INTERIM REPORT
U. S. Department of Energy

AUTOMATING SHALLOW SEISMIC IMAGING

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"Obtaining CMP Seismic Data using Interconnected Geophones" (DOE Atlanta 2001)

"Coincident Seismic and Ground-Penetrating Radar Images" (DOE Atlanta 2000)

New STIs

EXECUTIVE SUMMARY

This report summarizes work after 3.5 years of a six-year (renewed) project addressing the areas of geophysical imaging technology, subsurface characterization, and automated geophone placement. As of March 2001, we have successfully used seismic *P*-wave reflection to survey depths ranging from 0.6 to 3 m at our primary test site in Kansas. We were able to complement and, to a substantial degree, duplicate those results with GPR surveys along the same test lines. Finite-difference wave-equation modeling supported the results obtained from both types of surveys. Because of the unexpected detection of three *P*-wave reflections at depths of less than 3 m, we concentrated our efforts in a zone somewhat shallower than that envisioned in the original three-year proposal. In addition, we have acquired useful data using an automated geophone-planting device and have obtained accurate two-dimensional common-midpoint (CMP) data with rigidly interconnected geophones attached to pieces of channel iron. Our initial testing suggests that large numbers of geophones can be placed automatically using a mechanical device, which could make the application of shallow seismic research (SSR) methods considerably faster and cheaper. The focus of the current research is to continue developing an automated, cost-effective,

ultrashallow seismic imaging method applicable to DOE facilities and potentially to other near-surface environmental, engineering, and geological problems.

RESEARCH OBJECTIVES:

The current project is a continuation of an effort to develop ultrashallow seismic imaging as a cost-effective method potentially applicable to DOE facilities. The objective of the present research is to develop and demonstrate the use of a cost-effective, automated method of conducting shallow seismic surveys, an approach that represents a significant departure from conventional seismic-survey field procedures. Initial testing of a mechanical geophone-planting device suggests that large numbers of geophones can be placed both quickly and automatically. The development of such a device could make the application of SSR considerably more efficient and less expensive. The imaging results obtained using automated seismic methods will be compared with results obtained using classical seismic techniques. Although this research falls primarily into the field of seismology, for comparison and quality-control purposes, some GPR data will be collected as well. In the final year of the research, demonstration surveys at one or more DOE facilities will be performed.

An automated geophone-planting device of the type under development would not necessarily be limited to the use of shallow seismic reflection methods; it also would be capable of collecting data for seismic-refraction and possibly for surface-wave studies.

Another element of our research plan involves monitoring the cone of depression of a pumping well that is being used as a proxy site for fluid-flow at a contaminated site. Our next data set will be collected at a well site where drawdown equilibrium has been reached. Noninvasive, in-situ methods such as placing geophones automatically and using near-surface seismic methods to identify and characterize the hydrologic flow regimes at contaminated sites support the prospect of developing effective, cost-conscious cleanup strategies for DOE and others.

METHODS AND RESULTS

The most significant results stemming from our EMSP funding to date are summarized in the refereed scientific papers listed in the publications section of this report. These documents detail the procedures used to achieve seismic imaging at ultrashallow depths. Our progress in this area has been attributable largely to an improved ability to measure the near-source wavefield. To accomplish this, we collected data using a single, 100-Hz geophone-group interval of 5 cm. In contrast, typical seismic surveys that are referred to as being "shallow" often use geophone-group intervals of 1 m or more. Because we increased the spatial density of the geophones by a factor of 20 or more, our ability to delineate and improve the coherence of the ultrashallow reflections over other interfering phases was enhanced. Seismic-source energy was provided by a single shot from a .22-caliber rifle using subsonic, solid-point, short ammunition. We found that the larger, more powerful shallow seismic exploration sources tested at the site (i. e., commercial seisguns and sledgehammers) generated near-field nonlinear deformation strong enough to prevent the detection of ultrashallow reflection information (Baker et al., 2000, BSSA).

Moreover, we have had encouraging results in our attempts to demonstrate the use of an automated method of conducting shallow seismic surveys. Building on previous work indicating that a mechanical device could be used to place geophones both automatically and simultaneously (Steeples et al., 1999), we performed further experiments to show that good seismic information can be recorded when interconnected geophones are mounted on a rigid medium [Fig. 1] (Spikes et al., 2001, in press; Schmeissner et al., 2001, in revision). In addition, we have recorded high-quality near-surface 2-D CMP seismic data using this method (Fig. 2). Standard processing techniques were used to stack the recorded reflection data acquired from a conventionally planted geophone line and from a line of geophones mounted on a rigid medium. The stacked seismic sections showed a high level of similarity (Fig. 2) despite some noise problems (Fig. 3).

