Time-Series Monitoring in Fractured-Rock Aquifers

Carole D. Johnson, John W. Lane, Jr., and Frederick D. Day-Lewis, United States Geological Survey

Abstract

Time-lapse monitoring of subsurface processes is an emerging and promising area of hydrogeophysics. The combined use of non-invasive or minimally invasive geophysical methods with hydraulic and geochemical sampling is a cost-effective approach for aquifer characterization, long-term aquifer monitoring, and remediation monitoring. Time-lapse geophysical surveys can indirectly measure time-varying hydrologic parameters such as fluid saturation or solute concentration. Monitoring of time-varying hydrologic processes provides insight into aquifer properties and structure and aquifer responses to natural or induced stresses, such as seasonal fluctuations or fluid injection experiments for active remediation.

The U.S. Geological Survey (USGS) Office of Ground Water, Branch of Geophysics, in cooperation with USGS Toxic Substances Hydrology Program, Environmental Protection Agency (USEPA), Department of Defense, the University of Connecticut, and Stanford University researchers, has applied time-lapse geophysics for site characterization and remediation monitoring in a number of studies. Recent and ongoing examples of time-lapse monitoring in fractured-rock aquifers include: 1) application of attenuation-difference, borehole-radar tomography used to monitor a series of sodium chloride tracer injection tests in fractured crystalline rock; 2) application of attenuation- and velocity-difference tomography and radar-reflection data to monitor steam injection in a fractured limestone aquifer; 3) design of an electrical resistivity tomography investigation to monitor the injection of resistive water into brackish water in a fractured limestone aquifer for aquifer storage and recovery (ASR); and 4) combined application of borehole-geophysical logging with long-term discrete-interval monitoring of hydraulic head and water-chemistry in a fractured crystalline-rock aquifer. These investigations demonstrate the application of geophysical methods to provide quantitative information about the subsurface critical for characterizing aquifer structure, flow dynamics, and hydraulic processes.

Final copy as submitted to 2004 U.S. EPA/NGWA Fractured Rock Conference for publication as: Johnson, C.D., Lane, J.W., Jr., and Day-Lewis, F.D., 2004, Time-series monitoring in fractured-rock aquifers, *in* 2004 U.S. EPA/NGWA Fractured Rock Conference: State of the Science and Measuring Success in Remediation, September 13-15, 2004, Portland, Maine. Proceedings: National Ground Water Association, CD-ROM, p. 295-307.

Biographical sketches

Carole D. Johnson *is a Hydrologist with the USGS Office of Ground Water (OGW), Branch of Geophysics in Storrs, Connecticut. Her research interests* include *integrated analysis and interpretation of hydraulic and borehole- and surface-geophysical data, and the use of geophysics to inform the design and implementation of hydrologic investigations at fractured rock sites. She has worked for the USGS for 19 years, and has a B.S. in geology from Bates College and an M.S. in hydrology from the University of New Hampshire.*
USGS-OGW-BG, 11 Sherman Pl, U-5015, Storrs, Connecticut 06269, phone: 860-487-7402,
fax 860-487-8802 cjohnson@usgs.gov

John W. Lane, Jr. *is the Chief of the USGS OGW, Branch of Geophysics in Storrs, Connecticut. He started his career with the USGS in 1988 and has conducted extensive research in the use of surface- and borehole-geophysical imaging methods for water-supply and contamination studies. His recent work focuses on developing and testing of emerging geophysical methods to image near-surface geologic structure, measure hydraulic properties, and estimate physical properties that control hydrologic processes. He has also been involved in numerous training courses and workshops to bring the use of geophysics to ground-water investigations. He has served as an associate editor of Journal of Environmental and Engineering Geophysics and president of the Minerals and Geotechnical Logging Society. He holds B.S. and M.S. degrees in geology and geophysics from the University of Connecticut and is completing doctoral work at Columbia University.*
USGS-OGW-BG, 11 Sherman Pl, U-5015, Storrs, Connecticut 06269, phone: 860-487-7402

Frederick D. Day-Lewis *received a B.S. in Hydrology and a B.A. in English from University of New Hampshire in 1994, and a PhD in Hydrogeology from Stanford University in 2001. He is currently an Assistant Professor of Geology at Bucknell University, Lewisburg, PA, and a Hydrologist at the USGS, OGW, Branch of Geophysics, in Storrs, CT. His current research concentrates on near-surface geophysical aquifer characterization and the application of geostatistical methods to geophysical data. He has published journal articles in Water Resources Research, Geophysics, Geophysical Research Letters, and the Journal of Environmental and Engineering Geophysics. He serves as an associate editor for Hydrogeology Journal and Ground Water.*
USGS-OGW-BG, 11 Sherman Pl, U-5015, Storrs, Connecticut 06269, phone: 860-487-7402

Time-Series Monitoring in Fractured-Rock Aquifers

Carole D. Johnson, John W. Lane, Jr., and Frederick Day-Lewis, U.S. Geological Survey

Introduction

The three-dimensional geometry of fracture networks and the heterogeneous variability of hydraulic properties in fractured rock are highly complex. Typically, conceptual models of fracture geometry are based on sparse direct observations of hydraulic properties measured within a limited number of intervals in a limited number of boreholes; thus conventional methods of inferring fracture statistics and hydraulic properties use information from only a small portion of the subsurface. Hole-to-hole geophysical methods can provide valuable information about regions between boreholes that cannot be sampled directly. By collecting hole-to-hole geophysical surveys before, during, and after hydraulic or fluid chemistry changes are imposed on an aquifer, geophysical methods are able to image time-varying properties in the subsurface and effectively produce snapshots of the changes in the aquifer over time.

