Colorado School of Mines, Golden, CO, USA

Multiphysics Simulations Help Track Underground Fluid Movements

Multiphysics simulations are helping geophysicists at the Colorado School of Mines develop a way to track underground fluid flows and to better map and understand subsurface formations and dynamics. One potential application: tracking the fracking fluids used in unconventional natural gas and oil extraction.

BY GARY DAGASTINE

Geophysicists characterize underground formations and events by detecting and analyzing acoustic waves that propagate to the Earth's surface from seismic activity. These waves arise from earth movements caused by natural events such as earthquakes, from underground explosions deliberately set to explore geological features, and from the hydraulic fracturing, or fracking, of tight formations with the goal of increasing permeability.

Although acoustic waves can travel long distances, they have major limitations in providing details about formation properties. They can't be used to directly identify and track the liquids flowing through them, called pore water. Tantalizing research at the Colorado School of Mines, however, suggests that electromagnetic disturbances that can occur in association with seismic events might provide this missing information.

Electromagnetic waves don't propagate as far as acoustic waves, but theoretical models and laboratory experiments conducted with the aid of numerical multiphysics simulations show they can identify and track pore water. The evolving technique, based on work pioneered by Russian and Japanese researchers, opens the door to the complementary use of acoustic and electromagnetic analyses to create a more comprehensive view of the underground world than we now have.

Such a seismoelectric capability would enable better monitoring of shallow earthquakes along tectonic faults and active volcanoes. It also would lead to better tools for the safe development of unconventional energy resources via fracking, and for more effective secondary/enhanced oil recovery in previously worked oil reservoirs.

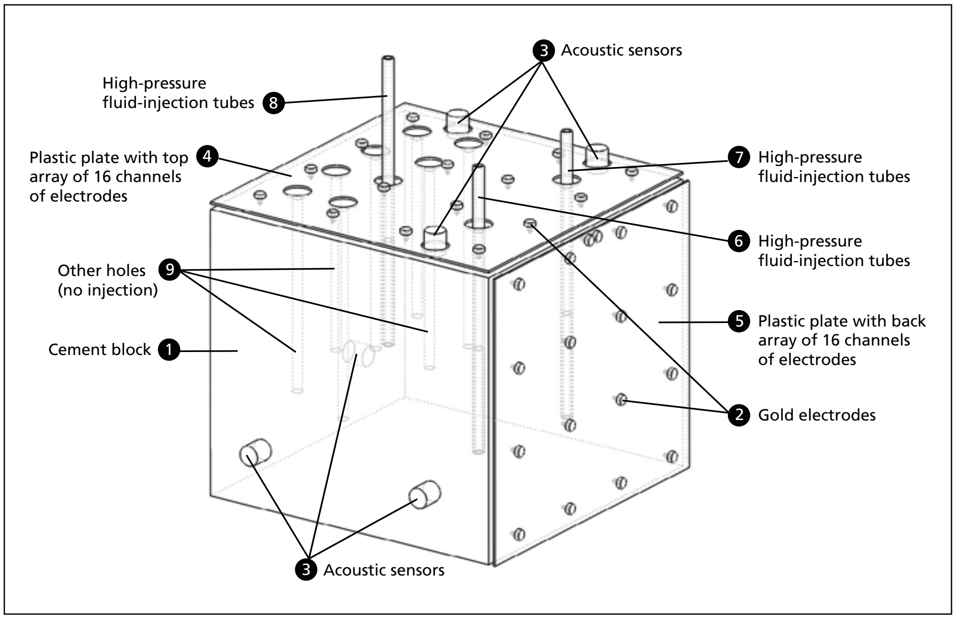

FIGURE 1: Illustration of the cement block used in hydraulic fracturing experiments. (1) Cement block, (2) Gold electrodes, (3) Acoustic sensors, (4) Plastic plate with top array of 16 channels of electrodes, (5) Plastic plate with back array of 16 channels of electrodes, (6-8) High-pressure fluid-injection tubes, (9) Other holes (no injection).

Fracking is a particularly critical and timely issue because of the growing use of the technique, in which fluid is injected into the ground at high pressure to fracture low-permeability shale formations to extract the gas and oil in them. It is vital to know where fracking fluid is going so that the fracking process can be optimized, and to avoid contamination of shallow aquifers.

