged into a lithospheric velocity stack.

Simulated structure

Although we are taking great measures to incorporate as much deterministic structure as possible, it is impossible to construct a model with sufficient detail without a major 3-dimensional imaging campaign. In order to better simulate the earth, we are using geostatistical simulation techniques to perturb geologic boundaries and elastic parameters within geologic units. Statistical characteristics are gleaned from densely sampled data sets, and these characteristics are then used to “roughen” the model in areas with few data constraints.

Figure 6 is an example of a conditional simulation of the upper contact of Paleozoic (Pz) sedimentary rocks near Rainier Mesa. The top of the Pz is one of the first major seismic contrasts encountered by the NPE wavefield. Therefore, proper simulation of this contact is critical for realistic evaluation of seismic scattering. Numerous boreholes define the Pz contact in the southeast portion of the model area. Elsewhere, only the general dip and depth of the Pz contact are constrained. If conventional interpolation is used to construct the Pz surface, then the surface is quite smooth in areas with sparse borehole sampling (Figure 6a,b). Figure 6c,d shows that a more realistic Pz surface can be constructed through conditional simulation. The new surface will scatter high-frequency energy more readily than a smooth surface and may help to explain the frequency dependence of Rg attenuation.

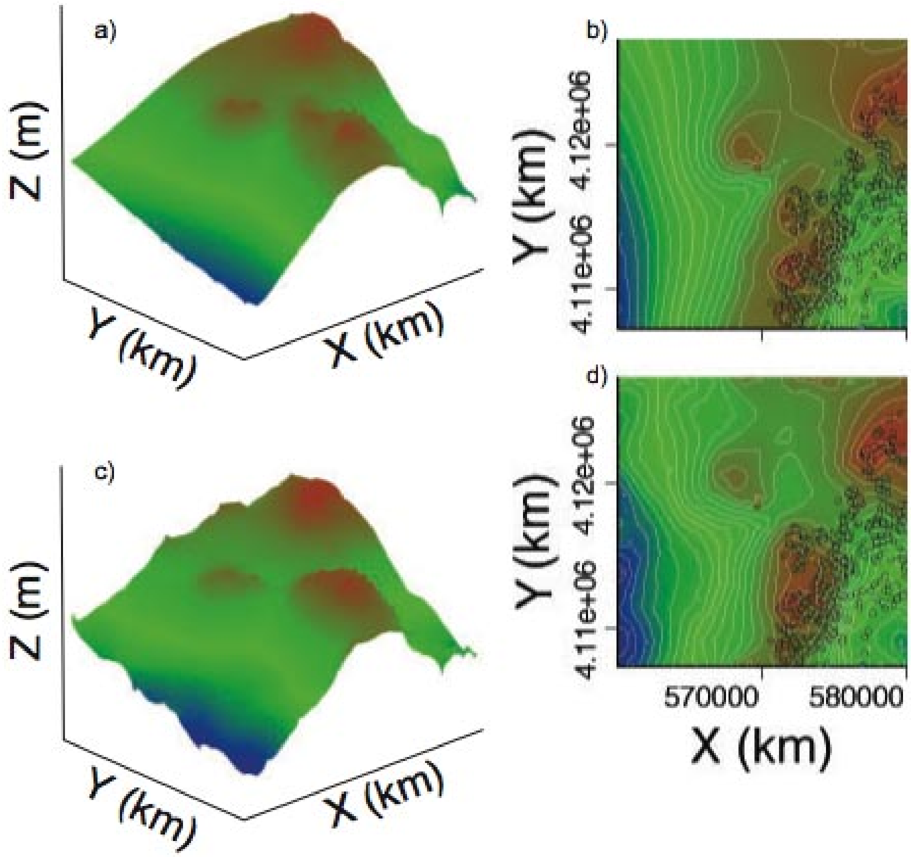

Figure 6. Conditional simulation of the upper contact for Paleozoic (Pz) rocks. a) Surface determined using borehole data, which are concentrated in the southeast portion of the model area, and a simple interpolation algorithm. b) plan view of a) showing borehole data (circles colored in accordance with borehole observation). Note the difference in the roughness of the surface between areas with and without borehole data. c) Conditional simulation of upper Pz surface using statistical characterization of surface roughness and constraints from borehole observations. d) Plan view of c) showing borehole observations and consistent surface roughness in areas with and without observations.