Time-lapse monitoring of subsurface processes is an emerging and promising area of hydrogeophysics. The combination of non-invasive or minimally invasive geophysical methods to indirectly measure time-varying properties (for example, fluid saturation and solute concentration) with direct hydraulic and geochemical sampling is a cost-effective approach for aquifer characterization and monitoring. Monitoring of time-varying processes permits an understanding of the dynamic properties of the aquifer and their responses to natural or induced stresses, such as seasonal fluctuations or response to a fluid injection used for active remediation. By using differencing techniques, where the data set from background conditions is subtracted from a data set collected under stressed conditions, an image of the changes between the two data sets is produced. These differences relate to hydrophysical changes within the aquifer that would be impossible to delineate with hydraulic testing alone. With a limited number of water-quality samples to corroborate the geophysical monitoring, the spatial and temporal distribution of the fluid changes can be geophysically imaged over a region of the aquifer. In some cases, automated geophysical monitoring can provide nearly continuous sampling, thus reducing the need for costly frequent water-quality samples at multiple sampling locations.

Examples of time-series monitoring in porous media have demonstrated a valuable role in design and interpretation of engineered remediation processes (Lane and others, 2004) as well as in assessment of transport and aquifer properties (Singha and Moysey, 2004). The USGS Office of Ground Water, Branch of Geophysics, in cooperation with USGS Toxic Substances Hydrology Program, USGS Ground-Water Resources Program, USGS Ground-Water Resources Program, USEPA, DOD, the University of Connecticut, has initiated time-lapse geophysics for site characterization, monitoring fluid movement, and remediation monitoring at a number of fractured-rock sites.

Field Experiments

Four recent and ongoing examples of time-lapse monitoring in fractured-rock aquifers are reviewed. They include: 1) application of attenuation-difference, borehole-radar tomography used to monitor a series of sodium-chloride tracer injection tests in fractured crystalline rock; 2) application of attenuation- and velocity-difference tomography and radar-reflection data to monitor steam injection in a fractured limestone aquifer; 3) design of an electrical-resistivity tomography (ERT) investigation to monitor the injection of resistive freshwater into a brackish fractured limestone aquifer; and 4) application of combined use of borehole-geophysical logging with long-term discrete-interval monitoring of hydraulic head and water-chemistry in a fractured crystalline-rock aquifer. These investigations demonstrate the application of geophysical monitoring methods to provide quantitative information about the subsurface critical for characterizing aquifer structure, flow dynamics, and hydraulic processes.

Borehole radar was used to monitor a saline-tracer doublet test in fractured igneous and metamorphic rock in FSE well field at the USGS Fractured-Rock Research site near Mirror Lake in Grafton County, New Hampshire (fig. 1A). This research was performed in cooperation with the USGS Toxic Substances Hydrology Program. Detailed results have been presented by Lane and others (1998, 1999, 2000) and by Day-Lewis and others (2003, 2004). The purpose of the experiments was to use attenuation-difference radar tomography to characterize a permeable fracture zone and image the movement of a saline tracer at a depth of about 40 meters (m) in the FSE1-FSE4 well cluster, which consists of four boreholes that approximate a 9-m square (fig. 1B). A slug of chloride tracer at a concentration of 30 grams/Liter was injected into a discrete-fracture zone in FSE1 at a constant rate of 1.9 Liters/minute (L/min) for 10 minutes, as FSE4 was pumped from an isolated zone at a rate of 3.8 L/min (fig. 2). Hole-to-hole borehole radar data were acquired between three well pairs during the tracer test (fig. 1B). Borehole-radar methods are effective for detecting saline tracers because of the sensitivity of electromagnetic waves to the electric properties of the medium through which they propagate. By injecting a saline, electrically conductive solution into the fracture system, the electric properties of the water in transmissive fractures are changed. These changes can be measured using both hole-to-hole radar tomography and single-hole radar reflection methods.

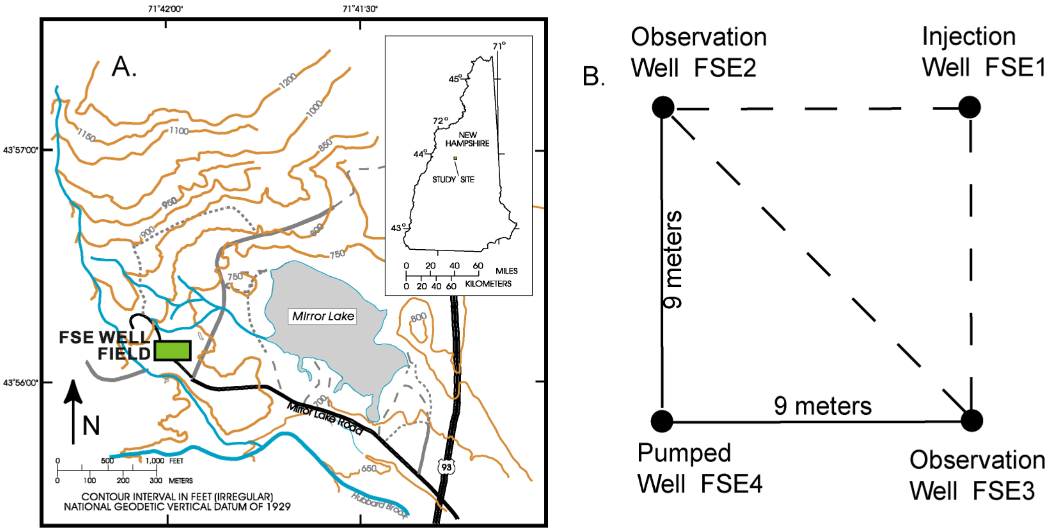

Figure 1. (A) Location of the FSE well field and the U.S. Geological Survey Fractured Rock Hydrology research site near Mirror Lake in Grafton County, New Hampshire and (B) location of wells FSE1-4 and locations of hole-to-hole radar surveys, which are shown as dashed lines.

