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Advanced Noninvasive Geophysical Monitoring Techniques

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Key Words

time-lapse, deformation, fluid flow, biogeochemical processes

Abstract

Geophysical methods can be used to create images of the Earth's interior that constitute snapshots at the moment of data acquisition. In many applications, it is important to measure the temporal change in the subsurface, because the change is associated with deformation, fluid flow, temperature changes, or changes in material properties. We present an overview of how noninvasive geophysical methods can be used for this purpose. We focus on monitoring mechanical properties, fluid transport, and biogeochemical processes, and present case studies that illustrate the use of geophysical methods for detecting time-lapse changes in associated properties.

1. INTRODUCTION

SP: self-potential

Monitoring structures and processes in the subsurface is of increasing importance. The focus of the petroleum industry has shifted from exploration to monitoring production. When tackling environmental problems, especially those associated with contaminant remediation, it is essential to monitor the processes in the subsurface. Monitoring is routinely performed to assess water resource quality and quantity. An important component in climate change studies is to monitor environmental parameters. Monitoring can be achieved most easily if it can be carried out in situ by direct sampling of the properties of interest. However, for Earth's subsurface this is often not feasible because of technical or economic limitations. Moreover, in situ measurements often have a much smaller support scale than the volume of interest, and the presence of measurement devices used for in situ measurements may disturb the properties that one seeks to measure. For these reasons, noninvasive monitoring techniques are increasingly important.

In this work, we present recent developments in the field of noninvasive geophysical monitoring of the subsurface. Although incomplete, this overview aims to describe ongoing work in research areas of increasing complexity. In Section 2, we discuss monitoring of mechanical properties of Earth, presenting an example of monitoring the deformation of Earth's surface. In principle, this is a simple, noninvasive, monitoring problem, but the required accuracy makes it a challenging problem. Monitoring the mechanical properties of the subsurface can be achieved with seismic waves. Recent research has shown that one can carry out seismic imaging with random noise, rather than controlled seismic sources as the source. This offers the opportunity to continuously monitor the subsurface using ambient noise. The next level of complexity is to monitor fluid flow in the subsurface. In Section 3 we show evidence of a fluid pulse that propagates along a fault zone, as inferred from seismic data, and give an example of monitoring infiltration processes using the self-potential (SP). Another challenge is that of monitoring biogeochemical processes remotely. We treat this problem in Section 4, and show an example of how the redox potential in the subsurface can be inferred from measurements of the self-potential. We also show an example of a controlled laboratory experiment wherein chemical changes caused by microbial activity can be monitored with seismic fields and with induced polarization measurements.

Together, these case studies highlight the potential that geophysical methods hold for monitoring mechanical, fluid, and biogeochemical processes. Although much of this research is in an early stage of development, the advances illustrated by these case studies suggest that further research is warranted.

2. MONITORING MECHANICAL PROPERTIES

2.1. Monitoring Vertical Ground Motion

The simplest way to monitor changes in the subsurface is to detect deformation of the Earth's free surface. Although conceptually straightforward, this is technically challenging because in many applications, to be useful the deformation must be measured with an accuracy smaller than a centimeter. Geodetic techniques are the

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tool of choice. Recent developments in the use of the Global Positioning System (GPS) (Dixon 1991, Enge & Misra 1999) and Interferometric Synthetic Aperture Radar (InSAR) (Massonnet & Feigl 1998, Bamler & Hartl 1998, Bürgmann et al. 2000) make it possible to measure the deformation of the Earth's surface with such an accuracy.

GPS: Global Positioning System

InSAR: Interferometric Synthetic Aperture Radar

InSAR relies on reflections of a radar beam from a satellite to Earth's surface and back. The phase difference of these reflections recorded during subsequent passes of the satellite can be used to create a map of the deformation of Earth's surface in the direction of the reflecting radar beam (Massonnet & Feigl 1998, Bamler & Hartl 1998, Bürgmann et al. 2000). The phase difference between the backscattered waves measured in the two passes of the satellite is based on an interferometric technique that quantifies to which degree the two waves are on phase or out of phase for each pixel on the ground surface. The used pixel size usually is 30 m. Adding an integer number of cycles to one of the waves does not change the interference of these two waves. The phase difference can thus be measured only modulo 2π, where deformation corresponding to a phase difference greater than 2π is shown in color images of the deformation as a repeat in the color palette. The magnitude of the surface deformations measured in one fringe (a phase difference between 0 to 2π) is governed by the satellite radar wavelength (European Space Agency ERS1, ERS2, and ENVISAT and the Canadian Space RADARSAT-1 and RADARSAT-2 all use 5.6 cm C-band) and is calculated by dividing the wavelength in half to account for the two-way travel path of the radar pulse. Therefore, if the land surface subsidence is 85 mm it would be seen as three repeating color cycles of 28.3 mm in the interferogram.

The vertical ground deformation measured with InSAR in **Figure 1** shows the observed subsidence north of Bakersfield, California, associated with hydrocarbon extraction between August 1997 and July 1998. The figure shows two distinct regions of subsidence. The northwest region subsides about 3 cm, and the southeastern region has an overall pattern with 3 cm of subsidence over an area approximately 5 km wide with as much as 5 cm of subsidence in two localized features on the western margin of the subsidence trough. The northwestern region of subsidence is limited by faults on both the eastern and southern margins. Because the faults delimit the subsidence associated with the hydrocarbon extraction, this implies that these faults likely act as barriers for the fluid flow. In this example, InSAR measurements can thus be used to make inferences about the fluid flow in the subsurface, and the sealing properties of faults. InSAR has been used to monitor coseismic and tectonic deformation (Massonnet & Feigl 1998), to monitor the deformation associated with the extraction of water or hydrocarbons (Bawden et al. 2001), and to monitor the heaving of the surface caused by cyclic steam injection in the recovery of heavy oil (Stancliffe & van der Kooij 2001).

2.2. Monitoring Compaction

It is also important to monitor the deformation within the Earth. The compaction of hydrocarbon reservoirs during production leads to mechanical changes in the

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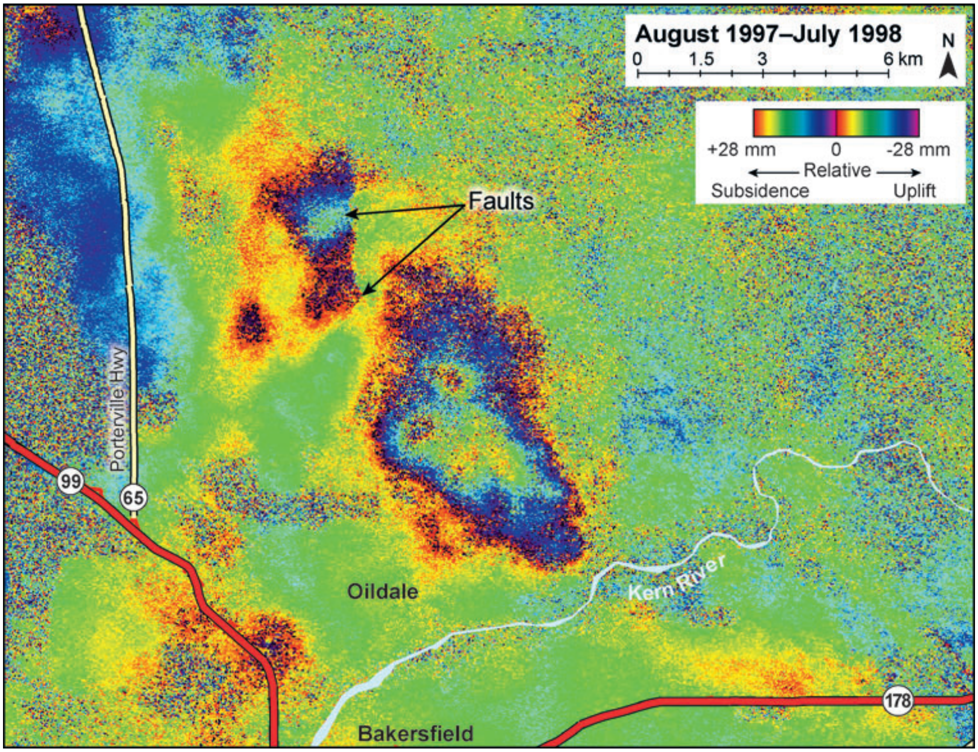

Figure 1

InSAR observed subsidence north of Bakersfield, California, associated with hydrocarbon extraction between August 1997 and July 1998. The color scale gives the phase-wrapped vertical displacement with one cycle of color corresponding to 28.3 mm.

subsurface in the vicinity of the reservoir. The regions above and below a reservoir usually are in a state of an extension to accommodate the compaction in the reservoir. This leads to detectable changes in the P-wave velocity above and below the reservoir that can be retrieved by a comparison of the reflections in time-lapse seismic data.

