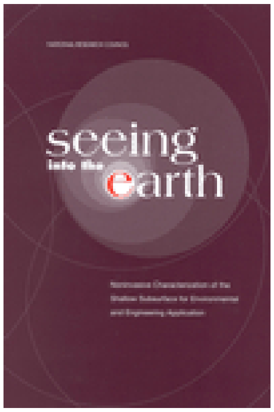

Seeing into the Earth: Noninvasive Characterization of the Shallow Subsurface for Environmental and Engineering Applications

Committee for Noninvasive Characterization of the Shallow Subsurface for Environmental and Engineering Applications, Board on Earth Sciences and Resources, Water Science and Technology Board, National Research Council

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seeing into the earth

Noninvasive Characterization of the Shallow Subsurface for Environmental and Engineering Applications

Board on Earth Sciences and Resources
Water Science and Technology Board
Commission on Geosciences, Environment, and Resources
National Research Council

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While the individuals listed above have provided many constructive comments and suggestions, responsibility for the final content of this report rests solely with the authoring committee and the NRC.

Preface

Earth science is at an unprecedented turning point at the start of the twenty-first century. The focus of the science is shifting increasingly toward the natural and built environment. Earth scientists are being called on by society to apply their knowledge and expertise to environmental and engineering problems, a trillion-dollar challenge for the United States and other industrialized nations.

As noted in two National Research Council (NRC) reports (*Solid-Earth Sciences and Society*, 1993; *Opportunities in the Hydrologic Sciences*, 1991), earth scientists have considerable expertise that can be brought to bear on environmental problems. This near-surface environment, especially within the top 30 m,[1] supports human infrastructure; yields much of the water, energy, and mineral resources; and is the repository for most municipal and industrial wastes. It is the region most susceptible to contamination and modification from human activity.

Tools to characterize the near-surface environment include invasive techniques, such as drilling and trenching, and a variety of noninvasive methods employing electromagnetic or acoustical energy sources (e.g., ground penetrating radar and seismic reflection) and chemical probes (e.g., soil-gas monitors). In polluted areas, invasive techniques pose a risk to workers and the environment because they can promote the spread of contaminants. Invasive techniques provide the most direct access to the subsurface, but they are generally expensive and provide information at points in a three-dimensional subsurface. Noninvasive techniques, on the

[1]Thirty meters is only an approximate number; many applications will need characterization at a much shallower depth, whereas others will extend the depth of interest. It follows that different techniques have optimal depth ranges for their results, which also depend on the composition and structure of the near surface

other hand, hold the promise for rapid and inexpensive characterization. Many can image, in three dimensions, large volumes of the subsurface, albeit at lower resolution than invasively characterized points. Advances in understanding and application of noninvasive techniques could potentially save billions of dollars through improved performance in environmental and engineering applications.

Considerable progress has been made over the past decade in the area of near-surface geophysical exploration. Some of this progress has occurred as a result of adaptations of techniques developed for petroleum and mineral exploration, and some has resulted from advances in instrumentation, electronics, and computer processing. Many of the advances have been driven by societal needs, such as the need to assess polluted sites that threaten groundwater supplies, the preservation of buried antiquities, and the need for reliability and cost-effectiveness in geotechnical engineering.

The National Research Council established the committee in August of 1995 and assigned it the specific tasks of (1) assessing current capabilities for characterizing the near-surface environment using noninvasive technologies; (2) identifying weak links in current capabilities; and (3) recommending research and development to fill these gaps. This report evaluates the state of the science, the state of the practice, and the potential for new and improved methods for noninvasive characterization of the near surface.

In assessing current capabilities and recommending research and development strategies, the committee has taken a broad, long-term view that considers new techniques and technologies, including ideas for truly revolutionary advances; new methods of processing data; and new theories and methods for relating indirect measurements to physical, chemical, and biological properties of the subsurface. The committee based its review and evaluation on existing published literature and discussions with experts in the field. The committee restricted itself to considering applications from land even though many of the same methods could be applied and deployed from a waterborne platform or from an ice surface to look at shallow subsurface materials beneath lakes and other water bodies.

The Committee on Noninvasive Characterization of the Shallow Subsurface for Environmental and Engineering Applications consisted of 18 earth and physical scientists and engineers with expertise in shallow, general, and applied geophysics, geotechnical engineering, soil physics, microbiology, geochemistry, hydrogeology, and remote sensing. The committee met six times during the study. In order to receive input from a broader audience, three of the meetings were held in concert with meetings of professional societies, including the Society of Exploration Geophysicists, the Environmental and Engineering Geophysical Society, and the American Geophysical Union.

This report should be useful in identifying significant new areas for research in the earth and environmental sciences to be pursued in universities and national laboratories during the next decade. The report should be of interest to policy makers in deciding where research dollars should be invested; to program managers, who fund R&D on subsurface characterization; to scientists and engineers at academic institutions, national laboratories, and private industry who develop these new technologies; and to scientists and engineers within government and industry, who need this new technology for engineering and environmental applications.

Contents

Executive Summary

Knowledge of the nature of the subsurface is critical for many environmental purposes and engineering applications. Projects requiring subsurface characterization are estimated to cost several trillion dollars over the next few decades. There is a need to "see into the earth," to determine physical, chemical, and biological properties and to detect, monitor, and predict natural and induced processes.

Direct or invasive methods of characterization (such as drilling and excavation) often can be expensive, cause disruption to human activities, and in some cases, create unnecessary damage to the environment. Drilling provides, in essence, a one-dimensional sample; multiple drillholes allow interpolation between such points but significant uncertainties can remain.

The primary questions addressed by this study are: (1) *How effectively can the shallow subsurface be imaged and characterized noninvasively?* (2) *Can the use of noninvasive methods increase the confidence of our characterization effort?*

A large suite of noninvasive methods has been developed and refined over the past few decades. Noninvasive methods for characterization of subsurface properties and processes are indirect. Interpretations are based on measured response of the subsurface to artificial or natural stimuli. Passive investigations use naturally occurring fields (the earth's gravity, magnetic, electric, thermal, radiometric, stress, solar irradiation, and hydraulic fields). For example, perturbations in the earth's gravity field are used to infer changes in the material density. Active investigations use a source of energy (e.g., seismic energy, radar pulses, electrical inputs) that creates a known field, and observations are made of the perturbations in that field or in the response of the earth. For example, seismic investigations use vibratory or explosive sources to propagate elastic waves, and travel times, wavelet changes, and scattering are measured to describe the heterogeneity of the shallow subsurface as well as the interior of the earth.

There is great potential for these methods to define subsurface details with a level of accuracy, precision, economy, and safety that can approach direct sampling but with a much greater areal coverage. (At all sites one needs to be cognizant of the various types of noise or other disturbances that might diminish the utility of one or more specific techniques.) Realizing the potential for noninvasive characterization will require concerted and cooperative interdisciplinary efforts by earth scientists, geotechnical engineers, government agencies, and the user community. Two broad areas of effort are discussed. First, additional *research and development* would improve and extend the capabilities of many noninvasive methods. Second, existing tools and methods are quite adequate for many characterization activities but are not being widely used in *practice* for a number of reasons—a major focus of this report is on improving the use of existing methods.

RESEARCH AND DEVELOPMENT

During the past two decades, advances in computing and microelectronics stimulated the production of an impressive array of tools and techniques for noninvasive characterization of the shallow subsurface. For the most part, these advances made existing tools and techniques faster, cheaper, or more effective. There have been relatively few fundamental innovations with regard to the phenomena being observed or the sensing devices that convert these phenomena into electrical signals. Additional research and development (R&D) is needed to enhance and extend current capabilities and to develop new measurement techniques (see Box 1).

Noninvasive site characterization would probably be used more frequently and efficiently if much of the data acquisition, data processing, and decision making could be automated. Automation, which will not replace skilled practitioners, could significantly increase the knowledge base that practitioners can use to accomplish their jobs. By producing a better result, more rapidly and at lower cost, robotics and decision support systems could be the key to more—and more effective—use of noninvasive site characterization methods. Automation of site characterization allows measurements and preliminary interpretations to be made in real time.

Characterization problems are complex and multifaceted. Noninvasive methods, ranging from electromagnetic and seismic techniques to remote sensing by aircraft and satellites to on-site soil-gas surveys, must be selectively used to provide complementary information that enhances our ability to resolve subsurface features. Basic research on physical, chemical, and biological properties is needed to establish fundamental relationships, including coupled relationships, that improve capabilities for rigorous interpretation. A significant effort should be directed to develop scientific visualization technology that is aimed at substan-

BOX 1
Recommendations Related to Research

Scientists and engineers should improve their ability to integrate multidisciplinary data for modeling, visualizing, and understanding the subsurface.

Government agencies should be encouraged to increase their investment in near-surface, characterization R&D in the areas appropriate to their mission.

Government and industry should cooperatively investigate mechanisms for coordination and support of site characterization research and development..

Research and development efforts applied to automation of data acquisition, data processing, and decision making could produce rapid improvement in all aspects of near-surface characterization and should be given a high priority for research funding.

Noninvasive measurements over prolonged periods of time should be investigated as a possible monitoring method for site characterization, underground construction, and remediation projects where monitoring is required.

As part of a basic research program, a significant effort should be directed toward quantification of physical and chemical realities of what is being sensed as well as possible interactions between in situ properties and processes.

Long-term research to develop new noninvasive tools and techniques should be given a high priority, with emphasis on research done by multidisciplinary teams.

tially enhancing three-dimensional interpretations based on multiple data sets. In addition, visualization technologies will help make the interpretations easier for decision makers to understand.

The spatial and temporal resolution demanded in a specific characterization study is a major factor in the choice of method, and resolution normally is a function of the scale of the survey. An understanding of resolution requirements and capabilities is essential to informed choice and application of specific techniques and will provide important guidance in establishing research priorities. Ongoing basic research is essential if we are to develop high-resolution techniques for application in a variety of geological conditions. Testing of data acquisition and analysis procedures to assess and improve the capabilities of existing technologies is needed. Integration of data from other invasive and noninvasive methods can be used to "verify" new capabilities, but one has to ensure that validations do not involve circular reasoning.

Historically, site characterization has focused on mapping the geometry of the subsurface (e.g., location of anomalies, shape of boundaries). However, physical, chemical, and biological properties and processes may be as important as geometry and require greater emphasis in both research and practice. Fundamental studies should be expanded and developed to establish theoretical and phenomenological relationships among the responses measured using noninvasive methods and the properties and processes of interest in environmental and engineering problems of the shallow subsurface. These studies could include controlled standard test sites and variable-scale testing that would involve both laboratory testing of cores and full-scale multitechnique examinations of relevant field sites.

In many cases—especially those involving groundwater, waste management, and hazards—subtle changes from a preestablished baseline are more important than current conditions. Fortunately, properly designed surveys often can monitor changes with high resolution.

Rigorous computer models based on an understanding of physical, chemical, and biological processes are underutilized in the understanding and interpretation of site investigation measurements. Modeling is necessary to allow firm linkage of the parameters of interest to the properties and processes occurring in the earth. Models could allow optimization of survey design, resolution of uncertainties and limitations associated with data acquisition, and validation of interpretations. There are many existing computer modeling programs that are potentially useful, but they must be catalogued, documented, and made both user friendly and easily accessible to fulfill their potential.

Much of this report focuses on the improvement, or improved use, of existing technologies. These technologies primarily measure physical properties and processes; a few measure selected chemical properties and processes; and currently, few if any are routinely applicable to subsurface biological properties and processes. There exists tremendous potential for the development of new methods that would allow the acquisition of more information about the chemical and biological state of the subsurface. To date, there has been little communication among geochemists, geophysicists, and geobiologists regarding the possible extension of existing measurement techniques to determine a different type of property (e.g., geochemical measurements to determine geobiological processes). New development has to focus on measuring new chemical and biological properties and processes as well as better processing, modeling, visualization, and concurrent utilization of the data from all measurements. Controlled test sites should be established for long-term research and used to validate the measurement-data processing-modeling-interpretation systems and to facilitate regulatory approval.

PRACTICE

Many current needs for near-surface characterization can be met with existing tools and techniques, but these tools and techniques are not widely used.

BOX 2
Recommendations Related to Practice

Government agencies, environmental and engineering contractors, and university researchers should work to analyze and document the potential costs and benefits of the use of noninvasive characterization methods in a wide variety of applications.

Government agencies (federal, state, and local) need to develop approaches to site characterization that focus on flexible program design procedures and decision-making processes that account for the unique character of each site.

Scientists and engineers have to place greater emphasis on communicating information about noninvasive tools and techniques and their recent advances to practitioners.

Government agencies and professional societies are encouraged to form partnerships in long-term efforts to distribute and share information on the capabilities and recent developments of noninvasive characterization methods.

Much of the site characterization conducted today uses techniques that are more than 20 years old. Widespread adoption of effective tools and techniques that currently exist offers the single greatest opportunity for dramatic, short-term improvement in site characterization (see Box 2).

Many clients and practitioners often exclude noninvasive tools in their arsenal of methods for subsurface characterization. For the demand for noninvasive technologies to increase, the techniques must be demonstrated either as being cost-effective or as providing information that is unavailable any other way. However, many potential clients today perceive characterization tools as increasing costs without providing a commensurate additional value. Their primary objective commonly is to satisfy externally imposed requirements (e.g., building codes, environmental regulations) at minimum cost. Many clients and practitioners rely on "tried-and-true" characterization methods rather than innovative noninvasive methods. To overcome this lack of incentive, case studies should be publicized that analyze the possible cost-effective use of noninvasive site characterization.

The gap between the state of knowledge and the state of practice in noninvasive methods can be addressed by improved communication with and education of practitioners (e.g., contractors who conduct the measurements in the field) regarding advances in techniques and methods. In addition, communication and education on noninvasive characterization methods should be extended to clients and regulators (who write specifications) and the general public. These efforts should include expanded university curricula and training, continuing education opportunities for practitioners and users, and general public education.

1

Introduction

Just beneath our feet is an environment that supports our built infrastructure, yields much of our water, energy, and mineral resources, supports agriculture, and serves as the repository for most of our municipal, industrial, and radioactive wastes. Processes within this environment can lead to a variety of soil instabilities that constitute natural hazards, such as landslides and sinkholes; the subsurface is also susceptible to contamination and modification by human activity. During the next century, there will be increasing pressures to use and understand the shallow subsurface for a myriad of applications (see Box 1.1). Safe, effective use of the near-surface environment of the earth will be a major challenge facing our global society in the twenty-first century. An accurate description or characterization of the shallow subsurface environment is critical to the solution of many resource, environmental, and engineering problems, but our ability to do so is often limited.

Applications of subsurface information abound. Figure 1.1 is a conceptual diagram that attempts to show four major types of applications, many with different motivations. For instance, basic science is driven largely by understanding and knowledge acquisition, whereas infrastructure applications tend to be driven by engineering needs and the use of subsurface knowledge. Subsurface applications of public health and safety are dominated by regulatory concerns, whereas resource extraction is driven by economic returns. These four general applications form a continuum of sometimes interrelated and sometimes competing objectives. Because those applications driven by economics tend to progress more rapidly, this report emphasizes the need for public sector involvement in developing applications relating to regulatory, health and safety, and scientific concerns.

BOX 1.1
Frequently Asked Questions

- Can you locate underground cables or water mains in an area being excavated?
- Can you locate underground gasoline tanks and determine if they are leaking?
- Can you locate buried containers that may need remediation at a Superfund site?
- Is the subsurface strong enough for the building foundation?
- Can you determine the extent of contamination in groundwater and monitor the movement of the contaminants?
- Can you safely locate buried land mines and unexploded ordnance?

These and many other environmental and engineering questions require subsurface characterization; many need *noninvasive* (i.e., without disturbing the ground) characterization, other questions can be addressed by drilling and direct sampling.

In the United States, the total cost of cleaning up an estimated 300,000 to 400,000 contaminated groundwater sites over the next 30 years may range as high as $1 trillion (NRC, 1994). Accurate subsurface characterization of a site (see Box 1.2) prior to cleanup is essential in designing and implementing effective remediation systems (NRC, 1997). Subsurface characterization is likewise critical to infrastructure development, repair, and replacement, the cost of which is estimated to be more than $1 trillion (American Society of Civil Engineers, 1998). Rapid, inexpensive, reliable characterization could save an enormous amount of money through improved performance in environmental and engineering applications.

Techniques for describing the subsurface environment involve many disciplines and have myriad potential applications. In this report, *characterization* of the subsurface refers to the determination of physical, chemical, and in some cases, biological information about subsurface properties and processes that we can neither see nor easily sample from the surface. At present, most subsurface characterization involves invasive methods—drilling, trenching, excavation—and the methodologies are well established.

Direct or invasive methods of characterization (such as drilling and excavation) can be expensive, and they often may disrupt human activities and cause unnecessary environmental damage. Indirect or noninvasive methods hold the promise for rapid, low-impact, and relatively inexpensive characterization of the earth's subsurface—just as X-rays, sonograms, and other medical imaging technologies have reduced the necessity for invasive diagnostic surgery and have revolutionized medical practice. As in medicine, there are many situations in which invasive methods are required to characterize the shallow subsurface.

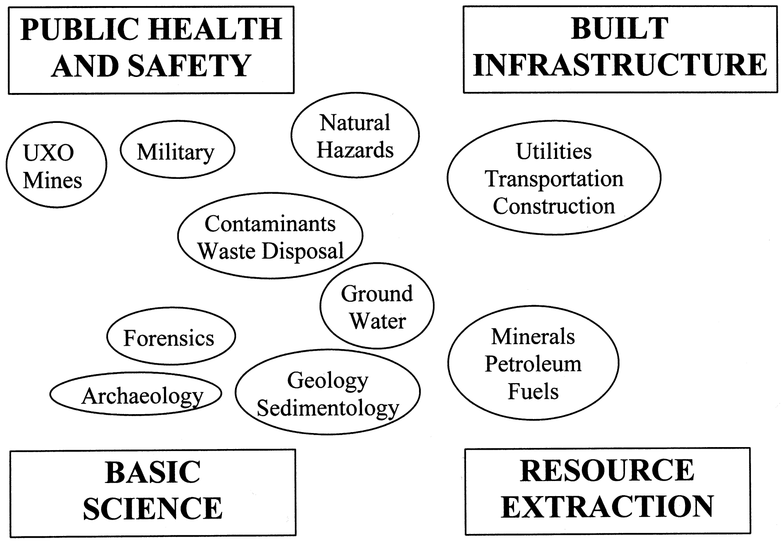

FIGURE 1.1 Four general agendas (rectangles) met by noninvasive subsurface characterization, and a spectrum of some representative applications (ovals) in relation to their corresponding agendas. In general, there is a trend from regulatory-driven applications in the upper left corner to more economically driven applications in the lower right corner; there is also a trend from knowledge acquisition in the lower left corner to knowledge application in the upper right corner.
NOTE: UXO = unexploded ordnance.

Advances in instrumentation, computation, transportation (in terms of robotics and aerial and space instrument platforms), and communication have significantly expanded the practice and the research opportunities for *seeing into the earth* noninvasively. These new advances and the resulting wealth of data they produce not only have intensified the task of data management, but also have presented problems for practitioners and site managers, who must decide what techniques are appropriate at a given site. Nonetheless, noninvasive characterization methods hold great potential for defining subsurface details with a high level of accuracy, precision, economy, and safety, if they are used consistently and effectively. Realizing this potential will require concerted interdisciplinary efforts by earth scientists, geotechnologists, government agencies and regulators, and the user community.

PURPOSE OF THIS REPORT

A variety of noninvasive techniques for subsurface characterization may offer distinct advantages over traditional invasive methods. This report focuses on techniques that hold the potential to reduce the need for invasive site charac-

BOX 1.2
Effective Assessment for Remediation Efforts

…the site assessment process is critical to making appropriate corrective action decisions. When site assessments are complete, they provide accurate information about the presence and distribution of contaminants, thereby facilitating cost-effective and efficient remediation. When they are incomplete, they can provide inaccurate or misleading information which can delay effective remediation, increase overall corrective action costs, and, result in an increased risk to human health and the environment.

SOURCE: (EPA, 1997)

terization by providing more continuous coverage of subsurface features and properties. The report (1) assesses current capabilities for characterizing the near-surface environment using noninvasive technologies, (2) identifies weak links in current capabilities and the potential for new and improved methods, and (3) recommends research and development to fill these gaps.

Following this introductory chapter, several illustrative applications are given in Chapter 2. Chapter 3 follows with a discussion of what is measured or characterized. The bases of the various noninvasive techniques are developed in Chapter 4, with an emphasis on the strengths and limitations of the techniques and the nature of the research and development needed to improve the capability of a specific technique. This is not an exhaustive treatment—some methods are only briefly mentioned, whereas most of the "standard" methods are treated more fully. The committee purposely avoided discussion of the pros or cons of specific commercial instruments and chose to treat the general method. Chapter 5 deals with issues of data interpretation—integration of data from multiple methods, modeling, and visualization. A discussion of some of the nontechnical issues that the committee found hampered the broader application of noninvasive techniques is given in Chapter 6. Finally, Chapter 7 looks at some steps that could further develop noninvasive characterization and their practice.

WHAT IS NONINVASIVE?

Noninvasive methods, involving little or no disruption of surface materials, are able to (1) sense and record the location of buried objects; (2) determine geological, geochemical, and geobiological properties; (3) detect and map contaminants and monitor their movement; and (4) assess structural, lithologic, stratigraphic, and hydrogeologic conditions. Many are geophysical techniques that measure responses to acoustic, electromagnetic, or electrical stimuli or detect changes in natural physical or chemical properties of the earth (e.g., gravitation,

TABLE 1.1 Relative Invasiveness of Measurements

Least Invasive	Example Technique
Satellites, aircraft	Remote sensing, aerial photographs
Helicopter-borne	Remote sensing, electromagnetics, magnetics
Walk on ground	Magnetics, gravity, conductivity, ground penetrating radar
Disturbance, <1 m	Surface seismic, resistivity, geochemical sampling, biological sampling, soil-gas sampling
Disturbance, <3 m	Shallow trenches, penetrometers, direct-push technologies
Drill holes *adjacent* to volume being investigated	Borehole methods (including tomography) using seismic, radar, electromagnetics, resistivity)
Drill holes into volume, trenching	Direct sampling
Most Invasive	

magnetic field, composition). Geophysical methods applied on the surface and from airborne and space platforms (including multispectral remote sensing techniques) are relatively mature, whereas noninvasive geochemical and geobiological techniques are less advanced.

Any physical measurement can potentially disturb the material being investigated. The significance of the disturbance, of course, depends on the application. A continuum exists from least invasive (remote sensing from satellites or aircraft) to highly invasive (drilling into and making direct measurements in the volume to be investigated). Several techniques may be minimally invasive, such as small-diameter penetrometers and soil probes that penetrate from a few tenths to several tens of meters into the subsurface. More invasive methods include borehole logging techniques and geophysical methods that use powerful energy sources and require larger-diameter boreholes.

Actions considered invasive and disruptive in one instance (e.g., driving a four-wheel-drive vehicle on tundra) may be benign in other circumstances (driving along a paved road). Drilling into the volume of earth being investigated would certainly be regarded as invasive, but drilling boreholes adjacent to the volume being investigated to perform cross-borehole measurements or measurement between the drill hole and the surface might not be. Table 1.1 lists some measurement techniques in relative order of increasing invasiveness. The concept of noninvasive must necessarily be flexible.

NEAR-SURFACE APPLICATIONS OF NONINVASIVE TECHNIQUES

Noninvasive characterization of the shallow subsurface can serve many ends (see Box 1.3). Many of the techniques have been developed from the decades-old geophysical methods used to explore for petroleum and other mineral resources.

BOX 1.3
Examples of Applications for Noninvasive Methods

- Characterization of subsurface for
  - waste disposal, containment, remediation
  - infrastructure construction (e.g., foundations, tunnels)

- Location of
  - voids (e.g., sinkholes, mined out areas)
  - resources (e.g., ground water, sand and gravel, clays, ores)
  - underground utilities and cables
  - buried land mines and unexploded ordnance
  - potential hazards (e.g., expansive soils, liquefiable soils)

- Monitoring of
  - ground movements
  - infrastructure decay (e.g., leaking tanks, pipe, sewers)

- Archaeologic or forensic investigations

- Search and rescue operations (e.g., collapsed structures, landslides)

The near-surface application of these well-established techniques, however, usually demands *higher resolution* than that commonly found in the petroleum industry. Sheriff (1991) defined resolution as "the ability to separate two features which are very close together; the minimum separation of two bodies before their identities are lost on the resultant map or cross section." The limits of both horizontal and vertical resolution for noninvasive methods can be determined from the laws of physics (e.g., Widess, 1973). There is a difference, however, between *resolving* a body and *detecting* a body, because detection does not imply determination of size. The physical requirements for detection are less stringent than those for resolving a body.

The extension of the established techniques to near-surface applications is relatively new, circa the 1970s, and less mature. For instance, the *practical* use of ground penetrating radar (GPR) and seismic reflection techniques for environmental purposes dates only from the mid-1980s, though many of the techniques themselves date from the 1920s. A survey of the evolution of geophysical methods applied to engineering and environmental problems is available through a series of manuals produced by the U.S. Army Corps of Engineers (Department of the Army, 1948, 1979, 1995).

The roots of many of the methods applied to noninvasive subsurface characterization go back decades. For example, measurements of natural voltages associated with weathering of sulfides in Cornwall, England, date to the 1830s. The first practical use of explosion seismology occurred in World War I, when the French used seismic refraction arrivals to locate German artillery emplacements. Seismic reflection was first used successfully in 1921, and the petroleum industry has routinely used reflection methods in its quest for hydrocarbons ever since. Except for magnetotelluric methods, almost all the other classical electrical methods of geophysics had been investigated to some degree by 1930.

In a sense, then, some of the noninvasive methods have come full circle from initial development for surficial research, to use for resource exploration at depths of a few kilometers, to renewed use in near-surface applications.

Geophysical surveys, soil-gas analyses, and interpretation of aerial and space imagery can help to characterize contaminant sources (e.g., location of buried tanks or abandoned wells), identify geological influences on fluid and contaminant movement (e.g., stratigraphy and faults), or determine and monitor the extent of subsurface contamination at environmental remediation sites. Such characterization can help plan the location of drill holes and physical sampling (and their representative nature). Noninvasive techniques can also be used as part of engineering design to prevent future engineering and environmental problems. Increasingly, geophysical methods are being used prior to construction to help assess the subsurface integrity of proposed locations for industrial and government facilities such as chemical plants and facilities for waste storage and disposal. Geophysical and other noninvasive methods continue to be developed for near-surface resource exploration, particularly mineral resources and groundwater. Finally, noninvasive methods are important for purposes of research and enhancement of basic geological and hydrologic knowledge.

Measurements made at or just below the ground surface using noninvasive methods can cost less than invasive methods that involve trenching or drilling, installation of monitoring wells, sampling, or chemical analysis. Digging holes into the soil and drilling wells into deeper layers are necessary to directly sample constituents and determine the exact composition of shallow and deeper layers underground. By itself, however, drilling provides a narrow, one-dimensional sample of the ground. Noninvasive methods can provide continuous coverage of features and properties and reveal trends and patterns that might easily be missed by drilling. Because drilling can be expensive, noninvasive techniques can save money by optimizing well placement and reducing the number of wells required. Further, there are many situations in which drilling or disturbing the earth is impractical, unsafe, or prohibited. In polluted areas, drilling may pose a risk to workers and the environment because wells could promote the spread of contaminants. Drilling on busy urban streets can be disruptive to traffic as well as being risky to buried utilities.

Table 1.2 lists the main classes of noninvasive techniques. Many of the relevant noninvasive geophysical techniques for characterizing the near surface were developed for the oil, water, and mineral exploration industries or for geotechnical applications in civil engineering. The detection of underground

TABLE 1.2 Principal Geophysical Methods and Determined Parameters

Method	Principle	Typical Measurement	Physical Property Measured	Interpreted Parameters
Gravity	Detects variations in the gravitational field of the earth caused by mass variations	Relative displacements of mass on a beam	Density	Depth, geometry, and density of localized subsurface features
Magnetic	Detects variations in earth's magnetic field caused by local variations in magnetic properties of subsurface materials	Electron or proton precession frequency; saturation of magnetic core	Magnetic properties	Depth, geometry, and magnetic susceptibility of localized subsurface features
Seismic	Sends vibrations (elastic waves) through the subsurface and analyzes changes in velocities (property dependent) and reflections or refractions as they pass through heterogeneities	Distances, times, and wave amplitudes	Compressional, shear, and surface waves; seismic velocities; and elastic moduli	Interface depths, layer velocities, geometry, or structure, elastic moduli, porosity
Electrical resistivity and electromagnetic (EM) induction	Detects natural or induced electrical current flow thorough subsurface materials; electrical properties controlled by material properties of the subsurface along with porosity and pore fluid compositions	Currents, voltages, and distances	Electrical resistivity, magnetic susceptibility	Depth, thickness, electrical resistivity, porosity, inferred fluid chemistry
Ground penetrating radar (GPR)	Sends high-frequency radar waves through the subsurface; analysis similar to seismic reflection and refraction velocities are property dependent	Distances, times, and amplitudes	Dielectric permittivity, electrical resistivity, magnetic susceptibility	EM wave speeds, depths, thicknesses, geometry
Integrated interpretation of multiple, complementary methods				Soil and rock type (lithology), structure and stratigraphy, porosity, permeability, fluid content

structures, caves, land mines, and unexploded ordnance has been a research priority of the U.S. Department of Defense, requiring very high resolution, noninvasive techniques.