Hole-to-hole tomography data collected before and during tracer injection were differenced, and the difference data were inverted to produce attenuation-difference tomograms that delineate permeable fracture zones affected by the presence of the electrically conductive saline tracer. Differencing methods remove anomalies in the tomograms that do not change over time, such as anomalies caused by lithology, thereby producing an image of the changes that occurred over the tomographic plane. The time-series attenuation-difference tomograms between FSE-2 and FSE-3 show attenuation over a zone at a depth of about 45 m. The three adjoining tomograms (between FSE-1 and FSE-2, FSE-2 and FSE-3, and FSE-3 and FSE-1) were combined into a single unfolded image in figure 3. The vast majority of the tomogram and the bedrock remain unchanged (dark blue) during the pumping test. The attenuation-difference anomalies occur near FSE1 early in the pumping test (at 20 and 50 minutes) and then on the FSE-2 side of the tomogram by 90 minutes (Lane and others, 2000; Day-Lewis and others, 2003). The maximum attenuation difference occurred at about 90 to 120 minutes into the test. After 200 minutes into the test, the attenuation had returned to background conditions, indicating that the saline tracer had moved past the FSE-2 to FSE-3 plane. Although there was a known hydraulic connection between the injection and the pumped zones, the geophysical imaging results indicate the flow between them is highly complex and indirect. Tracer does not migrate uniformly from FSE-1 to FSE-4, but rather is diverted toward FSE-2. These radar results along with the concentration breakthrough data at the pumped well showed that the saline tracer migrated though interconnected fractures inside and outside of the imaged planes to arrive at the pumped borehole. Collectively these results demonstrate how time-lapse monitoring can be used to image the hydraulic changes to the aquifer and the flow paths of a saline tracer during a tracer test.

By combining conventional tracer testing with time-lapse radar monitoring, an electrically conductive tracer can be tracked as it moves through a fracture network. The results of this experiment were used to calibrate a high-resolution flow and transport model (Day-Lewis and others, 2004) and improve the understanding of solute transport in the FSE well field.

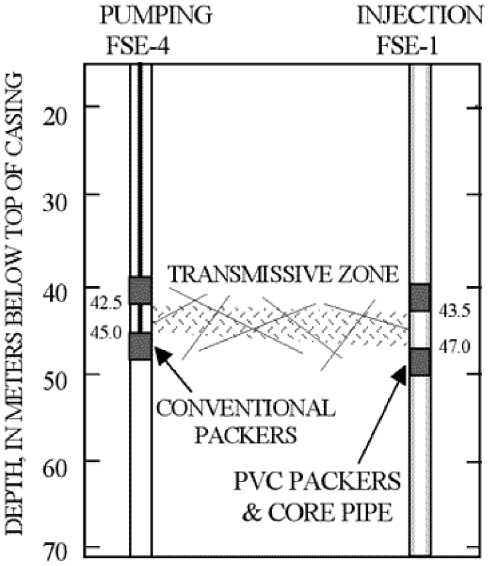

Figure 2. Arrangement of PVC and conventional straddle packers used to isolate a transmissive zone in FSE-1 and FSE-4 at the FSE well field, Mirror Lake, New Hampshire. (From Lane and others, 1999)

