

## Final Technical Report:

Grant Number: DE- FG02-03ER63662

3D Seismic Experimentation and Advanced Processing/Inversion Development for Investigations of the Shallow Subsurface

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The work plan for this project was to develop and apply advanced seismic reflection and wide-angle processing and inversion techniques to high resolution seismic data for the shallow subsurface to seismically characterize the shallow subsurface at hazardous waste sites as an aid to containment and cleanup activities. We proposed to continue work on seismic data that we had already acquired under a previous DoE grant, as well as to acquire additional new datasets for analysis. The project successfully developed and/or implemented the use of 3D reflection seismology algorithms, waveform tomography and finite-frequency tomography using compressional and shear waves for high resolution characterization of the shallow subsurface at two waste sites. These two sites have markedly different near-surface structures, groundwater flow patterns, and hazardous waste problems. This is documented in the list of refereed documents, conference proceedings, and Rice graduate theses, listed below.

Under this grant we conducted 4 seismic field experiments: The first was a multi-component source and receiver shear wave experiment at a superfund site at Hill Air Force Base, Ogden, Utah, which rounded out the 3 previous experiments at Hill AFB. [These were a pilot experiment, a 3D reflection survey, a 3D wide-angle survey, and a VSP/2D surface seismic experiment]. The second and third experiments were a vertical component source and receiver pilot experiment at the DoE test facility at Rifle, CO. This provided the design criteria for an extensive high-resolution vertical component source and receiver 3D seismic reflection experiment at Rifle. The fourth experiment consisted of a series of high-resolution multi-component source and receiver 2D shear wave profiles at the Rifle, CO, site.

This grant supported the research of 5 graduate students (3 PhD and 2 MSc) and one post-doctoral researcher working in reflection seismic imaging, and waveform tomography. The students and post-doc completed analysis of the Hill AFB data acquired under a previous grant, analyzed the seismic data from the shear wave experiment at Hill, and began analysis on the Rifle, CO, datasets. The students applied and developed various 2D and 3D seismic imaging (Fradelizio et al, 2008), seismic travel-time tomography (Zelt et al., 2006), and waveform tomography algorithms (Gao et al., 2006, 2007) including a shear-wave waveform tomography code (Chambers et al., 2009). Zelt and a graduate student worked on development of finite-frequency travel-time tomography algorithm, the results of which have now been submitted for publication (Chen and Zelt, 2014).

The grant also provided seismology field training for more than a dozen graduate students who participated in the experiments at Hill AFB, and the DoE Rifle, CO, site.

## Refereed articles

Chen, J. and C. A. Zelt, Application of frequency-dependent traveltime tomography and full waveform inversion to realistic near-surface seismic refraction data, *Journal of Environmental and Engineering Geophysics*, submitted, 2014.

Zelt, C. A., S. Haines, M. H. Powers, J. Sheehan, S. Rohdewald, C. Link, K. Hayashi, D. Zhao, H.-W. Zhou, B. L. Burton, U. K. Petersen, N. D. Bonal, and W. E. Doll, Blind test of methods for obtaining 2D near-surface seismic velocity models from first-arrival traveltimes, *J. Env. Eng. Geophys.*, 18, 183-194, 2013.

Fradelizio, G. L., A. Levander, and C. A. Zelt, Three-dimensional seismic-reflection imaging of a shallow buried paleochannel, *Geophysics*, 73, B85-B98, 2008.

Gao, F., A. Levander, R. G. Pratt, C. A. Zelt and G.-L. Fradelizio, Waveform tomography at a ground water contamination site: Surface reflection data, *Geophysics*, 72, G45-G55, 2007.

Levander, A., C.A. Zelt, and W.W. Symes, Active Source Seismology: A Primer, invited for the *Treatise on Geophysics, Volume 1: Seismology and Structure of the Earth*, B. Romanowicz and A. Dziewonski, editors, Elsevier, Amsterdam, 247-288, 2007.

Zelt, C. A., A. Azara and A. Levander, 3-D seismic refraction traveltime tomography at a shallow groundwater contamination site, *Geophysics*, 71, H67-H78, 2006.

Gao, F., A. Levander, R. G. Pratt, C. A. Zelt and G.-L. Fradelizio, Waveform tomography at a ground water contamination site: VSP-surface dataset, *Geophysics*, 71, H1-H11, 2006.