The top panel of **Figure 2** shows the change in arrival time of reflected waves in a North Sea Chalk Reservoir obtained from a comparison of time-lapse stacked field data. The top of the reservoir is marked with the solid line in that figure. Note that the change in the arrival time is not confined to the reservoir (two-way travel time larger than 2600 ms) and that waves reflected above the reservoir are slowed down appreciably.

The change in the arrival time caused by the extension arises from two factors. First, an extension of the subsurface produces a longer path length from the surface down to a reflector and back. For a vertically propagating wave, this geometric factor changes a depth interval dz into $(1 + \varepsilon_{zz})\,dz$. Using that the travel time is related to the seismic velocity v by $t = \int v^{-1} dz$, this gives the following geometric contribution

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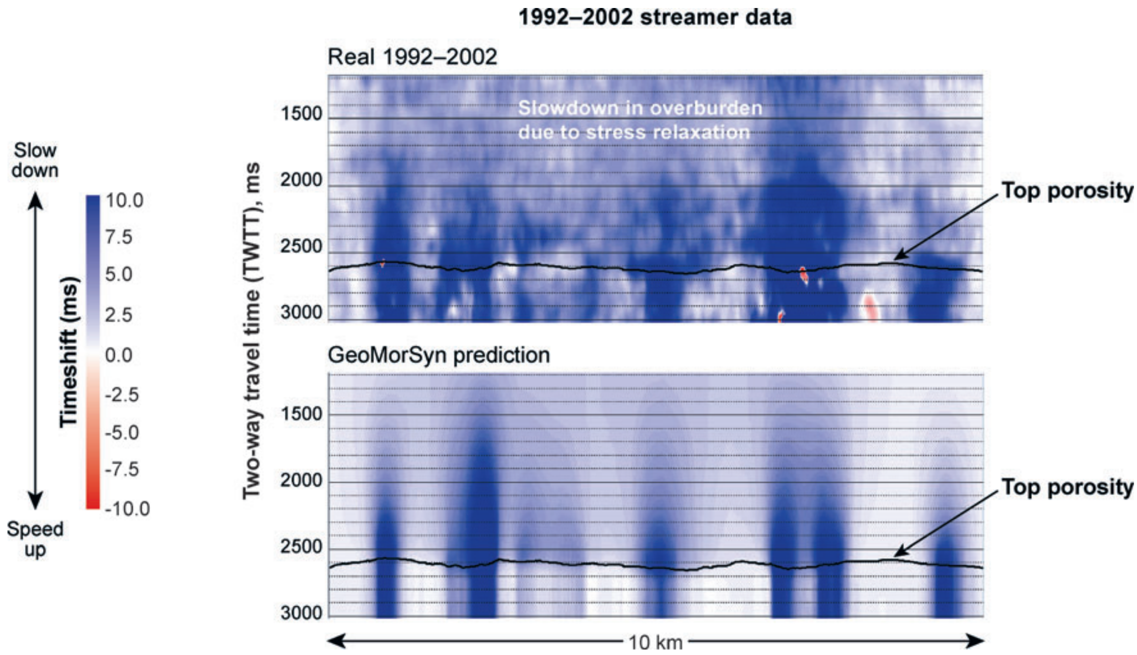

Figure 2

Top panel: The change in the two-way travel time over a chalk reservoir in Norway as obtained from stacked seismic data. Bottom panel: The change in the travel time computed from a geomechanical model of the reservoir and its surroundings using Equation (3) with the value $R = 5$.

to the travel time change δt:

$$\delta t_{geometric} = \int \frac{\varepsilon_{zz}}{v} \, dz. \tag{1}$$

The strain also introduces changes in the material properties, and the relative velocity change due to the strain is given by $\delta v / v = -R\varepsilon_{zz}$. The proportionality constant R depends on the rock properties and whether the strains are extensional or contractional. For a variety of different rocks, this dimensionless constant has values usually between 0 and 2 for rocks undergoing contraction and between 4 and 8 for rocks with extensional strains (Hatchell & Bourne 2005). The associated travel time is given by

$$\delta t_{properties} = \int R \frac{\varepsilon_{zz}}{v} \, dz, \tag{2}$$

This travel time change could have been expressed in the stress-change rather than the strain, but the corresponding value for R then would be much more variable for different rock types. Combining these expressions gives

$$\delta t = \int (1 + R) \frac{\varepsilon_{zz}}{v} \, dz. \tag{3}$$

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For the North Sea Chalk Reservoir, the travel-time change computed using Equation (3) and a geomechanical model of this reservoir is shown in the bottom panel of **Figure 2**. Note that the travel-time change measured from stacked seismic data (top panel) agrees well with the travel-time change computed from a geomechanical model (bottom panel). Such a comparison can be used to validate geomechanical models of the subsurface (Hatchell & Bourne 2005), especially when in addition to changes in the travel time, changes in reflection strength are also taken into account (Tura et al. 2005).

2.3. Seismic Interferometry

Interferometry is a sensitive method for detecting minute changes by using waves that bounce repeatedly within the medium that is probed (Lauterborn et al. 1995). This principle is widely used in optics and now also finds application for monitoring purposes in the geosciences. Coda wave interferometry uses the sensitivity of waves that have bounced repeatedly in the medium, thus enabling monitoring of minute changes in the medium (Snieder et al. 2002; Snieder 2004a, 2006b). This technique has been used to monitor volcanoes (Ratdomopurbo & Poupinet 1995, Grêt et al. 2005, Pandolfi et al. 2006, Wegler et al. 2006) and fault-zone properties (Poupinet et al. 1984), for the detection of velocity changes related to earhthquakes (Nishimura et al. 2000, 2005) or secular changes in tectonic stress (Furumoto et al. 2001), and for the detection of changes in materials using ultrasound (Roberts et al. 1992, Grêt et al. 2006a).

We illustrate the principle of coda wave interferometry with a controlled experiment wherein the stress in a mine pillar was changed using a hydraulic jack (Grêt et al. 2006b). The experiment was carried out in the Edgar Mine in Idaho Springs, Colorado, an experimental mine owned by the Colorado School of Mines. The geometry of the experiment is shown in **Figure 3**. The mine pillar shown in this figure is surrounded by tunnels that are approximately 3 m high. The stress-state in the pillar is changed by jacks that load two plates with a surface area of approximately 1 m^2 placed in a slit cut into the pillar (inset in **Figure 3**). Seismic waves generated with a hammer source are recorded on an accelerometer mounted on the tunnel wall (see **Figure 3**). The waveforms for two pressure-states of the jack are shown in **Figure 4**: the waves recorded for a pressure applied by the jack of 4.14 MPa are shown in blue, whereas the red line shows the waves recorded for a pressure of 12.41 MPa.

The early arriving waves are shown in the panel in the top-right. These first-arriving waves are so repeatable that based on these first arrivals, it is impossible to make any statements about the change in the seismic velocity associated with the change in stress. The panel in the bottom right shows a portion of the later-arriving waves. These later-arriving waves show a clear change in the phase with changing pressure. This phase change can be quantified using a time-shifted cross-correlation and used to estimate the change in seismic velocity (Snieder 2006b). Several nonoverlapping time windows provide independent estimates of the velocity change that can be used as a consistency check on the employed method and can also be used to estimate the uncertainty in the estimated change in the velocity