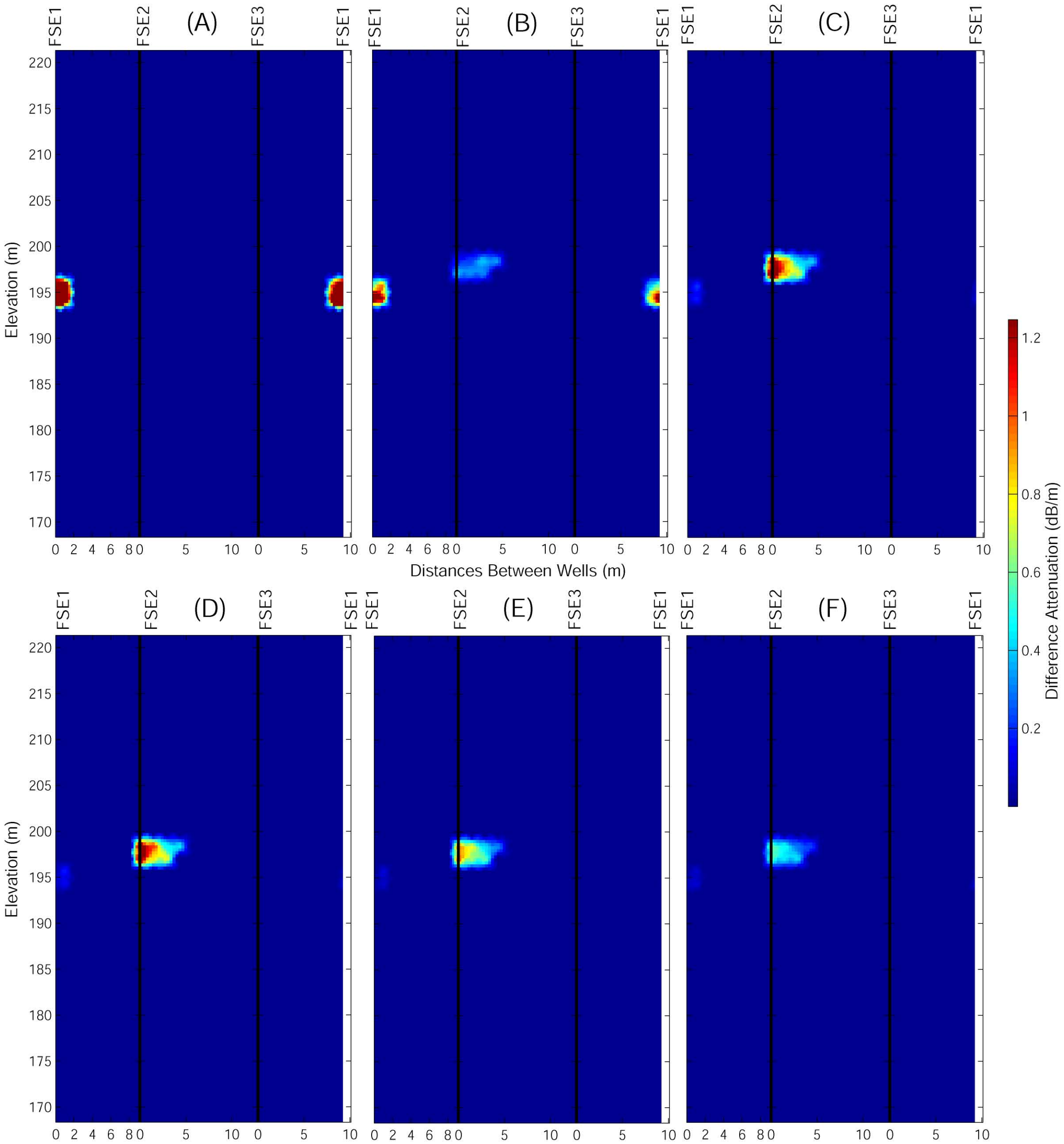

Figure 3. 100 megahertz time-lapse attenuation-difference radar tomograms between FSE-1 and FSE-2, FSE-2 and FSE-3, and FSE-3 and FSE-1 at the FSE well field, Mirror Lake, New Hampshire. Shown are (A) 20-minute, (B) 50-minute, (C) 90-minute, (D)120-minute, (E)150-minute, and (F) 200-minute difference-attenuation tomograms from constrained inversion (From Day-Lewis and others, 2003).

Radar reflection and hole-to-hole radar tomography data were collected as part of a an experiment to test the use of radar methods for monitoring a field-scale steam-enhanced remediation pilot project at the former Loring Air Force Base, in Limestone, Maine (fig. 4). The pilot project was undertaken by the USEPA and State of Maine Department of Environmental Protection to evaluate the effectiveness of steam to treat ground water in a fractured-limestone aquifer contaminated with chlorinated hydrocarbons (Davis, 2003). The objectives of the borehole-radar investigations were to delineate changes caused by injection of steam into the fractured-rock aquifer in the vicinity of two boreholes and to evaluate the effectiveness of borehole-radar methods to monitor the movement of steam and transport of heat in the subsurface. Single-hole radar-reflection and hole-to-hole radar tomography data were collected between two boreholes (JBW-7816 and JBW-7817A), which were separated by 7 m (fig. 4). The boreholes were located within the steam injection zone.

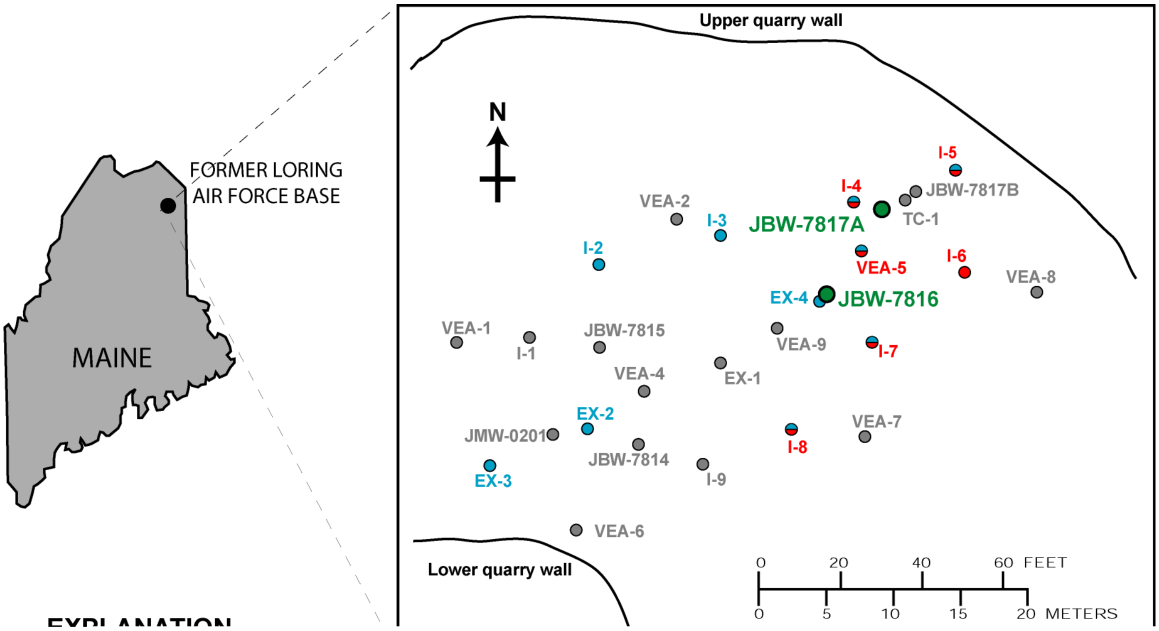

Figure 4. Location of the boreholes at the former Loring Air Force Base quarry site, Limestone, Maine. The single-hole radar reflection and hole-to-hole tomography surveys were collected in boreholes JBW-7816 and JBW-7817A.

Theoretical models predict changes in subsurface temperature cause changes in radar-wave velocity, attenuation, and reflectivity of fractures. 1) Radar-wave velocity is predicted to increase slightly in heated water, but is predicted to decrease in heated limestone. If steam replaces water in the fractures, the velocity of the radar wave in steam is higher than in water. 2) Radar-wave attenuation is predicted to increase slightly in heated water in the fractures and to increase more significantly in heated limestone matrix. The attenuation of the radar wave in steam in the fractures is slightly less than in water. 3) The radar-wave reflection coefficient (reflectivity) of a thin, water-filled fracture decreases with heating, and decreases by a factor of ten if steam replaces water in the fracture. The reflectivity increases if the conductivity of the water in the fractures increases (Grégoire and others, 2004, and in press).