### **Conference abstracts**

Chen, J., C.A. Zelt and A. Levander, Application of frequency-dependent traveltime tomography (FDTT) to 2D and 3D near-surface seismic data at a shallow groundwater contamination site, Rifle, CO, Symposium on the Application of Geophysics to Engineering and Environmental Problems, Boston, MA, 2014

Chen, J., C.A. Zelt and P. Jaiswal, Application of frequency-dependent traveltime tomography and full waveform inversion to the data used in the blind test at the 2011 SAGEEP meeting, Symposium on the Application of Geophysics to Engineering and Environmental Problems, Boston, MA, 2014

Zelt, C.A. and J. Chen, Frequency-dependent traveltime tomography for 2D and 3D near-surface seismic refraction data, Symposium on the Application of Geophysics to Engineering and Environmental Problems, Boston, MA, 2014

Chen, J., C. A. Zelt and A. Levander, A series of near-surface seismic surveys at Rifle, Colorado for water contamination risk assessment, American Geophysical Union, Fall Meeting, San Francisco, CA, 2013.

Zelt, C.A. and J. Chen, Frequency-Dependent Traveltime Tomography (FDTT) for 2D and 3D, P- and SH-Wave Near-Surface Seismic Data, American Geophysical Union, Fall Meeting, San Francisco, CA, 2013.

Chen, J., C. A. Zelt and P. Jaiswal, A case history: Application of frequency-dependent traveltime tomography and full waveform inversion to a known near-surface target, Society of Exploration Geophysicists, Houston, TX, 2013.

Chen, J. and C.A. Zelt, Calibration of Wavelength-Dependent Velocity Smoothing for Calculating a Frequency-Dependent traveltime, American Geophysical Union, Fall Meeting, San Francisco, CA, 2012.

Zelt, C.A., J. Chen and P. Jaiswal, Combining frequency-dependent traveltime tomography and frequency-domain Waveform tomography for near-Surface Seismic refraction data, SAGEEP, Annual meeting, Tucson, AZ, 2012.

Zelt, C.A., Frequency-dependent traveltime tomography, full waveform tomography and a 3D refraction experiment, SAGEEP, Annual meeting, Tucson, AZ, 2012.

Zelt, C.A., Seismic refraction traveltime inversion: Lessons learned from applying different inverse methods to the same data, SAGEEP, Annual meeting, Tucson, AZ, 2012.

Zelt, C.A., H. Liu and J. Chen, Frequency-dependent traveltime tomography for near-surface seismic data: sensitivity kernels and synthetic and real data examples, American Geophysical Union, Fall Meeting, San Francisco, CA, 2011.

Zelt, C.A., S. Haines, M. Powers, J. Sheehan and W. Doll, Seismic Refraction Shootout: Blind test of methods for obtaining velocity models from first-arrival travel times, SAGEEP, Annual meeting, Charleston, SC, 2011.

Zelt, C.A., S. Haines, M. Powers, J. Sheehan and W. Doll, Seismic refraction shootout: Presentation of true model and comparison with estimated model, SAGEEP, Annual meeting, Charleston, SC, 2011.

Zelt, C. A., and H. Liu, Frequency-dependent traveltime tomography for near-surface seismic data, 14th International Symposium on Deep Seismic Profiling of the Continents and Their Margins, Cairns, Australia, 2010.

Zelt, C. A., and H. Liu, Frequency-dependent traveltime tomography for near-surface seismic data, IRIS annual workshop, Snowbird, UT, 2010.

Zelt, C. A., Frequency-dependent traveltime analysis, SAGEEP, Annual meeting, Keystone, CO, 2010.

Zelt, C. A., Full Waveform Inversion and 3D, SAGEEP, Annual meeting, Keystone, CO, 2010.

Zelt, C. A., Frequency-Dependent Traveltime Tomography For Controlled-Source, Near-Surface Seismic Data, American Geophysical Union, Fall Meeting, San Francisco, 2009.

Zelt, C. A., Frequency-dependent traveltime tomography for near-surface studies, Society of Exploration Geophysicists, Near-surface seismology and GPR (workshop), Houston, TX, 2009.

Zelt, C. A., Frequency-Dependent Traveltime Tomography, SAGEEP, Principles and Applications of Seismic Refraction Tomography (workshop), Fort Worth, 2009.

Zelt, C. A., 3-D seismic refraction tomography, SAGEEP, Principles and Applications of Seismic Refraction Tomography (workshop), Fort Worth, 2009.