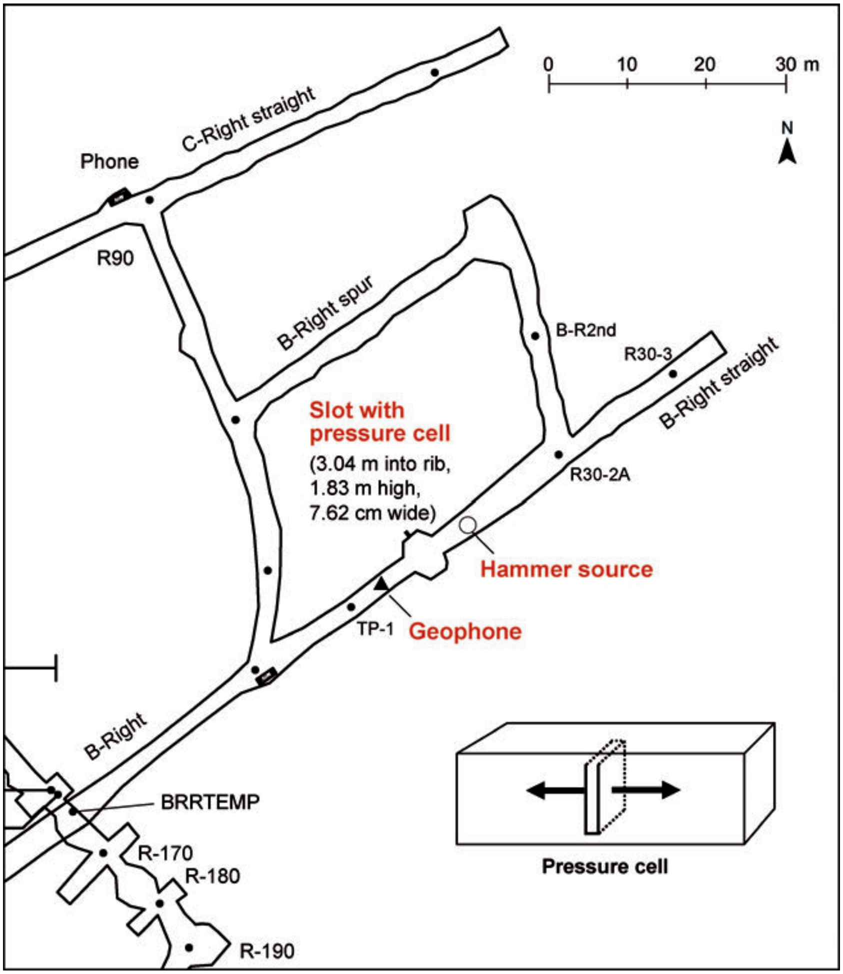

Figure 3

Geometry of the experiment in the Edgar Mine. Geophone and hammer source locations are labeled in the plan. The pressure cell in the slot is indicated by the small line between geophone and source location. The inset (*bottom right*) sketches the pressure cell installed in the pillar.

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(Snieder et al. 2002, Grêt et al. 2006a). For a change in pressure from 0 MPa to 8 MPa, the estimated velocity change is 0.25% with an uncertainty of 0.02% (Grêt et al. 2006b). The high sensitivity of this technique is due to the sampling of the region where the stress is changed by the later-arriving waves that bounce back and forth repeatedly within the mine pillar.

Another active area of research in seismic interferometry is the extraction of the response of a system from the measurement of incoherent signals in the system. By cross-correlating, or deconvolving, noise recorded at two receivers it is possible to retrieve the impulse response associated with the wave propagation between these receivers. (In mathematical jargon, the response of the system to an impulsive loading is referred to as the Green's function.) Derivations of this principle have been presented based on normal modes (Lobkis & Weaver 2001), on representation theorems (Wapenaar 2004, Weaver & Lobkis 2004, Wapenaar et al. 2005), on time-reversal

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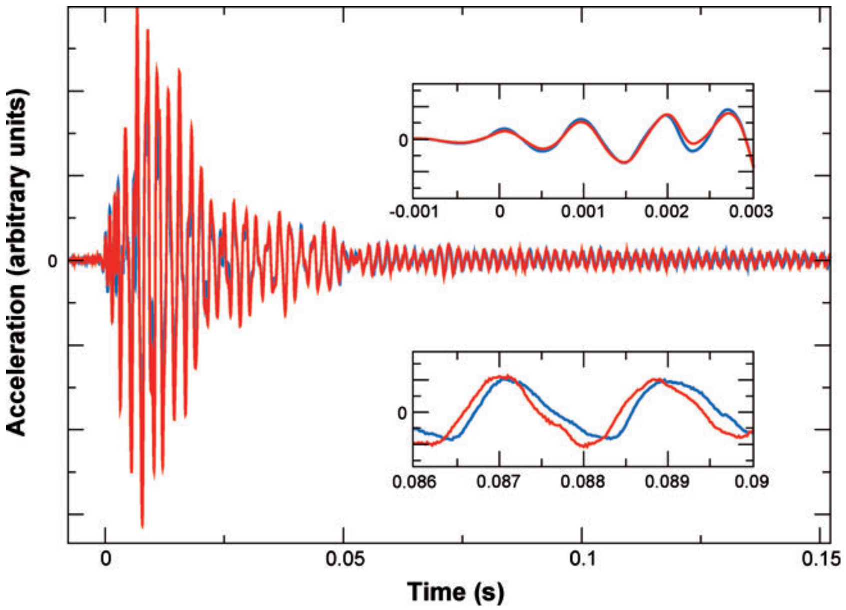

Figure 4

Waveforms measured at 4.14 MPa of pressure (*blue*) applied by the jack and measured at a pressure from the jack of 12.41 MPa (*red*). The upper panel shows the waveforms in the early time window and the lower panel those in a later window.

invariance (Derode et al. 2003a,b), and on the principle of stationary phase (Snieder 2004b, Roux et al. 2005b, Snieder et al. 2006b). This technique has found applications in ultrasound (Weaver & Lobkis 2001, Malcolm et al. 2004, Larose et al. 2006), crustal seismology (Campillo & Paul 2003, Shapiro et al. 2005, Roux et al. 2005a, Sabra et al. 2005), exploration seismology (Bakulin & Calvert 2004, Calvert et al. 2004), structural engineering (Snieder & Şafak 2006, Snieder et al. 2006a), and numerical modeling (van Manen et al. 2005). Snieder (2006a) showed theoretically that the Green's function for the diffusion equation can be extracted by correlating pressure fluctuations recorded at different locations within reservoir. This makes it possible to retrieve the impulse response for fluid transport from ambient pressure fluctuations.

As an example, we show in **Figure 5** the horizontal motion recorded in the basement and the 10 floors of the Robert A. Millikan Library of Caltech (Pasadena) after the Yorba Linda earthquake of September 3, 2002 (ML = 4.8, Time: 02:08:51 PDT, 33.917N 117.776W, depth 3.9 km). The excitation of the building by the earthquake is incoherent. The waveforms of **Figure 5** are the result of a combination of (*a*) the incoherent excitation, (*b*) the mechanical properties of the building, and (*c*) the coupling of the building with the subsurface. To unravel these different physical factors, Snieder & Şafak (2006) deconvolved the motion at different levels with respect to the motion at a target level. The motion at all levels, after deconvolution with the motion at the 10th floor, is shown in **Figure 6**. In contrast to the incoherent waveforms of **Figure 5**, the deconvolved waves are simple: they consist of one upgoing wave and one downgoing wave. These upgoing and downgoing waves can be used to estimate the shear velocity and attenuation in the Millikan Library. This method

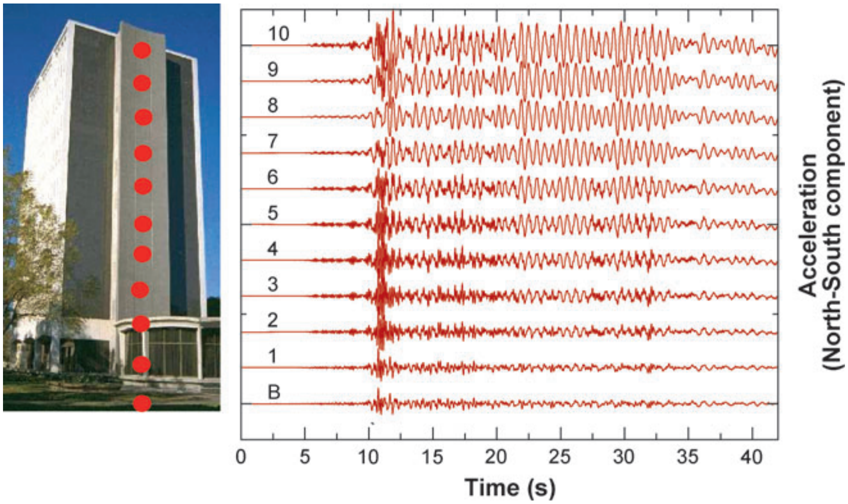

Figure 5

Left panel: The Robert A. Millikan Library in Pasadena and locations of the accelerometers (*red circles*). Right panel: The north-south component of the acceleration recorded at the west side of the building after the Yorba Linda earthquake of September 3, 2002 (ML = 4.8, Time: 02:08:51 PDT, 33.917N 117.776 W, Depth 3.9 km).

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can also be applied to sensors placed in the subsurface. Mehta et al. (2007) extract coherent P- and S-waves, as well as P- to S-converted waves, propagating along a borehole from incoherent waveforms. Snieder & Şafak (2006) show that the deconvolved waveforms depend neither on the specific excitation of the building nor on the coupling of the building to the subsurface (with the associated radiation loss). In fact, in seismic interferometry one can even create coherent wave states of the system under different boundary conditions than those of the physical system in which the waves are recorded (Snieder et al. 2006a).