For additional figures illustrating past and current work, see also "Obtaining CMP Seismic Data using Interconnected Geophones," presented at the DOE 2001 Atlanta Workshop, and "Coincident Seismic and Ground-Penetrating Radar Images," presented in Atlanta in 2000, both appended to this report in PDF format.

Results such as these may stimulate other efforts to automate ultrashallow CMP reflection surveys in the near future.

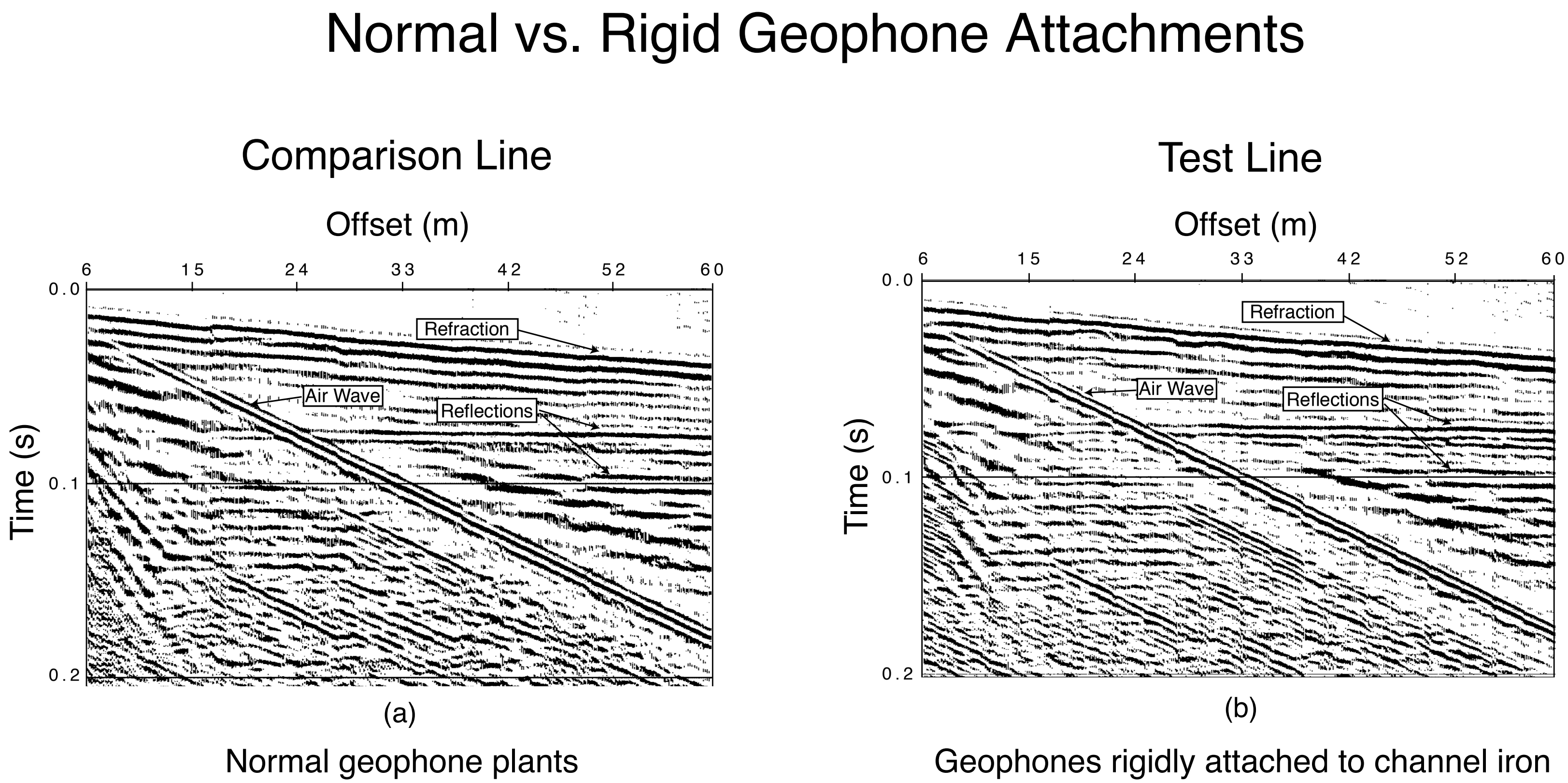

Figure 1. Comparison of walkaway wave-test data recorded using (a) geophones planted normally, and (b) geophones bolted to four, 2.7-m-long pieces of channel iron and then inserted into the ground. Note the similarities in phase and amplitude of the refractions on both records. Note also the similarity of the reflections at 72 ms and 94 ms, respectively. Also note that the 74-ms reflection can be followed continuously from ~ 15 m (inside the air wave) to 60 m for both (a) and (b), with no interfering modes visible in (b), in which the data come from geophones attached to the channel iron. The data were processed using a bandpass filter with 300-500 Hz, rolling off at 12 dB/octave and plotted with an AGC window of 25 ms. A 30.06 rifle fired into a shallow, prepunched hole provided the seismic energy recorded on both lines.

Stacked Seismic Sections

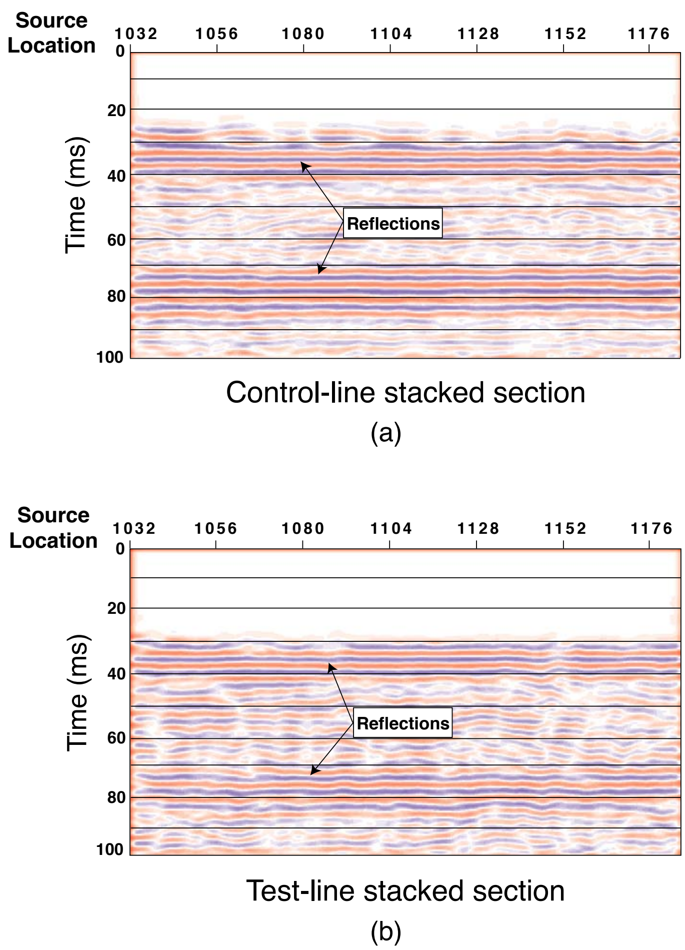

Figure 2. Conventionally processed stacked sections for control line (a) and test line (b). □ An ~1800 m/s consant-velocity stack was applied. The dimming of the ~75-ms test-line reflection may be due to the airwave diffractions in the test-line data that were not removed by the *f-k* filter. Display parameters include a 200- to 500-Hz bandpass filter, a 30-ms AGC window, and a 12-dB display gain. A 2-1 horizontal trace sum was applied for the display, □ and low-fold traces were removed from the edges of each.