USING THE TOOLS AND TECHNIQUES

Several geological, geochemical, and geophysical techniques are used in the field for characterization of the shallow subsurface with varying degrees of success and cost-effectiveness. Reviews of current applications of shallow exploration techniques, their methods, and a variety of case histories can be found, for example, in the three-volume book *Geotechnical and Environmental Geophysics* (Ward, 1990), in the annual *Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems* (e.g., SAGEEP, 1998), and in the *Journal of Environmental and Engineering Geophysics* as well as many other technical journals and texts (e.g., Sharma, 1997). Recently, the American Society for Testing and Materials (1999) issued a guide for selecting surface geophysical methods. All near-surface techniques sense some physical or chemical parameter at the surface of the earth. The resulting measurements are then used to infer permeability, porosity, chemical constituents, stratigraphy, geological structure, and other properties beneath the survey area (see Table 1.3). Where there is the need, the noninvasive characterization can be checked by invasive "ground truth" measurements, which may allow further calibration of the noninvasive methods and help in modeling the specific site's subsurface conditions. Resulting characterizations provide critical input to the development of a conceptual model for a site, which is the initial step in an "expedited site characterization process" (American Society for Testing and Materials, 1997).

Figure 1.2 schematically indicates representative steps that can be used for noninvasive characterization, if the objectives of the characterization effort are defined. As this figure illustrates, a series of steps links the technique used to the actual property that is to be estimated. A desired property, such as aquifer porosity, is not measured directly but rather must be determined from the measured parameters using models and interpretation. As implied by this figure, the process is inherently iterative. For example, the desired parameter to be measured is determined before beginning the survey design. However, modeling done during the survey design phase might show that the interpretation of this parameter will not produce the desired result; thus, it would be necessary to reconsider the characterization strategy and select a different parameter. Alternatively, real-time interpretation in the field might show that the geological basis for the survey design was wrong, making it necessary to interrupt data collection and redesign the survey.

In assessing the capabilities and limitations of a particular noninvasive tool (selected using steps 1 and 2 in Figure 1.2), the critical factors include the measurement process (step 3), the interpretive model (step 4), and the derivation of the desired parameters from the interpretation (step 5). Table 1.3 indicates gen-

TABLE 1.3 General Applicability of Selected Geophysical Methods to Typical Site Assessment and Monitoring Objectives.

Example Objectives	Seismic Refraction	Seismic Reflection	Ground-Penetrating Radar	Electrical Resistivity	Electromagnetics	Induced Polarization	Microgravity	Airborne Sensing	Magnetics
Geologic mapping	❶	❶	❶	❶	❶	②	②	②	②
Hydrogeology characteristics	❶	②	❶	❶	❶	③	②	③	na
Water table depth	❶	②	②	❶	❶	③	na	②	na
Top of bedrock	❶	❶	③	❶	❶	③	②	③	na
Cavity detection	②	②	❶	❶	❶	③	❶	③	③
Disposal trench mapping	③	②	❶	❶	❶	na	②	②	②
Nature of trench fill	③	na	❶	❶	❶	?	❶	na	❶
Inorganic contaminant plume	na	na	❶	❶	❶	❶	na	②	na
Organic contaminant plume	na	na	②	?	?	?	na	②	na
Disposal container (metal drum)	na	na	❶	②	❶	③	③	na	❶
Underground storage tanks	③	③	❶	②	❶	③	②	na	❶
UXO detection	na	na	❶	❶	❶	na	na	③	❶

KEY: ❶ = primary applicability; ② = secondary supporting applicability; ③ = limited applicability; na = no general applicability or not widely used; and ? = area of active research and rapidly evolving technology or questionable application.

NOTE: This table indicates the relative applicability of the various methods; however, there are many exception, and this should not be used as a basis for definitive planning and contracts. Similar tables have been constructed as general guides by others (e.g., ASTM, 1997).

eral applicability of individual noninvasive geophysical methods to various characterization goals. How the measurement process is designed and performed in the field and how the resulting data are processed, modeled, and interpreted will largely determine how accurately the desired parameters can be determined (e.g., Plate 1). Logistical decisions, such as the spacing of survey lines, and the inherent limitations owing to the physics of the measurement process will affect measurement accuracy and resolution. Modeling capabilities and our understanding of the relationship between the measured parameters and the estimated properties will control the accuracy and uniqueness of the final result. Furthermore, some properties simply cannot yet be deduced unambiguously using noninvasive methods. For example, groundwater flow calculations depend on estimates of hydraulic conductivity for which direct noninvasive measurement techniques currently do not exist. Other examples of parameters that cannot be unambiguously determined include porosity, grain size and orientation, and clay content and mineral-

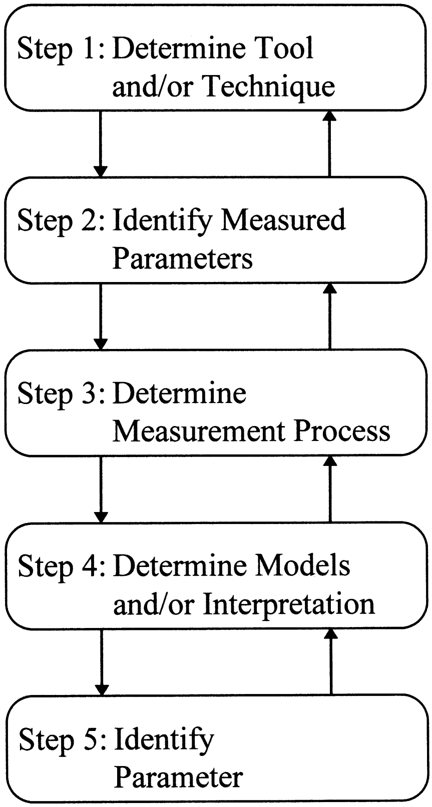

FIGURE 1.2 Steps in noninvasive parameter identification

ogical variations. More work is needed to develop new tools, techniques, and interpretive methods for determining such parameters. In general, there is also a difficulty in linking physical parameters to geological and hydrological features and processes.

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2

Why Characterize the Subsurface?

A large number of applications require the ability to "see into the earth," to determine physical, chemical, and biological properties and to detect, monitor, and predict natural and induced processes. The characterization of the earth's subsurface is motivated by a mix of economic, scientific, environmental, regulatory, and health and safety concerns. This chapter discusses a sample of the various applications. The foremost question is: What is there and what is its extent or boundaries? Information can be obtained from noninvasive observations from the earth's surface or from direct sampling. Depending on the application, noninvasive observations often have to be supplemented by direct sampling of the volume of ground under investigation.

Characterization needs or objectives are dependent on the specific application. These characterization objectives are described in greater detail in Chapter 3. In some applications, the required information involves determining the physical, chemical, and biological properties of the solids and fluids below the surface. Characterization also commonly involves obtaining information about the processes that occur in the subsurface. These processes include the natural processes that form and modify the geological materials and the structure of the subsurface, and induced processes such as fluid pumping or injection. The level of accuracy and spatial resolution required in the characterization of properties and processes is determined both by the application and by the motivation.

NATURAL RESOURCES

As the human population increases and developing countries become more industrialized, the demand for natural resources will continue to grow. Offshore exploration for oil is expanding into deeper water. Mineral and water resources are in ever-increasing demand. To find and extract these resources economically with minimal environmental impact requires technologies that can efficiently determine their location, extent, and quality.

The common characterization objective in resource exploration is the direct detection of the resource (e.g., ore body, groundwater aquifer, hydrocarbon reservoirs). The methods used depend on the physical and chemical contrast with the background or host geology. In some cases it is not the ore body, the aquifer, or the petroleum reservoir that is the target but a geological setting or structure likely to host the resource. An example is the location of a fault zone in the search for gold mineralization or the location of an anticline in the search for a gas reservoir. For many resources, noninvasive techniques, including remote sensing, represent a standard approach to initial characterization. Geophysical surveys, either airborne or ground-based, can be used to obtain reconnaissance data over large areas to determine regions with high resource potential. Such geophysical surveys have had many successes including the location of the multibillion-dollar Olympic Dam ore deposit in Australia (Roberts and Hudson, 1983).

More detailed assessment of an area requires higher-resolution geophysical and geological mapping along with drilling and direct sampling. Characterization at this stage is designed to obtain a more accurate determination of location and lateral distribution. A shortcoming of noninvasive techniques for these purposes in mineral exploration has been the limited depth of investigation and poor resolution at greater depths. Although not as widely recognized as a limitation, resolution, even at shallow depths, is often insufficient to produce the type of ore body discrimination that can be useful in modern exploration surveys and mine development activities.

In addition to locating a resource, a common goal of characterization is to determine the extent and quality of the resource. Although drilling and sampling can provide this information, noninvasive techniques may be useful for some determinations of resource quality. For example, induced polarization methods can discriminate certain minerals in an ore deposit, and electrical conductivity can indicate the salinity of a groundwater aquifer. In summary, noninvasive techniques are widely used in some resource exploration and well-integrated with the often more expensive drilling and direct sampling programs.

GROUNDWATER CONTAMINATION AND REMEDIATION

There is a growing concern about contaminated soil and groundwater, both from surface spills and from underground sources such as leaking storage tanks or landfill sites. Such contamination affects our natural environment and can have a direct impact on public health and safety and the utility of groundwater. Remediation of contaminated sites is often required, whereas at other sites, containment of the contaminants may be an option (National Research Council, 1994). Regardless of the action to be taken at a site, there is a need for accurate, high-resolution information about the physical and chemical state of the subsurface. (For a recent treatment of containment technology and site characterization needs for containment, see Rumer and Mitchell, 1996.)

Specific characterization objectives depend on the nature of the contamination (if known) and the type of remediative actions being considered at a site. A common objective is to determine the source or present location of a contaminant. Although drilling and direct sampling can be used to help locate a subsurface contaminant plume, such invasive methods may be undesirable because they can spread contamination to surrounding areas and may pose a safety risk. Noninvasive techniques can be used for initial characterization and as a guide for determining the location and density of required direct sampling. For this objective, the appropriate noninvasive technique is one that can directly detect the presence of the contaminant. Alternatively, the technique may detect the subsurface structures or pathways in which a contaminant may preferentially collect or flow. As discussed later, electromagnetic methods in some cases can directly detect inorganic contaminants, depending on the concentration of the contaminant and the geological setting. Direct detection of organic contaminants by noninvasive methods is considerably more challenging, with some reported success using resistivity sounding, ground penetrating radar (GPR), electromagnetic methods, and soil-gas measurements (Figure 2.1). For contaminant plumes, the sensitivity of the noninvasive technique can improve dramatically if the movement of the fluid can be monitored over time (see Plate 2).

A common problem at a contaminated site is the detection of a buried container, which may be a source of contaminant. The chemical and physical properties of the container material, as well as its size, shape, and depth of burial, can be highly variable. The location of underground storage tanks is a common characterization objective for the use of noninvasive technologies because invasive techniques risk damaging or puncturing the container.

In other cases, the characterization objective might be to determine a site's geological framework. Knowing the geological setting, including the heterogeneity (e.g., lithological and structural) and its associated anisotropy, is critical in predicting contaminant transport and planning future remediation efforts. Invasive techniques such as drilling and direct sampling can provide very accurate information about the subsurface, but only for the sampling location and for a limited volume of the subsurface. To obtain the resolution and coverage required for adequate site characterization, direct sampling can become time-consuming and expensive. Noninvasive techniques, on the other hand, can provide high-resolution information about the subsurface over a large area without any direct contact with the contaminated region.

Monitoring the remediation process can significantly improve effectiveness and reduce costs. A monitoring system makes possible ongoing, real-time modification of the remediation process. For example, some remediation methods

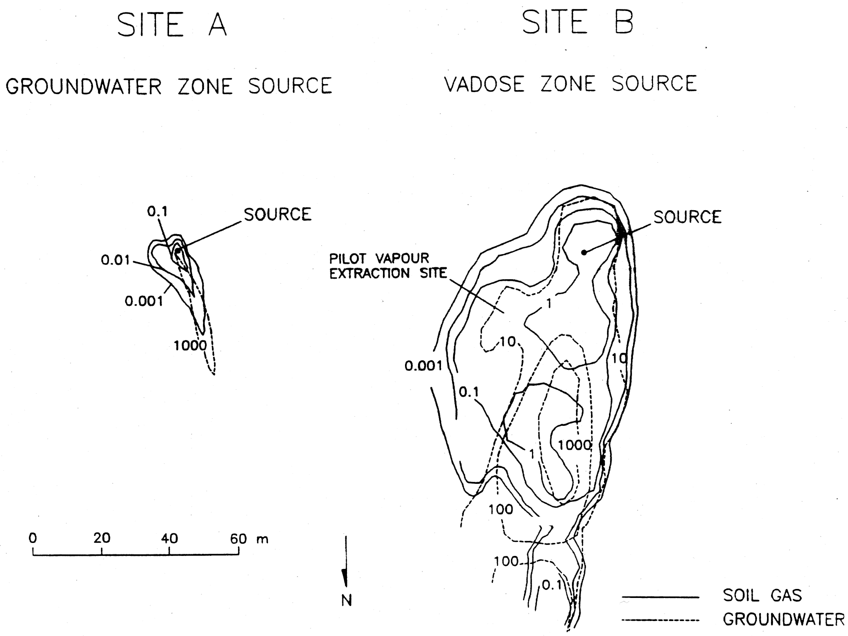


FIGURE 2.1 Areal extent of soil gas and groundwater contamination derived from TCE (trichloroethelene) emplaced below the water table (site A) and in the vadose zone (site B). (all units in grams per liter.) Figure from Rivett and Cherry (1991), which should be referred to for additional details.

usually involve displacing one fluid with another, which can produce spatial and temporal variations in the physical and chemical properties of the subsurface. Such temporal changes can be ideal targets for detection with noninvasive methods and provide an accurate monitoring tool. Noninvasive methods have had some success in this area, as discussed in detail in Chapter 3.

LAND MINES AND UNEXPLODED ORDNANCE

Noninvasive techniques are frequently used to locate buried land mines and unexploded ordnance (UXO). Safety concerns are paramount in such applications. There are an estimated 110 million unexploded land mines, and these "have maimed at least 250,000 people in the world and kill more than 10,000 people each year, more than 90 percent of whom are civilians" (Inter-Parliamentary Union, 1996). In the United States an estimated 15 million acres may be contaminated with UXO (Defense Science Board, 1998). Noninvasive technologies have the potential to reduce the danger by locating and identifying land mines and

BOX 2.1
Biological Detectors

"The most effective biological sensor for the detection of UXO is a trained canine. This semi-autonomous, high mobility platform housing multiple sensors and a million year old trained neural net has demonstrated high detection rates for shallow buried UXO and other explosive devices with low false alarm rates."

SOURCE: Joint Unexploded Ordnance Clearance Steering Group, 1997.

UXO, and obtaining sufficient information about the surrounding material to allow safe removal or detonation in place.

Methods of detecting of land mines and UXO differ considerably (U. S. Army Environmental Center, 1994; Joint Unexploded Ordnance Clearance Steering Group, 1997); see Box 2.1. Land mines are usually buried at shallow depths (tens of centimeters) and are designed to detonate if disturbed. The sensitive nature of land mines necessitates consideration of remote or standoff detection methods. The shallow depths make detection possible using standoff GPR, high-resolution induction electromagnetic (EM) systems, and infrared and multispectral scanners. Buried UXO, however, is encountered at depths up to 10 m and varies in size (from 20-mm projectiles to 2000-pound bombs). UXO detection requires not only high resolution but also a large depth of investigation. Low-metal-content land mines make detection with magnetometers difficult if not impossible, whereas magnetometers are the common "tool of choice" for UXO detection (see Figure 2.2).

Locating land mines and UXO involves both invasive and noninvasive technologies. Noninvasive technologies are usually the first step in determining the location and the identity of land mines and UXO. For certain types of land mines and UXO, it is reasonable to proceed with invasive methods to detonate in place or to excavate and neutralize a region. In other cases, the only safe decision may be to isolate and mark the region as a danger zone and prevent entry.

Land mine and UXO detection is an application area in which the technologies selected must, in some situations, be truly noninvasive because even placing a sensor on or in the ground could detonate a land mine or UXO. The great challenge in the use of noninvasive technologies for UXO detection is the enormous variety in the size, shape, and burial depth of the ordnance and the geological background and cultural clutter. These factors, combined with the demands for high measurement and positional accuracy and sophisticated data integration and interpretation for target discrimination and identification, make UXO detection an extremely challenging and critical area for the application of geophysical methods and help underscore the need for additional research and development.

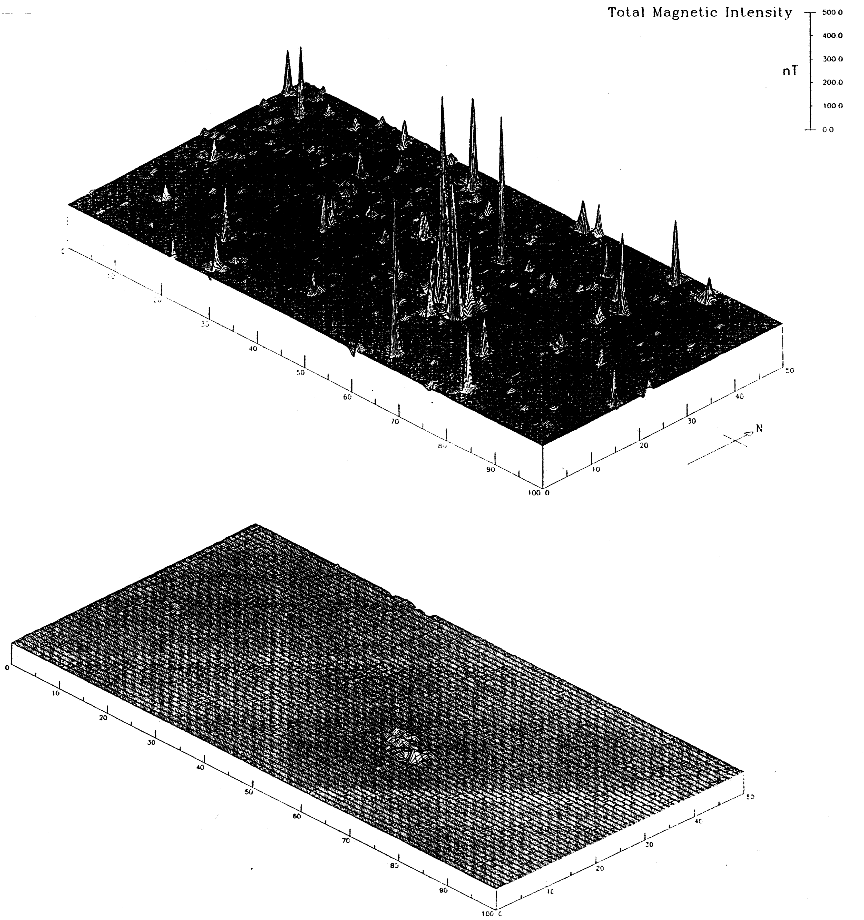


FIGURE 2.2 High-resolution magnetic survey for UXO detection

Unexploded ordnance (UXO) contamination exists on active and former military training and testing ranges. Environmental restoration of these sites to support future training and testing and return them to public use is a high priority. High-accuracy magnetic determinations can be particularly effective in the detection of ferrous UXO. If the type of ordnance is known, such surveys permit the areal location, depth, and approximate size of sub-surface UXO to be determined.

The top figure is from a high-resolution magnetic survey over a contaminated World War II artillery range. Data were collected with an automated survey system consisting of an array of optically pumped magnetometer sensors combined with a differential Global Positioning System, operated from an all-terrain vehicle. A similar survey (bottom) after the area had been cleared of ordnance produced a uniformly flat figure with the exception of residual rust flakes from other metallic debris. (Example courtesy of Geophysical Technology Limited, Armidale, Australia.)

CIVIL INFRASTRUCTURE

Many civil engineering projects require characterization of the shallow subsurface. Such projects include the design and construction of roads, airfields, bridges, dams, water supply and wastewater treatment facilities, housing, industrial and office buildings, tunnels, power plants, and safe storage facilities for wastes of all types.

In addition to design and construction, subsurface information is needed for the rehabilitation of existing underground infrastructure. A common application of noninvasive techniques is for locating existing underground utilities (e.g., telephone, gas, water, electric) and structures (see Plates 3 and 4). The National Transportation Safety Board (1997) cites the needs for proper use of geophysics in locating underground utilities before digging, excavating, or drilling, and for statistics on inadequate implementation of geophysical sensing. It also states that "a single pipeline accident has the potential to cause a catastrophic disaster that can injure hundreds of persons, affect thousands more, and cost millions of dollars in terms of property damage, loss of work opportunity, ecological damage, and insurance liability." Typically about 70 such events occur in the United States every year (National Transportation Safety Board, 1997).

Many geotechnical projects have traditionally relied on field penetration tests, in situ tests of various types, and laboratory tests on samples of varying quality and representation. However, noninvasive tests have been used increasingly in recent years because they often cost less, are relatively easy to conduct, and provide information not readily obtained by other means. In addition, noninvasive methods can test a much larger volume of the subsurface than traditional sampling or in situ testing approaches. These methods provide an excellent supplement than can limit the number of invasive methods used in most projects. A coordinated approach that combines invasive and noninvasive methods is likely to yield the most reliable site characterization.

Most infrastructure projects have several characterization objectives in common. At a minimum, geologists and engineers seek to know and understand the types of soil and rock materials and their stratigraphy, as well as the engineering properties of the different materials and the depth to groundwater. Construction in urban areas also requires information about existing underground works such as utilities, tunnels, and preexisting foundations. The engineering property requirements consist of five types: (1) volume change characteristics, so that settlements or heaves may be estimated; (2) strength, so that the stability of slopes, embankments, and excavations can be analyzed and the supporting capacities of foundations determined; (3) deformation characteristics, so that ground movements may be anticipated, dynamic response to earthquakes analyzed, and soil-structure interactions studied; (4) hydraulic conductivity properties (and in certain situations, thermal, electrical, and chemical conductivity) so that flow quantities can be estimated; and (5) the likelihood that these properties may change with time.

Current limitations of noninvasive methods for geotechnical applications include the inability to define boundaries and identify material types with sufficient accuracy, the inability to analyze small volumes or zones that may have a critical importance (e.g., failure to detect small-scale heterogeneity), and a lack of noninvasive methods for determining strength, volume change, and hydraulic conductivity properties (except as they might be deduced through correlations with material type). In addition, there is often a lack of unique interpretation from a given set of geophysical measurements.

HAZARDS

Noninvasive methods can play a critical role in characterizing certain natural hazards. Ground failure risks from natural hazards (e.g., surface manifestation of earthquakes, floods, landslides, and expansive or collapsing soils) require identification and mitigation to ensure public safety, as well as for reasons of economy. Knowledge of stratigraphy and engineering properties is essential for analysis of ground responses to forces of nature, such as gravity, earthquake ground motion, wind, and waves. Seismic methods are particularly well suited for evaluating the mechanical properties and interpreting ground behavior under dynamic loading.

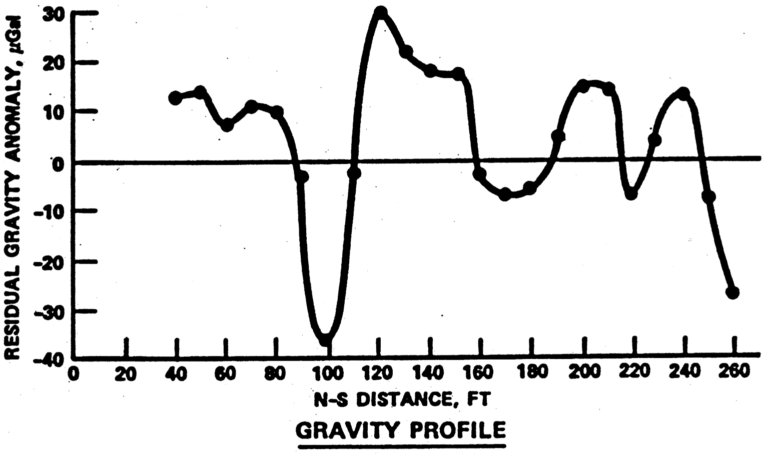
Subsurface cavities are another type of hazard commonly associated with sudden ground failure. These cavities, which include natural sinkholes and caverns as well as human-made tunnels or subterranean chambers, must be properly located (see Figure 2.3). Sinkholes might have no surface expression until they breach the surface and cause considerable damage to engineering infrastructure. By knowing where cavities are, one can avoid building on them. In addition, knowledge of underground cavity distribution often gives information on the water flow network that such cavities can provide.

Conduits and caves can act as pipes, allowing contaminated groundwater to migrate rapidly over great distances. Some of the more troublesome groundwater contamination disasters have occurred in karst (limestone) aquifers where the existence or location of conduits was initially unrecognized. Structural engineering projects can also be severely impacted if there are large openings in underlying bedrock.

On a much more localized scale, noninvasive techniques (particularly GPR) can be used in road maintenance, particularly in monitoring asphalt pavement thickness and detecting air-filled voids or bridge deck delamination (NRC, 1998).

ARCHAEOLOGY

Recent federal legislation such as the Native American Graves Protection and Repatriation Act, the Archaeological Resources Protection Act, and the Na-



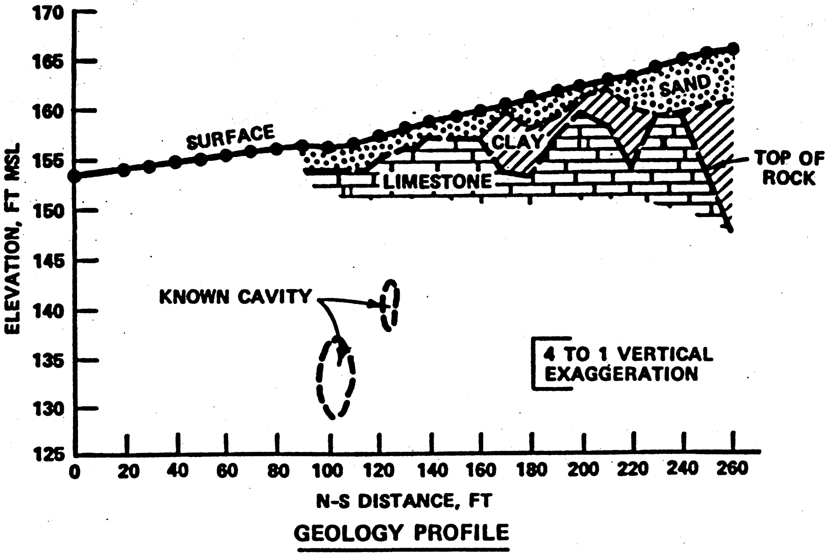


FIGURE 2.3 Microgravity profile (top) and corresponding geological section (bottom) determined by closely spaced drilling. Known air-filled cavities passing under the profile line are shown in the geological section. The gravity anomaly profile indicates a negative anomaly over the cavities and positive and negative anomalies correlating to limestone pinnacles and clay-filled pockets, respectively. The negative anomaly over the cavities is a superposition of the effects of the cavities plus solution-enlarged porosity and fractures above and around the cavities. Adapted from Butler (1984).

tional Historic Preservation Act of 1966 mandate cultural resource assessments prior to construction or other activity that could endanger either known or undiscovered cultural artifacts.

At an archaeological site, the overall characterization objective is to find the artifacts and features. Specific characterization objectives include the direct detection of these objects and the detection of disturbed ground that indicates past human activity. Traditional archaeological field research involves invasive methods such as the careful digging of pits and trenches to find, extract, and document artifacts. The time and cost involved in these methods have increased interest in the use of noninvasive techniques, particularly geophysical methods, to map archaeological sites and plan the locations of invasive sampling. In addition, geophysical methods often allow archaeologists to detect and map patterns at sites that are often extremely difficult to detect and visualize from standard procedures. For example, Katsonopoulou and Soter (1996) used GPR in the exploration of ancient Helike. Some geophysical investigations of archaeological sites have received considerable public and popular-scientific media attention—for example, Lakshmanan and Montlucon's (1987) discovery of hidden chambers in the Great Pyramid at Giza, Egypt.

Because geophysical anomalies caused by archaeological artifacts and features are often small and subtle, the geophysical methods and survey procedures used often must be high resolution and precise. They generally must be multimethod, integrated investigations. Archaeological application requirements often stimulate innovative, cutting-edge developments in geophysical equipment, field procedures, and interpretation methods. The work by Butler et al. (1994) to locate the exact site of the Wright brother's 1910 hanger demonstrated this multimethod, integrated approach through its use of scanned period aerial photographs georeferenced to the geophysical survey maps and site facility maps (see Figure 2.4). Their work also showed that archaeological investigations do not always involve ancient or prehistoric objectives and that anomalies due to even relatively recent cultural site features can be very small in magnitude and subtle in expression.