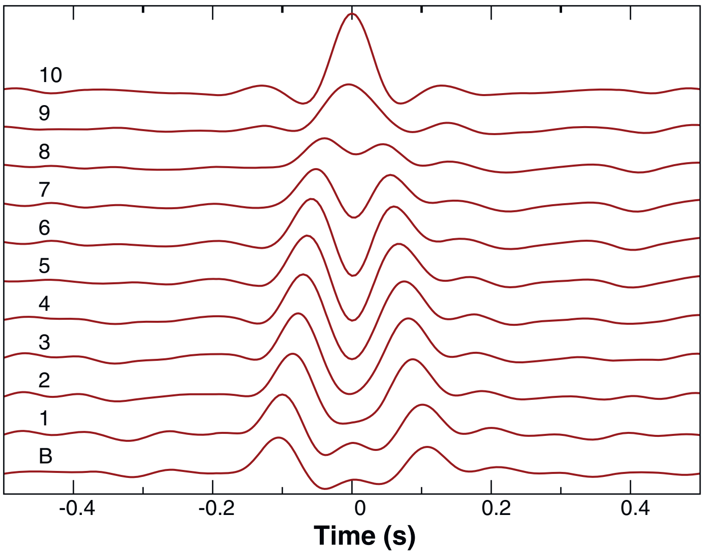

Figure 6

The waveforms of **Figure 5** after deconvolution with the waves recorded at the top floor.

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The advantages of seismic interferometry in the geosciences are twofold. First, the receiver whose signal is used as a reference for the correlation or deconvolution plays the role of a (virtual) source. This means that it is possible to diagnose the subsurface as if there were subsurface sources, although in reality only receivers are present in the subsurface. Second, because this technique is based on recordings of incoherent waves, it can be used to continuously monitor the subsurface using continuous noise recordings. One can combine this method with coda wave interferometry for continuous monitoring using ambient noise. This has been used to monitor daily variations in the seismic velocity associated with rainfall (Sens-Schönfelder & Wegler 2006) and with stress-changes caused by an earthquake (Wegler & Sens-Schönfelder 2006). For the Millikan Library, for example, one can use subsequent earthquakes to monitor temporal changes in the building. This technique can be extended to other structures (e.g., drilling rigs, bridges, aircraft) and is of particular interest for detecting changes in structures caused by traumatic events such as explosions, hurricanes, fire, and earthquakes.

2.4. Challenges and Future Directions in Monitoring Mechanical Properties

While the measurement of mechanical properties, such as seismic velocity, is fairly well developed, the connection of these mechanical properties with microstructure is often unclear. An example is seismic anisotropy. The theory of seismic wave propagation in anisotropic media is advanced (Tsvankin 2001), but the relation between temporal changes in seismic anisotropy and associated microstructure (such as rock formation, deformation, and fluid migration) is not nearly as well established.

Seismic attenuation is another physical property that can be measured, but whose connection with local material properties is often not clear. Because of the dependence of seismic attenuation on the presence of fluids, this quantity might be useful for diagnosing fluids in the subsurface. Attenuation can be attributed both to intrinsic attenuation and to scattering attenuation. (Intrinsic attenuation is the transfer of mechanical energy of wave propagation to other forms of energy, such as heat or squirt-flow, whereas scattering attenuation is the conversion of energy of a propagating wave to energy of scattered waves.) The separation of these different mechanisms of attenuation needs further research, as does the relation between instrinsic attenuation and properties of fluid-filled porous media (Pride et al. 2003).

Seismic interferometry has much potential for passively monitoring the mechanical properties of the subsurface and of structures such as buildings, bridges, pipelines, and drilling rigs. For these structures, the detection of incipient change is of special importance because it could lead to remediation of damage that is about to develop. This technique can also be important for assessing damage to structures caused by traumatic events such as hurricances or explosions. One hurdle in the application of new monitoring techniques is that legislation often is slow to take advantage of new technological developments.

Real-time diagnostics would be useful in a number of applications for monitoring the subsurface, which include monitoring reservoirs, remediation, and monitoring in civil engineering projects and construction. The development and utilization of permanent sensors can play an important role in permanent monitoring.

Temporal variations caused by natural sources can offer new ways to diagnose the subsurface. For example, the imprint of ocean tides on pore pressure has been measured in reservoirs (Furnes et al. 1991, Smit & Sayers 2005), and changes in P-wave velocity associated with the solid Earth tides have been measured as well (Yamamura et al. 2003). Microseismic events have been observed during the passage of Rayleigh waves excited by large earthquakes (Miyazawa & Mori 2006). The Earth response to these variations might carry important information about the mechanical properties and microstructure of rocks and their interaction with fluids.

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3. MONITORING FLUID TRANSPORT

Geophysicists often exploit the sensitivity of their recorded signals to the presence of fluids to address questions concerning subsurface fluid distributions. For instance, exploration seismologists invoke the Gassmann equation to interpret if reflected waveforms bear the imprint of fluid saturation. The Gassmann equation relates the elastic properties of a porous medium to the properties of the rock matrix and those of the pore fluid (Gassmann 1951, Wang 2000). Similarly, because pore pressures modify seismic velocities, reflection tomography can be used to predict pore pressures (Sayers et al. 2002). Although much is known about the fluid sensitivity of geophysical signals, the interaction of rocks and fluids continues to be an active research area. Current topics in rock/fluid properties are widening the scope of geophysical knowledge by studying fluid effects on poorly understood rock types, such as carbonates, fault gouge, and marine sediments containing gas hydrates (Chand & Minshull 2003). In addition, long-standing questions persist concerning the precise role of fluids in seismic wave attenuation (Pride et al. 2003).

With periodic time-lapse or even continuous monitoring techniques becoming more widespread, characteristic fluid signatures can be further exploited to study dynamic flow processes and mechanisms of fluid transport. Applications of these techniques with societal impact include the long-term sequestration (storage) of CO_2 in subsurface traps, delineation of the water table, and detection of fluid transport near radioactive-waste depositories (Long & Ewing 2004). Whether the cause of subsurface fluid flow is natural or induced, advanced monitoring techniques provide a more complete picture of various flow phenomena, such as pore pressure fronts, microseismicity, the interactions of fluids and fractures, flow-related interface phenomena, fluid migration, and pathways for flow in the presence of multiple fluid phases.

Fluid transport in the subsurface can arise from natural processes such as tides, earthquakes, and fluid migration. Several recent studies utilize monitoring techniques to reveal the dynamics of these events. Teanby et al. (2004) report temporal variations in seismic anisotropy caused by fluctuations of the stress field in response to ocean tides. A monitoring technique proposed by Silver et al. (2004) exploits this phenomenon to calibrate stress sensitivity of transmitted waves. Unusual earthquakes in the Long Valley Caldera, as observed by Hill et al. (2003), are attributed to fluid migration of magma or hydrothermal brine. These earthquakes are enriched in low

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frequencies and have non-double-couple source radiation patterns. Hill et al. (2003) make the case that understanding the earthquake source in these instances is a necessary part of effectively alerting the public to impending volcanic eruption. Crampin et al. (2003) observe water-level fluctuations in wells close to the Húsavík-Flately Fault in Iceland, where the water level is continuously monitored during times of increased seismicity. The theory of anisotropic poroelasticity is able to accurately explain these changes. Similar earthquake-related water-level fluctuations are described by Roeloffs et al. (2003).

Monitoring techniques have been applied to problems concerning flow induced by reservoir production, pumping, and drilling operations (Calvert 2005). For instance, absolute gravity measurements have been acquired in both petroleum and groundwater applications (Brown et al. 2002, Cogbill et al. 2005). In the case of groundwater, Cogbill et al. (2005) have observed positive changes in absolute gravity in a region surrounding a water well that are believed to be associated with nearby aquifer recharge. In contrast, no gravity changes were recorded in the immediate vicinity of wells being pumped, even though significant changes in the surface elevation had occurred as measured by GPS. The lack of a gravity signal during a time of surface deformation can be used to constrain models for how the fracture system has been modified by the pumping of water. As an example of a petroleum application of absolute gravity, Brown et al. (2002) have observed a clear and widespread change in absolute gravity and have mapped it to indicate where pumped saline water has replaced oil at Prudhoe Bay. In addition to these techniques based on gravity, the use of time-lapse radar and electrical tomographic methods for monitoring infiltration pathways and moisture variations in the near-subsurface is now fairly well-developed (e.g., Hubbard et al. 1997, Alumbaugh et al. 2002, Binley et al. 2002, Kowalsky et al. 2004).

Landrø & Stronen (2003) have demonstrated that when more than two time-lapse surveys are available, waterfronts in a reservoir can be tracked in differenced four-dimensional seismic images. They showed the use of CO_2 as a tracer to aid structural interpretation. The CO_2 in this case was not injected for the specific purpose of sequestration or enhanced oil recovery—it was simply used to highlight the permeable pathways in the reservoir. Such information can prove invaluable for planning drilling programs to optimally produce reservoirs. Time-lapse seismic techniques continue to be improved for the monitoring of CO_2 sequestration. At the West Pearl Queen Field, a DOE test site for CO_2 sequestration, Benson & Davis (2005) have reported on the detection of injected CO_2 from two high-quality, highly repeatable seismic surveys. Below, we review two examples of the novel use of geophysical data for monitoring fluid transport.