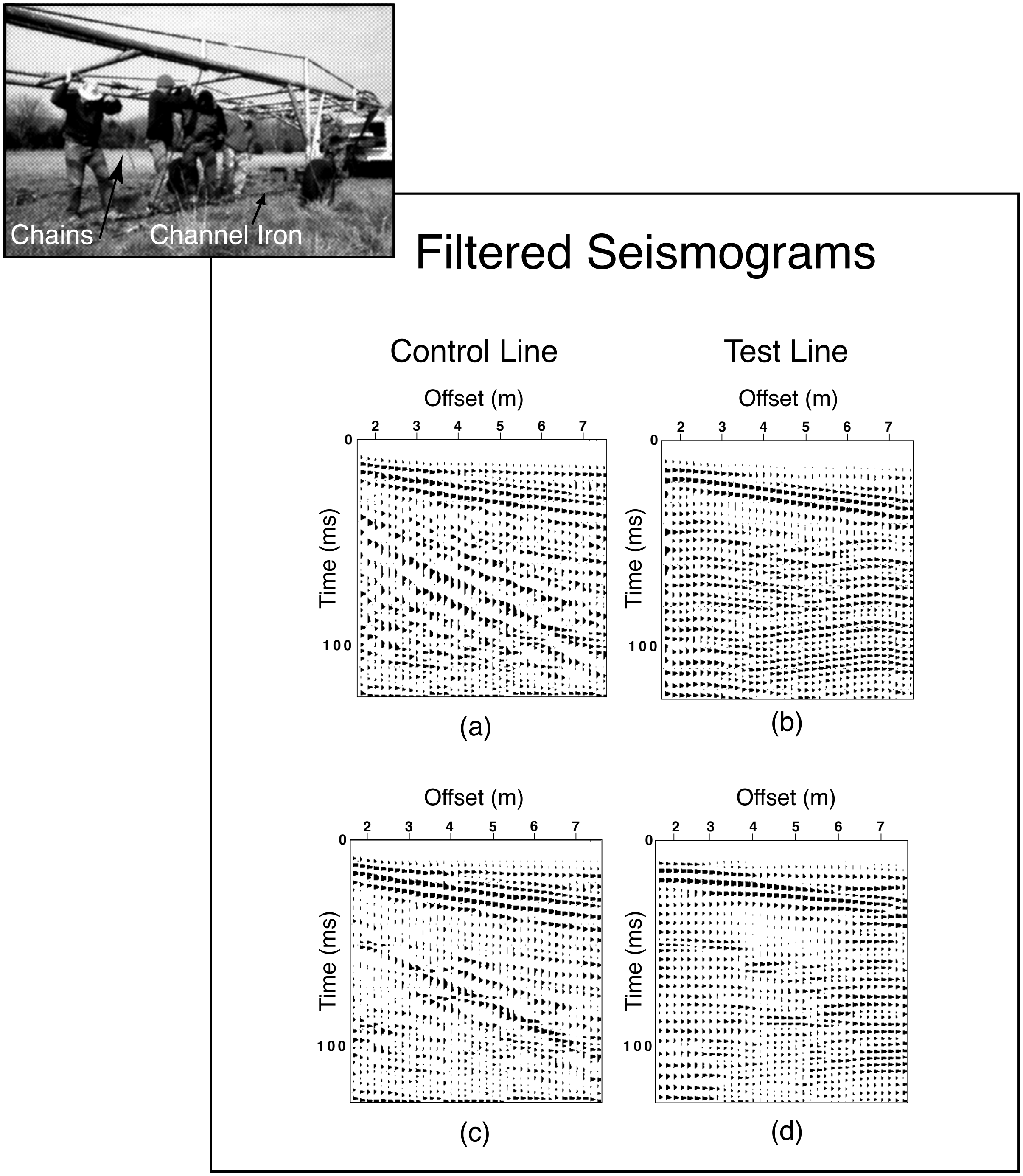

Figure 3. Coincident shot gathers from the control line (a) and the test line (b). In the test-line shot gathers, the airwave can be seen diffracting off the chains attached to the channel iron. Filtering in the *f-k* domain removed the airwave and the airwave diffractions [(c), (d)] that occurred in the test-line shot gathers. Records are displayed with a 50-ms AGC window and a 300- to 500-Hz bandpass filter.

To fulfill our stated plan of reoccupying the same survey line on a quarterly basis for two years to examine changes over time in the data acquired, we repeated field surveys employing both GPR and seismic methods between 1997 and 1999. This was important because soil-moisture conditions vary on a seasonal basis at the site, and the water table rises and falls about 1 m in response to changes in the level of the Arkansas River and to the presence of the many irrigation wells found nearby. At the test site, in the alluvial valley of the Arkansas River near Great Bend, Kansas, surface material consists of unconsolidated medium- to coarse-grained sand interspersed with clay stringers and clay lenses deposited by the Arkansas River. A hand-dug test pit about 10 m from the seismic line revealed the presence of a paleosol at a depth of about 0.6 m and cross-bedded sand descending to about 1.5 m. A sand and gravel layer was found between 1.5 m and the water table, at a depth of 2.1 m. A well drilled about 40 m away from the seismic line encountered bedrock--a fine- to medium-grained Cretaceous-age sandstone--at a depth of 29 m.