Radar data were collected in August 2002 before the steam injection; in September 2002, a week after the start of the steam injection,; and in November 2002, near the end of the steam injection. The differences in the geophysical data were attributed to changes made to the aquifer as a result of the steam injections. Additional borehole geophysical logs, including fluid temperature, electromagnetic (EM) conductivity, and borehole deviation, were collected to aid in the interpretation and processing of the radar data. In borehole JBW-7817A the temperature increased as much as 40 ^{o}C above background to a maximum of 47 ^{o}C; whereas in borehole JBW-7816 the temperature increased only 10 ^{o}C above background. The field data were interpreted in the context of theoretical petrophysical models that were developed to predict the effect of heating on radar wave propagation.

Single-hole radar reflection profiles indicate there is an increase in the radar attenuation, especially in borehole JBW-7817A in the November 2002 data set (fig. 5). Selected reflectors (shown with red arrows) were analyzed for changes in amplitude and phase of the reflection across the three temporal data sets. Based on this analysis, the single-hole reflection data did not indicate the presence of pure steam in the fractures. Two explanations for the data include (1) the steam did not completely replace the water in the fractures, but rather condensed following injection; or (2) pure-phase steam in the fractures could not be detected due to the small aperture of the fractures. One very strong reflector shows up in the September 2002 data set (shown as zone 3 with a yellow arrow); however, the reflection does not appear in either of the other two data sets. The cause of this feature cannot be explained by the petrophysical models for this site.

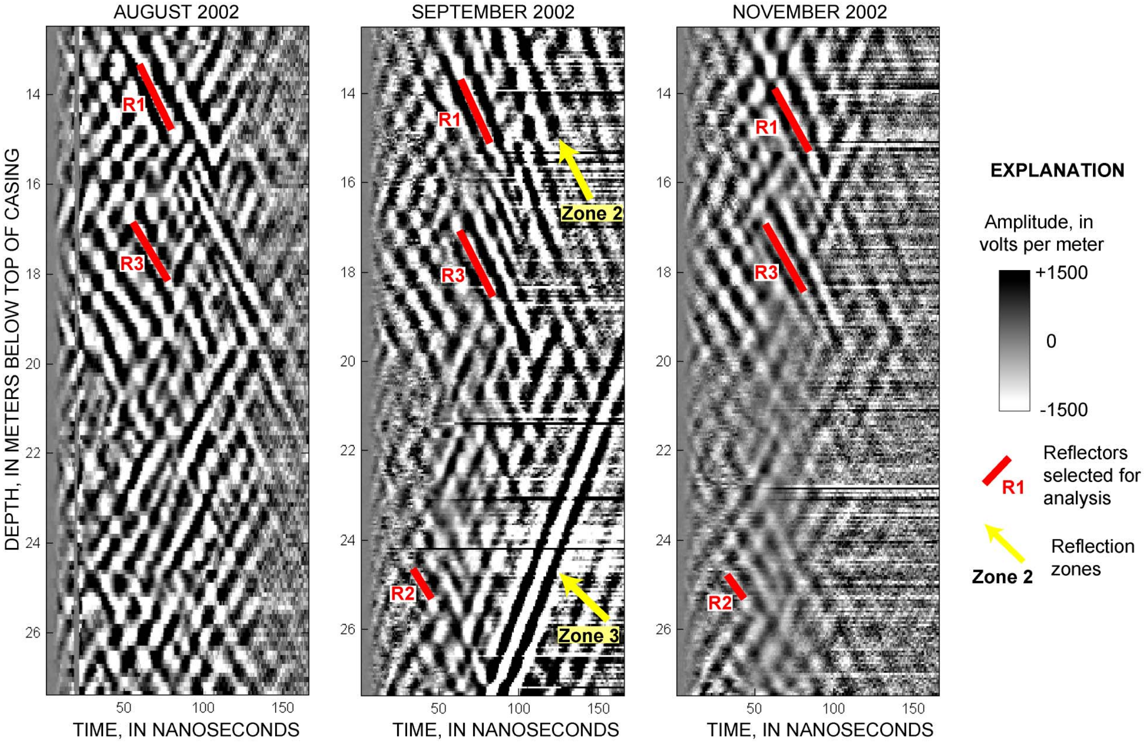

Figure 5. 100-megahertz omni-directional borehole-radar data collected in borehole JBW-7817A during August, September, and November 2002 at the former Loring Air Force Base quarry, Limestone, Maine. The gain function is the same for all profiles.

Small increases in the hole-to-hole radar attenuation were observed at a depth of about 20 m after the data were processed and adjusted for variations in the antenna power output (fig. 6). The attenuation difference tomogram, which was constructed by differencing the November and August 2002 data sets, shows a change in the attenuation below about 20 m. This anomaly was consistent with an increase in the temperature logs observed at that depth. The results showed an increase in the attenuation in the hole-to-hole data, which is consistent with the single-hole reflection data (from 7817A), suggesting that limestone electrical conductivity increased as a result of heating of the limestone matrix.

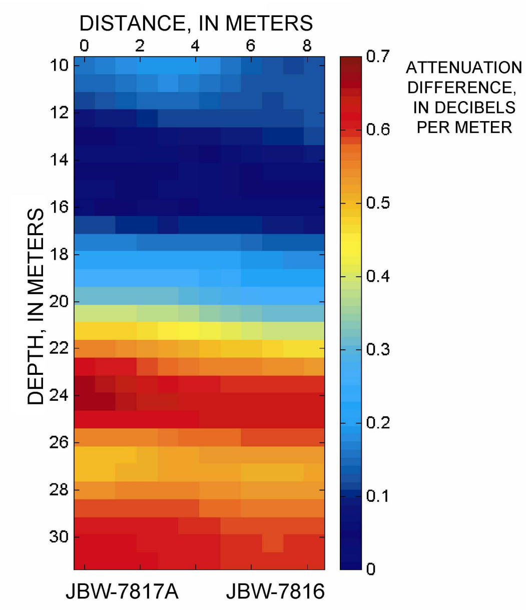

Figure 6. Results of the inversion of the attenuation-difference radar tomography data between boreholes JBW-7817A and JBW-7816 using November-August 2002 data from the former Loring Air Force Base quarry, Limestone, Maine at the former Loring Air Force Base quarry, Limestone, Maine.