BASIC SCIENCE

The upper tens of meters of the earth hold information critical to understanding many of the natural processes occurring within and on the earth. Studies of outcrops and of cores obtained through drilling have traditionally provided earth scientists with the samples used to investigate the properties and distributions of geological materials. These outcrops and samples are used to measure physical and chemical properties, to gain insights into the spatial distribution of these properties, and to develop models of the geological processes that formed the materials. For example, in studies of sedimentary deltaic environments, observed lithologic variation is used to develop models of the processes involved in the

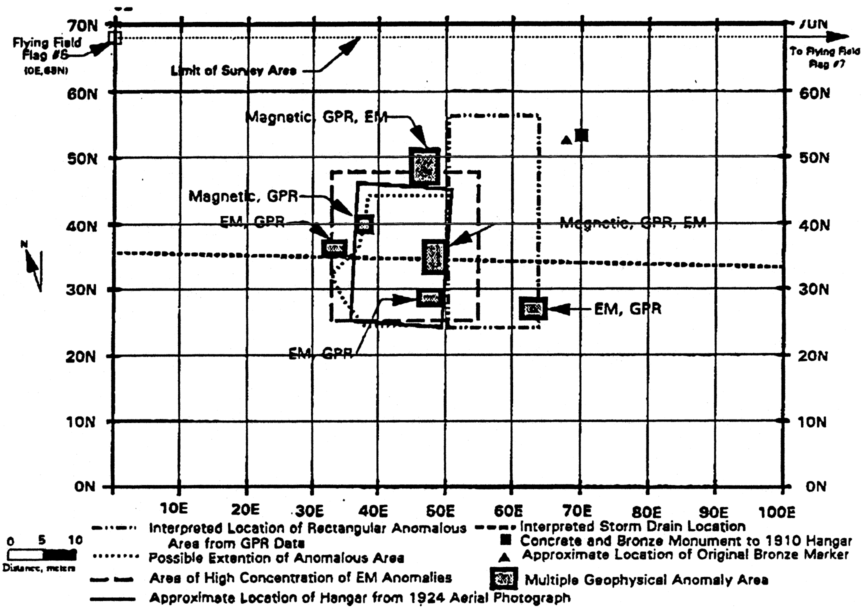


FIGURE 2.4 Wright Patterson Air Force Base plans to construct a replica of the 1910 Wright Brothers' hangar in the exact location of the original, especially for the centenary of powered flight in 2003. The original hanger was razed in the late 1930s or early 1940s and no surface indication of its exact location exists. An archaeological geophysics investigation was conducted to locate any remaining signature or evidence of the old hangar foundation. This integrated geophysical anomaly map was constructed using surveys of GPR, magnetics, and frequency-domain electromagnetic induction, which were georeferenced to a digitized 1924 aerial photograph that showed the hangar. Subsequent archaeological excavations confirmed the geophysical results by finding concentrations of period artifacts. Figure from Butler and Simms, 1994.

transport and deposition of sediments. In areas of recent volcanism, outcrops provide information about the stages of a volcanic eruption. In areas adjacent to a fault zone, sampling provides information about the style of mechanical deformation within the earth.

For all of these examples and many others, noninvasive characterization of a three-dimensional volume of the subsurface can provide valuable information about geological properties and processes. Rather than being restricted to a two-dimensional exposed section of material at the surface or a one-dimensional sample of the earth obtained from drilling, noninvasive characterization provides a unique opportunity to study an undisturbed region of the earth. In addition, noninvasive technologies can provide continuous sampling of a region at a sampling density unlikely to be obtained through more expensive invasive technologies. One recent example of the use of noninvasive technologies for the advancement of basic science is the use of GPR to image the volcanic deposits of Santorini (Russell and Stasiak, 1997). The clear delineation of the basement rocks and the various layers (corresponding to stages of volcanic activity) either provide information about the volcanic process that could not be obtained from other sampling methods or help interpret one-dimensional sampling methods.

Even in situations where extensive information can be extracted from surface outcrops, noninvasive techniques can provide continuous, high-resolution coverage in the third dimension. Studies of sedimentary environments require a quantitative description of the spatial variability in hydraulic properties for modeling fluid flow in groundwater aquifers. Although detailed analyses of outcrops can provide direct measurements of variation in properties such as porosity and permeability, noninvasive techniques can characterize the three-dimensional spatial variability of a region. The use of noninvasive technologies to characterize the heterogeneity inherent in geological systems will contribute directly to characterization needs for many applications, and may provide basic information required to understand geological processes. Noninvasive technologies provide a way of imaging the earth and quantifying many earth processes.

As noninvasive measurement techniques become more accurate, a new level of complexity will probably be revealed in physical processes of rocks and soils. For example, observations of nonlinearity and anisotropy of physical properties might result from improved techniques and sources. Such observations would provide new basic scientific information on subsurface materials.

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3

What Is Characterized?

As discussed in Chapter 2, characterization of the subsurface provides the information required for numerous applications from resource exploration to basic science. Although the applications and the motivations vary, in the broadest sense the specific characterization objectives often are similar. In most cases, information is required about the materials, their boundaries, and their properties (see Table 3.1); in many cases, knowledge is also needed about the physical, chemical, and biological processes in the subsurface and their variation in space and time.

PROPERTIES AND PROCESSES

Noninvasive determinations of subsurface properties and processes are indirect. Many properties are interpreted from measured perturbations in fields that are generated artificially or naturally. *Passive investigations* measure variations in naturally occurring fields (the earth's gravity, magnetic, electric, thermal, radiometric, stress, solar irradiation, and hydraulic fields). For example, perturbations in the earth's gravity field can be used to infer subsurface changes in the material density or the presence of voids. *Active investigations* use a source of energy that creates a known field, and measurements are made of the perturbations in this field or in the response of the earth to it. For example, seismic investigations use vibratory or explosive sources to propagate elastic waves and observe their travel times, wavelet changes, and scattering to describe the heterogeneity of the interior of the earth.

Many of the properties and most of the processes within the earth occur not in isolation but in relation to one another. Fluid flow through a porous material

TABLE 3.1 Example of Properties Often Needed for Characterization

Physical Properties	**Transport**—electrical, thermal or hydraulic conductivity, permeability, elastic attenuation **Storage**—dielectric permittivity, magnetic permeability, hydraulic storativity, elastic moduli **Strength**—mechanical, dielectric breakdown **Textural**—density, porosity, pore or grain size and shape distribution, water content **Morphological**—pore lining/bridging/blocking clays
Chemical Properties	Concentration, diffusion coefficient, reactivity, kinetics, solubility, mineralogy, phase
Biological Properties	Identity, abundance, diversity, ecology and overall physiological status and activity potential
Geological Properties	Stratigraphy, depth/thickness, dip/strike/azimuth, fracture presence/concentration/orientation, state of stress, migration pathways, water table depth

often will create an electrical current flow that generates a voltage called a streaming potential. A measurement of streaming potential sometimes can be used to locate flowing water (e.g., dam leaks). Many transport properties are dominated by the presence of water-filling pore spaces, which causes positive correlative behavior (or response) between conduction properties and environmental factors such as rainfall or freeze-thaw. Not all desired physical, chemical, and biological properties and processes can be determined noninvasively. Some have been measured for centuries (e.g., the earth's magnetic and gravity fields), whereas others are still on the horizon (e.g., biological activity).

Most subsurface physical processes involve either movement or storage of energy or mass; they can be described by either the diffusion or wave propagation equations. Heat flow, induced electrical current flow, and hydraulic fluid flow are all processes described by the diffusion equation, with the diffusion coefficient describing the property of conductivity. Mechanical particle movement and the coupled electromagnetic field behavior are described by the equations of wave propagation. The attenuation of the propagating wave is related to energy loss (and energy transport), whereas the velocity of propagation is related to the ability of the material to store energy.

A good deal of characterization has simply been anomaly detection (e.g., detecting where things differ from normal background or from the surface materials). From such measurements, the location and size of an anomaly can be determined. Detection of anisotropy (measurements in different directions giving different values for the same property) is especially important in systems dealing with fracture-dominated fluid flow. Determination of connectivity is important in mining clay and coal seams and environmental cleanup. Inadequate ability to describe and understand heterogeneity is probably the single largest reason for the failure of groundwater cleanup methods at hazardous waste sites. Measurements made at different scales are known to produce different responses. For example, the mechanical strength of a rock is inversely related to the size of the sample measured, and the hydraulic conductivity of fractured rock usually increases with the size of the sample measured. Such behavior often is not properly taken into account when such measurements are transferred from field surveys to site characterization models.

Many properties and processes are known to change with time, and knowing when a measurement was performed can be vital to its interpretation. This temporal perspective is especially important with regard to seasonal, freeze-thaw, and wet-dry variations that can affect not only properties but processes (e.g., erosion, stream flow, landslides, sinkholes, frost heaving, swelling clay). Contaminant plumes can move through the subsurface for long periods and can be disturbed or remobilized by site remediation activities. Stresses can build up over long periods and be released over shorter periods, as in earthquakes. Water tables rise and fall with tidal events, water well pumping, and climate changes.

EXAMPLES OF CHARACTERIZATION

Some selected examples of characterization follow. The discussion of each example focuses on a specific characterization objective (which might be common to many applications) and reviews the noninvasive techniques that can be used.

Geological Characterization

A site's geology defines the overall framework within which study of the subsurface environment is carried out. Questions relating to, for example, the occurrence and movement of groundwater, geotechnical investigations, resource exploration, the migration of chemical contaminants, and the subsurface environment's microbiology, must all be posed in the context of the site's geology. The nature and extent of the related physical, chemical, and biological processes are constrained by the structure and lithology of the bedrock and overlying surficial materials. All aspects of site characterization and remedial investigations are influenced by the geological setting.

Lithology

The different physical properties of different lithologies make it possible to obtain information about them from geophysical measurements. Commonly used measurements include differences in seismic velocity, electrical resistivity, and dielectric permittivity. In most cases there is not a unique relationship between a measured physical property and lithology; however, the combined use of different noninvasive techniques to measure complementary properties can help determine and analyze a site's lithology.

Different rock types, each with a characteristic mineralogy and geochemistry, react differently with water, solutes, suspended solids, and microorganisms. Often these reactions are poorly understood. Rock types also have typical physical characteristics or engineering properties and, thus, compact and deform in particular ways. In addition, there is a strong correlation between lithology and the occurrence of certain types of resources.

Detailed lithological maps can help evaluate the impact of aquifer contamination and various remediation schemes. The likelihood of migration of a dissolved contaminant in groundwater, for example, is influenced by adsorption to mineral surfaces, the dissolution or precipitation reactions of minerals, and oxidation-reduction reactions, which are often mediated by microorganisms. The reactions possible in a given aquifer are defined largely by the aquifer's lithology. Further, certain hydraulic properties may be characteristic of certain rock types.

Knowledge of lithology is also essential for engineering and construction in the subsurface. Lithological characteristics (e.g., hard rock, soft rock, intact rock, jointed rock) greatly affect such things as a site's suitability for foundation support, applicable methods for excavation, and groundwater flow conditions.

Some lithologies are especially important to identify. Limestone and other soluble rock types may be extensively dissolved at depth, creating secondary porosity and permeability. Being heterogeneous in their distribution, such subsurface conduits in limestone are difficult to map, though certain noninvasive techniques can detect large openings in shallow bedrock (see Figure 2.3 using a microgravity method).

Shale and clay are important to site characterization for engineering and environmental applications. Low-permeability shale layers that are not fractured can confine transmissive sandstone aquifers, trap migrating hydrocarbons, or prevent migration of landfill leachate. Exact knowledge of their location and continuity in the subsurface is critical to properly assessing their role in site or regional hydrogeology. Clay can occur dispersed as lenses within another lithology. For instance, clay lenses in a sandy aquifer can create perched water table conditions that could confound our understanding of flow conditions. Clay lenses also can act as reservoirs of immobile groundwater into which contaminants can diffuse and be retained in an aquifer undergoing traditional pump-and-treat remediation. The ability to recognize relatively small clay layers or lenses within an aquifer system would improve our ability to develop and protect groundwater resources. The presence of certain clays is also of concern in foundation design because it can lead to extensive settlement or heave (e.g., Chleborad et al., 1996).

Structure and Stratigraphy

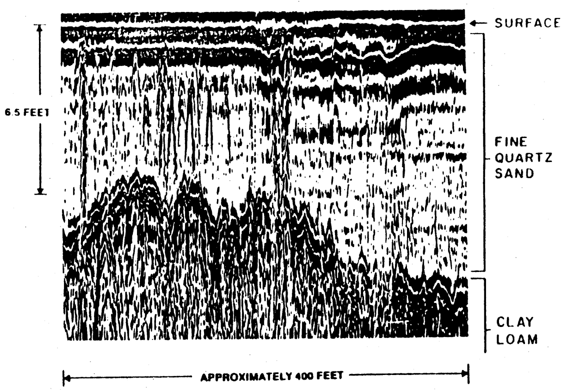
Porosity and hydraulic conductivity set the broad constraints on fluid migration in the subsurface, an important issue in environmental and engineering studies. These properties depend on structural features such as faults, fractures, folds, and lithological contacts (see Figure 3.1). Further, the actual location of groundwater, contaminants, ore deposits, and planes of weakness for engineering purposes may be constrained by subsurface structural features.

Fractures as well as contacts between different lithologies are often pathways for groundwater flow. Some rock types (primarily poorly cemented sandstone) have significant porosity and permeability, but most rock types, whether sedimentary, igneous, or metamorphic, do not. Ground water occurrence and movement in such rocks is almost entirely controlled by structural features. Bedding planes in sedimentary sequences and fractures in sedimentary, igneous, and metamorphic rocks may offer significant conduits for fluid migration.

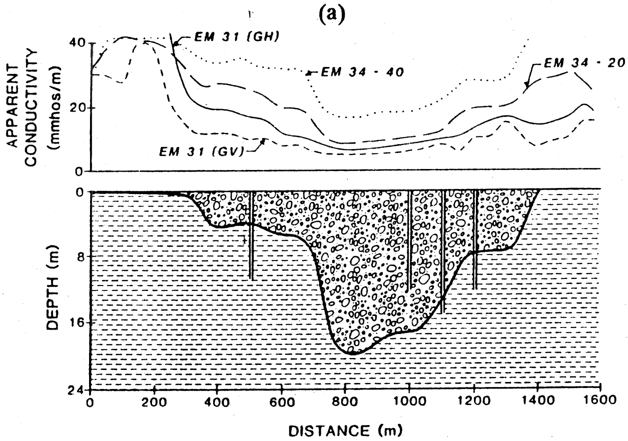
Structural features largely control communication among various water-bearing units as well. Even in a simple layer-cake sedimentary sequence (e.g., a water-saturated sandstone confined by low-transmissivity, clay-rich shales), assessing the fate of contaminants is difficult, if not impossible, without understanding cross-strata transport pathways. A confining layer can be breached by flow along faults and fractures, which can dramatically influence predictions about contaminant containment (see Figure 3.5). Many of the groundwater contamination sites that require restoration today resulted from mistaken presumptions about the integrity of engineered or geological barriers to fluid flow (National Research Council, 1984).

Noninvasive detection of these structural features (faults, fractures, folds, lithologic contacts) relies on the existence of a contrast in properties across these features or a unique response associated with them. Lithologies on either side of a feature, can have significantly different physical properties such as seismic velocity, dielectric constant, and electrical resistivity. Given that these features are often continuous over meters to tens of meters or kilometers, it is generally possible to locate such features with existing technology if the conditions at the site are appropriate. One example of mapping a lithological contact—the top of the bedrock—is given in Davis and Annan (1989), where ground penetrating radar (GPR) was used to image the interface between the granodioritic bedrock and overlying fine sands. The contrast in dielectric constant coupled with the continuity of the contrast made this an ideal target for GPR.

The noninvasive technologies can produce high-quality images of the near-surface structure and stratigraphy; however, their success can be highly variable. There can be a large influence of the very near surface on most noninvasive methods. For example, weathering within the vadose (or water-unsaturated) zone can produce submeter-scale heterogeneities in physical properties that cause significant problems with seismic reflection data; overcoming these "statics" re-



(a)



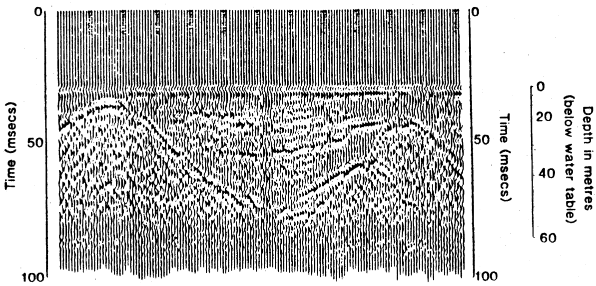
(c)

FIGURE 3.1 Examples of stratigraphic interpretations using subsurface geophysical surveys: (a) ground penetrating radar (from Benson et al., 1982); (b) delineating a bedrock channel by seismic reflection (from Benson, 1991); (c) relationship of EM

quires mixing of data that can lose resolution. In the use of GPR the most common limiting problem is the occurrence of clays, with a high electrical conductivity (>30 mS/m) that prevents the penetration of radar signals. The groundwater table can have a similar limiting effect if the conductivity of the water is high.

Fractures

Understanding the presence, distribution, and connectiveness of fractures is critical to site characterization. Fractures play a fundamental role in where and



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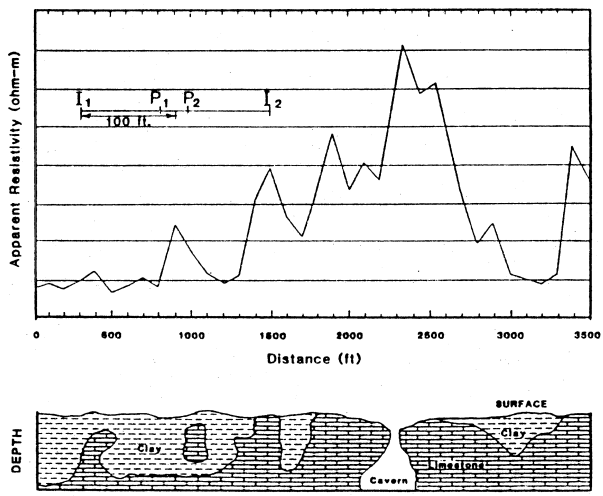

(d)

conductivity data and a sand and gravel channel (from Hoekstra and Hoekstra, 1991); and (d) electrical resistivity profile of karst terrain (from Hoekstra and Hoekstra, 1991). (Figure adapted from Cohen and Mercer, 1993).

how rapidly fluids can move through the subsurface and to the surface. A recent National Research Council report (NRC, 1996) provides a comprehensive review of research on techniques and approaches to fracture characterization and fluid flow in rock fractures.

Fracture detection depends on detecting physical property change across the fracture or within the fracture itself (see Figure 3.2). In addition to observing topographic expression using images and photographs, various remote sensing methods (including multispectral reflectance, imaging spectroscopy, thermal in-

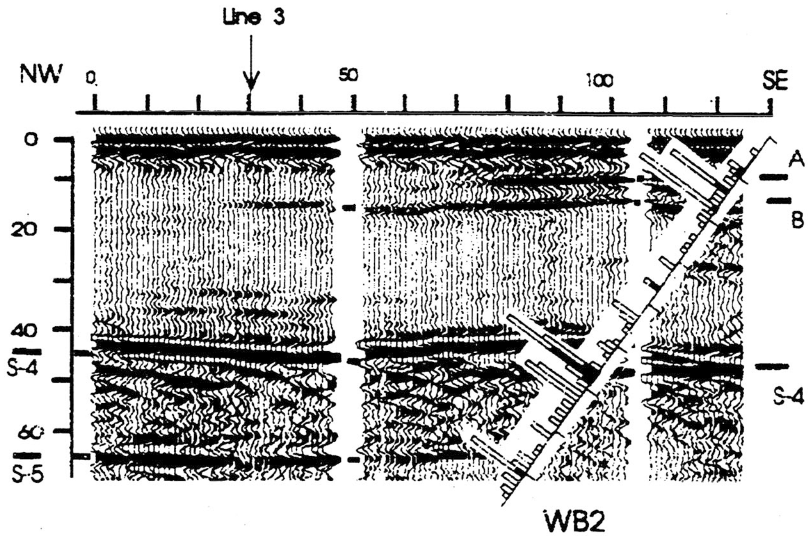

FIGURE 3.2 Semihorizontal fracture zones observed by ground penetrating radar along a profile measured on granitic outcrops at the Underground Research Laboratory, Manitoba, Canada, showing distribution of fractures along borehole WB2. Reflectors S-4 and S-5, seen at depths of 40 to 50 m and 65 m, respectively, are verified by increased fracture frequency observed in the slanted borehole. (From Holloway et al., 1992).

frared, and radar) have been used to detect juxtaposed lithologic contrasts at the surface. Thermal infrared images also have been used to infer fractures where moisture content differences in soil cause associated surface temperature changes. Detecting fractures beneath the surface often depends on observing contrasts in physical properties such as dielectric constant, electrical conductivity, P-wave seismic velocity and attenuation, magnetic susceptibility, and density—all of which can be related to interconnected void space or moisture content of the fracture zone. High spatial resolution is required for both location and detection of fractures. Frequently used methods for detailed work have been GPR (see Figure 3.2) and seismology. Resistivity surveys and detailed magnetic surveys also have had limited success. Resistivity soundings repeated over a range of azimuths at one location often can indicate the gross vertical fracture directions (see Figure 3.3). Generally, remote sensing methods lack the detailed follow-up work to verify results.

The connectedness of fractures is important to characterization because these connections affect whether and where fluids can flow as well as the flow rates. Hydraulically significant fractures may comprise only a small fraction of the total fractures present. Detailed three-dimensional mapping of properties (at scales that depend on the problem) is required to evaluate connectedness between fractures. Fractures may vary in length from hand specimen size to kilometers, with widths generally a couple of orders of magnitude less. Their presence at a site may be the source of anisotropy in an otherwise isotropic background. Because fractures are conduits for fluids, anomalous mineralization may occur with them. Where these minerals outcrop, they may be detected by imaging spectroscopy. If the minerals produce an electrical conductivity contrast, this can provide three-dimensional information about the fracture. In almost all cases, surface geophysical methods cannot characterize completely a fractured rock site because the fractures that have flow cannot be separated from fractures without flow. To characterize such sites, hydraulic testing and borehole geophysical methods usually are required.

Heterogeneity

Spatial heterogeneities in the physical properties of rock units prevent complete characterization of subsurface rock formations from observations made in outcrops or in cores. In environmental and engineering studies, properties of

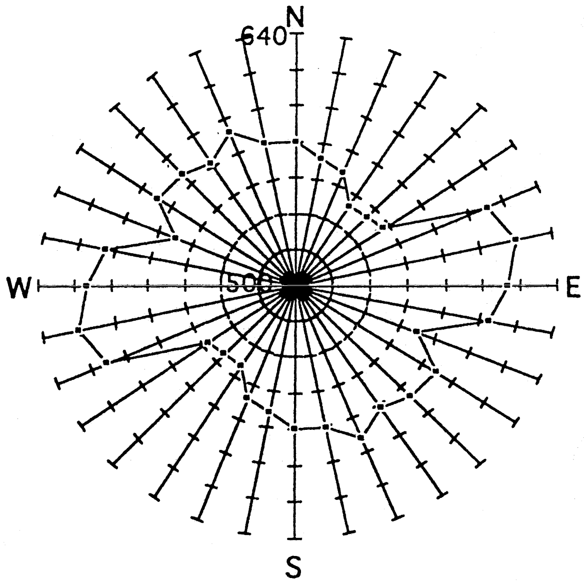

FIGURE 3.3 Resistivity measurements made in 16 different directions define a resistivity ellipse whose major axis is aligned with the fracture orientation. This example, from an open-pit quarry in southern Indiana, demonstrates that the dominant fracture direction is east-west. (From Cohn and Rudman, 1995.)

interest, such as porosity, hydraulic conductivity, and chemical or mineralogical composition might vary over short distances within a single geological unit. No reliable mathematical model for interpolating between observations exists. Most mapping of lithology is done by assuming continuity between observation points. Yet a single important discontinuity in material properties may dictate the fate and transport of contaminants or the stability of a rock slope. Many site remediation failures result from inadequate characterization of site heterogeneity (EPA, 1992). An ability to more fully describe the location and character of heterogeneities throughout an aquifer would yield a better description of hydraulic, geochemical, and biological responses to contamination or remediation.

The importance of minor geological details in geotechnical engineering is well known (e.g., Terzaghi, 1929). Thin clay layers may serve as slip surfaces, impairing the stability of both natural slopes and excavations. Sand lenses may act both as drains or sources of artesian pressure and water flow into an area, depending on the regional hydrogeology. The natural heterogeneity of sand and gravel deposits is the source of nonuniform settlements and uncertainties about resistance to liquefaction during earthquakes.

The key to effectively describing the subsurface's heterogeneous nature is most likely the integration of different types of information at different scales. Although noninvasive techniques can determine large-scale lithologic units, high-resolution, often invasive, measurements are required to detect meter- or submeter-scale changes in rock and/or fluid properties. There is considerable interest in the use of GPR to noninvasively image this small-scale spatial variability. Very closely spaced electrical and electromagnetic sounding techniques also have the potential to provide increased lateral resolution (see Figure 3.4). In addition, arrays of sensors and multicomponent measurements may provide more detail on the spatial variations in resistivity and electrical polarization.

Fluids

Subsurface fluids play a large role in resource recovery and storage, environmental protection and remediation, and civil engineering projects. In the unsaturated (or vadose) zone above the water table, there is generally a two-phase fluid system consisting of an aqueous phase and a gaseous phase. In areas contaminated with organic chemicals, a third nonaqueous-phase liquid (NAPL) may also be present. (The most frequently encountered NAPL contaminants are organic solvents and hydrocarbon fuels.) The aqueous phase may contain various dissolved natural and human-made constituents, such as salts, pesticides, and organic chemicals. Soil gas is primarily air, but also contains on the order of 1 weight percent water vapor and may contain trace amounts of organic chemical vapors as well as noncondensable gases such as CO_2 and radon. Beneath the water table, the gaseous phase is usually unimportant, and there is a single aque-

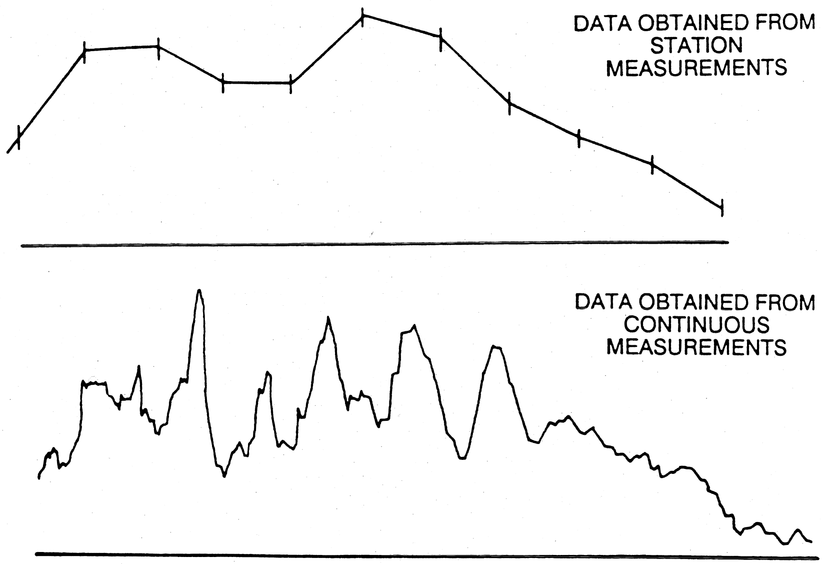

FIGURE 3.4 Comparison of station and continuous surface EM conductivity measurements made along the same transect. The electrical conductivity peaks are due to fractures in gypsum bedrock. (From Benson et al., 1982.)

ous phase or a two-phase (aqueous and NAPL) system. The interfaces between these fluid phases are often biologically active.

Generally speaking, all aspects of the presence and behavior of fluids in the subsurface are of interest—their distribution (e.g., Figure 3.5) and composition, their rates of migration, and the hydraulic properties of the subsurface media. Hydraulic properties include permeability, porosity, and when multiple fluid phases are present, relative permeability and capillary pressure characteristics. Hydraulic parameters tend to vary spatially; they can also depend on the scale of investigation. The desired level of detail for characterizing these parameters depends strongly on the engineering or remediation applications. Demands on spatial resolution and identification of minor fluid components tend to be greatest in the area of contaminant hydrology. Noninvasive techniques are usually incapable of unambiguously resolving site characterization needs relating to fluids, but they can contribute valuable information, especially when used in conjunction with a minimum amount of invasive methods for providing "ground truth."

Common site characterization tasks include two that are identified as part of geological characterization: the location of permeable features and the location of features with low permeability such as clay layers. In addition, common charac-

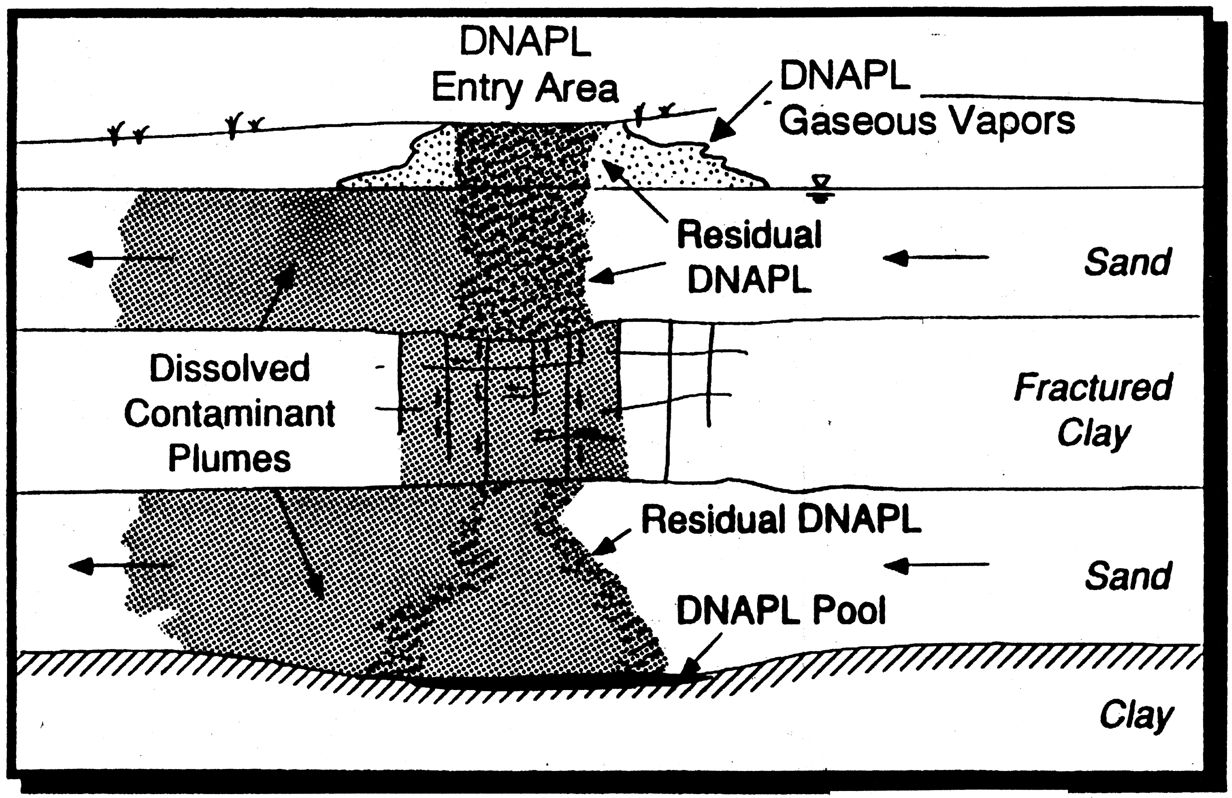

FIGURE 3.5 Schematic representation of PCE in an aquifer of sand and fractured clay. Some of the PCE volatilizes, some is trapped as a residual in soil pores, some migrates into the fractures, and some pools on the clay layers (from Cohen and Mercer, 1993).

terization tasks specific to addressing the distribution and migration of fluids include the depth to the water table and the chemical composition of the fluids. For some applications it is sufficient to know changes in fluid distribution over time rather than the current distribution of fluids.