In the past, shallow seismic-reflection methods have been capable of imaging the subsurface from about 2 to 30 m, but because of near-source nonelastic deformation and insufficient receiver density, these technologies have not been adequate for imaging ultrashallow subsurface geology. Modifying the field layout of the geophones and using an alternative seismic source have allowed us to image the subsurface from 0.6 to 2.1 m using seismic reflections. In our experiments, three distinct reflections were observed within this range while using surface sources and receivers at the test site in the Arkansas River valley. These were confirmed by synthetic seismograms generated by fourth-order, finite-difference wave-equation modeling.

RELEVANCE, IMPACT, AND TECHNOLOGY TRANSFER

Initial testing suggests that large numbers of interconnected, rigidly attached geophones can be placed automatically using a mechanical device, which could make the application of shallow and ultrashallow seismic research methods more attractive.

The results of experiments using near-surface seismic methods alone and in concert with ground-penetrating radar to identify and characterize the hydrologic flow regimes at contaminated sites support the prospect of developing effective, cost-conscious cleanup strategies that include these methods.

PROJECT PRODUCTIVITY

Reports based on this work have been published in *Geophysics*, *Geophysical Research Letters* (GRL), the *Journal of Geophysical Research* (JGR), the *Bulletin of the Seismological Society of America* (BSSA), and the *Environmental and Engineering Geoscience* (EEG) *Journal*. As of this writing, additional manuscripts have been submitted to the *Geophysics* and other publications. Expanded abstracts have appeared in the proceedings volume of the 1998, 1999, and 2000 Society of Exploration Geophysicists (SEG) meetings, and two additional abstracts have been submitted for the 2001 meeting. Poster sessions were presented at the American Geophysical Union's (AGU) annual meeting in San Francisco in 1998, the Geological Society of America (GSA) in Denver in 1999, the International Geoscience and Remote Sensing Society (IGARSS) meeting in Hamburg, Germany, in June 1999, and the Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP) in Washington, D. C., in 2000 (see following list of publications).

PERSONNEL SUPPORTED

Faculty: Don W. Steeples

Postdoctoral personnel: Chris Schmeissner

Graduate students: Greg Baker, Jason Blair, Beth Garnett, Matt Ralston, Chris Schmeissner

Professional staff: Lee Blackledge

Undergraduate students: Kyle Spikes, Paul Vincent

PUBLICATIONS

Published in Peer-Reviewed Journals

Baker, G. S., D. W. Steeples, C. Schmeissner, M. Pavlovic, and R. Plumb, 2001, Coincident imaging using seismic and GPR data: *Geophys. Res. Lett.*, **28**, 4, 627–630.

Baker G. S., D. W. Steeples, C. Schmeissner, and K. T. Spikes, 2000a, Source-dependent frequency content of ultrashallow seismic reflection data: *Bull. Seis. Soc. Amer.*, **90**, 494-499.

Baker, G. S., D. W. Steeples, C. Schmeissner, and K. T. Spikes, 2000b, Ultrashallow seismic reflection monitoring of seasonal fluctuations in the water table: *Environ. Engrg. Geosci.*, **6**, 271-277.

Baker, G. S., C. Schmeissner, D. W. Steeples, and R. G. Plumb, 1999a, Seismic reflections from depths of less than two meters: *Geophys. Res. Lett.*, **26**, 2, 279-282.

Baker, G. S., D. W. Steeples, and C. Schmeissner, 1999b, In-situ, high-frequency *P*-Wave velocity measurements within 1 m of the Earth's surface: *Geophysics*, **64**, 2, 323-325.

Steeples, D. W., Schmeissner, C. M., and Baker, G. S., 2000, Applications of and recent developments in shallow seismic reflection: Abstract, SSA 95th Annual Meeting, April 10-12, San Diego, CA, Seismological Research Letters, **71**, 2, 231.

Steeples, D. W., G. S. Baker, and C. Schmeissner, 1999a, Toward the autojuggie: Planting 72 geophones in 2 seconds: *Geophys. Res. Lett.*, **26**, 8, 1085-1088.

Steeples, D. W., G. S. Baker, C. Schmeissner, and B. K. Macy, 1999b, Geophones on a board: *Geophysics*, **64**, 3, 809-814.

Steeples, D. W., and Gregory S. Baker, 1998, Near-surface contributions to seismic static corrections: AAPG *Explorer*, **19** (June), 20-21, 29.

Published Abstracts and Expanded Abstracts

Baker, Gregory, Calista McIntyre, Laura Walczak, and D. W. Steeples, 2000, Improving ultrashallow seismic reflection data by reducing source energy: Exp. Abstr., SEG Intl. Exposition and 70th Annual Meeting, August 6-11, Calgary, Canada, II, 1267-1270.