Application of electrical resistivity tomography to monitor an artificial storage and recovery test

Electrical resistivity tomography (ERT) surveys and analysis produce an image of the spatial variability of resistivity between boreholes. ERT data collected before and during tracer injections can be differenced, thereby producing a tomogram that indicates electrical changes in the water and flow-paths between the well pairs. Methods for ERT imaging are described by Daily and Owen (1991) and by Slater and others (2000). ERT is being used to monitor the injection of electrically resistive water into brackish water as part of an artificial storage and recovery (ASR) experiment in fractured limestone in Charleston, South Carolina. This investigation was designed to monitor the injection, holding, and removal of water injected into the aquifer. This is an ongoing investigation, in which the equipment has been deployed, and real-time data acquisition, monitoring and remote controls of the ERT system have been installed. The injection test is scheduled for late 2004.

Three boreholes are arranged in a triangular pattern with an injection well in the middle of the observation wells, about 9 m from each of the boreholes. Three wells have been instrumented with electrodes extending across the two transmissive zones. Preliminary results and borehole geophysical data indicate the injected water will recharge two primary transmissive fracture zones at a depth of 120 and 134 m below land surface. Borehole geophysical data indicate the lower fracture zone is nearly three times as transmissive as the upper zone. There was minor ambient downflow at the site. Cross-hole flowmeter logs showed flow was more rapid through the lower aquifer than through the upper aquifer. Thus, injection of resistive water into the center borehole is likely to propagate more rapidly along the more transmissive zone followed by flow in the zone with the lower transmissivity. These preliminary insights facilitate design of time-lapse ERT monitoring schemes.

This ASR application follows an investigation that successfully used ERT to monitor saline-tracer movement through a sand and gravel aquifer at the Massachusetts Military Reservation Cape Cod, Massachusetts (Singha and others, 2003). In that investigation, tomographic images were collected in the image planes between four wells, nearly continuously for 20 days after a 9-hour slug injection of an electrically conductive sodium-chloride tracer. Three-dimensional tomograms were generated and compared to the concentrations measured at a 15-point multilevel sampler. The ERT tomograms delineate the spatial extent and temporal distribution of the saline tracer during the experiment. The results are being analyzed to estimate aquifer properties of the sand and gravel aquifer.

Integrated use of borehole geophysical logging and discrete-zone hydraulic and water-quality monitoring in a contaminated crystalline-rock aquifer

Integrated borehole-geophysical and hydraulic methods were used to design discrete-zone monitoring (DZM) systems to monitor changes in the hydraulic head and water chemistry in a crystalline-rock aquifer contaminated by former chemical-waste-disposal pits at the University of Connecticut landfill, Storrs, Connecticut (fig. 7A) (Johnson and others, 2002; Johnson and Kastrinos, 2002). DZM systems in bedrock wells were used to prevent cross contamination, obtain water samples, measure hydraulic head, assess hydraulic gradients between the bedrock and the glacial-drift deposits, and monitor the potential for ground-water flow spatially and temporally (Johnson and others, 2001). Manual and continuous discrete-zone water-level measurements were used to identify and characterize relationships between long-term water-level patterns and precipitation, topographic setting, contaminants at the site, and the conceptual ground-water-flow model. Water samples were collected quarterly from the DZM systems and from overburden wells and were analyzed for volatile organic compounds, metals, inorganics and other parameters to track the contamination from the landfill source and from the former chemical-waste-disposal pits. Two chemical signatures were identified and were used to track the chemical distributions within the bedrock. Discrete-interval hydraulic and chemical data collected for a period of two years showed that, over most of the study area, the ground-water flow direction remained constant seasonally and that the contaminant plumes are at a steady state (Haley and Aldrich, 2002). The combined head and water-chemistry data are shown in figure 6B for a single cross-section along the southern flow path at the site. The flow potential lines were determined from analysis of the discrete-interval head data and water-chemistry data (fig. 7B). The conceptual model for flow is superimposed on the water-chemistry data in the cross section (fig. 7B).

The results of this study illustrated the importance of discrete-zone isolation and long-term monitoring in fractured-rock aquifers to prevent cross-contamination while permitting head measurements and water-quality sampling that were used to characterize contaminant migration over time in the fractured-rock aquifer, which might not have been identified without the discrete-interval data. The discrete-interval, time-series data helped to establish, refine, and verify a conceptual model of ground-water flow in the study area that explained the distribution of contamination. These results were used by the University to inform their assessment of possible remedial alternatives at the site (Haley and Aldrich, 2002).