Geoelectric Signals

Subsurface electromagnetic disturbances stem from the net deficiency of electrical charges on the surfaces of minerals. This deficiency is compensated for by excess charges in the pore water. The flow of the pore water with these excess charges is responsible for an electrical current density (on the order of few milliamperes per square meter).

Because the current varies according to the kinds of formations the water passes through, the hope is that useful inferences can be made based on these electrical signals, which could be detected by a network of electrodes placed on the ground surface and/or in boreholes.

"This method is analogous to electroencephalography — EEG. In EEG, electrical signals are generated at the synapses between the neurons and recorded on the scalp. EEG has been a key method to understand how the brain is working," said André Revil, a leading researcher in this evolving branch of geophysics. "If you put electrodes on your head, you can monitor the electrical activity in areas of interest within your brain, and make informed inferences. We are trying to do the very same thing underground."

Revil is associate professor of geophysics at the Colorado School of Mines, one of the world's leading colleges of mineral engineering, and also a faculty member with the Centre National de la Recherche Scientifique (CNRS) in France. His team for this work includes students Harry Mahardika, who has done a great deal of forward modeling and some inverse modeling with multiphysics software; Allan Haas, who has been the lead experimental investigator; and Marios Karaoulis, research associate, who has co-supervised their work along with Revil.

The team is part of the Colorado college's Unconventional Natural Gas Institute (UNGI). UNGI serves as a focal point to facilitate and promote research and development in all areas of unconventional natural gas, encompassing coal bed methane, tight gas sands, shale gas, and gas hydrates. UNGI combines the resources of seven academic departments and 11 research centers and consortia, forming a critical mass of expertise in the fast-growing field.

Forward and Inverse Modeling

"We found that fracking releases both seismic and electromagnetic energy, and so we developed theories about what the electrical activity associated with these events should look like," Revil said. "To do this, we used COMSOL Multiphysics to simulate fracking events and to produce synthetic seismograms and electrograms, and we coupled MATLAB® and COMSOL to conduct many iterations of forward and inverse modeling thanks to the LiveLink *for* MATLAB®.

"COMSOL saved us a great deal of time because all of the necessary underlying physics, such as hydromechanical equations, is very well defined in the software and we didn't have to spend time calculating it."