Zelt, C. A., Full-waveform inversion, SAGEEP, Principles and Applications of Seismic Refraction Tomography (workshop), Fort Worth, 2009.

Chambers, G., A. Levander, C. A. Zelt, and B. Dugan, Seismic waveform tomography with multicomponent data at a groundwater contamination site, Society of Exploration Geophysicists, 28, 3994-3998, 2009.

Chambers, G., A. Levander, C. Zelt, and B. Dugan, Seismic Waveform Tomography Using Multi-component Data at a Shallow Groundwater Contamination Site, American Geophysical Union, Fall Meeting, San Francisco, 2008.

Zelt, C. A., Finite-Frequency Traveltime Tomography for Active-Source Seismic Data, American Geophysical Union, Fall Meeting, San Francisco, 2006.

Fradelizio, G., A. Levander, and C. Zelt, Using Elastic Wave Seismic Data to Image an Ultra-shallow Buried Paleo- channel, American Geophysical Union, Fall Meeting, San Francisco, 2006.

Fradelizio, G. L., C. Zelt, and A. Levander, Using elastic wave seismic data to image an ultra-shallow buried paleo-channel, Society of Exploration Geophysicists, 25, 1416-1420, 2006.

Gao, F., A. Levander, and C. Zelt, An iterative approach for geophysical diffraction tomography: Implication for true amplitude migration, Society of Exploration Geophysicists, 25, 3325-3329, 2006.

Fradelizio, G. L., A. Levander, and C. A. Zelt, Using elastic wave seismic data to image an ultra-shallow buried paleo-channel, SEG Hydrogeophysics Workshop, Vancouver, Canada, 2006.

Zelt, C. A., Finite-frequency traveltime tomography for active-source seismic data, 12th International Symposium on Deep Seismic Profiling of the Continents and their Margins, Hayama, Japan, 2006.

Gao, F., G.-L. Fradelizio, A. Levander, G. Pratt, and C. Zelt, Seismic Velocity, Q, Geological Structure and Lithology Estimation at a Ground Water Contamination Site, Society of Exploration Geophysicists, 1561-1565, 2005.

Fradelizio, G. L., A. Levander, C. A. Zelt and F. Gao, Depth Migration Comparison to Waveform Tomography from a high Resolution 3D Seismic Dataset, American Geophysical Union, Fall Meeting, San Francisco, 2004.

Gao, F., G. L. Fradelizio, A. Levander, G. Pratt, C. A. Zelt and W. Symes, Waveform tomography at a ground water contamination site: comparison with depth migration, American Geophysical Union, Fall Meeting, San Francisco, 2004.

Gao, F., A. Levander, R.G. Pratt, and S. Morton, Velocity analysis by waveform tomography: a few examples, Society of Exploration Geophysicists Expanded Abstracts, 74<sup>th</sup> Annual Meeting, Denver CO, 2004

Gao, F., A. Levander, G. Pratt, C. Zelt, Waveform tomography at a ground water contamination site: VSP and surface reflection datasets, American Geophysical Union, Fall meeting, San Francisco, 2003.

Azaria, A., C. Zelt, and A. Levander, High-resolution seismic surveying at a groundwater contamination site: Results From 3-D traveltimes tomography, IRIS-UNAVCO Joint Workshop, Yosemite, 2003.

Gao, F., A. Levander, G. Pratt, C. Zelt, and S. Ham, High-resolution seismic surveying at a groundwater contamination site: Combined surface reflection and VSP data, IRIS-UNAVCO Joint Workshop, Yosemite, 2003.

Azaria, A., C. Zelt, A. Levander, High-resolution seismic mapping at a groundwater contamination site: 3-D traveltimes tomography of refraction data, European Geophysical Society-American Geophysical Union-European Union of Geosciences Joint Assembly, Nice, France, 2003.

## **Theses**

A. Azaria, 2003, M.Sc., Three dimensional traveltimes tomography at a shallow groundwater contamination site, Rice University.

F. Gao, 2004, Ph.D., Waveform Tomography and its Application at a Groundwater Contamination Site, Rice University.

G.L. Fradelizio, 2007, Ph.D., Using Elastic Wave Seismic Data to Image an Ultra-Shallow Buried Paleo-channel, Rice University.

G. Chambers, 2009, M.Sc., Seismic Waveform Tomography With Multicomponent Data at a Groundwater Contamination Site, Rice University.