Depth to the Water Table

Knowing the location of the water table is essential for almost every environmental, resource recovery, and engineering application. There are significant contrasts in transport properties, chemical and microbiological reactions, and strength and deformation properties between the unsaturated vadose zone and the water-saturated zone.

The water table is an interface across which there may be a change in several physical properties (electrical conductivity, seismic wave velocity, dielectric constant), making it a viable target for detection with geophysical techniques. However, in some situations (e.g., coarse-grained sands and gravels), the contrast in physical properties is between the saturated and the unsaturated zone, so geophysical techniques may locate the top of the saturated zone, which might be different from the true water table. Complications in detecting this interface arise when air is trapped below the "water table" due to annual fluctuations in the level.

Geophysical methods commonly used include direct current (dc) resistivity, time- and frequency-domain electromagnetic soundings, seismic refraction, and GPR. Each of these methods, whether model based (e.g., dc resistivity) or image based (e.g., GPR), requires ancillary data—often a by-product of data processing (e.g., radar wave propagation velocity) or from drill holes—for complete interpretation. In addition to geophysical detection, increased biological activity at the water table may cause oxygen depletion, changes in pH and eH, production of biomass, specific mineral accumulations, and gas production (methane, CO_2, dissolved hydrogen).

Fluid Composition

Knowledge of the chemical composition of fluids in the subsurface often is required to assess groundwater quality, to track the movement of contaminants, and to monitor containment remediation. Fluid composition can affect the physical, chemical, and biological properties of these confining geological or soil units in ways that allow remote detection of the fluid's composition. Characterization involves assessing the nature and amount of dissolved and suspended inorganic and organic constituents.

In some cases, it is possible to directly detect the contaminant using electromagnetic methods. For example, recognizing electrically conductive water in the near surface (see Plate 5) caused by chloride ions from salt water is a relatively easy procedure using commercially available equipment and routine geophysical interpretation procedures. Similarly, chloride ions in soils from improper disposal of water co-produced from petroleum production can be detected easily. The signal levels associated with electrically conductive contaminants are often one to two orders of magnitude higher than background levels, which leads to a high degree of confidence (see Plate 6). The distribution of such near-surface contaminants often can be modeled in three dimensions (Danbom, 1995). With such a three-dimensional model, a limited direct sampling program could confirm and calibrate the electrical geophysical anomalies.

Many contaminants, such as petroleum hydrocarbons, are electrically insulative and, therefore, much more difficult to detect. However, Benson et al. (1997) provide an example of successfully detecting petroleum hydrocarbons using the offset sounding procedure variant in dc resistivity.

Immiscible fluids such as gasoline and chlorinated solvents can sometimes be found using complex resistivity (induced polarization) measurements to detect electrochemical reactions exhibited by these solvents in the presence of clay minerals.

Dissolved and immiscible organic contaminants remain virtually impossible to detect noninvasively; this vexing environmental problem is an opportunity for continued research. Under certain circumstances, nonconductive organic contaminants can be detected using GPR, which detects contrasts in the dielectric constants between materials such as pore water and organic compounds. An experimentally controlled spill of perchloroethylene (PCE), a dense nonaqueous-phase liquid (DNAPL), was successfully monitored using GPR and other techniques (Sander et al., 1992; Greenhouse et al., 1993). This study points out the need for time-differential measurements to remove background effects and allow the detection of small dielectric changes. The technique may be most useful for monitoring contaminant movement during remediation efforts.

Noninvasive geophysical techniques determine subsurface fluid distributions by finding a contrast in physical properties. A fundamental difficulty arises from the fact that geological media are often heterogeneous for a range of scales; single-method geophysical measurements cannot establish whether observed property variations are due to nonuniform fluid distributions or to formation heterogeneities. This nonuniqueness of the interpretation is reduced or eliminated if diverse data sets are available and if data can be collected over time to monitor changes associated with the movement of the fluid.

Increased biological activity often is found at the boundary of contaminant plumes. Evidence for this activity can be found in decreased concentrations of electron acceptors such as oxygen, nitrate, and sulfate, and in increased production of ferrous iron minerals and methane. Noninvasive detection of such microbial activity is not possible now, but is very desirable—hence, another research need. Minimally invasive sensing of microbial activity is possible through soil-gas surveys.

Biology

A wide range of organisms inhabit the soil and subsurface. More complex eukaryotic biota such as plant roots, earthworms, nematodes, insect larvae, and soil algae are limited to the upper regions of biologically active soil (Killham, 1994); simpler life forms such as bacteria, fungi, protozoa (and probably viruses) extend into deeper regions of the subsurface (Ghiorse and Wilson, 1988; Madsen and Ghiorse, 1993; Frederickson and Onstott, 1996; Amy and Haldeman, 1997; Ghiorse, 1997).

The properties of the biota of most interest to site characterization biologists may be the most difficult to determine noninvasively. The identity, abundance, diversity, and ecology of the resident organisms, as well as their overall physiological status, are the most important general properties to assess. Some of these properties can be assessed by minimally invasive methods such as soil-gas analysis and selective culturing techniques. Noninvasive remote sensing technology shows some promise in such assessments, but until more research is done to develop other methods, characterization of site biology will still depend to a large degree on analysis of samples obtained by invasive methods.

There is a possibility that some biologically mediated environmental properties might be detected by noninvasive or minimally invasive geophysical techniques. These properties could be targeted to indicate near-surface biological activity.

Buried Objects

The location of buried objects is a relatively common objective in subsurface and site characterization. The information required about the object usually includes the following:

- Where is it (lateral position)?
- How deep is it (vertical position)?
- How large is it?
- What is around it (context)?
- What shape is it?
- What is its composition (metal, plastic, void)?
- What is it (pipe, bomb, drum, etc.)?

The specific set of parameters (physical, chemical, and biological) that need to be measured at a site to characterize buried objects depends on the defined target of interest and the host medium in which it is buried. The measurements must also take into account any sources of noise or interference. If the goal is to detect the presence of the object itself, the set of crucial parameters is determined by the contrast between the properties of the object and the medium in which it is buried.

(In addition to considering the initial state of the object at the time of burial, investigators must consider the possibility that there can be time-dependent changes in the object and the geological background due to processes such as weathering or corrosion.) These can produce distinct physical, chemical, and biological changes that can be monitored and used in locating and identifying the object. The detection of an object may also rely on more indirect measurements. One common example is the detection of the disturbed ground surrounding a buried object.

To review the parameters used in the location of buried objects, it is convenient to divide the topic into metallic and nonmetallic materials. Location of underground cavities and voids is also treated in this section, because many of the principles are similar.

Metallic Objects

Metallic objects, which include buried drums, underground storage tanks, well casing, metal pipes, and UXO (see Figure 2.2), can range in size from millimeters to meters and can be buried at depths up to 10 m.

Given present geophysical techniques, the most useful physical property in terms of detection is the high electrical conductivity and magnetic permeability of these objects. Electrical conductivity can be measured remotely using electromagnetic methods. Adaptations of these methods are hand-held terrain conductivity meters, trolley-mounted transient electromagnetic gradiometers, and metal detectors used by the utility industry in locating underground cables and also used by “treasure hunters” (see Box 3.1). There are limitations in the use of any of these methods with respect to the accuracy with which the size and location of the object can be determined. An additional limitation is that near-surface anomalies can mask the presence of a deeper target.

A buried ferromagnetic object will also exhibit a magnetic anomaly that can be modeled to locate the object. The magnetic anomaly will have an induced component (proportional to the earth’s magnetic field) as well as a permanent “remanent” component. However, magnetic properties (as well as electrical conductivity) can change with time if oxidation to nonmagnetic oxides occurs, resulting in noticeable difference between “new” objects and rusted objects. Also, as with other potential-field methods, other material distributions sometimes found in the subsurface can produce similar anomalies.

Metallic (and nonmetallic) objects in the subsurface will interact with high-frequency electromagnetic waves in such a way as to cause diffraction hyperbolas in unprocessed GPR data. These distinct patterns in GPR data often are used to locate buried objects.

It is often more feasible to detect the disturbed zone around the buried object than the object itself. The disturbed zone may differ from the surrounding region in its density, dielectric constant, and electrical conductivity. The small-scale

BOX 3.1
Treasure Hunters

Metal detectors respond to the contrast in electrical conductivity between a buried metal object and the ground. There are various types of metal detectors. With a two-coil system, a transmitter coil generates an alternating magnetic field around itself; this field is measured with a null-coupled or "balanced" receiver coil, oriented perpendicularly to the transmitter. If a metal object is encountered, eddy currents are generated that interact with the transmitter field to upset the original balanced condition; when this occurs, the instrument responds. The "treasure hunter"-type metal detectors often combine the transmitter and receiver functions in one coil, which responds to the field emanating from the object in different ways. Typical metal detectors have a relatively shallow range of operation; their response to a given object decreases at the rate of the target's depth to the sixth power ($1/D^6$). Small objects may be found to a depths of just up to a meter, whereas larger objects (e.g., 55-gallon drums) might be detected to depths of a few meters; these depths are dependent on many factors such as the size of the instrument's primary coil, coil separation, receiver sensitivity, the contrast in electrical conductivity, and the volume of the metal object.

structure will also be disrupted in the zone, which can produce a "jumbled" appearance in the GPR or high-resolution magnetic response from the area (see Figure 3.6).

Nonmetallic Objects

Nonmetallic objects of interest in site characterization include containers, pipes, UXO, and other waste. These objects commonly range in size from millimeters to meters and are buried at depths up to 10 m. Noninvasively detectable physical properties of nonmetallic objects include electrical conductivity, density, dielectric permittivity, and seismic velocity.

The detection of nonmetallic objects using electrical conductivity is possible only when there is a contrast with the background material. However, it is difficult to detect a resistive object within a conductive medium using electromagnetics. There is currently much interest in the location of nonmetallic objects using GPR (e.g., Bradford et al., 1996) to detect the contrast in electrical and dielectric properties between the objects and the background. High-frequency antennae, with theoretical resolution on the order of centimeters, could potentially be very useful for detecting small objects such as pipes.

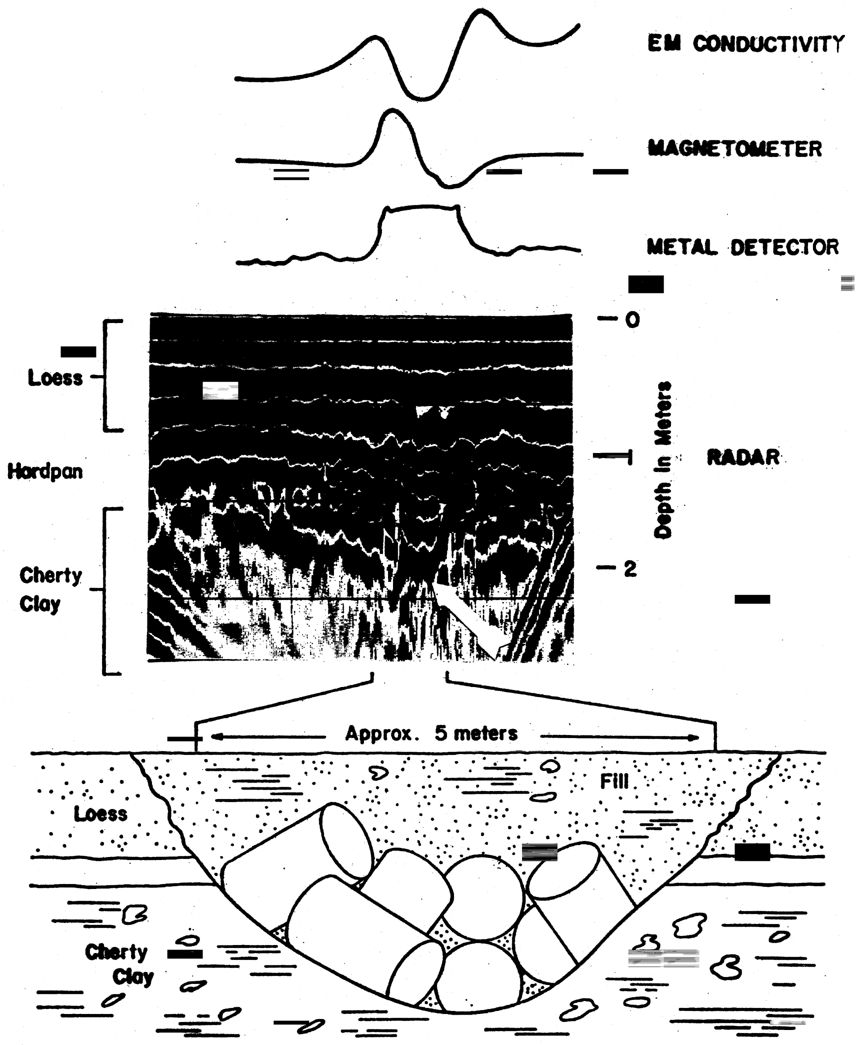

FIGURE 3.6 Buried metallic drums with representative magnetic and EM signatures; GPR signals show disturbed ground and surrounding stratigraphy. (After Benson and Glaccum, 1980.)

Cavities

It is important to locate subsurface cavities in karst areas prior to building or road construction in order to avoid potential future collapse (Franklin et al., 1981). Cavern systems can also provide preferential flowpaths for water and contaminants, knowledge of which may be important in water resource investigations or hazardous waste characterization. Noninvasive techniques helpful in locating cavities include certain geophysical techniques (e.g., microgravity) and fracture-trace analysis using aerial photographs.

Cavities in the subsurface can be either natural, such as caves in karst areas, or human-made, such as tunnels or shafts in mines. Detecting cavities in the subsurface involves locating a region with properties close to those of air or water surrounded by a region with properties of the background geology. Cavities can produce contrasts in a number of physical properties including gravity (see Figure 2.3), dielectric constant, seismic velocity, and electrical conductivity. In addition, cavities may contain increased biological activity due to steep geochemical gradients and interfaces within the cavity. As a result, there may be biogeochemical indicators of the presence of the cavity, such as gases, microbial mats, or bionic mineral accumulations, that can be detected remotely. As in the detection of other objects, the problem of resolution must be considered for any method that is used. The cavities of interest usually range in size from centimeters to tens of meters.

Microgravity surveys are also useful in detecting cavities (Butler, 1984; Hinze, 1994). The contrast in P-wave velocity between the water or air in the cavity and the background geology makes cavities targets for seismic reflection and diffraction methods as well (Steeples and Miller, 1987; Branham and Steeples, 1988). There can be a distinct GPR response associated with the presence of cavities (e.g., Gourry et al., 1995). The dielectric constant of a void filled with air or water will be significantly different from that of the surrounding material.

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4

Methods of Characterization

The principal methods for determining subsurface properties are reviewed in this chapter. The methods are reviewed briefly (scientific and technical details can be found in the referenced literature), followed by their range of application and limitations, and the prospects for their improvement. The major noninvasive characterization tools involve geophysical sensing of potential and propagating fields. In addition, a limited number of noninvasive geochemical and geobiological measurements can be made.

Measurements for characterizing the subsurface may be performed from laboratory to planetary scales; from instrument platforms in boreholes, on the surface, and in vehicles (trucks, boats and airplanes); and from satellites in orbit. Some methods work only from certain platforms (e.g., seismic measurements cannot be made from satellites or aircraft), and a few can be done from all (e.g., electromagnetic observations). In general, the closer the instrument is to the material being measured, the higher is the resolution. Measurement techniques "at a distance" (usually from aircraft or satellites) are remote-sensing methods with meter to tens of meter resolution. Measurement techniques requiring boreholes (single-hole well logging; geophysical sensing from hole to hole, hole to surface, surface to hole, hole to tunnel, etc.) are invasive, requiring the drilling of a hole. However, they can often provide greatly improved resolution compared to surface measurements. Many of these invasive well-logging techniques are thoroughly reviewed by Ellis (1987). In noninvasive characterization, the depth of investigation is highly dependent on technique, logistical constraints, and other factors discussed below, ranging from no surface penetration (surface photoimaging) to hundreds of kilometers in depth (seismic and electromagnetic induction).

Independent of sensor type, all of these methods of characterization also can produce anomaly maps. Such maps yield information about the location of places or regions that are somehow different (or anomalous) from other places. Even if only anomaly information is available, it at least guides later invasive investigation (drilling) to sample these differences.

To go beyond simple anomaly maps requires knowledge of the sensor function, logistics of deployment, sensor location and orientation, sources of noise and interference, and so forth. Such information allows computer processing to correct for biases introduced in the measurement process, for example, because of limitations of the instrument (the instrument transfer function), logistical constraints, or sources of noise. Further, such detailed information can allow the modeling of the measurements and prediction of success in problem application as well as interpretation of derived quantities. For example, if fluid flow is of interest, because the techniques only directly measure changes in some physical field (such as electric or elastic fields), the fluid flow parameters have to be derived through modeling.

In all of the methods of characterization, there are certain common problems. Historically, the single largest error often has been precise knowledge of the location and orientation of the measurement sensor. It does not help to have a good measurement but be unable to relocate the measurement site to guide a drill rig to penetrate a contaminant plume. This location sensitivity is especially true of moving sensors in vehicles and satellites, but also of fixed sensors (such as seismic geophones) where later processing and modeling brings out features in the data that must be located. Inadequate locational information has been rumored to be the reason for the failure of more than one site characterization or exploration survey. Adequate location surveying may also take longer and cost more than the geophysical survey, although the growing use of GPS (Global Positioning System) technology is ameliorating this problem.

Another common problem is lack of property contrast. In comparison to lack of optical contrast, which makes it difficult to find a black cat in a dark coal bin, it is easy to find a furry cat against hard coal by touch. Thus, it is important to consider the available contrast in properties between the target and the host background materials.

In a practical sense, many environmental and many engineering geophysical surveys are conducted under less than ideal conditions; for example, often a site is disturbed by human activities including prior excavation of soil or delivery of fill material. Other problems include the presence of either buried or surface utilities such as tunnels, gas lines, sewer drains, and water mains. The mere presence of these more or less passive anthropogenic features disturbs the signals that would otherwise be obtained.

Other noise sources include active field disturbances caused by human activities such as interferences (electromagnetic methods pick up all nearby good conductors, e.g., metallic pipes, wires, and fences), and sources of noise (seismic noise from wind or nearby traffic; electromagnetic noise from radio stations, cellular phones, and so forth). Seismometers can be susceptible to 60 Hz noise from power lines, as well as higher modes of 60 Hz (such as 120 Hz, 240 Hz, etc.). In addition to noise problems, there are often logistical constraints (e.g., denial of access to secure or hazardous areas) and physical requirements (e.g., seismic methods require ground contact and are not often effective through concrete) that are difficult to meet. Each of these is discussed in further detail for the individual method.

There are two major types of geophysical measurements. One is measurement of potential fields that result from forces decaying away from a source of stored energy. The most common potential-field techniques measure gravitational and magnetic fields; less commonly used are thermal and stress fields, which exhibit a quasi-static, nearly time-invariant (or slowly varying) dependence on a force generated by a gradient in a field. For all of these methods, the depth of investigation and the resolution are controlled by the measurement sampling interval. Closely spaced measurements give higher resolution for nearby changes in properties, but the resolution decays exponentially with increasing depth. In general, a discrete object with a high contrast against its background is detectable at a depth ten times the size of the object. Measurements of small perturbations in the large source field are made with part-per-million precision and accuracy.

The other major type of geophysical measurements, uses propagating fields. Propagating fields result from a disturbance in a field within a material medium that has the capability to store energy. Principal techniques include various adaptations of seismology and ground penetrating radar (GPR). Resolution is controlled by the frequency and the velocity of the propagating wave and is generally comparable to a wavelength. Resolution is also related to the geometry of the sensors and may be much better than one wavelength for arrays of sensors. The depth of penetration is linear with the inverse of frequency (period) and controlled by the losses that cause the eventual decay of the propagating wave. Measurements are made of scattered waves in the absence of the source field.

POTENTIAL-FIELD METHODS

Gravity Measurements

Gravity (a potential field) methods measure changes in the earth's natural gravitational field caused by internal variations in bulk density. Density is a basic property of all materials describing the volumetric packing of mass in space. Gravity describes not only the density of minerals but also the packaging of minerals, including fluids and voids in the interparticle spaces (porosity) between mineral grains. The gravity field is a vector quantity pointed toward the center of the earth, with a minor horizontal component near extremes of topography (mountains and canyons). Commercially available sensors are quite simple in principle—measuring the vertical field strength, but they are delicate, expensive, and sophisticated in practice owing to the required precision of measurement (parts per billion) and necessary corrections for location on the earth (altitude and latitude) and for environment (temperature, barometric pressure, tides). Fundamental principles are described in Blakely (1996) and Hinze (1994).

The subsurface condition that leads to a surface anomaly in the gravitational field is a density variation that changes with horizontal location (lateral density contrast) or depth. A variety of geological conditions cause lateral density contrasts (e.g., lithologic changes, cavities, faults, folds) as do buried human-made features (e.g., trenches, tunnels, disposal containers). For example, Roberts et al. (1990a) detected density differences within landfill material in a glaciated area in the U.S. midcontinent.

Applications and Limitations

Applications of gravity address engineering, environmental, groundwater, and archaeological requirements, such as detection of cavities and tunnels, mapping of density variations in landfills or aquifer materials, location of underground storage tanks, location of buried river channels, detection of faults and fracture zones, and infrastructure assessments. Butler (1984) discusses the use of gravity gradients for near-surface investigations. Because gravity measurements can be taken virtually anywhere, surveys are possible on, inside, and immediately adjacent to structures; on pavement and concrete slabs; and under conditions where other noninvasive methods are not always applicable (Yule et al., 1998). However, certain frequencies of mechanical vibrations can make attaining precision measurements difficult.

Future Prospects

Because most technical and theoretical aspects of gravity measurements are quite mature, future improvements will probably be evolutionary in nature. New possibilities are starting to be realized by the application of airborne gravity surveys, which combine gravity determinations with accurate land and sensor positioning using the GPS in a differential mode (NRC, 1994). At present, the resolution of airborne gravity systems are on the order of a few milligals (1 gal = 1 cm/s^2), which is about a thousand times less accurate than microgravity surveys on land. However, the resolution will probably improve with increased attention to this relatively new approach, particularly since it can cover large areas at a smaller cost than land surveys. For certain types of applications, gravity measurements from satellites will be possible (NRC, 1997).

A Department of Defense program in the 1980s helped develop a viable gravity gradiometer system (Jakeli, 1993). The system allows determination of all independent components of the gradient tensor from moving platforms. Diverse applications of the gravity gradiometer measurements are a rapidly evolving area of research (Bell, 1997).

Magnetic Measurements

Magnetic methods measure changes in the earth's natural magnetic (potential) field caused by variations in magnetic susceptibility and remanence. Magnetic susceptibility is the property of some minerals (mostly iron bearing) that describes their ability to be magnetized by an external magnetic field. Magnetic remanence is the property that describes the ability of a material to retain magnetic field strength and direction in the absence of an external magnetic field. Magnetic fields are static vector fields with three-dimensional variation in direction over the surface of the earth with a small superimposed time-varying component. It is sometimes important to measure both field strength and direction. Modern commercial sensors are simple in principle, measuring either the total field strength (a scalar) or the three-components of the directional field (a vector). Gradient measurements (derivatives of the field) are less often measured. Measurements are performed easily and routinely at the part-per-million level. The techniques are quite mature. Fundamental principles are described in Blakely (1996) and Hinze (1994).

Magnetic interpretation is similar to gravity interpretation because both are based on potential-field theory, except that magnetic anomalies are almost always asymmetrical. It is important to realize that anomalies express the net effect of two bipolar vector magnetic fields (induced and remanent) that usually have different intensities and directions of magnetization. Wavelength filtering can be used to better separate the effects of shallow versus deep-seated sources. Using a high-pass filter brings out anomalies at greater depths. Derivative methods accentuate the boundaries of anomalies, both shallow and deep.

As with all potential-field techniques, it is impossible to calculate the anomaly's depth unambiguously without knowing the shape and magnetic properties of the source of a magnetic anomaly. However, with a prior knowledge about the source, it is often possible to estimate depths to within a factor of 10 to 20 percent depending on the complexity of the anomaly and site noise conditions.

Magnetic gradiometry involves simultaneous measurement by two magnetometers close to each other (about 0.5 m). The interval gradient is the difference in magnetic intensity readings divided by the distance between sensors. Commonly, two total field instruments are placed on a vertical staff and the vertical gradient is determined. Two key advantages of gradient surveys are (1) they tend to resolve complex anomalies into their component parts (higher resolution than the magnetic field alone), and (2) because the readings are taken simultaneously, it is not necessary to correct for diurnal variations and magnetic storms. The orientation of the line between the two sensors must be kept constant, or at least monitored, because the gradient will vary with the orientation of this line. In addition, the magnetic cleanliness of the operator (belt buckles, watches, etc.) and magnetic cleanliness of the surface of the area surveyed become even more important than for simple total field measurements. The gradiometer technique is extremely sensitive to surface debris such as nails, cans, wire, and other metallic objects.

Applications, Limitations, and Prospects

In site characterization, magnetic methods commonly are used for finding buried objects such as drums and abandoned underground fuel storage tanks. Often, the analysis can be very simple. A survey is carried out on a grid or profile line, the results are contoured or plotted, and anomaly locations are noted. Buried metallic objects usually show up as dipolar anomalies (magnetic highs with an adjacent low on their north sides in the Northern Hemisphere). However, sophisticated filtering and analysis techniques for separation of superimposed anomalies and depth determinations can make processing and interpreting magnetic surveys more complicated (e.g., Telford et al., 1990; Burger, 1992).

Where there are localized changes or contrasts in magnetic properties, the earth's field will induce a secondary or anomalous magnetic field. For buried ferrous metal objects, the magnetic permeability is large relative to surrounding soil and rock and results in a large induced magnetic field. Many magnetic objects, particularly ferromagnetic objects, also have a large remanent or permanent component. Accurate interpretation of magnetic data depends on being able to distinguish between the induced and remanent components.

Gravity and magnetic methods can be used in a complementary fashion to more tightly constrain geological interpretations. Roberts et al. (1990b) give an example in which magnetic data recorded over a landfill was enhanced by digital processing. Hinze et al. (1990) show how the gravity and magnetic data from the landfill can be combined to assist in the interpretation of its extent and of the material within it.

Future prospects include several innovations related to increased use of GPS, high-temperature superconductivity, and cheaper electronics. Increased use of GPS could lead to robotic control of magnetometers, including unmanned aircraft. High-temperature superconductors may lead to additional sensitivity for portable magnetometers. Cheaper electronics and computing could lead to real-time contouring of data in the field and to increased use of magnetic gradiometry in which two or more magnetometers are read simultaneously at slightly different locations.

ELECTRICAL AND ELECTROMAGNETIC METHODS

"Electrical methods" refer to measurements of natural or impressed electrical fields (potential fields) at low-frequency alternating current (ac) or direct

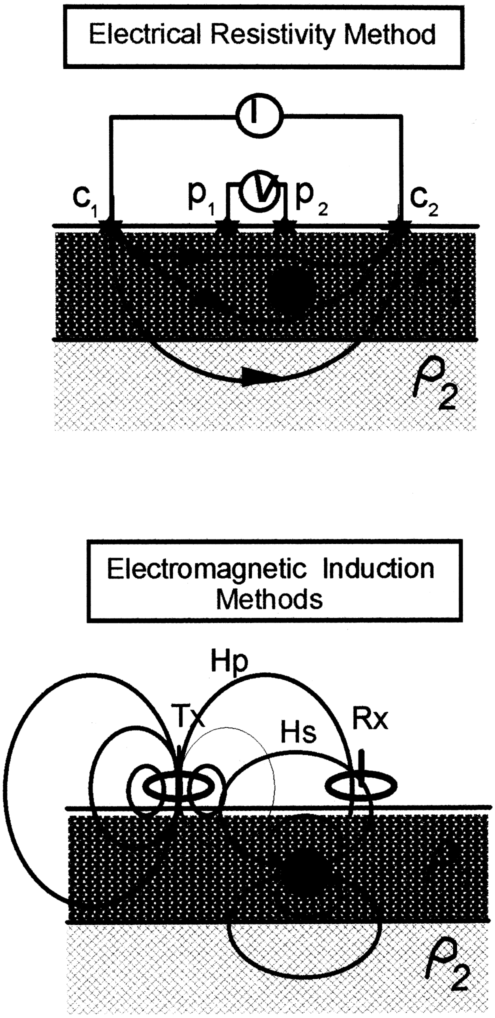

FIGURE 4.1 Simple comparison of electrical resistivity methods and electromagnetic induction (EM) methods. EM methods are generally noncontact, whereas resistivity methods require driving metal electrodes into the ground.

current (dc) using electrodes attached to the ground. By contrast, electromagnetic (EM) methods measure magnetic fields associated with time-varying subsurface currents induced by a natural or artificial electromagnetic source (propagating fields). A schematic comparison of the two is shown in Figure 4.1. GPR is based on high-frequency electromagnetic wave propagation.