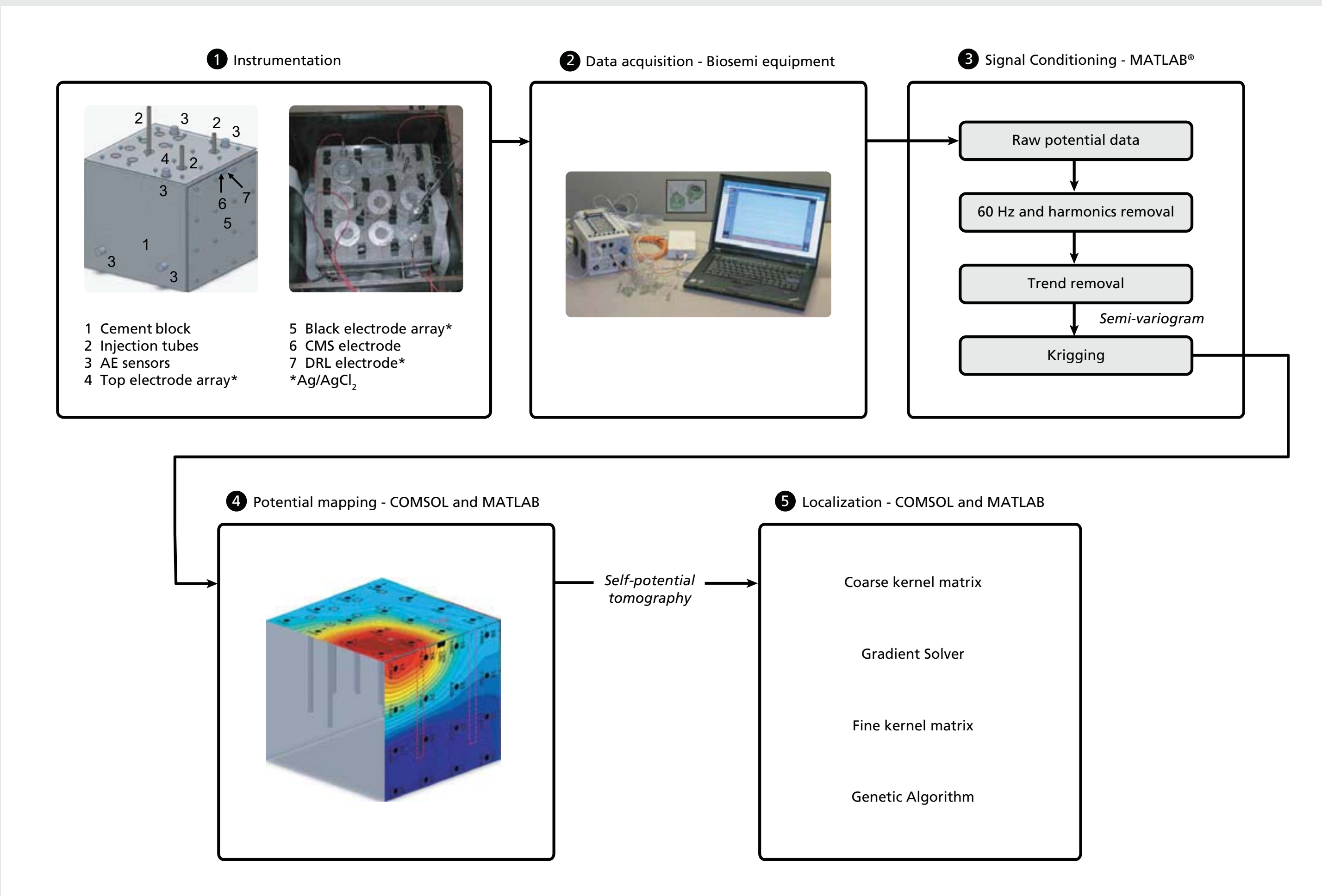

FIGURE 2: Flow chart for the processing of the electrical data. (1) Instrumentation of the porous cement block, (2) Data acquisition system, (3) Signal conditioning of the raw data, (4) Mapping the voltage response using ordinary kriging (geostatistical inferences), (5) Localization of the causative sources in the block.

The forward modeling generated synthetic seismograms and electrograms corresponding to simulated fracking events, while the inverse modeling did the opposite: the inverted simulations calculated all of the possible parameters of the fracking events from the synthetic sensor data. The differences between the forward and inverted results narrowed with repeated adjustments and iterations until a match was obtained.

The next step was to determine how well all of this corresponded to reality. The team designed a laboratory experiment in which they would repeatedly hydraulically fracture a porous cement cube by pumping in saline water under high pressure. The purpose was to see if electric signals could be passively recorded and then inverted to pinpoint the positions of actual fluid leakages over time. They drilled several 10-mm-diameter holes, or "wells," at varying depths in the 30.5 × 30.5 × 27.5 cm cube (see Figure 1).

Various ways to seal the well bores were tested, and stainless steel tubing with a 9.5 mm outside diameter was placed into the holes to simulate well casing. The cube was instrumented with 32 nonpolarizing silver/silver chloride electrodes for voltage measurement, 16 each on the top and one side of the block, plus six acoustic emission sensors mounted on three sides (see Figure 2).

Experiments Validated the Simulations

During the tests, electrical signals were detected that corresponded to fluid leaks along the well seal (see Figure 3), as were bursts of acoustic emissions and fluid pressure changes.

"We used a two-step process to invert the electrical data to pinpoint the position of these leaks," Revil said. "First, we applied a deterministic least-square algorithm to retrieve the source current density at a given point in the block at a given time. Then, we used a genetic algorithm, or probability sampling, to refine the position of the source current density.

"The results of the inversion were in excellent agreement with the location of the wells in question, and also with the acoustic emissions in the vicinity of the wells," he said. "This showed us definitively that passively recorded electric signals can be used to monitor fluid flow along wells during leakages. It also suggests they might be able to monitor fluid flow in numerous other applications that involve hydromechanical disturbances."

The Next Step: Field Trials

The next step is to develop field trials to investigate this technique further, from a few meters to several kilometers in scale.

