This report summarizes work in Year 3 of a three-year project addressing the areas of geophysical imaging technology and subsurface characterization. As of July 2000, we have succeeded in using seismic *P*-wave reflection surveys at depths of 0.6 to 3 m at our primary test site. We have been able to complement and, to a substantial degree, duplicate those results with ground-penetrating radar (GPR) surveys performed along the same line. The results from both types of surveys have been supported by finite-difference wave-equation modeling.
Our experiments with GPR have included antennas with 110-, 225-, and 450-MHz center frequencies. Both common-offset and common-midpoint (CMP) surveys have been conducted. The CMP surveys greatly improved the signal-to-noise ratio but did not increase significantly the depth from which we were able to acquire interpretable data. When using the 110 MHz GPR, we were able to image the water table at a depth of about 2 m (Pavlovic, 2000). In addition, we found indications of stratigraphic variation at depths of less than 3 m along the line, which matched the results of the seismic reflection surveys (Baker, 1999; Baker et al., 2000). Incorporating techniques of this type may useful in establishing contaminant transport-flow directions, which is essential to developing effective cleanup strategies at DOE sites.

RESEARCH OBJECTIVES:

1. To examine the complementary site-characterization capabilities of modern, three-component shallow seismic reflection (SSR) techniques and ground-penetrating radar (GPR) methods at depths ranging from 2 to 8 m at an existing test site;
2. To demonstrate the usefulness of the two methods when used in concert to characterize, in three dimensions, the cone of depression of a pumping well that will serve as a proxy site for fluid-flow at an actual, polluted site;
3. To use the site as an outdoor mesoscale laboratory to validate existing three-dimensional ground-penetrating radar and seismic-reflection computer models developed at the University of Kansas.

To do this, seismic and GPR data are being collected along the same line(s) and within the same depth range. The principal investigators selected a site in central Kansas as a primary location. Although the site itself is not environmentally sensitive, the area offers attributes that are particularly useful for this research and allow the site to serve as a proxy for areas that are contaminated.

As part of an effort to evaluate the strengths of each method, the seismic and GPR surveys have been repeated on a seasonal basis to establish how the complementary information obtained varies over time. Because the water table fluctuates seasonally at this site, variations in the two types of data over time also can be observed. Such noninvasive, in-situ methods of identifying and characterizing the hydrologic flow regimes at contaminated sites support the prospect of developing effective, cost-conscious cleanup strategies in the future.

RESEARCH PROGRESS AND IMPLICATIONS:

The first field survey employing both SSR and GPR was conducted in October1997, the second in March 1998, and additional experiments were performed in June, September, and November of 1998 and March1999. Additional GPR data were collected in July of 1999.

One of our stated tasks has been to reoccupy the same survey line on a quarterly basis for two years to examine changes in both the SSR data and the GPR data over time. Two factors drive such changes: First, soil-moisture conditions vary on a seasonal basis at the site. Secondly, the water table rises and falls about 1 m in response to changes in the level of the Arkansas River and in response to the presence of many irrigation wells nearby.

At the test site, in the alluvial valley of the Arkansas River near Great Bend, Kansas, the 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 coarser sand and gravel layer was found between 1.5 m and the water table. At the time of the seismic and GPR surveys, the water table was at depths ranging from 1.7 to 2.8 m, based on measurements taken in a test well located 25 m from the seismic line. A well drilled about 40 m from the seismic line encountered bedrock (a fine- to medium-grained Cretaceous-age sandstone) at a depth of 29 m.

Our experiments with GPR have included antennas with 110-, 225-, and 450-MHz center frequencies. Both common-offset and common-midpoint (CMP) surveys have been conducted. The CMP surveys greatly improved the S/N ratio but did not increase significantly the depth from which we were able to acquire interpretable data. Using GPR, we were able to image the water table at a depth of about 2 m; we found indications of stratigraphic variation along the line as well.

In the past, shallow seismic-reflection methods have been capable of imaging the subsurface from about 2 to 30 m. By modifying the field layout of the geophones and using an alternative seismic source, we have been able to image the subsurface from 0.6 to 2.1 m using seismic reflections. In our experiments, three distinct reflections within this range were observed while using surface sources and receivers at the test site in the Arkansas River valley. These were confirmed by 4th-order, finite-difference wave-equation modeling.