Field Electrical Measurements

Electrical field methods measure changes in the earth's natural and induced electrical fields caused by changes in the source origins of the fields and in the electrical properties of the earth. Electrical field methods include dc resistivity, complex resistivity, and self potential. Electrical properties of interest are (1) the electrical conductivity, which describes the ability of a material to transport electrical charge, and (2) certain electrochemical and coupled processes. Sources of the electrical fields are the natural fields in the earth caused by the natural magnetic field, solar-wind interaction with the earth, lightning from storms, electrochemistry (e.g., the battery-like corrosion of naturally occurring sulfide minerals in water), and coupled processes (e.g., a voltage called the streaming potential is generated by fluids flowing through pores). Human-made sources also exist from grounding of power grids, corrosion of buried metallic objects, and intentional artificial sources connected to the ground (dc resistivity sounding).

Electrical fields are time-varying vector fields with three-dimensional variation in direction over the surface of the earth. Commercial electric field sensors are simple in principle, consisting of a porous container filled with nonpolarizing electrolyte and electrode. Measurements are made by connecting voltmeter terminals to electrodes in the ground at two locations. Measurements are easily and routinely performed at the microvolt or millivolt level. Fundamental principles are described in Keller and Frischknecht (1970), for example.

dc Resistivity

The dc resistivity method is a widely used, inexpensive technique for near-surface investigations. Electrical resistivity methods measure the bulk electrical resistivity of the subsurface directly by measuring the voltage generated by transmission of current between electrodes implanted at the ground surface (Figure 4.2). Resistivity data are collected using single or multiple pairs of current and voltage electrodes (dipoles) with known relative positions. They are interpreted by matching them to theoretical models having a subsurface structure of varying conductivity.

In the past, resistivity measurements were usually taken in a straight line on the surface, and the interpretation was done in terms of one-dimensional or two-dimensional models. In a sounding, the measurement array can be expanded about a central position and the data interpreted with a vertical one-dimensional model. In profiling, the relative array geometry and electrode spacing are fixed, but the entire array is moved laterally. Variations indicate lateral or two-dimensional changes in subsurface resistivity. This work can be reviewed in texts such as Keller and Frischknecht (1970) and Koefoed (1979).

Sounding provides a resistivity map as a function of depth, comparable to drilling a well and logging it for this information. Resistivity measurements are

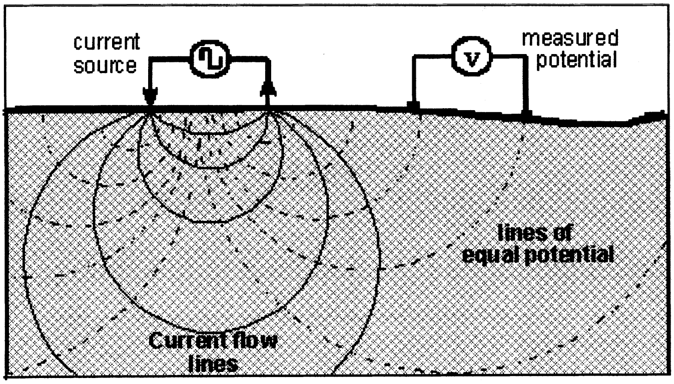

FIGURE 4.2 Schematic of a resistivity survey.

made at a variety of electrode separations, the depth of the investigation increasing with larger separations. Electrode geometry can differ among various applications of this method. Profiling is performed using a constant spacing between electrodes (two outside current electrodes and two inside voltage probes), in which case the arrangement is known as a Wenner configuration (Figure 4.2), and sounding using the Schlumberger configuration where the potential electrodes are located in the center of two widely spaced current electrodes. Modern resistivity systems use a multicore cable, multiple electrodes, and computer-controlled switches in a noise-reducing and field-efficient procedure that speeds the data collection process. Depth and resistivity estimates are made with one- or two-dimensional inversion programs.

Complex resistivity or induced polarization measurements refer to nonlinear or frequency-dependent resistivity measurements and are treated later in this chapter.

It was clear even from early studies (Schlichter, 1933; Pekeris, 1940) that results of the resistivity method must account carefully for both nonuniqueness and resolution issues. More recently, there have been systematic studies of the uniqueness of one-dimensional resistivity sounding results (Parker, 1984; Zohdy, 1989; Simms and Morgan, 1992). A number of easy-to-use one-dimensional inversion programs are commercially available.

Recently, a number of approximate imaging schemes have been developed (e.g., Niwas and Israil, 1987; Zohdy, 1989) that give a better representation of a spatially varying geoelectric section than simple layered-earth models.

Two-dimensional resistivity models of the subsurface avoid some of the limitations in one-dimensional models. Clearly, they also entail the collection of much more data. The first step in data processing is usually to display the data graphically in a pseudosection, which is constructed by assigning a resistivity value, measured with a specific geometry, to an approximate position at depth. The pseudosection is a data display, not a geoelectric section. Unfortunately, some practitioners mistakenly contour this pseudosection and use it as the end product for interpretation. Resistivity data may be inverted on a computer using algorithms (e.g., Tripp et al., 1984).

Today, the state of the science is to collect extensive current and electrical potential data not in one direction but rather in two surface directions. These data are then interpreted by computer inversion in terms of two-dimensional or three-dimensional subsurface models. Hundreds to thousands of data points must be collected. The generation and inversion of a full three-dimensional subsurface model requires complex computer codes (Ellis and Oldenburg, 1994; Li and Oldenburg, 1994; Zhang et al., 1995). However, the general uniqueness and resolution of three-dimensional resistivity inversion have not been investigated sufficiently thus far.

Self Potential

Self potentials (SP) (sometimes called spontaneous potential) are natural dc voltages that exist in the earth. They are measured with a high-input impedance voltmeter using nonpolarizing electrodes, often as a by-product of a dc resistivity measurement. Natural voltages rarely exceed 100 mV over several hundred meters, and they usually average to zero over distances that are a few times larger than whatever size anomalies may be present. These electrical fields are caused by fluid flow, subsurface chemical reactions, and temperature differences. Depth of placement of the electrodes can have an effect on the reliability of the readings, as can roots and nearby vegetation.

Through the fluid flow streaming-potential mechanism, the SP method represents the only known noninvasive passive method directly related to subsurface fluid flow (the seismoelectric method also can measure fluid flow). Small fluid flows associated with cracks in contaminant containment barriers are probably too small to be observed. However, significant fluid movement associated with remediation, such as pump-and-treat and sparging, should produce measurable anomalies. Furthermore, significant fluid flow from leaking dams can be monitored and modeled (e.g., Wurmstich et al., 1991; Wurmstich and Morgan, 1994).

Underground chemical pollution, by definition, produces chemical concentration or diffusion potentials. However, a number of factors must be favorable for surface anomalies to be detectable. Large chemical concentration differences, shallow depth, and a high electrical resistivity background all contribute to enhancing the effect. Furthermore, the specific chemistry involved in setting up the diffusion potentials will determine the level of sustainable electric current available from such an electrochemical battery.

The SP method is one of the oldest geophysical methods and shows significant correlation with subsurface processes. Field data are also relatively easy and inexpensive to obtain. However, detailed interpretation is relatively difficult. Because the voltages are low, they are subject to noise from power lines, pipelines, electrical storms, and other environmental sources. Care must be taken with the data acquisition field procedures to ensure that the data are repeatable.

Induced Polarization (IP)

Using an electrode setup identical to that of the resistivity method, the response of the ground to the removal of an induced electrical signal can be investigated. The IP method involves measurement of the decay of voltage in the ground following the cessation of an excitation current pulse (time-domain method) or low-frequency (less than 100 Hz) variations of earth impedance (frequency-domain method). Most of the stored energy involved is chemical, involving variations in the mobility of ions and variations due to the change from ionic to electronic conduction where metallic minerals are present, and can be likened to a capacitive discharge. Various electrode configurations can be used, commonly dipole-dipole arrays.

In the resistivity method, the passage of electric current through the pores of rocks and soils is dominated by the movement of ions in the pore solution. The earth behaves capacitively at low frequency. Induced polarization measures the low-frequency or capacitive behavior. As ions progress through the pore fluid of rocks they also accumulate along and across surface boundaries. It is this induced accumulation of charge that produces the capacitive effect.

Induced polarization is present in varying degrees in all earth materials. However, it manifests itself strongly in two situations. When electrically conducting metallic minerals are present, charges accumulate at surface boundaries as charge flow changes from ionic in solution to electronic through the mineral. IP effects are also significant in earth materials such as clays with high internal surface areas. Here the charge accumulation or capacitance is associated with the ubiquitous electrochemical boundary layer.

Application, Limitations, and Improvement of IP Methods

Traditionally, IP was assessed in the field by measuring the resistivity at two frequencies or by monitoring the change in decay in response to a current pulse. Modern instruments can also measure the phase difference between the real and imaginary parts (complex conductivity) over a wide range of frequency. Such instrumentation opens a new domain because it allows a broad frequency or spectral response to be recorded in the field. The idea is that the spectral response will have behaviors characteristic of the specific chemical reactions taking place.

Historically, IP has been used mainly to locate metallic minerals in the near surface (Wait, 1959; Madden and Cantwell, 1967; Bertin and Loeb, 1976; Sumner, 1976). There were a few early attempts to use the method in groundwater studies (Vacquier et al., 1957). Currently, with the widespread emphasis on environmental problems, there has been renewed interest in IP. The idea is that pollutants may alter or influence the surface chemistry and attendant chemical reactions in such a manner that the IP response will be anomalous relative to unpolluted areas. How successful this will be is still a matter of debate, but IP represents one of the few means of possibly performing noninvasive chemistry. As a parallel to the above, because IP is sensitive to clays at depth, it is often of tremendous use in mapping low-permeability clay zones that impede pollutant movement. The negative side of this sensitivity is that it is not possible to uniquely determine if an IP anomaly is due to the actual contamination or to the confining clay zone.

The current status of practice is to perform single-frequency, time-domain or phase IP and to plot this as a pseudosection at an approximate depth. Layered-earth IP inversion is the current state of the art, but is not widely practiced. In addition, techniques for two-dimensional IP inversion have also been developed (e.g., Pelton et al., 1978), and attempts are being made to perform three-dimensional IP inversion (Oldenburg and Li, 1994). The main limitations appear to be lack of consistent high-quality, high-volume data and dissemination of computer codes.

The IP method has some unique features and possibilities in terms of noninvasive chemical characterization. Good instrumentation is available for embarking on the more interesting spectral IP and three-dimensional interpretation methods, and the subject is moving mainly in this direction. Recommendations for needed research in IP are given by Ward et al. (1995), and condensed below:

- Opportunities exist in the areas of controlled laboratory and in situ measurement to better understand IP signatures of various chemical contaminant situations, especially rock-fluid interactions at a wide range of frequencies.
- Further development of digital signal processing and both forward and inverse modeling techniques for IP methods could enhance the extraction of relevant geophysical parameters from IP data.
- For environmental work, research in IP data acquisition using the order of 100 data recording channels is needed, along with systems that would quickly, efficiently, and safely control a large array of electrodes with minimal human intervention.

Low-Frequency Electromagnetic Field Measurements

Electromagnetic induction techniques operate at frequencies less than 1 MHz and are based on inducing eddy currents at the surface. Eddy currents diffuse into the earth at a rate that depends on the electrical conductivity and, to lesser extent, the magnetic susceptibility of the earth. At induction frequencies, the attenuation of electromagnetic waves is proportional to the square root of conductivity and frequency.

At high frequencies (generally greater than 1 MHz), electromagnetic fields propagate like seismic waves, responding mostly to the complex dielectric permittivity and, to a lesser extent, to the electrical conductivity and complex magnetic susceptibility. Electromagnetic measurements above 1 MHz are generally referred to as GPR, which is discussed later in this chapter. Electromagnetic waves are three-dimensional, time-varying, complex vector fields, propagating with directional and polarization properties. Electromagnetic waves may be of natural or induced origin, such as power grids, electric subways, and communications broadcasts.

At lower frequencies, the commercial sensors are coils of wire (magnetic sensors or induction coils), and at high frequencies, the commercial sensors are electric field antennas. Measurements are made of the strength (magnitude and phase) and orientation (direction and polarization) of the complex vector fields.

Frequency-Domain Electromagnetics

This active (as opposed to passive) induction technique uses a transmitting coil that emits a fixed- or swept-frequency EM oscillation and a receiving coil that measures changes in amplitude and phase of the secondary magnetic field associated with eddy currents induced in the ground. These eddy currents and their associated secondary magnetic fields are directly proportional to the electrical properties of the shallow subsurface sediments and fluids beneath and between the two coils. The simplest frequency-domain EM instruments, known as terrain conductivity meters, yield depth-integrated measurements of soil conductivity from a depth of a meter to more than 30 m. Conductivity data can be interpreted qualitatively or quantitatively, often in conjunction with other procedures designed to directly measure conductivity as a function of depth, such as resistivity sounding. The depth of investigation from frequency-domain EM procedures is a function of coil separation, transmitted frequency, and transmitter power. The end product is a map showing conductivity (millisiemens or millimhos per meter) as a function of lateral position and is used for reconnaissance of a site's electrical properties from the surface down to some depth of interest. Results from a high-resolution frequency-domain EM system at the University of Arizona are shown in Plate 2.

Recently, there has been interest in high-frequency EM surveys (Sternberg and Poulton, 1997). At frequencies of 1 to 30 MHz, it is possible to measure both conductivity and dielectric constant. At these frequencies, the depth of penetration of the EM energy is much greater in conductive soils, compared with standard GPR, which typically uses frequencies of 30 MHz to 1 GHz. The measurement of both conductivity and dielectric constant provides greatly enhanced capability to infer more about the earth's properties (e.g., presence of organic contaminants, engineered structures, and buried nonmetallic objects).

Time-Domain Electromagnetics

Time-domain EM techniques are fundamentally similar to frequency-domain EM methods, except the transmitted signal is in the form of discrete pulses and the secondary magnetic field is measured during the interval between pulses. The rate of decay of the secondary magnetic field depends on the electrical conductivity structure in the earth. In the presence of highly conductive bodies, the decay is slower than in a less conductive earth. The decay signal can be interpreted in terms of lateral and depth variations in conductivity. The depth of investigation increases with sample time and decreases with ground conductivity, but it can penetrate more than 100 m in some cases. For near-surface investigations, very early time systems have been developed with small portable transmitter loops suitable for rapid profiling. An application of time-domain EM is illustrated in Plate 3.

Very Low Frequency Electromagnetics

This technique measures the magnetic (and sometimes electric) components of the electromagnetic field generated by long-distance radio transmitters in the very low frequency (VLF) band. These transmitters are used for long-distance naval communication with submarines and operate in the 10- to -30-kHz frequency range. Conductive structures on the surface or underground, even when covered with thick overburden, locally affect the direction and strength of the field generated by the transmitted radio signal. The method can locate structures where quantities of groundwater may be held in rock fractures or cavities, and it is sensitive to geological features with long strike length. Large anomalies are associated with electrical cables and buried metallic pipes in urban areas. Commercial adaptations display the in-phase and quadrature magnetic field tilt-angle components from which interpretations of lateral changes in conductivity are made. If topsoil is electrically conductive, it is difficult to obtain information from deeper structures. Some VLF equipment also measures the electric field, allowing calculation of average ground conductivity.

Applicability of Electrical and Electromagnetic Methods

Electrical and electromagnetic methods have tremendous potential for significant advancements in the field of near-surface investigations. They are currently among the most used techniques for environmental and engineering site investigations, however their potential is far greater than is currently being realized. Applications include site stratigraphy, depth to the groundwater table or electrically conductive contaminant plumes, and buried wastes. Time-lapse measurements can help detect leaks in engineered contaminant barriers or in tracking the movement of contaminant plumes.

Electromagnetic methods (in contrast with seismic or GPR) have relatively low resolution. Nevertheless, theoretical studies show that EM techniques can have much higher resolution than is achieved currently in normal field surveys. For example, Fullager (1984) showed that these methods "are, in principle, imbued with unlimited resolving power … provided no noise is present." A small amount of noise, which is always present to some degree, can have significant degrading effects on the resolving power.

Electromagnetic methods can be particularly sensitive to the parameters of greatest interest in near-surface investigations. These methods include direct detection of contaminants in the subsurface, sensitivity to geological formation changes, and a correlation with parameters of interest in geotechnical studies. Although there have been controlled demonstrations indicating sensitivity of the EM fields to some of these parameters, much more development of this technology is needed to apply this in routine field surveys.

Electromagnetic systems are in many respects relatively crude in comparison, for example, to standard three-dimensional seismic survey systems used in the petroleum industry. Some of the pressure to use simpler and relatively unsophisticated instrumentation comes from the desire to emphasize low cost, easy-to-use, and easy-to-understand techniques. Unfortunately, this has limited the usefulness of the techniques and has resulted in much greater expense during drilling and excavation phases in some site investigations.

Electromagnetic measurements can use an almost endless variety of sources, instruments (e.g., receivers, array types, recording techniques) and techniques (e.g., those discussed above). On the one hand, this is a great advantage because of the wide diversity of measurements and the opportunity for novel techniques. On the other hand, it is also a disadvantage because much of the past effort in this field has been diffused over a great many different, and incompatible, techniques. Controlled tests are needed to help define the best approaches for each problem of interest in near-surface investigations.

Potential Improvements of Electrical and EM Capabilities

There are a great many potential research and technical improvements in capabilities. Among those that can be undertaken are the following:

- More sophisticated arrays of sensors and sources.
- Further development of broadband measurements from dc to gigahertz frequencies.
- More rapid data collection to allow essentially continuous profiling and areal coverage.
- Greatly enhanced capabilities to handle cultural interference, in particular grounding-line interference, not just electrical noise.
- Sophisticated systems for critical applications where the alternative would

be expensive excavation, as well as more economical, easier-to-use systems that contain a subset of new capabilities for EM systems that could be operated in smaller-scale surveys by skilled technicians.

- Interpretations that more often include complex resistivity at low frequencies and combined use of conductivity and dielectric constant at higher frequencies.
- Published case histories are essential for showing applications of improved EM techniques for mapping properties of interest in near-surface investigations, including more studies of contaminant mapping, permeability determination, formation type, rock strength, and water chemistry. There has been a number of case histories studying some of these properties, but, few have used the full capabilities of EM, including novel arrays, wide bandwidths, complex resistivity and dielectric constants, and high data density measurements.
- New field acquisition methods will require greatly improved interpretation techniques that allow handling of complex geometries and widely varying background responses. These techniques include analytical, numerical, and physical modeling as well as novel methods of transforming the raw data into a meaningful image of the subsurface.
- Easy-to-use interpretation techniques that allow some of the interpretation to be done in near real time in the field.
- More laboratory electrical property measurements are needed to determine what can be interpreted reliably from surface electrical and electromagnetic measurements. For example, are there distinctive electrical property changes due to contaminants, what is the relationship between engineering properties such as rock strength and electrical properties, and how well can hydraulic permeability be predicted from electrical properties? Another crucial area for laboratory electrical property studies is to find ways to better relate laboratory-scale measurements to field-scale measurements.

GROUND PENETRATING RADAR

GPR is similar to the seismic reflection method in the basic wave propagation physics, but uses high-frequency electromagnetic waves in the tens of megahertz to gigahertz range. Details of the acquisition process differ markedly from the seismic method, most notably because only one channel is acquired. The contrasts being measured with GPR are differences in dielectric permittivity across earth boundaries. The dielectric permittivity is a measure of the ability of a material to store electrical charge (like a capacitor or battery) and principally determines the velocity of propagation of the electromagnetic wave. The product of the dielectric permittivity and the magnetic permeability is analogous to seismic impedance. The real part of this product (complex modulus) usually describes how the material stores energy and the imaginary part describes how the material loses (or dissipates) energy.

The EM wave propagates in the earth at the speed of light divided by the square root of the dielectric constant of the geological material. The depth of investigation is inversely proportional to the near-surface conductivity of soils and pore fluids. Due to the smaller wavelengths used in the GPR method, resolution is commonly as much as one order of magnitude better than current seismic reflection techniques.

The quality of GPR data and its usefulness in site characterization are determined by (1) the electrical properties of the site, (2) the equipment used, (3) data acquisition procedures and parameters, (4) data processing, and (5) methodologies for interpretation and visualization. The greatest limitation to the widespread use of GPR is the electrical conductivity at a site, which determines the depth of penetration. As a rough guide, GPR is considered to be most useful when the conductivity is less than 10 mS/m (Davis and Annan, 1989); this generally prevents effective applications of GPR in clay-rich environments.

Applications of Ground Penetrating Radar

GPR is used to delineate near-surface site stratigraphy, map the extent of buried waste, locate the water table, and find buried utilities. Recent developments in GPR allow direct detection of organic contaminants by observing changes in scattering properties (the texture of the radar record) or dielectric contrast (e.g., oil floating on water).

GPR can contribute to site characterization in three ways. The most common use of GPR is in obtaining information about the large-scale (meters to tens of meters) geological structure at a site. A second common use is to detect anomalous regions superimposed on the natural geological background; this includes the possible detection of liquid contaminants and the detection of buried objects. The third, and most challenging, potential use of GPR is to obtain information at the meter scale (or less) about the specific physical or chemical properties of the subsurface. The first two applications emphasize the use of GPR as a means of imaging the subsurface; in the third, information about dielectric properties is extracted from GPR data and then related to physical and chemical properties. Each of these is expanded upon below.

Large-Scale Imaging

The first step in site characterization often involves determining the geological setting and locating key geological boundaries. Given a site with suitable electrical conductivity, GPR can obtain excellent images of the subsurface that can be used for this purpose. With detailed horizontal and vertical sampling, it is possible to obtain high-resolution (tens of centimeters to meters) images of the subsurface to average depths of 10 m or more. To extract information about the geological structure, the approach usually taken is to identify within the GPR section reflectors with a distinct geometry or orientation, or packages of reflectors with a characteristic appearance.

There are a number of examples in the literature in which GPR data have been used to reconstruct the geological setting by relating the GPR image to the subsurface stratigraphy and sedimentary facies. In such studies there is always prior knowledge from surface outcrop or wells of the lithologies likely to be present and of the depositional environment. Published examples include the use of GPR images to determine the geometry of Pleistocene gravel deposits (Huggenberger et al., 1994), the orientation of major sedimentary structures, and facies thickness and depths in deltaic environments (Jol and Smith, 1991). An example of the GPR image of a deltaic deposit is shown in Figure 4.3. The distinct appearance of the radar reflections makes it relatively easy to locate some sedimentary units in the subsurface. In addition, GPR data can be used to help target the anisotropy expected in hydraulic properties in this sedimentary package. The structure seen in a radar section contains information about the spatial heterogeneity of the subsurface and provides a basis for mapping the geological units in the subsurface.

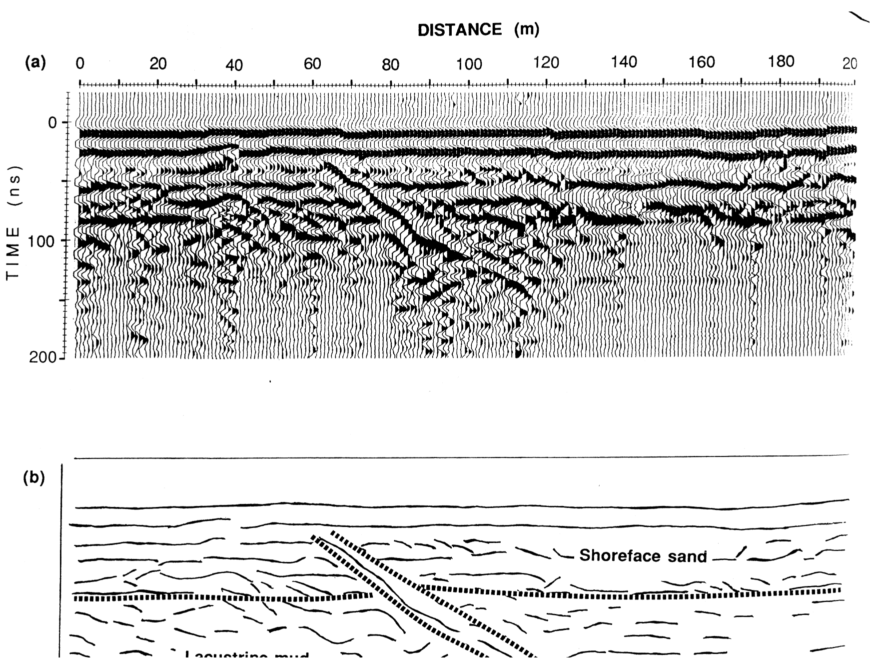

FIGURE 4.3 GPR profile along the escarpment of the Slave River Valley, Fort Smith, North West Territories, Canada. Early Holocene wave-influenced deltaic deposits with possible postdepositional slumping. (From Jol and Smith, 1992.)

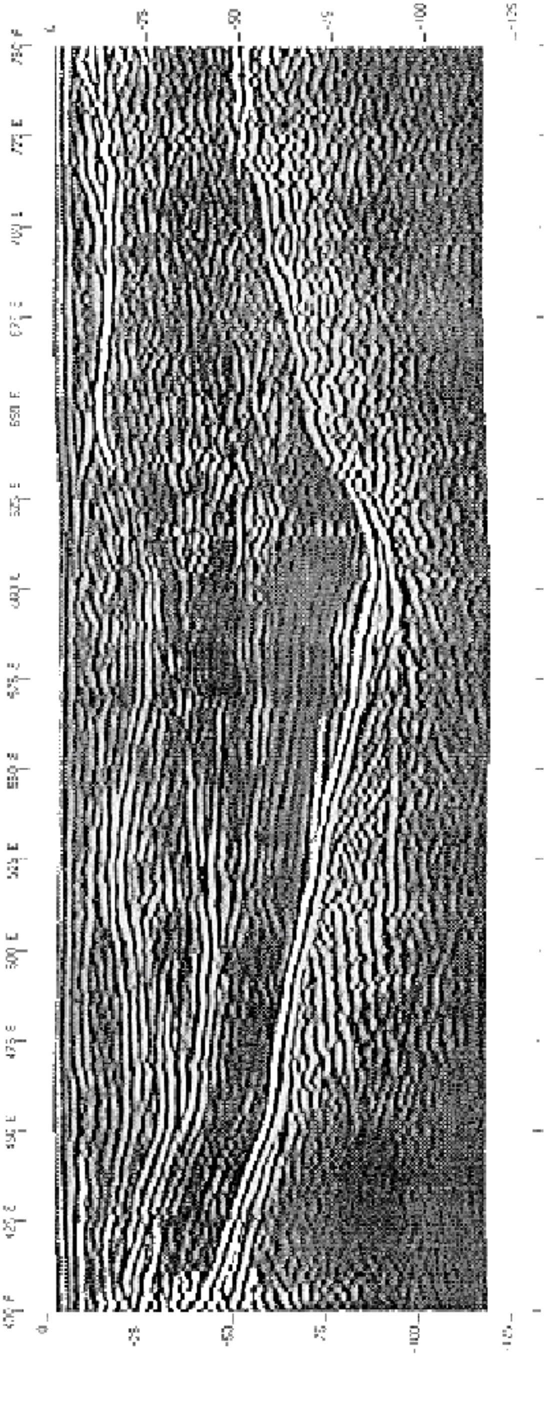

FIGURE 4.4 GPR data presented as a gray-scale shaded section rather than the traditional wiggle trace. The purpose of the survey was to determine the location and shape of a buried river channel.

An important aspect of characterizing the geological setting is to locate the boundaries that can affect the physical, chemical, and biological behavior of regions of the subsurface. One of the key geological boundaries of interest in a number of different applications is the top of the bedrock. This often can be imaged with GPR due to the contrast in dielectric properties between the bedrock and the overlying material. In an example of a GPR image of the bedrock topography under a fine sand overburden (Davis and Annan, 1989), the contrast in dielectric constant between the overlying sand and the granodiorite bedrock and the lateral continuity of the feature made this a relatively easy target for GPR imaging. Further processing of GPR data can improve the presentation of the information (see Figure 4.4).

Determining the depth to the water table is a characterization objective for which GPR is well suited if the electrical conductivity at the site is not high. The water table can be identified as a flat-lying, high-amplitude reflector in a GPR section (Knoll et al., 1991; Sutinen et al., 1992). A dominant reflector is seen due to the contrast between the dielectric constant of the unsaturated and the fully saturated materials; therefore the "water table" reflector seen in GPR sections may actually be the top of the capillary fringe. The clearest images of the top of the saturated zone are obtained in coarse-grained materials where the capillary fringe does not "smear" the dielectric contrast.

Significant progress has been made in the collection and display of GPR data. With current technologies, it is possible to collect and display three-dimensional data in a way that makes it relatively easy for the nonexpert to visualize useful information. This user-friendly aspect of GPR is likely to contribute significantly to the increased use of GPR in site characterization.

In all of the above applications the objective is to obtain a representation of the subsurface in which geological units and boundaries are located. As a useful caveat, the vertical positioning of any feature seen in a GPR record is only as accurate as the velocity determination of the radar signal at that site.