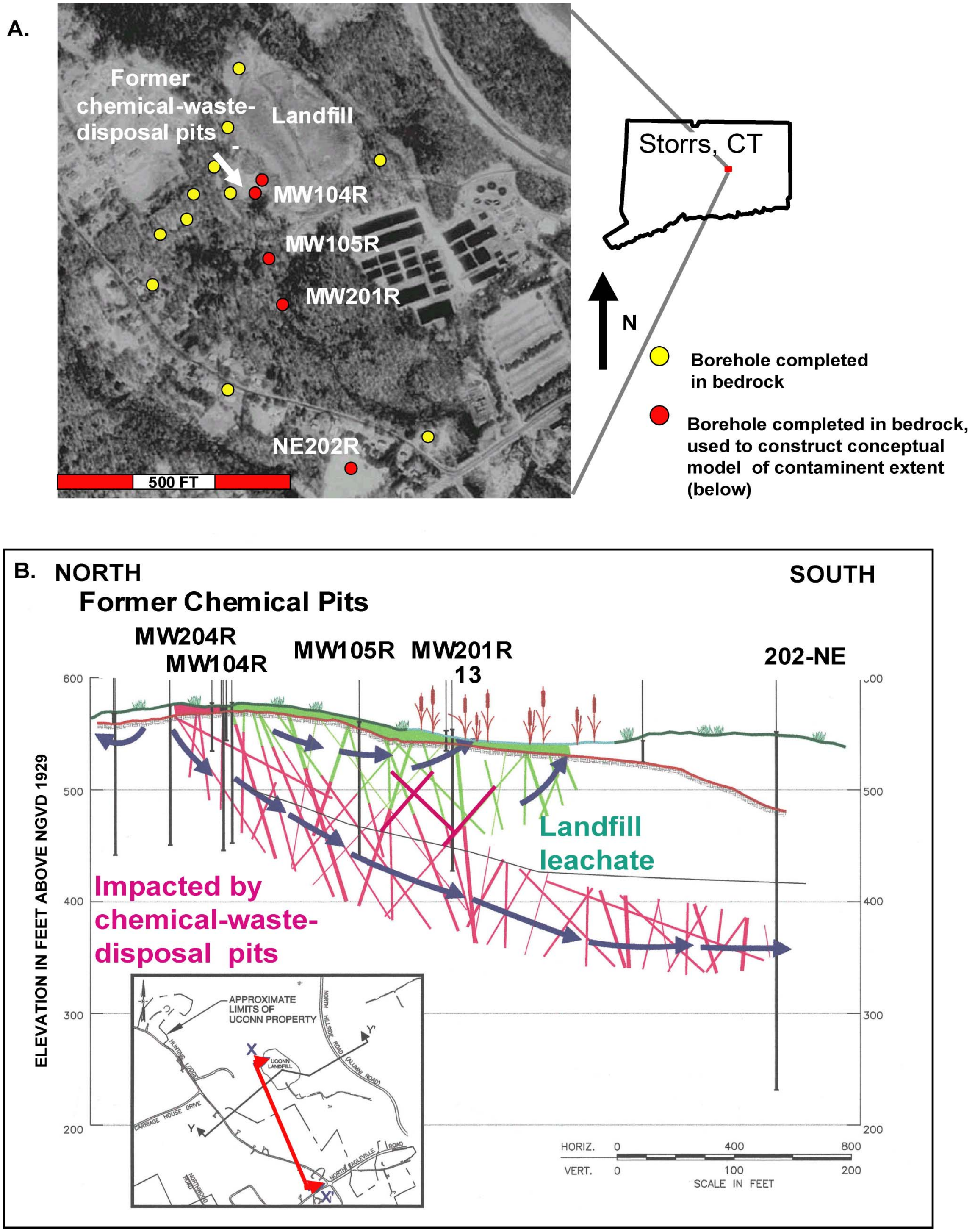

Figure 7. (A) Location of the landfill, former chemical-waste-disposal pits, and boreholes completed in bedrock at the University of Connecticut, Storrs, Connecticut, and (B) conceptual flow lines (shown by blue arrows) and contaminant distribution along a flowpath southwest of the landfill. Red hatches indicate areas impacted by chemical-waste-disposal pits, and green hatches indicate areas impacted by landfill leachate.

Conclusions

Investigations of time-series monitoring conducted by the USGS Office of Ground Water, Branch of Geophysics have focused on testing and improving geophysical and hydraulic methods to identify the spatial and temporal distributions of contamination, tracers, and injections used to enhance degradation of contaminants. The experimental results from these investigations indicate that time-lapse geophysical imaging and hydraulic methods can provide valuable insights on the flow dynamics in fractured rock aquifers. These methods can provide detailed characterization of the fracture network and hydrologic properties that are important for ground-water flow and transport investigations. In addition, time-series monitoring provides nearly real-time understanding of flow dynamics and insights for design, verification, and modification of complementary monitoring operations such as water-quality measurement sites, sampling intervals, or for planning remediation strategies.

Acknowledgments

The authors would like to acknowledge Steve Gorelick and Jerry Harris from Stanford University as well as Paul Hsieh and Allen Shapiro of the USGS for their contributions to the geophysical monitoring of a saline-tracer test at Mirror Lake. The authors appreciate the work of Colette Grégoire of Katholicke Universiteit Leuven, Department of Civil Engineering and Peter Joesten of the USGS who conducted much of the research for the Loring SER investigation. The authors gratefully acknowledge the assistance of Mike Nalipinski, Richard Steimle, and Eva Davis, all of the USEPA; Greg Crisp, formerly of SteamTech Environmental Services, Inc.; and Naji Akladiss, of Maine Department of Environmental Protection, with the Loring SER investigation. The authors are grateful to Roelof Versteeg of Idaho National Environmental and Engineering Laboratory and Kamini Singha of Stanford University for their technical guidance and assistance in the ERT investigation at the ASR site. In addition, we are grateful to Mathew Petkewich, Kevin Conlon, and John Williams of the USGS for their assistance in data collection and field assistance at the ASR site. We are also grateful to the numerous USGS employees, especially F. Peter Haeni, who contributed to the UConn Landfill investigation.

References

Day-Lewis, F. D., Lane, J.W., Jr., Harris, J.M., and Gorelick, S.M., 2003, *Time-lapse imaging of saline tracer tests using cross-borehole radar tomography:* Water Resources Research, v. 39, no. 10, 14 p., 1290, doi:10.1029/2002WR001722.

Day-Lewis, F. D., J. W. Lane, Jr., and S. M. Gorelick, *in press, Combined interpretation of radar, hydraulic and tracer data from a fractured-rock aquifer*: Hydrogeology Journal.

Day-Lewis, F. D., and J. W. Lane, Jr., 2004, *Assessing the resolution-dependent utility of tomograms for geostatistics*: Geophysical Research Letters, v. 31, L07503, doi:10.1029/2004GL019617, 4 p.