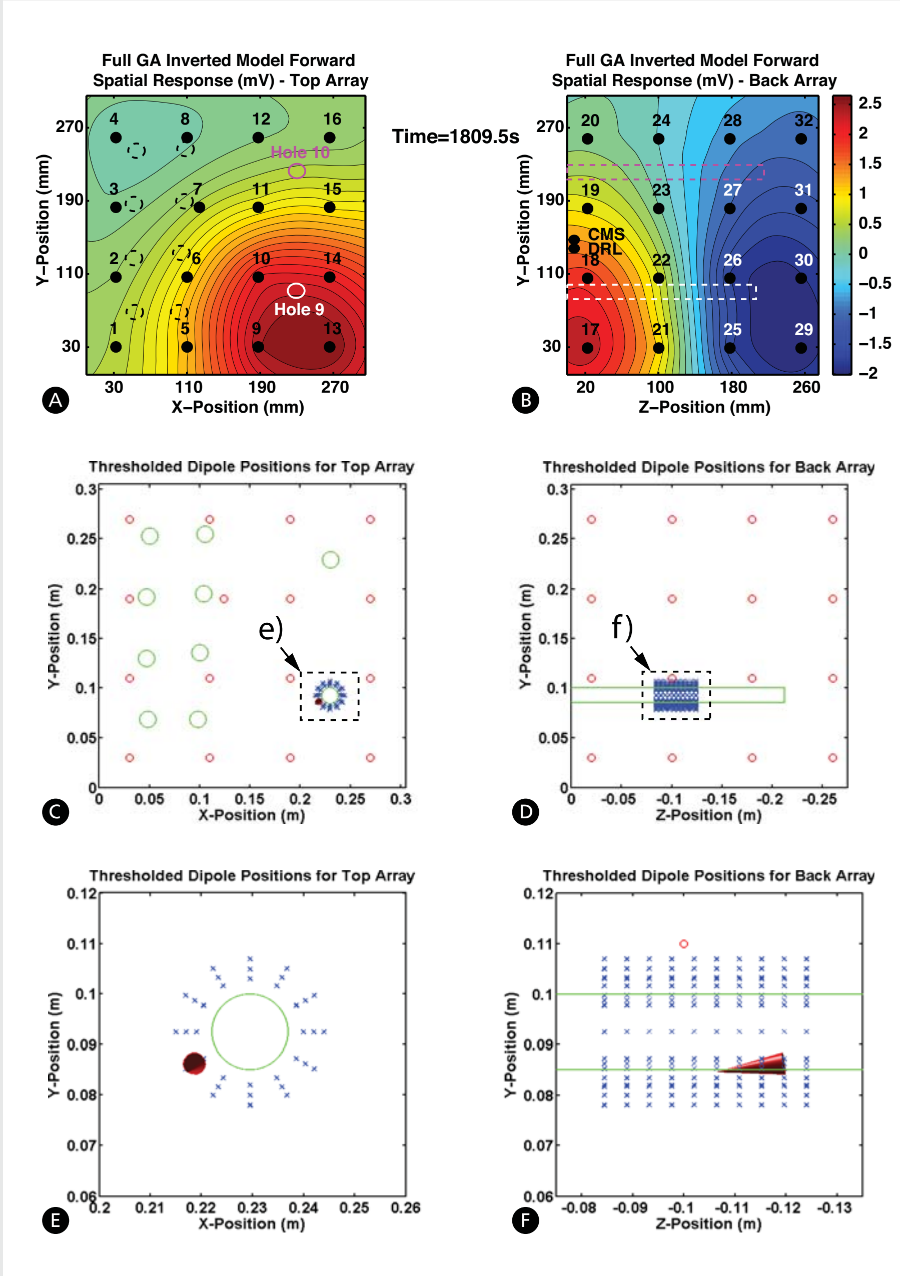

FIGURE 3: Forward-modeled voltage distribution of a dipole for one event (a and b), Spatial location of the dipole within the concrete block (c and d), Close-up of the dipole location (e and f), showing an off-vertical orientation of the dipole moment.

If all goes well, long-sought solutions to important problems may be at hand, such as development of aquifer monitoring and safety systems; better ways to assess the integrity of old, plugged, and abandoned wells; and perhaps even the ability to characterize fractured rock systems via the movement of the fluids within them.

The ultimate goal, said Revil, is to combine the electric data with pressure and acoustic data for a fully integrated analytical capability.

"That level of data fusion has never been done before," he said. "It is a tremendously exciting time to be working in this area." ■