Detection of Organic Contaminants Using GPR

There have been a number of examples in which GPR has been used to image the presence of organic contaminants in the subsurface. The contrast between the low dielectric constant of most organic contaminants and the high dielectric constant of water, and the availability of pre-spill radar data are what make detection possible. A recent example is the direct monitoring of a sinking organic liquid (tetrachloroethylene) during a controlled spill (Annan et al., 1992; Greenhouse et al., 1993; Brewster et al., 1994). This investigation was conducted under the most ideal of conditions: the background geology was a homogeneous sand, and a GPR profile was available from the site before the spill. The collection of GPR data as a function of time during this experiment greatly simplified the interpretation by making it possible to relate the time-dependent changes in the data to the movement of the contaminant. Monitoring such a process is an application for which GPR is well suited.

In a more typical situation, GPR is used after the spill of a contaminant, and time-dependent data are not collected. In some case studies the presence of an organic contaminant has been associated with the region in the GPR record where there is a "washed-out" appearance (Olhoeft, 1986). This change in character of the radar reflectors is by no means a conclusive way of determining the presence—or lack—of a contaminant. This change in GPR signals can lead to a high degree of uncertainty when GPR is used for contaminant detection without additional information from other types of data.

Detection of Buried Objects Using GPR

GPR has been found to be a useful technique for the detection of subsurface voids, buried drums, bodies, storage tanks, and utilities. In some cases, an object can be located using the changes in the dielectric properties in the surrounding zone disturbed during the digging and burial of the object. The main limitations to the use of GPR for these purposes have been the background electrical conductivity of the site, the resolution of the GPR data, and cultural interference.

In many of the GPR searches for buried objects, the procedure is simply to use unprocessed data and look for anomalous regions in terms of the appearance of the GPR reflectors. Looking for anomalous regions is usually what is done in archeological and forensic studies, where there are many examples of the successful use of a GPR image to locate an object in the subsurface. Undoubtedly, there have also been numerous times that regions identified as "anomalous" have not corresponded to the target of interest; unfortunately, it is more difficult to find published examples of these failures. A description of various case studies in which GPR was used both successfully and unsuccessfully to find buried bodies is given by Mellett (1996), with a discussion of the various reasons a GPR anomaly can be associated with the burial.

If digital signal processing capabilities are available, the ability to resolve the presence of a buried object can be improved dramatically. Examples are given in Bradford et al. (1996), where advanced processing methods were used to improve the resolution of GPR data for the purpose of locating metal and polyvinyl chloride (PVC) pipes. Clear images were obtained of pipes with diameters near the limits of resolution (2 inches in this case) for the antennas used in the survey.

Characterizing Small-Scale Properties by GPR

In the above applications, the GPR was used to obtain information about the geological structure of the subsurface or the presence of anomalous fluids or solids. It is the geometry and character of the reflectors in the GPR data that are used in a predominantly qualitative way to characterize the subsurface. It is for imaging the subsurface in this way that GPR is currently most widely used and, given the current technology, most ideally suited for. There is, however, additional information contained in GPR data that can, ideally, be extracted for the purposes of site characterization.

GPR image obtained at a site is one representation of the recorded changes in .dielectric properties of the subsurface. Given that dielectric properties are related to the physical and chemical properties of the subsurface, it should be possible to extract information about these properties from GPR data. Determination of the dielectric properties is not commonly done in practice and represents one of the current limits (or forefronts) in applying GPR to site characterization problems. The two main challenges are in collecting sufficient data to allow inversion for dielectric information and in relating dielectric properties to the physical and chemical properties of interest. A recent example (Greaves et al., 1996) in which GPR data were used to obtain estimates of water saturation at a site illustrates both the problems with and the enormous potential for using GPR data in this way. Currently, GPR can provide excellent images; the future is to provide detailed information about physical, chemical, and biological properties that can be used in characterizing the subsurface.

Opportunities for Improvement of GPR

GPR is a relatively young observational technique. Research needs in GPR, to some degree, resemble those of reflection seismology about 40 years ago. Research is needed in data acquisition, data processing, and inversion and interpretation of the data. Some specific examples in these four areas are given below.

- The use of multichannel receiving antennas would allow much faster recording of data with different distances between source antenna and receiving antennae.
- Multichannel receiving antennae would also allow the use of true three-dimensional recording in an efficient manner.
- New strategies for introducing GPR source energy into the ground, including pulse coding and swept frequency techniques, should improve the penetration depth and image resolution.
- Collection of cross-polarized data would make it possible to characterize the full vector nature of the electromagnetic wave field. This would lead to new ways of discriminating among subsurface targets.
- Digital signal processing of GPR data using reflection seismology data processing software has been on the increase, but algorithm development is needed that accounts for the aspects of GPR data that are not common to seismic methods. For example, processing is required to account for dispersion due to frequency-dependent attenuation and scattering, both of which are much more dominant in GPR data than in seismic data.

• A better understanding of factors that affect the source waveform (e.g., antenna radiation patterns, antenna-ground coupling) would lead to improved deconvolution techniques, which would enhance the temporal resolution. Characterizing the source waveform is also a critical part of developing full waveform inversion techniques.

• Inversion of the GPR data to obtain a dielectric model is a critical step in using GPR data to describe the structure and properties of the subsurface. Inversion methods are needed that account for the complex nature of EM wave propagation.

• An understanding of the link between the dielectric properties of the subsurface, as imaged in GPR data, and material properties (water content, porosity, permeability) is fundamental if we are to use GPR data to describe the magnitude and spatial variation of material properties in the subsurface.

SEISMIC METHODS

Sound waves propagate through air or water as waves (like the ripples around a rock thrown into a pond). In the earth at lower frequencies, such waves are called seismic waves. In fluids (air or water), the mode of propagation is as a pressure wave with particle motion in the direction of wave propagation (called a compressional wave). In solids, there are both compressional waves and shear waves (where particle motion is perpendicular to the direction of propagation, like the motion of a rope laid on the ground and wiggled sideways). At interfaces between two different materials there are a variety of surface wave modes of propagation. The property to which the seismic wave responds is the complex elastic modulus of the material (density dependent), which determines the velocity of propagation and the rate of decay of the propagating signal. The real part of the complex modulus describes how the material stores energy, and the imaginary part describes how the material loses (or dissipates) energy. Seismic waves are three-dimensional, time-varying, complex vector fields, propagating with directional and polarization properties. Seismic waves may be of natural or anthropogenic origin.

Seismic waves are generated naturally by earthquakes (the breaking of rocks under stress), landslides, and events in the ocean and atmosphere (like thunder from lightning). Seismic waves are also generated from anthropogenic sources such as explosions, hammer strikes, and vehicular traffic.

Seismic methods are concerned with the production, propagation, and measurement of elastic waves that travel within earth materials. The variety of seismic sources commonly used for shallow environmental and engineering investigations includes sledgehammers, weight-drop devices, and explosive sources—often in the form of large-gauge shotgun shells fired by percussive or electrical means. Two commonly measured elastic body waves that propagate in the earth are compressional (P) and shear (S) waves. P- and S-waves have veloci-

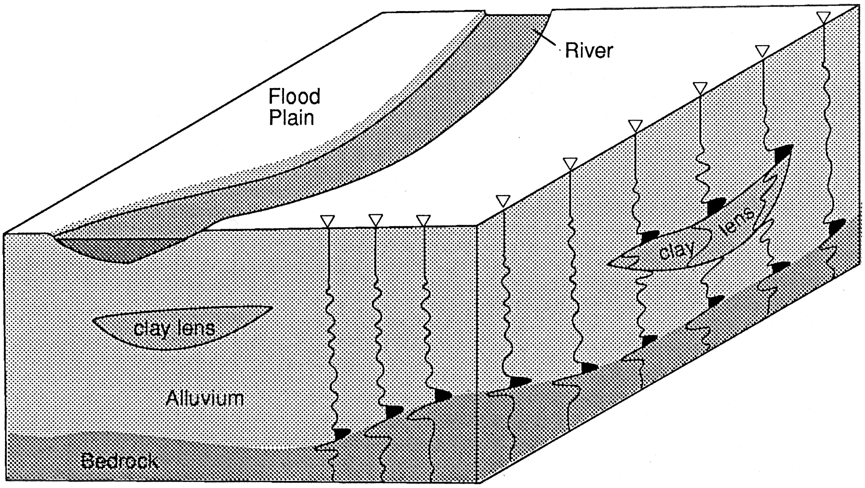

FIGURE 4.5 Simplified cartoon showing the "mapping" of bedrock and other features by seismic waves traced to individual geophone receivers.

ties related to the physical properties of the material in which they travel.[1] The wave velocities are inversely proportional to the square root of density and directly proportional to the square root of the shear modulus for both types of elastic waves and, in addition, bulk modulus for compressional waves.

Detectors (geophones) are implanted in the ground and arrayed at known distances and locations from the controlled energy source (see, for example, Figure 4.5). Precise times of the arrival of the initial seismic waves and subsequent vibrations are recorded at each geophone; also recorded are the amplitude and period of the waves. The receivers are digital, multichannel detectors that respond to particle-velocity changes associated with the passage of the elastic wave. Seismic methods have also been applied in cross-borehole environments, where the geophones are deployed down boreholes to a known depth. In addition to the physical parameters affecting their velocities, seismic waves are reflected, refracted, and variably attenuated (absorbed) as they pass through media with different elastic properties. These properties allow their use in the interpretation

[1]The P-wave velocity is $V_p = \sqrt{\left(\frac{K + \frac{4\mu}{3}}{\rho}\right)}$, and the S-wave velocity is $V_s = \sqrt{\left(\frac{\mu}{\rho}\right)}$, where K is the bulk modulus, μ is shear modulus, and ρ is the density of the material.

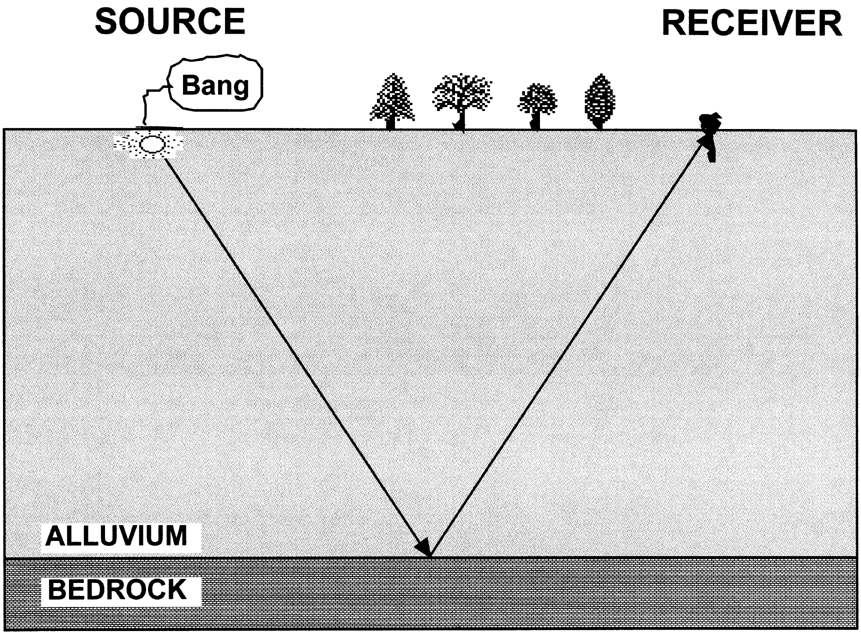

FIGURE 4.6 Simple reflection from bedrock. Either a seismic wave-velocity contrast or a mass density contrast is required for seismic waves to be reflected from the geological interface.

of geological layering and waste-zone geometry based on analysis of signal travel time and frequency content.

The seismic *reflection* method is an image-based technique that produces a cross section of the volume of earth under investigation and shows acoustic-impedance contrasts. The cross section (image of the actual data) has traverse distance as the abscissa and reflected-wave travel time as the ordinate. These acoustic-impedance contrasts can be associated with both fluid and rock boundaries within the earth. The returning signals that constitute the image are stored as traces associated with a particular ground position along the traverse. Each trace is a mathematical vector of particle velocity as a function of time for that position (see Figure 4.6). As these traces are lined up side by side and corrected for geometrical aspects of their acquisition, the individual responses make an echo mosaic that has the appearance of an image of the shallow-earth cross section.

The seismic *refraction* technique uses a series of geophones arrayed on the surface to analyze the refraction of seismic waves along subsurface interfaces of differing materials, as indicated in Figure 4.7. The technique records the time of the first response of each geophone. Plotting these responses as a function of location from the source and processing the information produces a cross section of seismic wave velocity, which reflects geological layering of the subsurface.

Many seismic methods were first developed in the petroleum industry as a way of interpreting the geological structure of sedimentary basins. The signals can be processed by a computer to produce an image—a seismic reflection profile—of the subsurface to depths of several kilometers. An uninterpreted profile is not a true geological cross section, although the gross geometry of the bedrock can be determined from it. Normally seismic methods do not provide any information about the chemical makeup of pore fluids.

Recent developments include the adaptation of reflection seismology for uses as shallow as a few meters and the civil engineering adaptation of spectral analysis of surface waves (SASW) used in determining shear wave velocity profiles and soil stiffness for ground response analyses. The SASW method has a variety of earthquake, environmental, and other geotechnical engineering applications; a recent review is given by Stokoe et al. (1994).

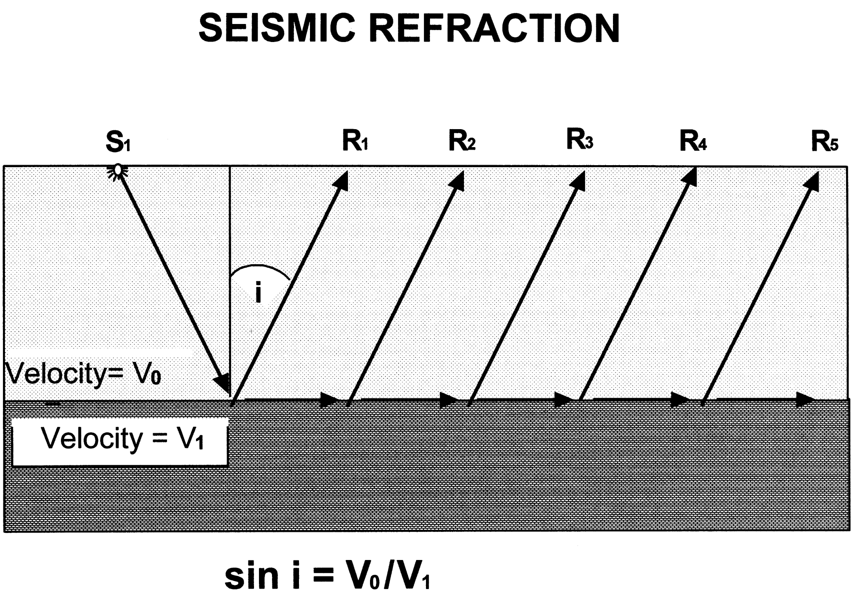

FIGURE 4.7 Seismic refraction. Seismic energy produced by source (S) is detected at a series of geophone receivers (R) after traversing the surface layer and refracting along the interface between layers having two different seismic wave velocities. The velocity in the lower layer must be higher than that in the surface layer for the method to work properly.

Applications of Near-Surface Seismology

There are relative advantages and disadvantages of both refraction and reflection seismic techniques (Table 4.1). The reflection technique can be more powerful in terms of generating interpretable observations over complex geological structures. This power, however, comes at a cost, because reflection surveys are more expensive than refraction surveys and more computationally intensive. Also, usable reflections are often not obtained in shallow surveys. As a result, many engineering and environmental concerns generally opt for refraction surveys when possible. On the other hand, the petroleum industry uses reflection seismic methods almost exclusively.

As more channels become available, the increased use of three-dimensional engineering surveys can be expected along with additional applications. The successful use of near-surface seismology spans the spectrum of applications—from those that are well understood and routine to those that are beyond present understanding and technical capabilities. It is important to distinguish where these limits are because vendors and consultants sometimes make unrealistic claims about the capabilities (particularly their capabilities) of near-surface seismic techniques.

Seismic Refraction

Historically, the use of seismic refraction techniques in geoscience and civil engineering investigations has been widespread (Stam, 1962; Redpath, 1973; Mooney, 1977). The method has advanced throughout the past half-century, which parallels the use of portable, multichannel seismographs. Improvements in both acquisition and processing of data have allowed geophysicists to account for layer dip and spatial velocity variations of both the target refractor and the overburden soil velocities. Resolution of the geometry of the target refracting surface has been another source of improvement.

Development of the method reached maturity in 1980 with the publication of the generalized reciprocal method (GRM) of seismic refraction interpretation (Palmer, 1980). Since then, most papers on seismic refraction have described refinements of the GRM technique or explained the method to a larger audience through clarification and example (Lankston and Lankston, 1986; Lankston, 1988).

A developing alternative to GRM analysis is refraction travel time tomography (e.g., Zhang and Toksoz, 1998). Tomography tends to work better than GRM when the near-surface seismic velocity structure is not discrete, continuous, gently dipping homogeneous layers. The method is analogous to medical computerized axial tomography (CAT) scans, except that the measurements are made along the earth's surface rather than around a three-dimensional volume. One

TABLE 4.1 Advantages and Disadvantage of Seismic Refraction and Seismic Reflection Methods.

Refraction Method		Reflection Method	
Advantage	Disadvantage	Advantage	Disadvantage
Observations generally use fewer source and receiver locations; relatively cheap to acquire	Observations require relatively large source-receiver offsets	Observations are collected at small source-receiver offsets	Many source and receiver locations must be used to produce meaningful images; expensive to acquire
Little processing is needed except for trace scaling or filtering to help pick arrival times of the initial ground motion	Only works if the speed at which motions propagate increases with depth	Method can work no matter how the propagation speed varies with depth	Processing can be expensive as it is very computer intensive, needing sophisticated hardware and high-level of expertise.
Modeling and interpretations fairly straightforward	Observations generally interpreted in layers that can have dip and topography; produces simplified models	Reflection observations can be more readily interpreted in terms of complex geology; subsurface directly imaged from observations	Interpretations require more sophistication and knowledge of the reflection process

approach employs a two-point ray tracing technique to calculate forward travel times for a model, followed by a least-squares inversion to fit the data to a model that is iteratively adjusted to reduce the misfit between the data and the modeled traveltimes (White, 1989).

Applications in Which Shallow Refraction Usually Works. A common use of the GRM technique is determining the thickness of the soil column (depth to bedrock) and thereby producing an image of a layer (soil) over a half-space (bedrock). Locating channels in the bedrock surface and the fill material in these channels that differentially control the flow of fluids in the subsurface is another important use of the GRM refraction technique. These channels represent a natural "French drain" that needs to be known and charted in the subsurface in order to install the proper remediation system at the site (Young et al., 1995). If information about the subsurface is obtained on the basis of drill hole information alone, the phenomenon of "spatial aliasing" of these crucial channels could create a distorted view of the subsurface (Henson and Sexton, 1991).

Applications in Which Shallow Refraction Sometimes Works. One current use of GRM seismic refraction is finding zones of increased fracture density within areas of bedrock where flow and transport of groundwater might occur. Several investigators have succeeded in seismically finding fracture zones by noting decreased target refractor velocity along a segment of the bedrock.

Applications in Which Shallow Refraction Does Not Work. One basic theoretical assumption with seismic refraction is that seismic velocity increases with depth. If this assumption is not true at a given site, refraction methods will give incorrect depths or thicknesses of one or more layers. Lankston (1988) discusses ways to detect these errors and to estimate how large such errors might be.

Seismic Reflection

Three conditions must exist for shallow seismic reflection to work. First, the frequency must be high enough for the reflection to be separable from other arrivals in the early part of the seismogram. In general, 3 to 5 cycles of dominant period of the data in time must pass after the onset of the first arrival before the reflection can be easily separated from the direct waves, refractions, and air blast. In some exceptional data sets, this might be reduced to 1.5 to 2 cycles, but investigators who claim such early reflection arrival times must be able to defend such claims with scientific rigor. In a practical sense, for most data sets with dominant frequencies of less than 150 Hz, reflections at times smaller than 50 milliseconds must be demonstrated as valid by the use of phase identification on unstacked data with the phases traceable through the intermediate processing stages.

Second, acoustic impedance contrasts between layers must be large enough to give rise to detectable reflections. These contrasts require a variation in either seismic velocity or material density, or both. Third, the seismic system (energy source, receivers, and seismograph) must work together with sufficient seismic energy and signal sensitivity to register the desired information coming from the ground motion.

Three-dimensional seismic reflection has been widely adopted in the petroleum industry since the mid 1980s. The use of three-dimensional seismic reflection in near-surface work has not been widespread because of the high costs involved. For example, Buker et al. (1998) reported requiring 85 days of field work with a crew of 5 to 7 people to perform a shallow three-dimensional seismic reflection survey of an area 357 m wide by 432 m long.

Applications in Which Shallow Reflection Usually Works. Although one cannot tell in advance of field testing whether shallow seismic reflection will work at a particular site or for a particular objective, it often works in the applications discussed below. Data quality is commonly better where the water table is at a depth of only a few meters and where the near-surface materials have not been

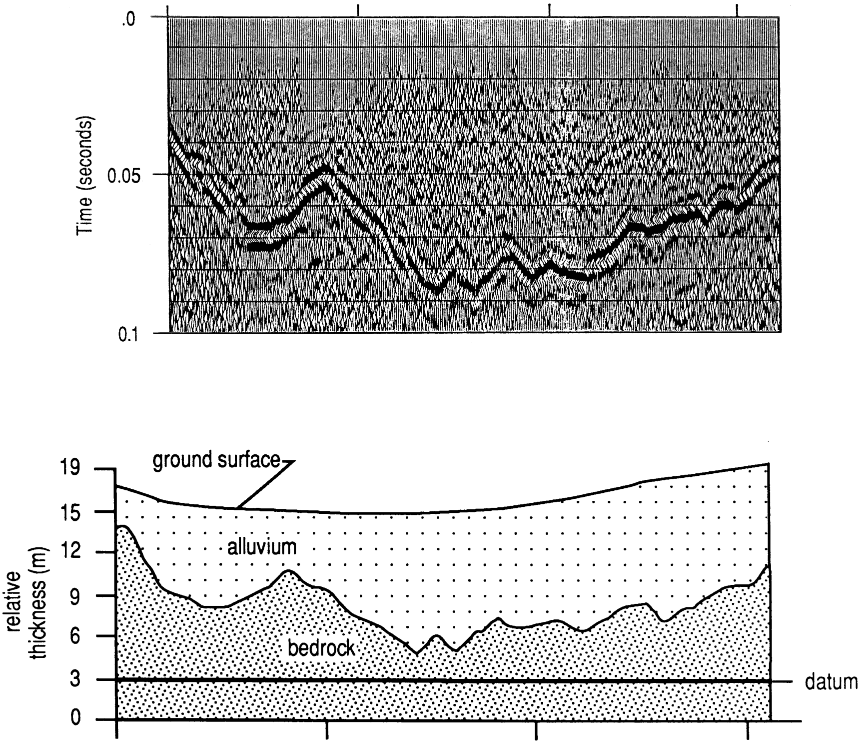

FIGURE 4.8 Seismic reflection cross section and interpreted cross section. The purpose of the characterization was to determine the placement of a monitoring well, which was designed to be placed at the deepest bedrock-alluvium contact. From D. Steeples.

disturbed by construction fill materials or by recent mass wasting such as earthflows or landslides. Working on top of paved surfaces is difficult.

Determining gross geological structure is one of the classic uses of seismic reflection, and the technique works well in near-surface applications if the impedance contrast and frequency are sufficiently large. Examples of this application include determining depth to bedrock (see Figures 4.8 and 4.9) and producing a contour map of bedrock beneath alluvium or till.

Fault detection is another major use of shallow reflection, primarily for earthquake hazard studies, detection of near-surface pathways of high permeability, and geological mapping. Offset detection limits under favorable conditions may be as small as one-tenth of the wavelength of the dominant wave frequency. Because of the reflection time uncertainty introduced by static corrections (e.g.,

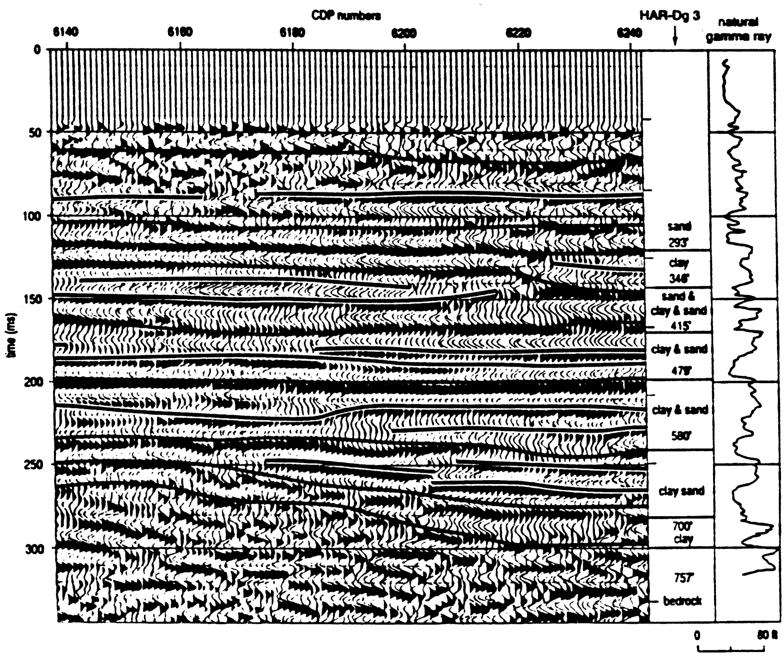

FIGURE 4.9 Seismic reflection profiling for geological variability.

Shallow seismic reflection profiles can provide a picture of geometric complexity and variability of contacts between different types of unconsolidated sediments and the sediment-bedrock interface. Based on a seismic study of the sediments overlying bedrock (depth of about 700 feet) at the Aberdeen Proving Ground in Maryland (Miller et al., 1996), the detail and horizontal interpretation confidence provided by shallow seismic profiles are not possible from drillhole data alone. Extrapolation of drill data from borehole to borehole required significant speculation and assumptions about lithologic correlations.

The seismic investigation was able to describe and detect subtle features of potential local hydrologic and geological significance, such as scour and infill patterns (horizontal expanse of less than 200 feet and vertical extent of less than 20 feet). The figure illustrates one of the seismic sections, which is correlated with lithologies determined from well logs. To even detect these features (and by no means to image them) with drilling methods would require closely spaced holes and significant expense. Seismic profiling proved to be a cost-effective method for interpolation between boreholes.

near-surface velocity anomalies), auxiliary use of the presence of diffractions from broken layers is sometimes needed to detect small offsets.

Stratigraphic studies can also be done successfully with shallow reflection, although the limits of resolution are debatable. Vertical resolution limit (seeing both top and bottom of a bed) is commonly described as a quarter-wavelength of the dominant frequency (Widess, 1973). In a practical sense, however, Miller et al. (1994) have shown that half-wavelength is sometimes a better (or at least more conservative) estimate of vertical resolution limit.

The water table usually presents a contrast in seismic wave velocity and a smaller contrast in density, both of which are likely to produce seismic wave reflections. Consequently, the detection of unconfined and perched water tables is often successful. Indeed, in some cases the water table reflection can be strong enough to make detection of slightly deeper reflectors difficult.

Applications in Which Shallow Reflection Sometimes Works. Shallow reflection seismology sometimes works in applications that require very high resolution, which necessitates both broad bandwidth and high frequencies. Because high frequencies usually fade rapidly or attenuate with increasing depth, the time window during which these applications work in a satisfactory manner is often quite small. Confidence in the validity of reflections usually increases at times >3 to 5 dominant-frequency cycles after the first break. In contrast, high frequencies are often lost at times greater than perhaps 150 to 200 ms. Consequently, the most commonly successful time window for the applications listed below is from 50 to 200 ms.

Detecting voids and tunnels is difficult, although a few occurrences are noted in the literature (e.g., Branham and Steeples, 1988; Miller and Steeples, 1991). There do not appear to be any examples of direct detection of voids using seismic reflection at depths exceeding 20 m. Robinson and Coruh (1988, p. 215) described a case of indirect detection of underground coal mining where reflections from times exceeding 120 ms are masked or attenuated by the presence of voids in coal seams.

Shallow reflection techniques can sometimes detect and delineate facies changes in the shallow subsurface. The detection of facies changes requires a high signal-to-noise ratio and expert interpretation skills. The facies changes often manifest themselves as subtle changes in amplitude or other seismic attributes loosely referred to as "seismic character." Occasionally, stratigraphic detail such as foreset beds on the scale of a few meters can be seen in deltaic deposits and other favorable environments. Intra-alluvial reflections can sometimes be seen on the scales of a few meters in thickness.

Delineation of beds thinner than a quarter-wavelength—based on the shape of the reflection wavelet—requires a higher-than-normal signal-to-noise ratio and substantial experience on the part of the interpreter (Widess, 1973).

Applications in Which Shallow Reflection Does Not Work. Currently, shallow seismic reflection techniques appear unable to discriminate the interface between two liquids in near-surface materials, such as between water and dense, nonaqueous-phase liquids (DNAPLs) or other chemicals. Modeling suggests that the velocity contrasts at the interfaces may be too small to detect with current technology. Furthermore, frequencies at least an order of magnitude higher than those available in shallow seismic reflection are needed to detect such chemical saturation lenses at the thicknesses commonly encountered in real-world pollution situations.

Direct detection of tunnels or other voids at depths of 100 m or more with surface-seismic reflection appears to be unlikely at this point. Cross-borehole seismic methods, with their substantially higher frequencies, may be able to detect voids a few meters across at these depths under favorable circumstances.

Improving Near-Surface Seismic Methods

Though relatively well established in petroleum exploration, the use of seismology for near-surface applications is still in an emerging state. Areas of potentially fruitful research and new applications follow.