3.1. Detection of a Fluid Pulse Migrating Along a Fault Zone

Recently, Haney et al. (2005) investigated the mechanism of strong fault-plane reflections from a growth fault at the South Eugene Island Field in the Gulf of Mexico. Fault-plane reflections, unlike reflections from sedimentary layers, might not be primarily associated with lithological differences. Because faults often act as either fluid

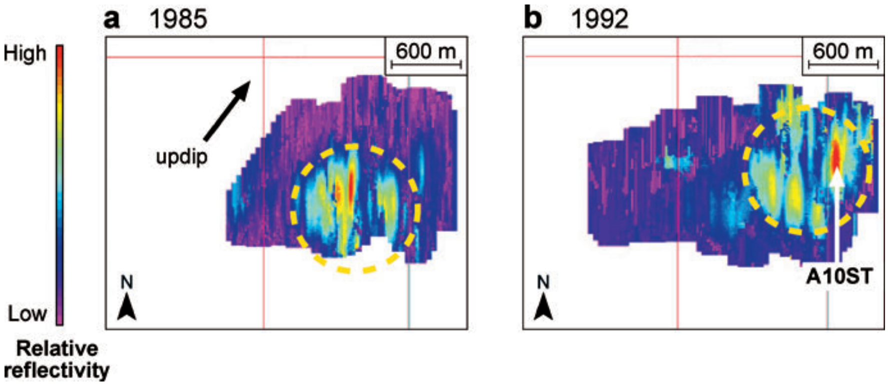

Figure 7

Evidence of fluid transport along a fault in the Gulf of Mexico inferred from seismic images constructed from seismic data recorded in 1985 and 1992. (*a*) Map view of fault-plane reflectivity from a growth fault known as the B-fault in 1985. The area of highest fault-plane reflectivity is circled in gold. (*b*) Map view of the B-fault reflectivity, as in (*a*), but from 1992. The data extend over a slightly larger area than in (*a*); however, the spatial perspective is identical. The area of highest reflectivity, circled in gold, is shifted roughly 1 km NE in the updip direction relative to its location in 1985, as is expected for a fluid pulse ascending the B-fault (Revil & Cathles 2002). This movement is represented by the arrow in (*a*). Also shown is the location of the A10ST well intersection, where exceptionally high fluid pressures were encountered while drilling into the B-fault zone in 1993, a year after the 1992 seismic survey (Losh et al. 1999).

seals or conduits (Hooper 1991), strong pore-pressure differences in and around faults can give rise to fault-plane reflectivity (Haney et al. 2006). By examining two seismic images, one from 1985 and another from 1992, Haney et al. (2005) observed that an area of strong fault-plane reflectivity associated with a fault known as the B-fault appeared to move 1 km along the fault-plane in the up-dip direction. This up-dip movement is depicted in the two reflectivity maps of **Figure 7**.

Fluid movement up the fault-plane is particularly noteworthy at South Eugene Island because several lines of evidence exist suggesting that natural fluid migration is presently occurring in the mini-basin petroleum system (Anderson et al. 1991, 1994; Losh et al. 1999; Whelan et al. 2001, Revil & Cathles 2002; Haney et al. 2005). The pulsing of fluid up a permeable fault zone is also consistent with a nonlinear permeability model first introduced by Rice (1992) and later proposed by Revil & Cathles (2002) to be directly applicable at South Eugene Island. In this model, the fluid pulse is a pore-pressure shock wave that moves along the fault with a velocity determined by the local hydraulic properties. Miller et al. (2004) use the same shock-wave model to explain the migration of fluid-related earthquake hypocenters along an active fault in Italy. These pore-pressure shock waves arise owing to the deformation of the porous media in response to pore-pressure variations. The existence of the shock wave thus provides direct evidence of a coupling between the fluid flow and deformation of the host rock (Minkoff et al. 2004).

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3.2. Direct Measurement of Fluid Flow with the Self-Potential

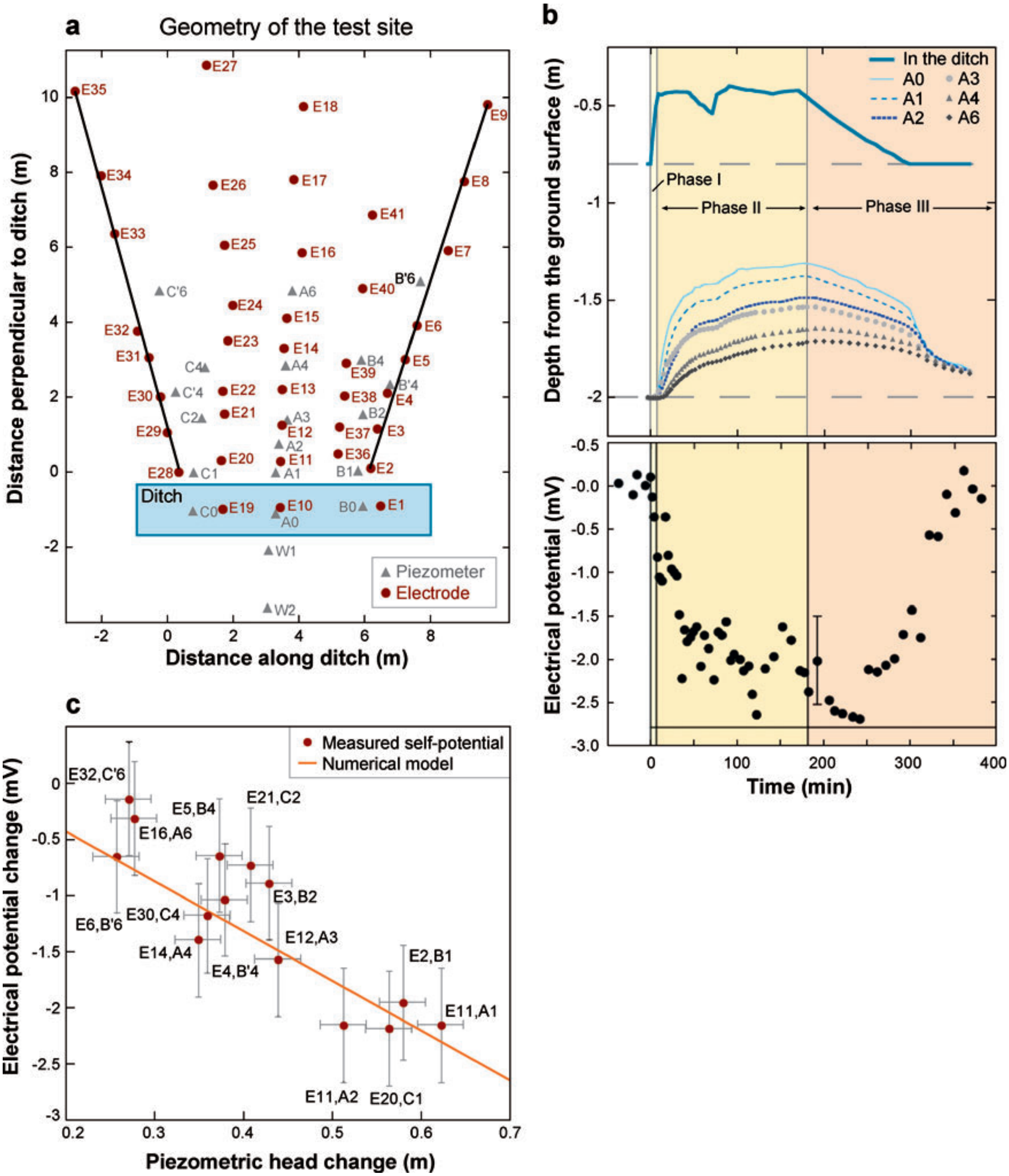
Through combined numerical, laboratory, and field experiments, Suski et al. (2006) have made significant progress toward showing how to successfully monitor the water table using SP methods. SP signals originate from a variety of mechanisms, including electro-kinetic (the so-called streaming potential) and electro-redox effects (which are discussed in Section 4.1 of this work) (Nyquist & Corry 2002). Electrokinetic effects (Revil & Linde 2006) are the same phenomena responsible for coupling seismic and electromagnetic fields in the field of electroseismics (Pride & Morgan 1991).