CONCLUSIONS AND RECOMMENDATIONS

We review the first three months of progress on the SIRES project. During this period we made use of geologic and geophysical studies at NTS to construct a detailed earth model within 20km of the NPE shot. We use geostatistical simulation to make geologic contacts and elastic parameters within geologic units as realistic as possible. This level of local model detail is needed to evaluate the Rg-to-S transfer function.

Our next step is to imbed the local, detailed model in a regional model (out to ~400 km). The regional model draws on previous studies of crustal scale structure. Like the local model, conditional geostatistical simulation will be used to produce a realistic model at relevant wavelengths. Seismic simulation will be used for validation during model construction and will culminate in a Tera-Scale, 3-dimensional simulation.

ACKNOWLEDGEMENTS

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.

REFERENCES

Dainty, A. M., Studies of coda using array and three-component processing, *Pageoph*, **132**, 221-244,1990.

Denny, M.D., S.P. Stull, Proceedings of the Symposium on The Non-Proliferation Experiment (NPE): Results and Implications for Test Ban Treaties, Rockville Maryland; Lawrence Livermore National Laboratory,1994.

Glenn L. and S. Myers (1997). Depth of Burial Experiment at Balapan, *Proceeding of the International Symposium on Monitoring and Discrimination of Underground Nuclear Explosions and Earthquakes*, Moscow, Russia, November 17-21, 1997 (229-235); see also LLNL UCRL-JC-128313.

Gupta, I.N., T.R. Zhang, R.A. Wagner, Low frequency Lg from NTS and Kazakh Nuclear Explosions – observations and interpretations, *Bull., Seismol. Soc. Am*., **87**, 1115-1125, 1997.

Healey, D. L. and Miller, C. H., 1963. Gravity survey of the Gold Meadows Stock, Nevada Test Site, Nye County, Nevada. USGS Technical Letter NTS-40.

Jih, R.S., Numerical investigation of relative contribution of Rg scattering and incomplete dissipation to Lg excitation, Proceedings of the 17^{th} Seismic Research Symposium on Monitoring a Comprehensive Test Ban Treaty, PL-TR-95-2108, 1995.

Johnson, L.R., and C.G. Sammis, Effects of rock damage on seismic waves generated by explosions, *Pageoph*, **158**, 1869-1908, 2001.

Larsen, S. C., and C. A. Schultz, ELAS3D: 2D/3D elastic finite-difference wave propagation code, LLNL internal report, 18 p., 1995.

Larsen, S., and J. Grieger, Elastic modeling initiative, Part III: 3-D computational modeling, Soc. Expl. Geophys. Confer. Proceed., 68,1803-1806, 1998.

Levander, A. R., Fourth-order finite-difference P-SV seismograms, Geophysics, 53, 1425-1436, 1988.

Myers, S.C., W.R. Walter, K. Mayeda, L. Glenn, Observations in support of Rg scattering as a source for explosion S waves: regional and local recordings of the 1997 Kazakhstan depth of burial experiment, *Bull. Seismol. Soc. Am*., **89**, 544-549, 1999.

Nuttli, O.W., Yield estimates of Nevada Test Site explosions obtained from seismic Lg waves, *J. Geophys. Res*., **91**, 2137-2151, 1986.

Patton, H.J., Regional magnitude scaling, tranportability, and Ms:mb discrimination at small magnitudes, *Pageoph*, **158**, 1951-2015, 2001.

USGS, 1983. Geologic and geophysical investigations of Climax Stock Intrusive, Nevada. USGS Open-file Report 83-377.

Walter, W.R., K. Mayeda, and H.J. Patton, Regional seismic observations of the Non-Proliferation Experiment at the Livermore NTS network, in *Proceedings of the Symposium on The Non-Proliferation Experiment (NPE): Results and Implications for Test Ban Treaties,* Denny and Stull eds., 1994.

Whitney, J. W., W.R. Keefer, Geologic and geophysical characterization studies of Yucca Mountain, Nevada, a potential high-level radioactive-waste repository, USGS Digital Data Series 58, 2001