Our progress to date toward achieving workable ultrashallow seismic reflection imaging is largely attributable to an improved ability to measure the near-source wavefield. To accomplish this, we have collected data using a single, 100-Hz geophone group interval of 5 cm. In contrast, typical "shallow" seismic surveys have receiver-group intervals of 1 m or more. Because we increased receiver coverage by a factor of 20 or more, our ability to delineate and improve the coherence of 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. The larger, more powerful shallow seismic exploration sources tested at the site (commercial seisguns and sledgehammers) generated enough near-field nonlinear deformation to render near-source (i. e., ultrashallow) reflection information undetectable.

Reports based on this work have been published in *Geophysics*, *Geophysical Research Letters* (GRL) the *Bulletin of the Seismological Society of America* (BSSA), the American Association of Petroleum Geologists' *Explorer* and other journals as listed. As of this writing, manuscripts have been submitted to *Geophysics*, *Environmental and Engineering Geoscience* (in press), and *Geophysical Prospecting*. Abstracts have appeared in the expanded abstracts volume of the 1998 and 1999 Society of Exploration Geophysicists (SEG) meetings, and two additional expanded abstracts have been accepted for the 2000 meeting in Canada. Poster sessions were presented at the American Geophysical Union's (AGU) annual meeting in San

Francisco in 1998 and the International Geoscience and Remote Sensing Society (IGARSS) June 1999 meeting in Hamburg, Germany.

PLANNED ACTIVITIES

In the third year of this project, we are applying the combined seismic and GPR techniques to the characterization of the cone of depression of the irrigation wells pumping during this time. Data sets are being collected at each well prior to pumping, when equilibrium is reached, and several weeks after pumping stops. The remainder of the third year also is being used to finish processing data and to prepare manuscripts for publication.

INFORMATION ACCESS

A list of published papers and abstracts follows. For supporting figures and documentation, please see our DOE Atlanta Workshop 2000 poster (expanded) describing work to date (attached).

Published Papers and Abstracts

Baker, G. S., D. W. Steeples, C. Schmeissner, and K. T. Spikes, 2000, Source-dependent frequency content of ultrashallow seismic reflection data: *Bull. Seis. Soc. Amer.*, **90**, 2, 494-499.

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

Steeples, D. W., G. S. Baker, and C. Schmeissner, 1999, 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, 1999, 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.

Dissertations and Theses

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

Pavlovic, Mario, 2000, Ground-penetrating radar in shallow aquifer monitoring, Master's thesis, The University of Kansas, Lawrence, KS (May), 152 p.

Manuscripts Submitted, in Revision, or in Press

Baker, G. S., D. W. Steeples, C. Schmeissner, and K. T. Spikes, "Ultrashallow seismic reflection monitoring of seasonal fluctuations in the groundwater table," *Environmental and Engineering Geoscience*, in press.

Baker, G. S., D. W. Steeples, C. Schmeissner, and M. Pavlovic, "On coincident seismic and radar imaging," *Geophysics*, in revision.

Baker, G. S., D. W. Steeples, C. Schmeissner, M. Pavlovic, and R. Plumb, "Improved vadose-zone imaging," submitted to *Geophysical Research Letters*, in review.

Baker, G. S., D. W. Steeples, and C. Schmeissner, "The effect of seasonal soil-moisture conditions on near-surface seismic reflection data quality," *Geophysical Prospecting*, in review.

Baker, G. S., C. A. McIntyre, L. A. Walczak and D. Steeples, "Improving ultrashallow seismic reflection data by reducing source energy," Expanded Abstracts, SEG 2000 International Exposition and 70th Annual Meeting, Calgary, Canada, in press.

Schmeissner, C., D. W. Steeples, Mario Pavlovic, Renato Prado, and Kyle Spikes, Recording seismic reflections using rigidly interconnected geophones: Expanded Abstracts, SEG 2000 International Exposition and 70th Annual Meeting, Calgary, Canada, in press.

Spikes, K. T., D. W. Steeples, C. Schmeissner, and R. Prado, Varying effective mass of geophones: SEG 2000 International Exposition and 70th Annual Meeting, Calgary, Canada, poster session.

Published Abstracts

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, 1998, 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, 1998, 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.

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.

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, Hamburg, Germany, June.