Figure 8 shows details of the infiltration experiment conducted by Suski et al. (2006). The experiment is based on the idea that groundwater flow in soil produces a SP signal that can be measured at the surface. Hence, the SP method detects and maps out the effects of dynamic flow. **Figure 8*a*** is a map view of the field layout used by Suski et al. (2006) consisting of 18 piezometers and 41 (Pb/PbCL_2) nonpolarizable electrodes. To monitor the changes in the piezometric surface caused by fluid infiltration, the ditch, shown in **Figure 8*a***, is filled with water. The filling of the ditch comprises the short time-duration Phase I of the infiltration experiment pictured in **Figure 8*b***. The other two phases cover the episodes of constant water level in the ditch (Phase II) and relaxation, or drainage, of the head (Phase III). The data plotted in **Figure 8*b*** include the water level in the ditch, the depth to the piezometric surface measured at several piezometers, and the corresponding SP signal measured at the electrodes. The trend of the SP signal correlates well with the latter two phases of fluid infiltration.

Figure 8*c* compares the measured SP signals to changes in piezometric head. The SP signal depends more or less linearly on the piezometric level, with a slope of -5.5 ± 0.9 mV/m. From soil samples taken at the test site, Suski et al. (2006) independently find in the laboratory that the slope can be between -4.0 mV/m and -5.9 mV/m, depending on the type of fluid saturating the pore space of the soil. Finally, the solid line in **Figure 8*c*** is the result of a finite-difference numerical model (Titov et al. 2005). The agreement with the field data shows that the hydrological and SP properties of the subsurface are modeled well. With these results, Suski et al. (2006) demonstrate the ability of the SP method to noninvasively monitor groundwater flow. An important property of these SP measurements for the

Figure 8

Experimental setup and results of a fluid infiltration test by Suski et al. (2006). (*a*) An array of 18 piezometers and 41 nonpolarizable electrodes arranged in and around a rectangular ditch (*blue*). The soil at the site is comprised of clay and silt with porosity that varies between 0.2 and 0.3. (*b*) This panel shows three quantities: the water level in the ditch (*thick solid line*), depths to the piezometric surface (*thin solid*, *dotted*, *and dashed lines*), and self-potential signals (*black filled circles*, *lower panel*). The measurements capture three different stages of infiltration:
(I) beginning of infiltration, (II) maintenance of constant head in the ditch, and (III) relaxation of the head. (*c*) A comparison between measured self-potential signals versus the isometric head change (*solid points with error bars*) and the results of a finite difference numerical model (*solid line*).



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purposes of continuous monitoring is that they are inexpensive to acquire (Nyquist & Corry 2002) in contrast to three-dimensional seismic data acquisition. In addition, the SP method is applicable to the problem of monitoring of CO_2 injection (Moore et al. 2004).

3.3. Challenges in Monitoring Fluid Flow

Many challenges lie ahead for the advanced monitoring of fluid transport. The sensitivity of advanced monitoring techniques aiming to track fluid transport must be maximized with respect to fluid saturation, pressure, and flow. Crampin (2003) argues that certain techniques (e.g., shear-wave splitting) inherently are extremely sensitive because they probe a critical system (e.g., cracks and fractures). In geophysics, the concept of criticality is often invoked when describing the stress state of fault systems in the crust (Zoback & Townend 2000). Extreme sensitivity and criticality are linked to nonlinearity, and nonlinear rock moduli have recently been implicated by Gomberg & Johnson (2005) as a cause of dynamic triggering—a phenomenon in which microearthquakes are initiated on critically stressed faults by passing seismic waves from earthquakes more than 1000 km away (Freed 2005). The dynamic strains in these cases are on the order of only a few microstrains (10^{-6}) (Gomberg & Johnson 2005). In addition to criticality, enhanced sensitivity can also be achieved with methods based on monitoring seismic waves by exploiting the multiply scattered coda (e.g., coda wave interferometry, as discussed in Section 2.3). Perhaps the most daunting challenge is that to move in the future from periodic time-lapse measurements to continuous monitoring, the methods used for monitoring cannot be costly. It is worth emphasizing again that the SP method employed by Suski et al. (2006) is relatively inexpensive. In contrast, the method of using injected CO_2 as a structural tracer to find permeable pathways, although promising, is currently vastly more expensive.

Advanced monitoring plays a prime role in the growing field of CO_2 sequestration. To make sequestration successful, it is necessary to determine whether the injected CO_2 is sequestered or is leaking to the surface. Leakage to the surface can occur via fracture systems and fault zones, or simply through the casing of injection wells. Finally, it remains a challenge to fully understand the hydraulic properties of a field area. The method described by Shapiro et al. (2002), which uses microseismicity triggering fronts to measure the (possibly anisotropic) permeability tensor, is one way to achieve this goal through advanced monitoring. Other examples, which focus on the development of approaches to jointly invert time-lapse tomographic radar data and hydrological data (such as well-bore measurements or tracer tests) have illustrated the utility of geophysical methods for providing high-resolution estimates of hydraulic conductivity (e.g., Kowalsky et al. 2005).

4. MONITORING BIOGEOCHEMICAL PROCESSES

Successful management of subsurface systems often requires information about biogeochemical properties and processes, such as the type and concentration of pore fluids or sediment geochemistry, redox zonation, and the transformation of and

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interactions between species as a system being manipulated. In addition to using geophysical methods to track fluid distribution, as was described in the previous section, there is also a need to track the onset and characteristics of geochemical changes that occur in response to fluid introduction or replacement. For example, the potential of using geophysical techniques to monitor CO_2 distribution associated with petroleum and sequestration applications was previously discussed. In addition to the fluid migration, introduction of CO_2 can cause dissolution of minerals or can mobilize trace metals (e.g., Kharaka et al. 2006). A current challenge is to use geophysical methods to monitor these geochemical changes. Although many studies have focused on investigating the geophysical signatures of pore fluid substitutions associated with infiltrating soil water, hydrocarbon extraction, or saltwater intrusion, few studies have explored the impact of other types of (bio)geochemical alterations on the effective geophysical signature.

GPR: ground penetrating radar

Recent investigations have explored the use of different types of geophysical methods for monitoring biogeochemical changes, some of which are microbially mediated. Several studies have revealed anomalously higher electrical conductivity signatures associated with hydrocarbon-contaminated sites, which has been attributed to altered fluid chemistry associated with biological degradation (e.g., Atekwana et al. 2005). Abdel Aal et al. (2004) explored the effects of microbial processes on electrolytic and interfacial electrical properties. Ntarlagiannis et al. (2005b) explored how induced polarization measurements changed as a function of microbial cell concentration and grain surface coating. The use of SP methods to map large-scale variations in redox conditions was described by Naudet et al. (2004). Chen et al. (2004) illustrated how ground penetrating radar (GPR) amplitudes could be used to estimate sediment geochemistry. Williams et al. (2005) and Ntarlagiannis et al. (2005a) describe seismic and induced polarization (Fink et al. 1990) responses to biomineralization under controlled column conditions. The results from these and other recent studies highlight the potential that geophysical methods have for monitoring complex biogeochemical processes, which is a prerequisite for successful management of subsurface problems or resources. Two of these studies are briefly described below.

4.1. Characterization of Redox Potential

The observed distribution of redox processes is an important factor in the design of remedial strategies for contaminated groundwater systems. Redox potential, or Eh, indicates the tendency for oxidation-reduction reactions to occur. A series of redox gradients often is established adjacent to contaminant plumes (e.g., Loveley et al. 1994). Understanding redox zonation is a particularly important factor in designing an optimal remediation approach. Under equilibrium conditions, in situ measurements of redox potential can be obtained through well-bore measurements, although disturbance and contamination associated with drilling often corrupt these measurements. The distribution of the kinetic redox processes can also be deduced by observing patterns of electron acceptor consumption, final product production, and concentrations of dissolved hydrogen based on measurements retrieved from well-bores. However,

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many studies suggest that inference of redox processes using such approaches is not straightforward.

A recent study assessed redox potentials associated with a landfill contaminant plume using the SP technique (Naudet et al. 2004). SP signals measure the potential difference between a fixed reference nonpolarizable electrode and a roving electrode using a high-input impedance voltmeter. In near-surface systems, the SP response depends on the groundwater flow (electro-kinetic contribution) and redox conditions (electro-redox contribution). Naudet et al. (2004) used the variation in hydraulic head measurements in an aquifer near a landfill to estimate the electro-kinetic contribution (**Figures 9*a*** and **9*b***), which was subsequently removed from the effective SP signal. The residual SP signal correlated well with redox potential measurements collected in well-bores, and was used to provide spatially extensive estimates of redox potential (**Figures 9*c*** and **9*d***). This study illustrates the value of an inexpensive geophysical technique to provide information about redox potential over field-relevant spatial scales and in a noninvasive manner. Such information can be used to design remediation treatments or to choose the locations of monitoring wells.