Schmeissner, C., D. W. Steeples, Mario Pavlovic, Renato Prado, and Kyle Spikes, 2000, Recording seismic reflections using rigidly interconnected geophones: Exp. Abstr., SEG Intl. Exposition and 70th Annual Mtg., August 6-11, Calgary, Canada, II, 1279-1282.

Spikes, K. T., D. W. Steeples, C. Schmeissner, and R. Prado, 2000, Varying the effective mass of geophones: Exp. Abstr. SEG Intl. Exposition and 70th Annual Mtg., August 6-11, Calgary, Canada.

Baker, G. S., D. W. Steeples, and C. Schmeissner, 1999, On coincident seismic and radar imaging: Exp. Abst., SEG 1999 International Exposition and 69th Annual Meeting, Houston, TX, 484-487.

Baker, G. S., R. G. Plumb, D. W. Steeples, M. Pavlovic, and C. Schmeissner, 1998a, Coincident GPR and ultrashallow seismic imaging in the Arkansas River Valley, Great Bend, Kansas: Exp. Abstr., SEG 1998 International Exposition and 68th Annual Meeting, New Orleans, 859-861.

Baker, G. S., D. W. Steeples, C. Schmeissner, and B. K. Macy, 1998b, In-situ, high-resolution *P*-wave velocity measurements within 1 m of the Earth's surface: Exp. Abstr., SEG 1998 International Exposition and 68th Annual Meeting, New Orleans, 856-858.

Steeples, D. W., G. S. Baker, C. Schmeissner, and B. K. Macy, 1998, Geophones on a board: Exp. Abstr., SEG 1998 International Exposition and 68th Annual Meeting, New Orleans, 852-855.

Dissertations and Theses

Pavlovic, Mario, 2000, Ground-penetrating radar in shallow aquifer detection and monitoring, Master's thesis, The University of Kansas, Lawrence, KS, May.

Baker, G. S., 1999, Seismic imaging shallower than three meters: Ph.D. dissertation, The University of Kansas, Lawrence, KS (May), 328p.

Schmeissner, C., 1998, Seismic detectability of vertical transverse isotropy in the near surface, Ph. D. dissertation, The University of Kansas, Lawrence, (Dec.) 142 p.

Proceedings, Technical Reports, etc.

Baker, G. S., D. W. Steeples, C. Schmeissner, and K. T. Spikes, 2000, Collecting seismic-reflection data from depths shallower than three meters*:* *in* Proc. of the Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP), Washington, D. C., 1207-1214.

Plumb, R. G., D. W. Steeples, G. W. Baker, C. Schmeissner, and M. Pavlovic, 1999, A combined ground-penetrating radar and shallow seismic reflection approach to characterizing hydrological flow: International Geoscience and Remote Sensing Society (IGARSS) Meeting (Poster), Hamburg, Germany, June.

Spikes, K. T, D. W. Steeples, C. Schmeissner, M. Pavlovic, and R. Prado, 1999, Weights on geophones: Abstracts of the Geological Society of American Annual Meeting (Poster), October 24-28, Denver, CO, USA.

Steeples, D. W., Baker, G. S., and C. Schmeissner, 1998, Toward the autojuggie: Planting 72 geophones in 2 seconds: Abstr., American Geophysical Union, 1998 Fall Meeting, Dec. 6-10, San Francisco, CA.

Accepted/Submitted for Publication

Baker, G. S., D. W. Steeples, and C. Schmeissner, 2001, The effect of seasonal soil-moisture conditions on near-surface seismic reflection data quality: *First Break*, in revision.

Ralston, M. D., K. T. Spikes, and D. W. Steeples, 2001, Near-surface three-component seismic data acquisition using rigidly inter-connected geophones: Exp. Abstr., SEG Intl. Expo. and 71st Annl. Mtg., in review.

Schmeissner, C., D. W. Steeples, and K. Spikes, 2001, Recording seismic reflections using rigidly interconnected geophones: *Geophysics*, in revision.

Spikes, K. T., M. D. Ralston, and D. W. Steeples, 2001, Obtaining CMP data with automatically planted geophones: Exp. Abstr., SEG Intl. Expo. and 71st Annl. Mtg., in review.

Spikes, K. T., D. W. Steeples, and C. Schmeissner, 2001, Varying the effective mass of geophones: *Geophysics*, in press.

FUTURE WORK

Research efforts over the next year will be concentrated on the design of an effective and efficient automatic geophone-emplacement device. The following year, we will demonstrate the device, collect data, and compare the results to seismic data collected conventionally.