- The combination of GRM refraction of the compressional wave (P-wave) with the second body wave (S-wave) opens many new possibilities (Hasbrouck, 1987). For instance, various soil and rock mechanical parameters (e.g., Poisson's ratio, Young's modulus, and shear modulus) can be determined from the combination of compressional wave velocity (Vp), shear wave velocity (Vs), and density (possibly derived from a gravity survey). These elastic constants can help identify rock type and possibly fluid content of pore space (Domenico and Danbom, 1987).
- The combination of GRM refraction of the compressional wave (P-wave) with the second body wave (S-wave) also allows differentiation of "true" geometrical relative minima for the surface of a target refractor from artifacts of overburden (soil) velocity variations. Confirmation of existence and correct position of relative minima is important in potentially locating DNAPL pools in the subsurface (Brewster et al., 1995).
- Research is needed to compare VSP (vertical seismic profile) surveys with those of shallow three-dimensional surveys. Multioffset, multiazimuth VSP may have some advantages in resolution at many locations where boreholes are available. Hole-filling pressurized bladders, which would allow the use of hydrophones at shallow depths above the water table, require further development. Hydrophones have some advantages over geophones because they are less sensitive to the passage of non-P-wave modes and to distortional surface waves.
- Three-component seismology at small-interval (<1 m) offsets is virtually

nonexistent in the literature. Research in this area is necessary to examine the unaliased high-frequency components of the seismic wavefield, which could lead to improved use of shallow S-wave reflection and to simultaneous use of surface wave (both Love and Rayleigh) inversions to help constrain the near-surface velocity models. Such research could lead to a better understanding of anisotropy of the near-surface materials.

- Shallow (1- to 15-m depth) S-wave reflection seismology (e.g., Goforth and Hayward, 1992; Hasbrouck, 1993) is far from routine, but improvements could be of great assistance in engineering seismology, particularly for predicting amplification during earthquakes (Miller et al., 1986).
- When seismic P-wave reflection surveys are conducted, a large portion of other seismic information is unanalyzed. There is a need for collection and analysis of whole three-component seismograms that would also allow analysis of S-waves, mode converted waves, and Love waves.
- In the petroleum industry, time-varying reflection surveys are now being used to monitor reservoir conditions during hydrocarbon production, including following velocity variations within the reservoir induced by enhanced production procedures such as steam injection. Time-varying near-surface surveys could possibly be used to good advantage in a number of research applications. Birkelo et al. (1987) have shown that the top of the saturated zone can be monitored during a pumping test. Bachrach and Nur (1998) monitored tide-induced variations in near-surface velocity on an ocean beach in California. Jefferson and Steeples (1995) noted amplitude changes of 12 dB or more in reflection signals as soil moisture varies from about 18 to 36 percent by volume. Time-varying applications of near-surface seismic surveys in the future might include pre- and posttunnel construction to examine the effects of a tunnel's presence.

Some possible improvements involve seismic equipment and associated technologies including the following.

- There will always be a need for improved seismic sources. With the use of explosives becoming more difficult for various social reasons, the need for improved vibratory and impact sources will increase.
- One way to reduce the cost of data acquisition is to improve the speed of acquisition. Fifteen years ago the cycle time between shotpoints was about 20 seconds; today it is down to about 5 seconds. However, as the cycle time between shotpoints decreases, an attendant increase in the rate of geophone emplacement must occur. Consequently, there is a need to develop a way to rapidly or automatically plant geophones. One way to rapidly deploy geophones might be a draggable or automatically movable set of geophones, similar in concept to a hydroplane streamer used in marine applications but adapted for land applications. Such a low-frequency set of sensors has been used for several years by C. B. Reynolds Associates (Foster et al., 1992), but the primary challenge with their

use is effective coupling to the ground to obtain the broader bandwidth and higher frequencies necessary for high-resolution near-surface applications.

- For many years, the seismic receivers of choice in reflection seismology have been velocity geophones. However, manufacturers' specifications sometimes do not reach to the high frequencies used in shallow reflection surveys. Consequently, an unbiased and independent research evaluation of receiver attributes of high-frequency geophones, following the work of Duff and Lepper (1980), could be useful. Tests should include amplitude, phase, spurious response analysis over a broad bandwidth, at least from 10 to 2 kHz. For shallow high-resolution purposes, accelerometers have become a possible alternative. Other motion-sensitive technologies may be applicable in the future.

REMOTE SENSING

Remote sensing offers unique observations of the earth's surface and shallow subsurface that complement conventional mapping and exploration methods. When employed in timely conjunction with field observations, remote sensing can be used to extrapolate local observations over extensive regional areas. A report summarizing remote sensing from satellite and aircraft (Watson and Knepper,1994) provides a comprehensive evaluation of the state of the art for geological mapping, mineral and energy resources, and environmental studies. It recognizes the evolution from aerial photography to multispectral systems that record solar reflected, thermal emitted, and radar illuminated radiation, and the emergence of imaging spectrometers, which acquire data with spectral resolution comparable to laboratory instruments. There are also several texts on remote sensing. A good source for explaining the physical basis is Elachi (1987); a report that summarizes many of the opportunities for remote sensing was issued by the National Research Council (NRC, 1995). An annual conference with published proceedings is sponsored by the Environmental Research Institute of Michigan and is a good source for current application focus. Technical instrument workshops on instruments are sponsored by the Jet Propulsion Laboratory, and substantial information and illustrative material are available on the Internet.

Aerial Photography

An ideal environmental remote-sensing system requires high spatial resolution, high sensitivity to changes in baseline characteristics, proven and accessible technologies, and low cost. Airborne photography, which is familiar and relatively inexpensive, is still ubiquitous in environmental studies despite obvious limitations—awkward archiving, lack of spectral resolution and sensitivity, and difficult integration with correlative geospatial data and digital technologies. Historical photos may provide evidence of waste sites and facilities that are now abandoned. Recent photography facilitates the analysis of current waste disposal practices and locations, drainage patterns, geological conditions, signs of vegetation stress, and other factors relevant to contamination site assessment. Additionally, aerial photograph fracture trace analysis is used at sites where bedrock contamination is a concern. Overlapping photo pairs can be used to model topography. Photography is gradually being replaced by digital image data, a trend that will be hastened as commercial satellites with spatial resolution in the 1- to 5-m range are launched in the next few years.

Multispectral Scanners

Multispectral scanners digitally record several images simultaneously at different wavelength bands. The bands are selected to exploit the greatest sensitivity to features of interest and allow significantly more definitive characterization of surface composition and state than does photography. The data are processed using computer image analysis algorithms based on physical or statistical models and knowledge of laboratory-measured physical properties. The most familiar system is the 30-m-resolution TM (Thematic Mapper) satellite instrument that has six reflectance channels (and a 120-m-resolution thermal channel). A number of aircraft systems are available to acquire additional spectral channels with comparable spectral resolution and somewhat higher ground resolution. Imaging radar, acquired as part of a national program is archived (along with photography from a similar program) at the U.S. Geological Survey's EROS Data Center. These data and their derivative images provide uniform spatial coverage, availability at different resolutions, and the digital format that are important for geographic information systems (GIS) analysis. Reflectance data have been successfully used to distinguish among geological units, to find hydrothermally altered rocks, to infer tectonic setting and local fold and fault structures, to map linear features that may indicate fracture controls, and to indirectly infer lithologic and structural information in heavily vegetated areas based on empirical correlations between vegetation type, density, distribution, and local geological conditions. Thermal infrared data can be used to map silicification and igneous lithologies, fractures, heat (due to near-surface exothermic reactions or underground coal fires), and changes in near-surface thermal properties and to examine surface water changes and groundwater discharge and seepage. Airborne and satellite radar provides all-weather weather capability to define terrain units, to map topographically expressed features that reflect local and regional geological structures, and in hyperarid terrain, to penetrate the upper meter or two.

Imaging Spectroscopy

Imaging spectrometry can be used to map minerals at the surface for a wide variety of environmental studies. An excellent example (see Plate 7) is the mapping by aircraft of acid-generating minerals at the Superfund site in Leadville, Colorado (Swayze et al., 1996). Mine waste material is dispersed over a 30-km^2 area in which oxidation of sulfides releases heavy metals that are carried into the Arkansas River, a major source of water for urban centers and agricultural communities along the Rocky Mountain Front Range. The spectroscopy identified areas with higher acid-generating capacity based on the identification and mapping of distinctive zones of iron-bearing minerals.

Research Instruments

There are also a number of remote sensing instruments that have considerable promise for surface characterization but are not yet well established.

Passive Microwave Radiometry

Natural surfaces radiate mainly in the thermal infrared region; however, radiation at lower intensities extends throughout the electromagnetic spectrum into the submillimeter and microwave region. The radiant power emitted is a function of the surface temperature and its emissivity, which in turn are functions of surface composition and roughness. The large emissivity difference between ice and open water makes mapping polar ice cover and its change one of the most useful applications of microwave radiometry. The high dielectric constant (low emissivity) of water relative to most natural surfaces leads to applications involving mapping of soil moisture variation. However, because large variations can also result from differences in surface roughness or composition, repeat measurements are required to resolve ambiguities in interpretation. Microwave data can also be used to infer snow extent, onset of snowmelt, and water equivalent of snow. Limitations are the availability of data and the low spatial resolution. (For passive electromagnetic radiation, resolution is proportional to the ratio of receiver diameter to wavelength; thus, to preserve spatial resolution, very large receivers are required at longer wavelengths.)

Radar Interferometry

Radar interferometry from satellites can be used to detect minute changes in land surface geometry by comparing the phase difference between observations at two different times. Because the method is sensitive to differences as small as a few centimeters, it is sensitive to active faulting, subsidence caused by fluid withdrawal, pre-eruption volcanic swell, erosion, or tectonic creep. Atmospheric differences between the two observation times can cause substantial errors, and it is necessary that the surface has not been too greatly disrupted. This technique appears to have substantial potential for worldwide study of geological hazards once a good database and case history experience have been established.

Lasers

A number of experimental laser systems have been used from aircraft to illuminate the ground in order to measure surface conditions including surface texture, composition, elevation (decimeter accuracy), and water quality and depth (using fluorescence).

GEOCHEMICAL METHODS

Assessment of the subsurface geochemistry involves describing the chemical composition of solids, liquids, or gases. That is, the geochemistry of the subsurface may be defined as the chemical composition of bedrock and soil, groundwater and its dissolved or suspended load, and the atmosphere in the unsaturated zone. It is unlikely that all aspects of subsurface geochemistry can be determined remotely. In fact, relatively few chemical parameters can be readily detected without direct sampling and analysis. However, remote methods of chemical sensing for some constituents of interest in contaminated aquifer systems show promise.

Volatile Gas Emission

Wide use of organic solvents in the industrial and commercial sectors and of refined petroleum as fuels in numerous applications has led to nearly ubiquitous contamination of the environment with volatile organic compounds (VOCs) of a variety of compositions.

Volatilization at the surface of the water table and diffusion through the air-filled pore spaces in the vadose zone cause VOCs to be present at the surface overlying a contaminated site (see, for example, Figure 2.1). Soil-gas analysis became a popular screening tool for detecting VOCs during the 1980s. Soil-gas surveys can generate extensive chemical distribution data quickly at a fraction of the cost of conventional invasive methods and offer the benefits of real-time data. There are two types of soil-gas sampling. Grab sampling typically involves the insertion of a hand-held probe to depths of only tens of centimeters, with the volatiles pumped directly into a portable gas chromatograph. Passive sampling provides a measure of VOCs over time. It uses a sorbent material, such as activated carbon, that is placed below ground and later retrieved for analysis.

VOCs and gases can also be important as indicators of biological degradation reactions proceeding at depth. Isotopic information on these gases, obtained through mass spectroscopic methods in the laboratory, may yield even more information about the nature and extent of biodegradation reactions occurring within an aquifer.

Water Composition

Ground water moves into, through, and out of a given portion of the shallow subsurface. In doing so, reactions occur among the components of the aquifer system (water, minerals, atmosphere, and associated biota) that can lead to a change in the composition of the groundwater. Sampling the groundwater in wells or springs downgradient of the site may allow inferences to be made about a portion of the subsurface that we cannot sample directly. That is, the composition of the dissolved or suspended load in the groundwater may be used as an indicator of the composition of the solids, liquids, and gases in the study area, as well as of the reactions they are undergoing. (Many of the principles are similar to the geochemical water sampling developed in ore deposit exploration.) Tracers may be passive or natural products of the environment, or they may be introduced purposefully for the purposes of sampling. Natural or artificial tracers may be introduced and sampled without disturbing the physical integrity of the study site. Analysis of the outcome is by traditional chemical methods in the field or the laboratory.

Most solutes in natural and contaminated groundwater are ionic; that is, they are present as charged cations and anions in solution. Dissolved ions can carry an applied electrical current; if they are present in high enough concentrations in groundwater, noninvasive electrical geophysical methods can detect their presence and location. An example of a useful and successful application is in the mapping of saltwater intrusion fronts in coastal water supply aquifers. Fresh groundwater has highly contrasting electrical properties to the intruding seawater, and because of density differences and poor mixing in a porous medium, the contact between the two types of water can be fairly sharp and, in these cases, relatively easily detected and mapped.

Another widespread problem is the presence of plumes of landfill leachate within an otherwise clean groundwater system. Electrical methods can map such plumes as well as their migration because the leachates are typically high in dissolved salts and metals and contain a variety of organic compounds. Similarly, acid mine drainage can also be mapped because of high concentrations of dissolved solids and metals. Significant challenges remain in detecting nonionic contaminants, including many dissolved organic compounds such as pesticides.

Composition of the Solid Phase

Remote assessment of the chemical composition of the subsurface's solid portions (soil and bedrock) is problematic. Relatively few material properties that can be remotely measured yield information about the chemical composition of solid materials, although the presence of some minerals can be modeled. One approach to the composition would be to use a combination of the knowledge of site geology with geophysical determinations of density or porosity contrasts to support an interpretation of rock type, but this does not go much beyond what a geologist can do without noninvasive technologies. A metallic object can be detected from the surface through the contrast of its electrical or magnetic properties with the enclosing silicate, carbonate, or oxide rock, but little specific knowledge can be gained about chemical composition. Use of self potentials and induced polarization methods potentially could be applied to such chemical determinations.

Radioactive Methods

Detection of natural radioactivity (or that resulting from disposal of radioactive materials) can be of use in characterizing the shallow subsurface. Applications include, for example, regional mapping, prospecting for some minerals, and detection of leaking storage facilities containing radionuclides. The same properties that make radionuclides dangerous also make them easy to track in the environment. "The Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) provides a nationally consistent consensus approach to conducting radiation surveys and investigations at potentially contaminated sites" (Environmental Protection Agency, 1997). The manual describes well-tested methods and details the specific methodology and analysis that should be used. Several other aspects of radioactivity that can be valuable in site characterization involve invasive (e.g., borehole logging [Ellis, 1987]) or direct sampling (e.g., tritium or bomb-pulsed chlorine tracers in subsurface water).

GEOBIOLOGICAL METHODS

Properties of the biota of most interest to site characterization biologists may be the most difficult to determine noninvasively. The identity, abundance, diversity, and ecology of the resident organisms, as well as their overall physiological status, are the most important general properties to assess.

Biological processes in the near surface ultimately depend on the genetic makeup of the near-surface biota, which in turn depends on physical and chemical environmental factors that select the biota at a given site. Generic properties of the biota (identity, abundance, diversity, and ecology and their overall physiological status and activity) will be important in most site characterizations. However, given the spatial variability and heterogeneity of geological settings, large variations in metabolic activities may occur across a given site. For example, a process such as aerobic respiration of a pollutant chemical (or biomineralization) depends upon the availability of oxygen, which itself can be controlled by water content, inorganic oxidation-reduction reactions, and content of exchangeable organic compounds. The pollutant chemical itself may be more or less available for respiration depending on its solubility in water, its octanol-water partition coefficient, its organic matter content, or competition with soil particle surface adsorbers. Finally, the total abundance of aerobic heterotrophic organisms controlled by oxidizable organics will greatly influence the oxygen available for respiration of the pollutant.

Presently there are no noninvasive methods for direct measurement of biological presence or metabolic activity in the near surface. However, in some geological settings, subsurface biological activity can be inferred indirectly from near-surface biogeochemical activity, which might be measurable using noninvasive methods. For example, near-surface biogeochemical activity in the vicinity of oil reservoirs has been mapped by electrical resistivity methods (Sternberg, 1991), and airborne imaging spectroscopy has been used to detect and map biogenic minerals in acid and neutral drainage areas of acidified watersheds (see Plate 7). Minimally invasive methods such as soil-gas analysis by gas chromatography, chemical assays of bioaccumulating plants, and bacterial indicator culturing of surface soil have been used to a limited extent for petroleum and mineral exploration as well as environmental pollution studies. Noninvasive technologies show some promise in biological assessments, but until more research is done to develop other methods, the characterization of site biology will still depend to a large degree on analysis of samples obtained by invasive methods. Development of coordinated noninvasive and minimally invasive methods for geobiological site characterization remains a challenge (e.g., Ghiorse, 1997).

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5

Interpretation

In characterizing a site, existing data often guide the specific methodology of additional data collection and should be integrated with the newly collected information. This integration is part of the modeling process. Modeling also includes the interpretation of data from specific instruments prior to integration efforts. Model output can be visualized to check for consistency as well as for presentation to the client.

REVIEW OF EXISTING DATA

Efforts to examine and interpret the near-surface portion of the earth usually involve multiple types of data. In addition to basic geographic map data, there are usually some geologic and hydrological data initially available, at least on a regional scale. Perhaps there might be some geophysical data that were collected for a particular project at a nearby location. One or more boreholes also may be available, often including natural gamma radiation and electrical resistivity logs.

These various types of auxiliary data may be of unknown and variable quality, and collected with instruments often of unknown calibration. Even nearby "ground-truth" borehole data may not be very useful or reliable. Not all descriptions of sample cuttings from a drilling operation are equally useful—for example, some observations may have treated changes in color as the most important attribute rather than grain-size observations, which are technically more valuable.

Hence, before interpretation is begun a *critical review* must be done of all existing data. This review serves to identify gaps and errors in the existing data, which can be addressed in subsequent field efforts. Data gaps may occur when data are not sampled often enough in space or time to prevent aliasing, as mentioned briefly in the seismology section of Chapter 4. A common example of aliasing occurs in western movies when the wheels on a forward-moving buggy appear to spin backward because the visual field is not sampled often enough to represent the true picture. Consequently, data review should include consideration of the adequacy of the sampling, with respect to the project objectives, for each type of data.

The process of assessing data to identify errors and omissions requires close attention to detail and is a laborious effort. A solution is to use well-trained and experienced people who are able to focus upon basics and are sensitive to the fact that errors and omissions can and do occur. Complex statistical methods or sophisticated computer imaging cannot substitute for invalid or missing data.

One of the most common methods of data display in two dimensions is through the use of contouring. Although human interpretive contouring is often difficult to beat in the geologic sense, machine contouring algorithms are now routinely used to prepare displays of geological and geophysical data, especially structural contour maps and potential field data maps. More recently, three-dimensional displays of seismic data have been used to beneficial effect (e.g., Dorn, 1998).

Multiple sources of data must be used to confirm site-specific conditions. When measurements by different methods agree, our interpretations will have a higher level of confidence. By virtue of redundancy, this process also provides a secondary form of quality assurance for individual sets of data, offering a reliable, defensible means of testing the hypothesis embedded in the conceptual site model.

DATA INTEGRATION

When a single geophysical method is used to survey a complicated site, it usually is possible to create multiple models of the subsurface that fit the resulting data. Another method, measuring different phenomena, will produce a different set of plausible models. In most cases, the intersection of the two sets of possible models is a smaller set that reduces the number of possible interpretations. More surveys that measure even more phenomena will further constrain the interpretation. In an ideal case, enough data will be collected to produce a unique geologic or hydrologic model. In many cases, ground-truth data from boreholes and outcrops can be used to calibrate the geophysical parameters and result in model interpretation with a higher degree of confidence.

Most site characterization projects use several types of geophysical measurements and sources of data. Data from each of these measurements often are interpreted in isolation; when this occurs, such data are neither integrated (a process sometimes called data fusion) nor interpreted simultaneously with data from other techniques. In those cases where an attempt is made to combine data

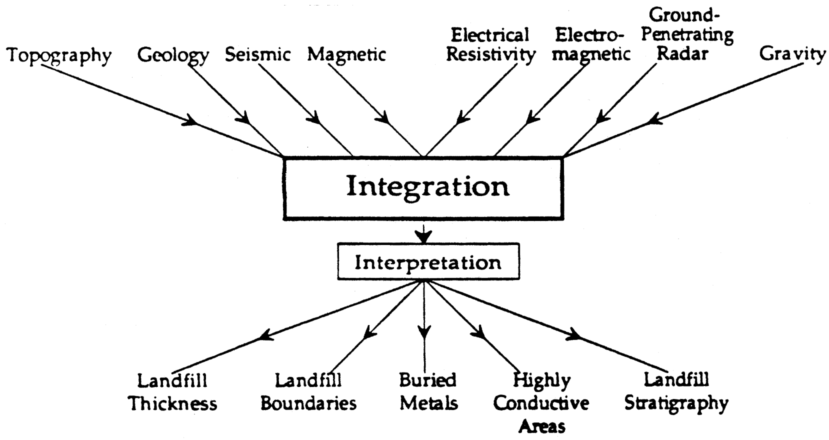


FIGURE 5.1 Schematic diagram of the concept of integrating geologic information and data from diverse geophysical methods for determining properties of a landfill. (After Roberts et al., 1989.)

sets, the data may be integrated and interpreted in only a qualitative fashion. Intrinsic relationships among different types of data often are uninvestigated, setting the stage for conflicting and irreconcilable interpretations.

Successful site characterization often combines several different objectives and requires multiple measurements. Combining data from numerous methods might help resolve ambiguities and prevent faulty interpretation of individual measurements. In data interpretation it is important to take advantage of complementary and redundant information in all available data from a site (see Figure 5.1). However, because data can be combined and manipulated in so many ways, the end user or client (e.g., the site manager) is often confused, with no guide to determine the meaning of the composite results.

Data integration should consider all of the data, not just geophysical data, acquired during a site characterization. Multiple sources of data provide the ability to check the quality of individual data sets against each other. Data integration also provides an estimate of the statistics involved in characterizing a site and the uncertainty in the overall solution. Each observation contains an associated error, and each data set is the result of a statistical distribution in space and/or time.

If disparate data sets are mapped into some common equivalent space, they should overlap. If not, a closer examination of the possible measurement or processing errors may be needed. For example, using Poisson's relation, it is possible to transform a magnetic map into a "pseudogravity" map by assuming some value of magnetic susceptibility for rock materials below the earth's surface. If the resulting pseudogravity map does not resemble an actual gravity map, one can assume that the magnetic susceptibility used in the calculation was not correct.

Seismic, magnetic, electrical, gravity, and GPR signals arise from different subsurface physical parameters. The data can be inverted to obtain three-dimensional estimates of the constitutive properties of the ground. However, because the data sets arise from different physical properties, the various data sets cannot be readily combined *before* inversion. Data integration, then, is most often performed after cross-sectional, areal, or three-dimensional maps of the intrinsic physical properties uncovered by each of the imaging methods have been prepared. The process is iterative; each data set is reinterpreted, taking into account interpretation from other data sets until a consistent interpretation is obtained.

For example, information obtained from GPR can be compared with that obtained from shallow seismic reflection, both of which are based on wave propagation. When different methods provide complementary information at a particular site, combining the data is likely to provide more information than using any one method alone. The use of shallow, high-resolution seismic reflection techniques in concert with GPR has the potential to assist in characterizing sites in environmentally sensitive areas.

Seismic and GPR techniques measure different physical parameters, but as shown in Figure 5.2, the two techniques can yield consistent results. At other sites, the two techniques might respond to changes in different regions of the subsurface and not yield a consistent interpretation. Seismic reflections arise from changes in acoustic impedance, that is, the product of seismic wave velocity and density must change for a seismic reflection to occur. If seismic velocity increases by the same amount that density decreases at a given interface, no seismic reflection is produced from the interface. An example occurs in salt deposits, which commonly do not yield good seismic reflectors at internal interfaces.

Ground penetrating radar, on the other hand, responds to changes in the constitutive electrical parameters (permittivity and conductivity) of the subsurface. If either of these electromagnetic parameters changes at the interface used in the example given above, a radar reflection may occur where no seismic reflection would occur. Imagine an opposite example where the constitutive parameters are constant across an interface at which either bulk density or seismic wave velocity varies. In sum, seismic data and GPR data tell us about different physical parameters of the earth material being surveyed and often can be used to compare each other's results.

Important geologic and hydrologic interfaces often represent changes in properties that include density, seismic velocity, electrical conductivity, and dielectric permittivity. Knowledge of these four parameters enhances the possibility of predicting fluid flow paths, particularly in fractured media. For example, seismic velocity usually decreases in fracture zones, and radar wave velocity may increase in these same fracture zones, particularly when a large increase in air-filled pore space is involved. Conversely, where a fracture and the pore spaces are filled with precipitated minerals, seismic waves may propagate more quickly and radar waves more slowly. Clay tends to attenuate radar energy, whereas seismic energy often is not attenuated rapidly by propagation in clays. At other sites, seismic waves might be attenuated rapidly in dry, quartzitic sand, whereas radar waves propagate well in the same medium.

Depending on local geologic and hydrologic conditions certain types of stratigraphic variation may be detectable directly (by the presence of a reflection), indirectly (by the disruption of some other reflector), or not at all. The presence or absence of a reflection can also depend on the seismic or radar parameters used (see Figure 5.3). The absence of evidence of an seismic or GPR reflection is not necessarily evidence of the absence of a stratigraphic variation.

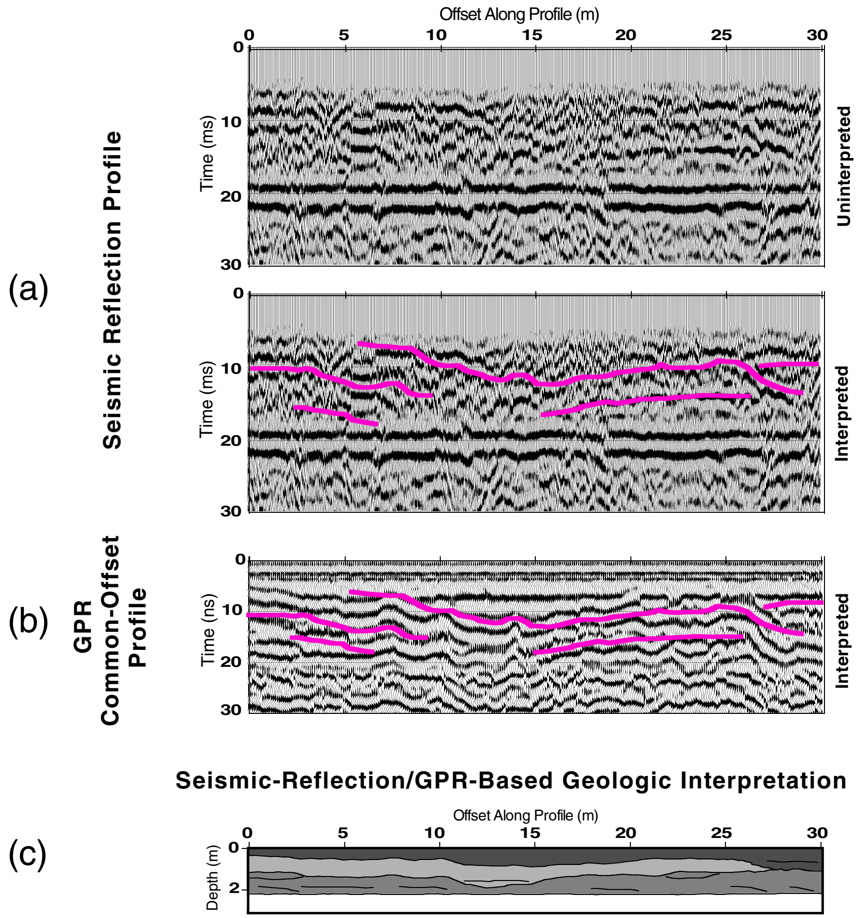
Analysis of both elastic and radar-frequency electromagnetic survey data with densely spaced measurements is essential to the construction of a high-quality subsurface image. Although a variety of field procedures has been used to produce such coverage in individual seismic and GPR surveys, little is known about how the two techniques might practicably be combined in very high resolution site characterization surveys.

In the same set of data it is possible to show large differences in the resolution and accuracy of features depending on a priori assumptions about what is in the subsurface. Therefore, inappropriate visualization of data and integration of multiple sources of data could be misleading. Developing the process of data integration requires considerable future research. How do we integrate disparate data sets from geophysics, geochemistry, hydrology, and biology, and map the multidimensional data into an integrated solution? What kind of statistics should be used, and what levels of confidence are required? Further investigation of such questions is needed to optimize data integration and interpretation.

MODELING

Models based on an understanding of physical, chemical, and biological properties and processes (in contrast to those based on empirical correlation) are of great value in the effective use of noninvasive methods in site investigations. Numerical models can provide linkages between the phenomena being measured and the properties and processes occurring in the earth. They provide tools for optimizing survey design, quantifying uncertainties and limitations associated with data acquisition, and validating interpretations. There are many existing numerical models that are potentially useful, but they should be catalogued, documented, and made user friendly and easy to locate to fulfill their potential.

Our understanding of, and ability to exploit, a particular characterization phenomenon can be improved by an iterative process involving the following approaches: (1) empirical (observation of an apparent relationship between the phenomenon and a property or process of interest), (2) analytical (experimental



and theoretical research to explain the relationship), and (3) numerical (computer models of cause and effect, which can be useful in a predictive sense). If models are well designed and easy to use, they (1) make analytical expertise available to practitioners, (2) enable conceptual understanding of the relationships between the phenomenon and the properties or processes, and (3) help practitioners and clients understand the capabilities and limitations of the measurements.