4.2. Monitoring Biogeochemical Dynamics Using Seismic and Induced Polarization Methods

Remediation treatments may induce dynamic transformations in biogeochemical and hydrological properties in the subsurface. Potential alterations owing to remediation treatments include, for example, dissolution and precipitation of minerals, surface complexation, gas evolution, changes in soil water and oxygen levels, sorption, attachment/detachment, oxidation and reduction, biofilm generation, and changes in permeability and porosity. Although understanding and ultimately manipulating these transformations is critical for sustainable in situ remediation, developing such an understanding is hindered by our inability to observe biogeochemical dynamics in situ over a spatial scale relevant for investigating the macroscopic behavior of a system in the presence of natural heterogeneity.

Recent research has explored the use of time-lapse seismic and induced polarization methods for detecting the evolution of gasses, biofilms, and precipitates associated with processes that commonly occur during biostimulation, such as during denitrification and sulfate reduction. Biostimulation involves the addition of carbon sources, nutrients, and electron acceptors or donors into the subsurface to increase,

Figure 9

The streaming potential component of the self-potential signals is calibrated outside the contaminant plume by plotting the kriged self-potential signals and the hydraulic heads. The arrows provide the direction of ground water flow and are proportional to the hydraulic head gradient (*b*). The streaming potential component is then estimated everywhere using the kriged hydraulic heads (*a*). The residual self-potential signals are obtained by removing the streaming potential component from the measured self-potential signals (*c*). This residual self-potential map is proportional to the redox potentials measured in the aquifer in a set of piezometers (*d*).

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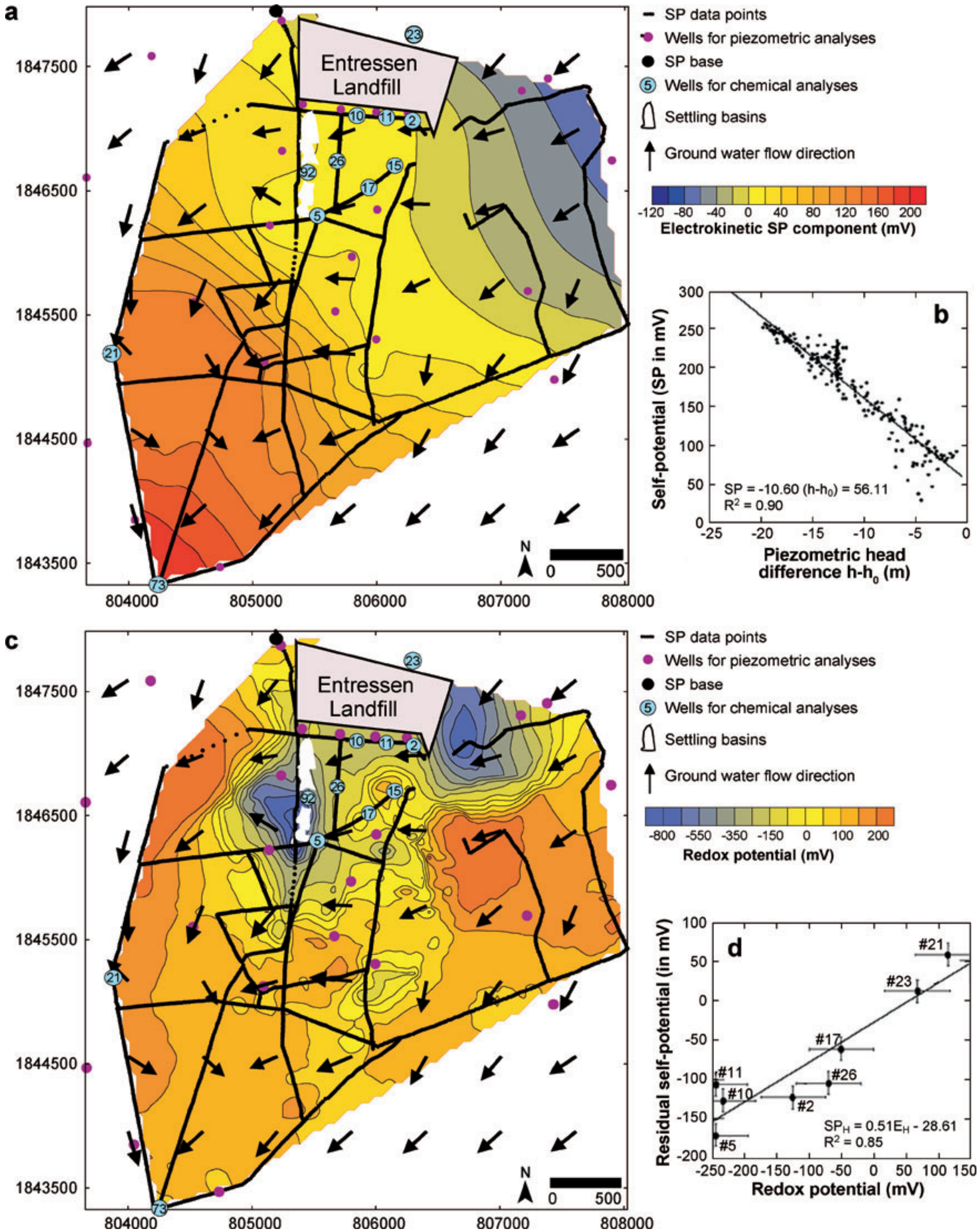

or stimulate, the activity and growth of naturally occurring microorganisms. Once stimulated, these organisms can mediate processes that beneficially change the toxicity and mobility of contaminants (Palmisano & Hazen 2003). Williams et al. (2005) conducted laboratory biostimulation experiments under saturated flow conditions to monitor the biogeochemical, hydrological, and geophysical responses associated with sulfate reduction using a suite of columns having vertically distributed samplers and geophysical sensors (**Figure 10*a***). This study indicated how microbe-mediated zinc and iron sulfides, which developed along grain surfaces within the pore space,

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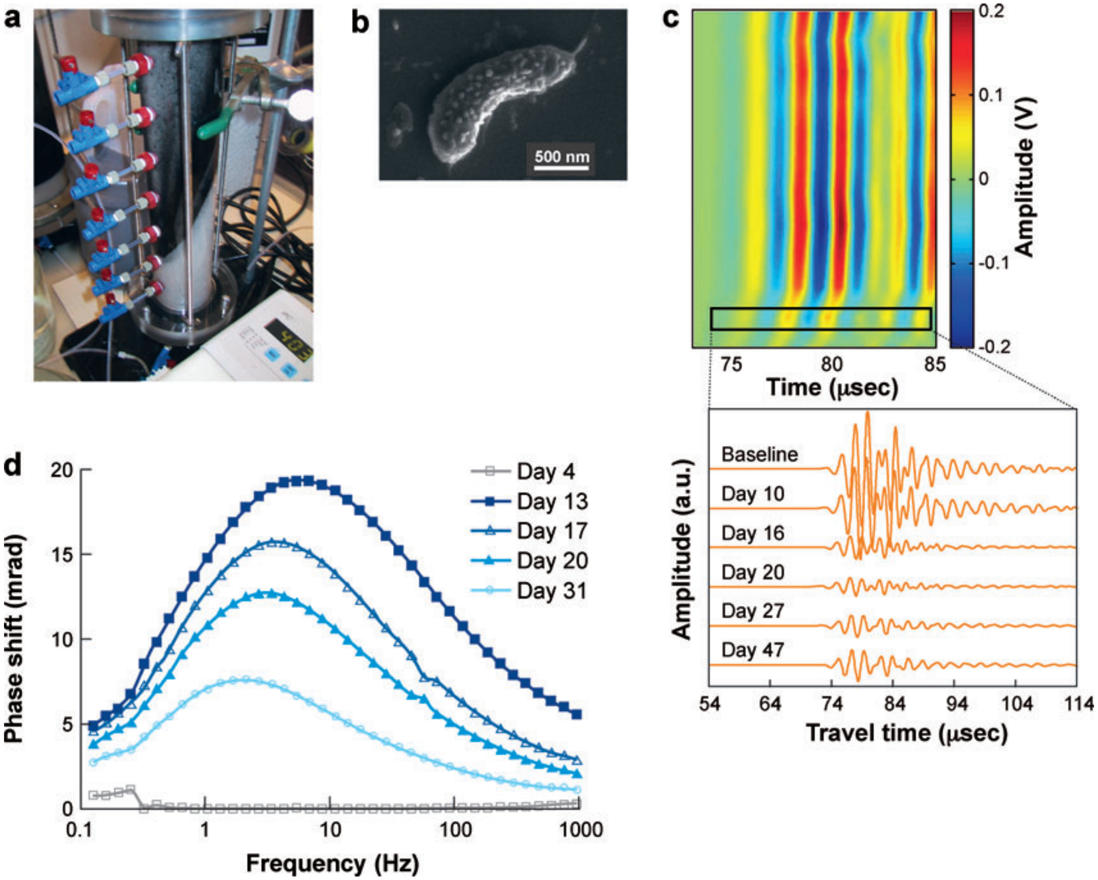

Figure 10

(*a*) Example of an experimental column illustrating how measurements are collected down the length of the column and the presence of a developed sulfide precipitation front associated with sulfate reduction. (*b*) TEM image illustrating the mineralized encrustation on the experimental microbe due to the formation of sulfide precipitates (scale approximately 1 μm), changes in (*c*) seismic amplitude and (*d*) induced polarization response associated with the initiation and aggregation of sulfide precipitates. Modified from Williams et al. (2005).

were attached to microbial cells (**Figure 10*b***). The acoustic amplitude and induced polarization signatures were altered as the nanocrystals formed, attached to the migrating microbes, and eventually aggregated (**Figure 10*c,d***). These results illustrate the potential that geophysical methods have for elucidating important biogeochemical processes over space and time, such as those that often accompany bioremediation of metal-contaminated aquifers.