Davis, Eva, 2003, *Demonstration Bulletin: Steam enhanced remediation, Superfund innovative technology evaluation*: U.S. Environmental Protection Agency, April 2003, 2 p. (EPA/540/MR-03/503).

Daily, W. and Owen, E. 1991, *Cross-borehole resistivity tomography*: Geophysics, v.56, p. 1228-1235.

Grégoire, C., Lane, J.W., Jr., and Joesten, P.K., *in press*, *The use of borehole radar tomography to monitor a steam injection pilot study in a contaminated fractured limestone, in* EAGE (European Association of Geoscientists and Engineers) Near Surface Geophysics meeting, 6-9 September, 2004, Utrecht, The Netherlands, Proceedings: European Association of Geoscientists and Engineers, 4 p.

Grégoire, C., Lane, J.W., Jr., and Joesten, P.K., 2004, *Application of borehole radar for monitoring steam-enhanced remediation of a contaminated site in fractured limestone, Maine, USA*, *in* Hack, R., Azzam, R., and Charlier, R., eds., Engineering Geology for Infrastructure Planning in Europe--a European Perspective, Lecture Notes in Earth Sciences: Springer-Verlag, p. 385-392.

Haley and Aldrich, Inc.; Environmental Research Institute; Epona Associates, LLC; F.P. Haeni, LLC; and Regina Villa Associates, Inc., with technical oversight by Mitretek Systems, Inc., 2002, *Draft comprehensive hydrogeologic investigation and remedial action plan, University of Connecticut, Storrs, Connecticut*: Haley and Aldrich, Inc., File No. 91221-513.

Johnson, C.D., Haeni, F.P., and Lane, J.W., Jr., 2001, *Importance of discrete-zone monitoring systems in fractured-bedrock wells - a case study for the University of Connecticut landfill, Storrs, Connecticut*, *in* Fractured Rock 2001 Conference, March 26-28, 2001, Proceedings: University of Waterloo Solvents-in-Groundwater Research Program, CD-ROM.

Johnson, C.D., Haeni, F.P., Lane, J.W., Jr., and White, E.A., 2002, *Borehole-geophysical investigation of the University of Connecticut landfill, Storrs, Connecticut*: U.S. Geological Survey, Water-Resources Investigations Report 01-4033, 187 p.

Johnson, C.D., and Kastrinos, J.R., 2002, *Use of geophysical, hydraulic, and geochemical methods to develop a site conceptual ground-water flow model in central Connecticut, in* Fractured Rock 2002, Denver, Colorado, March 13-15, 2002, Proceedings: National Ground Water Association.

Lane, J.W., Jr., Casey, C.C., Day-Lewis, F.D., Witten, A., and Versteeg, R.J., 2004, *Use of borehole radar methods and borehole geophysical logs to monitor a field-scale vegetable oil biostimulation pilot project at Fridley, Minnesota, in* Proceedings of the Fourth International Conference on Remediation of Chlorinated and Recalcitrant Compounds, May 24-27, 2004, Monterey California. Battelle Memorial Institute, CD-ROM, 9 pages.

Lane, J.W. Jr., Joesten, P.K., Haeni, F.P., Vendl, Mark, and Yeskis, Doug, 1998, *Use of borehole-radar methods to monitor the movement of a saline tracer in carbonate rock at Belvidere, Illinois*, *in* Symposium on the Application of Geophysics to Engineering and Environmental Problems, March 22-26, 1998, Chicago, Illinois, Proceedings: Environmental and Engineering Geophysical Society, p. 323-332.

Lane, J.W., Jr., Haeni, F.P., and Day-Lewis, F.D., 1998, *Use of time-lapse attenuation tomography methods to monitor saline tracer transport in fractured crystalline bedrock*, *in* the Seventh International Conference of Ground Penetrating Radar (GPR'98), Lawrence, Kansas, May 27-30, 1998, Proceedings: University of Kansas, Radar Systems and Remote Sensing Laboratory, p. 533-538.

Lane, J.W., Jr., Wright, D.L., and Haeni, F.P., 1999. *Borehole radar tomography using saline tracer injections to image fluid flow in fractured rock, in* Proceedings of the U.S. Geological Survey Toxic Substances Hydrology Program: U.S. Geological Survey Water-Resources Investigation Report 99-4018C, v. 3, pp. 747-756.

Lane, J.W., Jr., Day-Lewis, F.D., Harris, J.M., Haeni, F P., and Gorelick, S.M., 2000, *Attenuation-difference radar tomography—Results of a multiple-plane experiment at the U.S. Geological Survey Fractured Rock Research Site, Mirror Lake, New Hampshire, in* Noon, D.A., Stickley, G.F., and Longstaff, D., ed., GPR 2000 - Proceedings of the Eighth International Conference on Ground Penetrating Radar: University of Queensland, p. 666-675.

Singha, K., Binley, A.M., Lane, J.W., Jr., and Gorelick, S.M., 2003, *Electrical imaging of tracer migration at the Massachusetts Military Reservation, Cape Cod*, *in* Symposium on the Application of Geophysics to Engineering and Environmental Problems, April 6-10, 2003, San Antonio, Texas, Proceedings: Environmental and Engineering Geophysical Society, CD-ROM, 11 p.

Singha, K., and Moysey, S., 2004, *Application of a new Monte Carlo approach to calibrating rock physics relationships—examples using electrical resistivity and ground penetrating radar tomography, in* Symposium on the Application of Geophysics to Engineering and Environmental Problems February 22-26, 2004, Colorado Springs, CO, Proceedings: Environmental and Engineering Geophysics Society 20 p.

Slater, L., Binley, A. M., Daily, W., and Johnson, R., 2000, *Cross-hole electrical imaging of a controlled saline tracer injection:* Journal of Applied Geophysics, v. 44, p. 85-102.