4.3. Challanges and Future Directions in Monitoring Biogeochemical Processes

Advances in monitoring changes in biogeochemical properties have to date primarily been applied to environmental problems, where there is a significant interest in manipulating biogeochemical processes to render contaminants less mobile or less toxic. However, these approaches could also be used to assist in petroleum reservoir investigations, such as to monitor reservoir stimulation or well-bore completion procedures. For example, a new chemical injection treatment has recently been developed to increase sand consolidation and cementation in the near vicinity of the borehole, thereby significantly decreasing sand production (Kotlar et al. 2005), and injection of bacterial suspensions following water flooding has been explored as a technique to enhance oil recovery, which has been shown to increase the recovery factor by 3%–5% (Crecente et al. 2005). In these cases, time-lapse three-dimensional VSP surveys, where waves excited by sources on Earth's surface are recorded by sensors in a borehole, could likely provide valuable information about the spatial distribution of the treated zones, and the quality and distribution of the cementation.

Quantitative geochemical characterization using geophysical methods poses several challenges. Perhaps greatest among these are the challenges associated with scaling, nonuniqueness, and data fusion. Scale-matching issues are significant because many of the biogeochemical properties or processes occur at microscopic scales that are much smaller than the smallest scale resolved by the geophysical measurement. Nonuniqueness of the geophysical responses is a problem because geophysical signatures often respond to hydrogeological as well as geochemical heterogeneity. Additionally, as a system is treated (for example, during environmental remediation), multiple biogeochemical transformations often occur simultaneously over the support scale of the geophysical measurement (e.g., Hubbard et al. 2006), and modified biogeochemical properties can in turn alter hydrological properties (such as pore clogging associated with gas or precipitate development), thereby further modifying the geophysical response. Together, these complex and coupled transformations hinder the ability to uniquely interpret system transformations given a particular geophysical response. Understanding of the full capacity of geophysical methods for characterization of geochemical properties and processes is expected to improve through increased laboratory and field experimental efforts, through development of rock physics relationships and estimation approaches, and through comparisons of geophysically obtained geochemical parameter estimates with numerical modeling predictions of geochemical transformations.

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5. DISCUSSION AND FUTURE CHALLENGES

MEMS: micro electro mechanical systems

Although much progress has been made in noninvasive monitoring, there are several open research questions. Some of these research questions are related to technical aspects of specific monitoring techniques. Other research questions are common to many different aspects of noninvasive monitoring. We introduce these overriding research questions using **Figure 11**.

In a physical experiment data are collected. These data are determined by the true Earth model through the physics of the forward problem (geomechanical, hydrological, biogeochemical). From the data, one can estimate an Earth model, or in the case of monitoring, changes in the Earth model. Because the data are limited, contaminated with noise, and often sampled at disparate scales, these model estimates differ from the true model. Quantifying these differences and associated uncertainty is the appraisal problem. In practical implementations of monitoring techniques, measuring the changes in geophysical attributes or even estimating the change in subsurface properties using the geophysical data is not sufficient. Instead, these data must be integrated with other information to ascertain the impact that the estimated changes have on how a system should be managed or treated to solve problems of scientific, economic, or other societal relevance.

Figure 11 illustrates several research challenges in optimally using noninvasive monitoring. The forward problem, which gives the data for a given model, often is well known, as in the case of InSAR where the change in the phase of the radar waves is connected by well-known physics to the deformation of Earth's surface. In other applications, the forward problem is not well known. Examples include the relation between compaction and seismic velocity (Section 2.2) or between various geophysical attributes and biogeochemical properties (Section 4).

Data collection is changing because of new developments of instrumentation and the capability to handle increasingly larger continuous data streams. Cheap microinstrumentation, such as smart dust (Kahn et al. 2000) as well as micro electro mechanical systems, or MEMS (Gibson et al. 2005), make it possible to carry out

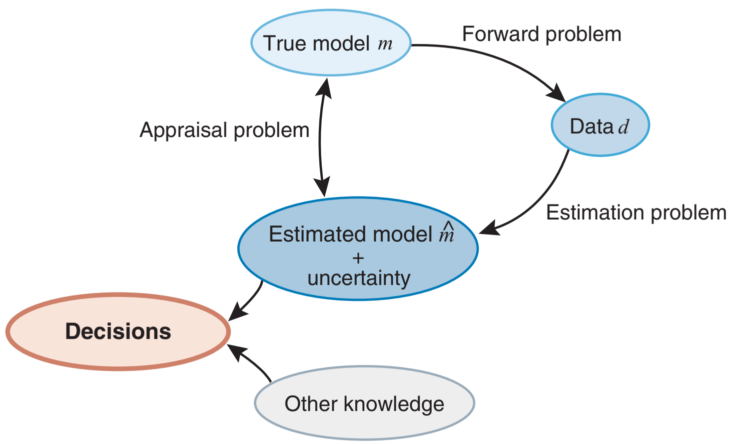

Figure 11
Different elements in creating an interface between geophysical measurements and decision making.

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measurements at an unprecedented scale. This has led to the concept of the instrumented oilfield (Tura & Cambois 2001). Research challenges in this area include the transmission of information of large numbers of subsurface instruments to the surface, and handling the data streams of large networks of sensors that operate continuously.

The estimation of uncertainty is a long-standing problem in model estimation, and the same holds for monitoring techniques. For the linear inverse problem, the assessment of uncertainty is well developed (e.g., Tarantola 1987, Parker 1994, Aster et al. 2004). The application to the current large-scale estimation problem is still problematic (e.g., how does one visualize a correlation matrix for 10^6 parameters?). For nonlinear estimation problems, there is no general theory to estimate the uncertainty (Snieder 1998). In this case, numerical techniques are presently the only available tool (e.g., Mosegaard & Tarantola 1995, Sambridge 1998, Sambridge et al. 2006), but the computational cost for many problems is prohibitive.

In many practical problems, different kinds of data are collected. Combining these disparate data streams is a challenge. Data fusion, where different data are combined, and data assimilation, where new data are used to update existing models for the subsurface, still are challenging issues when it concerns the implementation in practical monitoring problems.

As indicated in **Figure 11**, decisions are often based on the outcome of monitoring experiments and other knowledge. The integration of these different pieces of information is often achieved by the expertise of the decision makers and their advisers. There is a lack of techniques to integrate the a priori knowledge of the problem effectively in the mathematical formulation, and numerical implementation of the estimation problem. For example, model parameterization and estimation of uncertainty are often more driven by mathematical and/or numerical considerations than by the geological reality of the subsurface. Geologically realistic information is often difficult to glean from experts owing to standard, human cognitive biases (Baddeley et al. 2004), and real-world knowledge is often difficult to parameterize. Nevertheless, it is critical that such information is introduced correctly, as it directly affects not only model estimates but their associated uncertainties. Consequently, research into methods to include reliable information in monitoring-type problems has begun in a variety of fields (e.g., Thore et al. 2002, Wood & Curtis 2004).

The interface with the decision makers is often not optimal. The outcome of the monitoring experiment as a change in the model parameters, plus its uncertainty, is often not in the form that is useful for the decision maker. Knopman (2006) described the importance of scientists engaging with decision makers during the research stage, rather than first focusing on understanding or predicting processes and subsequently informing decision makers after completion of the research. He suggests that with early inclusion, scientific experiments and decision-making tools can be designed that optimally guide the choices about the level of complexity that is needed to guide decisions about large environmental problems, such as climate change, nuclear waste storage, or sustainable water management. Another problem in using monitoring techniques effectively is the gap in the time scale with which the decision maker needs results, and the time scale on which a monitoring experiment can be carried out. In this context, it is also important that monitoring techniques can be carried out economically because this allows the monitoring to be carried out more frequently.

Much progress has been made in noninvasive geophysical monitoring of the subsurface, but as shown here, there are numerous open research questions. Resolving these research questions is crucial for optimally exploiting our technological capabilities for monitoring the subsurface.

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