In addition, rigorous numerical models can be used to improve the quality and reliability of nonintrusive site characterization surveys. During survey design, numerical models can be used to help choose the characterization method, quantify the anticipated signal and noise, and optimize the proposed survey parameters. Processing and interpretation make extensive use of computer models,

FIGURE 5.2 An example of qualitatively merged geophysical imaging of the shallow subsurface. (a) An uninterpreted and interpreted seismic reflection profile along a 30-m transect in the Arkansas River alluvial valley ~1 km southeast of Great Bend, Kansas. Geophone spacing was 10 cm and the seismic source was a 22-caliber rifle with subsonic short ammunition fired 10 cm downhole. (b) A common-offset GPR profile using a 225 MHz antenna coincident with the seismic profile. The seismic interpretation is overlain on the GPR section. (c) Geological interpretation of the 30 m transect created by merging the individual interpretations of the seismic and GPR data and adjusting coincident reflectors. The three main layers, from top to bottom, represent the Platte series soil profile, an unstratified medium sand (bound on the top by an erosional unconformity), and a cross-stratified medium sand to medium gravel with various bounding surfaces (identified as individual lines on the interpretation). The interpretation was field constrained by a nearby ~2-m-deep hand-dug hole. At –2.1 m is the top of the saturated zone, constrained by a nearby monitoring well. The water table is easily identified on the seismic section but absent on the GPR section (possibly related to the diffuse nature of the boundary relative to the GPR wavelength). Although not quantitatively "fused" by some inversion technique, the coincident profiling using seismic and GPR methods improved the detail and confidence of the interpretation. Figure courtesy of Gregory S. Baker, 1999, University of Kansas).

especially for inversion techniques. For critical (e.g., hazardous) sites, the most important use of models is to validate interpretations and do quantitative sensitivity analyses.

Models, whether physical, chemical, geological, or hydrological, must be mathematically validated by use of easily verifiable cases. One way to do this is to compare results for cases that have known analytical solutions. Another way to analyze models is to use sensitivity analysis (e.g., McElwee and Yukler, 1978) in which the response of a model is examined in terms of the mathematical derivatives of the constitutive equations.

VISUALIZATION

An important advance of recent years is in the visualization of geophysical data. Previously, data were usually presented as measured field values, corrected for drift with other simple corrections. For example, with electrical and electromagnetic data, a common form of data processing is still to normalize to apparent resistivity or apparent conductivity, which simply matches the data to a homogeneous earth model. Plotting the data in "pseudosection" form using simple guidelines provides depth interpretation. The impact of this presentation is limited; an experienced interpreter usually is needed to convert these plots to a geologic model of the earth. Interpretation with such displays usually consists of locating

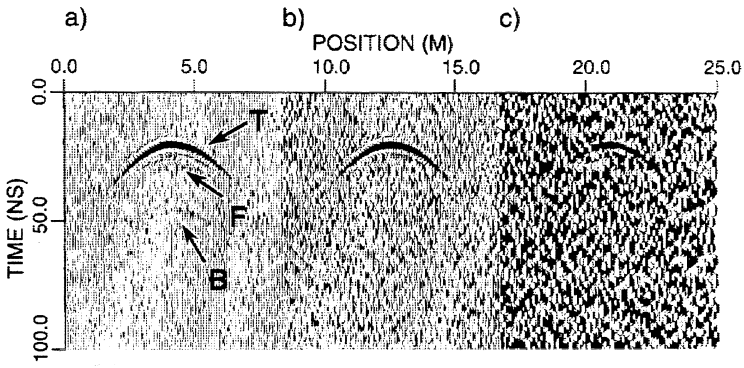


FIGURE 5.3 Visibility of GPR reflections decreases as the signal-to-noise (S/N) ratio increases; (a) is for S/N of 15.0, (b) for S/N of 7.5, and (c) for S/N of 1.5. T is the reflection from the top of a buried tank, B from the bottom of the tank, and F from a fluid (air/gasoline) interface inside the tank. Figure is from Zeng and McMechan (1997).

anomalies ("bump hunting") and ascribing geologic significance. These presentations can be misleading because pseudodepth may not be true depth and data artifacts might appear as geologic features.

Advances in modeling, inversion, and visualization now make it possible to present data in a geologically and visually meaningful way. Shaded relief maps, for instance, have revolutionized the presentation of potential field data (e.g., Plate 3). The shaded surface can reveal features that may be invisible when displayed using contouring or simple pseudocolor. Color presentations also convey a great deal of information to users and often enable easier recognition of significant features. However, with the introduction of displays that are pleasing to the eye comes the danger of misleading viewers—a change of color scale or rendering can often completely alter the significance an interpreter places on a feature. It is incumbent on the individuals presenting the data that their presentation conveys as accurately as possible the actual geology or geologic process. Error estimates should be displayed with each presentation, along with alternative displays.

In addition to visualization of the subsurface, the data can be integrated with many other types of data about the site's location (e.g., transportation networks, population, ecosystems, topography, resources, land-use, and other locationally referenced themes) using geographic information systems (GIS). When integrated within a GIS context, models or "what-if" scenarios can be tested for use in a broader decision-making process.

RECOMMENDATION

Scientists and engineers must improve their ability to integrate multidisciplinary data for modeling, visualizing, and understanding the subsurface.

The interpretation of characterization data has both creative and quantitative components. The creative component consists of conceiving all of the possible geologic models likely to explain the data; the quantitative component involves generating synthetic data for every possible model to demonstrate whether a particular model is consistent with the field data. Generating multiple synthetic data sets from a single geologic model, although not done routinely, is technically feasible. It requires only the development of modeling codes based on an accepted set of programming standards. Conceiving a geologic model that will fit multiple data sets is much more difficult. Advances in this area will include both technical (e.g., simultaneous inversion) and human (e.g., studies of team dynamics) elements.

Interpretations of any set of multiple measurements will be strengthened, and ambiguity reduced, if they are the result of early integration and simultaneous inversion of diverse data types. The following areas of research are needed to improve the efficacy and rigor of data fusion and integrated interpretation:

- Develop a better understanding of the coupling and interactions among the physical, chemical, and biological properties and processes that affect the measurements done in characterization surveys.
- Develop integrated models that allow simultaneous modeling of simulated data sets from several multiple surveys over a single geologic model.
- Based on the understanding of physical, biological, and chemical properties and processes, develop mathematical tools and computer programs that are able to perform simultaneous, quantitative inversion of multiparameter data sets.
- Create three-dimensional scientific visualization tools and techniques that will allow human interpreters to monitor the inversion process, assess the resulting geologic models, and improve the quality of the interpretation.

In the area of modeling, a variety of needs can be identified:

- Many numerical modeling programs currently exist in universities and government laboratories. However, some are obscure, are difficult to use, and require computing facilities not readily available to many practitioners. Major benefits can be achieved in a short time by adapting existing codes to "standard" computing platforms and by adding interfaces that make them easy for the average practitioner to find and use.

• Numerical models become, in effect, "expert advisers" to the practitioners who use them. In some cases they have great influence because of the human tendency to believe what comes out of a computer. Therefore, it is important that the expertise embedded in numerical models be up-to-date and correct. Appropriate regulatory agencies or professional societies should establish a program of certification of numerical models to be used in site characterization surveys.

• Some phenomena have not yet been modeled; others have been modeled with so many simplifying assumptions that the models often are not realistic. Universities and government laboratories should be encouraged and supported to identify deficiencies and develop rigorous computer models that provide realistic descriptions of subsurface properties and processes.

• Given the need for data fusion and integrated interpretation, universities and government laboratories also should be encouraged to develop and validate integrated modeling software explicitly designed for site characterization.

• To facilitate the broader use of computer modeling there should be a clearinghouse or repository to (1) facilitate discovery of available modeling software; (2) provide standard data sets against which codes and models can be tested; and (3) assist the private, academic, and government sectors in developing training curricula in the use of computer modeling.

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6

Nontechnical Issues

Subsurface characterization is an essential component of many environmental and engineering applications. If noninvasive methods are to become an important component of subsurface characterization, a number of issues, which have little to do with the state of technology or the availability of competent geoscientists and engineers, have to be addressed. Similar nontechnical issues are discussed in two recent reports (Federal Facilities Policy Group, 1995; National Research Council, 1997).

This chapter explores a variety of nontechnical barriers to the application of noninvasive technologies to characterize the subsurface environment. Insufficient economic incentives are a major impediment to the effective use of modern noninvasive technology. Legal and institutional constraints also can be impediments to the effective use of noninvasive methods. These constraints include statutory and regulatory requirements, health and safety concerns, and the nature of standards and certification procedures. These impediments have the potential to inhibit creativity and discourage the development of effective solutions to site-specific problems. In some cases, institutional pressures and other demands can take precedence over scientific and technical judgments concerning a site, and this can be compounded by lack of information, misunderstandings, or misconceptions on the part of one or more of the stakeholders involved (contractors, clients, regulators, and the public).

INCENTIVES

Researchers in the resource industries, federal laboratories, and universities have made significant advances in both instrumentation and methodologies. However, few of these innovations have found their way into routine practice in near-surface characterization. In a related area, a 1997 NRC report (*Innovations in Ground Water and Soil Cleanup: From Concept to Commercialization*) assessed various reasons for the difficulty in applying innovations to environmental cleanup. These reasons include lack of market stimulation, information, technology testing, and cost comparisons. Similar nontechnical impediments appear to apply in the area of noninvasive technologies. According to the 1997 NRC report (pp. 7-8), "Lack of information has contributed to the slow transfer of new ideas for remediation technologies from the laboratory to the field and from one site to another. Technology reports are often incomplete and lacking in critical scientific evaluation and peer review. Reliable cost data are also lacking, Moreover, much information on prior experiences with remediation technologies is proprietary."

A company faced with the responsibility of a hazardous waste cleanup might choose the needed site characterization and remediation methods on the basis of what will satisfy regulatory and legal requirements at minimum cost (NRC, 1997). When dealing with a problem such as hazardous waste, in situ sampling is often required in designing cleanup methods. In such a case, many involved with a project may have the perception *that noninvasive site characterization adds cost without commensurate benefit* and that the added cost will not be recovered during the life of the project. Alternatively, some contractors have invested in a particular characterization method and often rely almost exclusively on this capability. They may be reluctant to consider other characterization methods because of possible additional capital investment and/or the need to subcontract these methods. As such, the clients' perception of added costs of noninvasive characterization can be reinforced by many contractors' reliance on a specific, often invasive, technique.

A key to greater use of noninvasive characterization is to demonstrate net economic benefits. The oil industry, for example, is quick to make large investments in new technologies because even small improvements in exploration and production can significantly improve revenue and profit. Although the oil industry developed three-dimensional seismic methods over twenty years ago, these methods remained little more than a research curiosity for at least a decade. During that time three-dimensional seismic images became widely used to guide drilling, and three-dimensional seismic reflection surveys are now the standard procedure for major oil companies and many independent oil companies. For example, ARCO averaged fewer than three three-dimensional seismic surveys per year during 1980 to 1982, but it averaged nearly 40 such surveys per year in 1993 to 1995 (Dorn, 1998). The costs of research and development for the three-dimensional seismic methods and the costs of more extensive data collection efforts in the field were more than offset by the savings associated with fewer dry holes; there have been unsubstantiated claims of success ratios of over 80 percent.

The economic benefits of noninvasive methods in resource exploration and recovery are apparent. For an engineering or environmental application, the use of properly evaluated and designed noninvasive characterization can have two benefits: the overall cost of the program can be reduced (due to the difference in cost between noninvasive characterization and drilling), and the invasive sampling points can be chosen to give maximum information (see Figure 4.9).

Noninvasive methods have the potential to reduce characterization costs. In many cases, noninvasive characterization provides comparable information at a cost that may be less than that of intrusive techniques such as drilling. In some cases, intrusive methods (e.g., drilling or digging) can engender major financial and environmental risks that can be avoided with noninvasive technologies. For example, a major oil company in Texas was faced with financial penalties relating to a refinery unless a leakage mitigation plan was developed quickly for a chemical storage pond. Drilling on approximately 50-m centers revealed the presence of, but did not delineate, a buried bedrock valley. A seismic reflection survey at the site sampled the subsurface at 0.7-m intervals, delineating two buried valleys, which enabled the refinery operator to develop a contingency plan that satisfied the state regulatory agency (Miller et al., 1989). As another example, inadvertent disruption during construction of buried utility cables and gas pipelines is frequently in the news; noninvasive characterization might help avert such disruptions and their associated costs (National Transportation Safety Board, 1997).

Documentation of these benefits in the public domain is rare, and therefore, the cost-effectiveness of noninvasive characterization is difficult to establish. Most of the literature concerning noninvasive characterization emphasizes technical developments. However, useful information about such economic benefits exists in related areas and could be made available.

Government agencies, environmental and engineering contractors, and university researchers should work to analyze and document the potential costs and benefits of the use of noninvasive characterization methods in a wide variety of applications. There is a large amount of data (in the form of government-funded projects) that could be subjected to analyses, and an evaluation of alternative scenarios could demonstrate the potential benefits of noninvasive characterization. Documenting these benefits can demonstrate possible economic incentives for the use of noninvasive technologies in site characterization efforts.

OPERATIONAL CONCERNS

To be effective, subsurface characterization efforts should have the flexibility to design for site-specific conditions and to change or modify the characterization program as results become available. However, certain laws such as Superfund and the Resource Conservation and Recovery Act (RCRA) "provide a disincentive to change the selected remedy even if a much better solution evolves" (NRC, 1997; see Box 6.1). Other nontechnical impediments to the application of noninvasive characterization arise from concerns related to (1) regulations, (2) standards of performance, (3) health and safety, and (4) institutional barriers.

BOX 6.1
Innovation and Regulations

The regulatory structure for implementing hazardous waste cleanups, especially at Superfund and Resource Conservation and Recovery Act (RCRA) sites, has added to the inherent difficulties that remediation technology vendors face in bringing new products to the market. The fundamental problem of these programs is that they rely on regulatory push rather than market pull to create demand. The process of technology selections is strictly regulated.…Providers of new technology have trouble staying in business while awaiting client and regulatory acceptance of their processes…

The Superfund and RCRA corrective action programs leave little room for customer (or consultant) choice and no room for a "try as you go" concept. Regulators must "sign off" on the customers choice of a technology through an official Superfund record of decision or RCRA corrective action plan. Mechanisms for adjusting the remedy once it is officially approved are bureaucratically cumbersome and provide a disincentive to change the selected remedy even if a much better solution evolves. [pp. 46-47]

In the private-sector market, inadequate cost containment has decreased the incentives for selecting innovative technologies. Often federal remediation contractors are placed on "auto pilot" after being awarded the cleanup contract on a cost-reimbursable basis, so there is little incentive for cost-effectiveness (GAO, 1995). According to an audit by GAO [General Accounting Office] (1995), cost overruns are common to remediation efforts at federal sites, due in part to inadequate oversight of contractors. GAO found evidence of fraud, waste, and abuse by federal remediation contractors (GAO, 1995). With no incentive to reduce costs, there is no incentive to search for new solutions. [pp. 55]

SOURCE: *Innovations in Ground Water and Soil Cleanup: From Concept to Commercialization* (NRC, 1997).

One or more of these impediments have been experienced by committee members while conducting or examining site characterization programs; others in the characterization community have expressed related experiences (e.g., Freeze and Cherry, 1989). Similar concerns are discussed in reports of the Federal Facilities Policy Group (1995) and the NRC (1997).

Regulations

Regulatory requirements may inhibit flexibility (NRC, 1997). Both contractors and regulators have a vested interest in adopting and following detailed, rigid, generic regulatory requirements regardless of site-specific conditions. If they can show that they followed every regulation to the letter, contractors have some protection from lawsuits regardless of the quality of their results. Regulators can similarly protect themselves by trying to cover every possible eventuality with a regulation. These approaches can lead regulators to require—and contractors to provide—subsurface characterization programs that are *regulation driven rather than solution driven.*

Practitioners may satisfy regulatory criteria at the expense of sound professional practice. Decisions are legally correct if the regulations are followed, and practitioners cannot afford the risk of deviating from the regulations.

At present, requests for proposals and contracts for shallow subsurface characterization often prescribe methods and survey designs without consideration of site-specific conditions. Contractors or consultants with vested interests in certain technologies or geographic regions may be tempted to encourage regulators and clients to continue this practice to avoid competition.

To maximize the net benefits achieved from investments in federal facilities cleanup, the Federal Facilities Policy Group (1995) recommended (1) more rigorous risk-based priority setting and management oversight, both within and across sites; and (2) statutory and regulatory reforms to remove impediments to success. The report argues that regulators often specify *how* a site is to be characterized (i.e., what data should be collected by the specified technique) rather than specifying the overall *objectives* of the characterization effort. For example, if a regulator required that a ground penetrating radar (GPR) survey be done at a site, the presence of a subsurface clay layer could make GPR less useful than electrical methods at the same site (see Plate 6). To provide the flexibility necessary to deal with such situations, regulations should specify *how* such decisions are to be made at each site rather than attempting to specify *what* the decisions should be. The Environmental Protection Agency's (EPA) Office of Solid Waste and Emergency Response began in 1997 to implement a program called the Performance-Based Measurement System (PBMS) that aims to reduce the burden on the regulated community associated with the use of new site characterization and monitoring techniques. The objectives of PBMS are to improve data quality, reduce the cost of compliance by lowering regulatory barriers, and stimulate the development and use of innovative monitoring technologies (*www.epa.gov/ooaujeag/notebook/pbms.htm*). Under PBMS, EPA would no longer prescribe the use of specific technologies but would specify an acceptable data quality level, which serves as a criterion for technology users to select the appropriate site characterization or monitoring techniques.

Standardized Practices

Laws and regulations may encourage or require the implementation of standardized practices in site characterization, which offers some liability protection to practitioners. Standardized practices usually assume some consistency in problems and conditions. However, each site has unique conditions and problems that require site-specific considerations. The choice of characterization methods, design of the

TABLE 6.1 Examples of Standard Approaches for Site Characterization

Organization	Effort
American Society of Testing and Materials (ASTM, 1997)	Accelerated Site Characterization Committee D-18 on Soils and Rocks
U.S. Environmental Protection Agency (EPA)	Superfund Accelerated Cleanup Model
EPA Office of Underground Storage Tanks (EPA, 1997)	Tools for Expedited Site Characterization
Department of Energy (DOE), Ames Laboratory	Expedited Site Characterization
DOE, Argonne National Laboratory	Expedited Site Characterization (QuickSite)
California Environmental Protection Agency	Environmental Technology Certification Program

data acquisition program, and interpretation of results will be different for each site. This situation makes it difficult to develop generally accepted "best practices."

Conflicts between scientific and technical issues and legal and regulatory concerns often beset site characterization projects. A high priority of the client (or owner of the site) is to ensure that all applicable laws and regulations are satisfied fully so that decisions and actions can be defended in court, if necessary. To achieve this objective, a "cookbook" approach is often followed, which may limit the flexibility needed to assess certain site-specific considerations. If clients can demonstrate that the prescribed procedures were implemented faithfully, they may be protected from legal action even if the results are less than optimal.

The engineering community is generally comfortable working with a structure of relevant certification and standardized approaches. Several groups (see, Table 6.1) have developed or are developing standard approaches or guidance to site characterization. These standard approaches are designed to promote proper techniques for site characterization and reduce the possibility of questionable site characterization practices.

Incidences of questionable practices (Shuirman and Slosson, 1992), which could be called charlatanism, misuse, and fraud, led the Society of Exploration Geophysicists (SEG) to amend its charter to exclude corporate membership from companies whose practices were not based on accepted scientific principles. The SEG amended its constitution to say, "The services or products provided must be demonstrably based upon accepted principles of the physical sciences" (SEG Constitution, Article III, Section 9). Upon adoption of this language, several companies were asked to disassociate themselves from the SEG. Such actions help raise the level of credibility of characterization efforts.

Subsurface characterization programs should be customized for every site to achieve specific objectives within financial and time constraints. Some tools exist to assist nonexperts in the design and justification of such customized efforts. For example, the Geophysics Advisor Expert System (Olhoeft, 1992) can help select the appropriate geophysical tools to apply to EPA Superfund site problems. However, the details of such efforts should be planned and executed by multidisciplinary teams that may include geophysicists, geologists, chemists, geochemists, geotechnical engineers, biologists, and others as required to achieve the site-specific objectives. Relevant disciplines should be represented from the outset of a major project, and members of the team should understand and adhere to a common set of decision-making processes and standards.

> ***Government agencies (federal, state, and local) need to develop approaches to site characterization that focus on flexible, program design procedures and decision-making processes that account for the unique character of each site.***

Design and decision-making processes and procedures should achieve a balance between accountability and flexibility. Highly constrained procedures ensure accountability, but they can inhibit the implementation of programs customized to the unique characteristics of the site. Removing constraints ensures flexibility at the expense of accountability. Standardizing and documenting the structure and rationale behind the decision-making processes can provide legally defensible characterization programs that are well suited to the unique problems of a given site. Successful implementation will require that decision-making processes be peer-reviewed and certified and that universities offer academic programs that teach the processes as well as the technical foundation.

Health and Safety

Site characterization activities involve collection of data in the field and have some associated hazards related to worker safety and health; these can be quite varied. (Hazards related to the possible spread of contaminants from invasive sampling are addressed earlier in this report.) For noninvasive field methods, the hazards can be as simple as tripping and falling or as complex as those associated with using explosives. For explosive hazards the perceived risk can sometimes stop or alter the nature of seismic measurements.

Seismic experimentation often uses explosive charges because of the wide bandwidth of the energy spectrum of vibrations these sources produce. In large-scale petroleum exploration, the explosives are extremely safe to handle but still produce large energy releases that can be dangerous. Near-surface seismics often use smaller explosive sources, similar to those contained in large-gauge shotgun shells that are detonated using a modified shotgun (Miller et al., 1986). The shotgun-shell explosive source is relatively safe to handle, ship, and use. Yet many individual sites often limit the use of such relatively benign explosive seismic sources.

Site-specific rules that may inhibit the use of such common explosive charges generally fall into two categories—weapons or fire. For weapons, a site might have rules that prohibit firearms. Exception to this policy may be difficult to obtain even when the actual practice involves augering a hole and shooting a specialty rifle into the hole for the sole purpose of exciting elastic vibrations. With pressures on site managers to adhere to stringent safety rules, such permission is often hard to get.

Regarding the issue of fire, the concern of those in authority is more understandable. Even though the shotgun-shell source is a contained explosion in an augered hole that is a few feet deep, there is a small possibility that the explosion could start a fire. Therefore, if flammable materials are present on-site, it is difficult to receive permission to use small explosive devices.

As a result of such site-specific rules, seismic sources such as weight drops are often used instead of explosives. These alternative seismic sources are often adequate for the task, but in other cases, they are less than optimal and may not be able to produce the characterization objectives.

Institutional Barriers

A broad category of institutional barriers, discussed in a report by the Federal Facilities Policy Group (1995), includes statutory decisions, competitiveness and infighting among agencies and contractors, the "not-invented-here" syndrome, and "turf" protection.

A relatively recent example of a congressionally mandated program involved buried UXO and mine detection advanced technology demonstration (ATD; U.S. Army Environmental Center, 1994). The statutory provisions of the ATD program specified where the demonstration was to be conducted, which agency was to manage the demonstration, and technical details constraining the demonstration. The ATD was funded at approximately $30 million over a three-year period (1994-1996). Congress reacted to the complex technological requirements by attempting to specify the "solution," requiring off-the-shelf-technology demonstrations in the form of a contractor competition. The ATD program was prompted by the recognition of UXO and mine detection as an extremely high-priority issue and a desire to find the nonexistent "silver bullet" (see Box 6.2).

Several important elements were not included in the program. There was no comprehensive site characterization in advance of the ATD. No phenomenological predictions or assessments of results were conducted. Results reported by

BOX 6.2
UXO Detection and Lack of Universal Solutions

Because of the enormity and diversity of the UXO problem, there is not a single technological "silver bullet" that will provide a universal solution. Detection solutions include aggressive investigations of a variety of sensor technologies, singly and in combination and a thorough understanding of the signatures of UXO and the cluttered environments in which they are located.

SOURCE: Joint Unexploded Ordnance Clearance Steering Group, 1997.

various contractors were not complete enough to allow a detailed phenomenological assessment (Altshuler et al., 1995; Butler et al., 1998). Details of the UXO and mine types and locations were not released to contractors or other government agencies, which would have allowed independent assessments and contractor self-evaluations.

Competition among agencies, turf protection, and the not-invented-here syndrome can lead to major inefficiencies and barriers to effective subsurface characterization programs. A 1996 NRC report (*Barriers to Science: Technical Management of the Department of Energy Environmental Remediation Program*) identified many of these barriers as factors that have hindered environmental restoration efforts of the Department of Energy's Office of Environmental Management. In addition, the Federal Facilities Policy Group (1995) reported similar barriers in an assessment of complex environmental restoration programs. This assessment found that not only is there competition among agencies, but there is also potential for overlapping regulatory authorities between state and federal governments that can lead to inefficient site characterization efforts (e.g., see Box 6.3). Because of the pressures often involved in subsurface characterization and environmental remediation, agencies might attempt to redefine their mission areas and develop programs to address these problems.

INFORMATION AND COMMUNICATION

As with most areas of emerging technologies, transfer of research advances into applications poses a challenge (i.e., closing the gap between the state of knowledge and the state of the practice). With noninvasive characterization methods, such transfer presents a two-pronged challenge. One is to ensure that advances in techniques and methods are communicated to the practitioners of characterization efforts; the other challenge involves the clients or owners of the site that is being characterized and those that set and enforce regulations.

Practitioners are typically contractors (e.g., consulting firms or individuals)

BOX 6.3
Conflicting Approaches

...uncertainties are compounded by the potential overlay of one regulatory authority upon another. States have invoked their authority under RCRA or state law at Superfund sites, and in some cases have imposed additional requirements beyond those required under CERCLA [Comprehensive Environmental Response, Compensation and Liability Act]. Conversely, a site that is being remediated under a state RCRA or other program may be subject to listing on the NPL [National Priorities List] under CERCLA, introducing a different regulator and different cleanup criteria.

SOURCE: Federal Facilities Policy Group (1995; Section 4.C.2)

that provide characterization services to clients that have a site-specific need. In most situations the consulting (service) firms that do near-surface characterization are small (an order of magnitude or more smaller than similar service firms in the oil industry) and are often specialized in their applications and techniques. Practitioners should have an in-depth knowledge of the various methods involved—theory, data acquisition, and processing and interpretation—and an understanding of how to design and carry out multidisciplinary characterization surveys. However some contractors that would like to use noninvasive tools may find it difficult to stay abreast of developments in one specialty, let alone multiple fields or integrated design and interpretation. The gap between the state of knowledge and the state of practice in noninvasive methods may be due, in large part, to a lack of awareness on the part of the practitioners.

Scientists and engineers need to place greater emphasis on communicating information about noninvasive tools and techniques and their recent advances to practitioners.

Limitations of time, money, and personnel make it difficult for contractors to stay current about the latest tools and techniques being developed in universities and government laboratories. This problem can be addressed by efforts that make such information more easily located and readily available. The rapid growth of use of the Internet and the World Wide Web helps to solve the distribution problem (see Box 6.4); the challenge is to develop a process and mechanisms whereby unbiased assessments of new developments can be validated and posted in a timely fashion.

Competition (by bidding) for characterization jobs, compounded by regulatory pressures and legal liability, can discourage the adoption of new tools and techniques unless contractors (1) have access to documentation of the methods'

BOX 6.4
Internet Site Characterization Resources

Sources of information on innovative site characterization technologies are available through the following Internet sites:

- Characterization, monitoring, and sensor technologies: www.cmst.org
- Consortium for site characterization HREF=""
- Environmental technology verification program: www.epa.gov/etv

applicability and acceptability, (2) have information to help them persuade clients that the benefits will justify the costs, and (3) can get the training they need to implement the new methods. These issues could be addressed by development of an aggressive continuing education program to distribute information about the capabilities and use of the new tools and techniques. However, to be effective in the competitive environment in which near-surface contractors operate, delivery of the continuing education programs must be independent of time and location. Again, the Internet and the World Wide Web offer opportunities for new approaches to continuing education.

Clients, practitioners, and regulators have varying levels of need to understand the science and technology underlying the various physical, chemical, and biological measurements that can be made to investigate the shallow subsurface (see Box 6.5). To bridge the possible differences in scientific and educational backgrounds, it is important to communicate what is actually measured, how it relates to the desired parameter, and what the probability of success will be. In this way, expectations are appropriately adjusted, and the best noninvasive method(s) can be selected to achieve the desired goal. For example, GPR was used with limited success in an attempt to locate pieces of ValuJet Flight 592 that crashed in May 1996 and was buried in the muck of the Florida Everglades. Investigators expected to locate metal pieces; however, GPR does not measure

BOX 6.5
Keeping Current

With the emergence of an enormous number of new site assessment tools recently, regulators are often hard pressed to keep current with the latest technologies and maintain their other duties of reviewing site assessments, evaluating corrective action plans, and/or issuing regulations.

SOURCE: EPA, 1997

metal directly. Instead, GPR responds to changes in electrical properties (dielectric and conductivity). The success of GPR depends on how it is applied, how the results are interpreted, and whether what GPR measures can be related successfully to the desired measurement goal (in this example, metal pieces).

The committee encourages government agencies and professional societies to form partnerships in long-term efforts to distribute and share information on the capabilities and recent developments of noninvasive characterization methods.

Possibilities include the following:

- Develop a series of "handbooks," organized according to characterization methods, that document their applicability and limitations and provide sources of information about the latest tools and techniques.
- Develop simplified decision support materials that practitioners can use to identify the most appropriate and most modern techniques to consider in solving a particular problem.
- Support the establishment of an on-line resource center where information about new tools and techniques can be distributed efficiently.
- Encourage development of continuing education programs that utilize the latest advances in distance learning and on-demand access to information.

The users (clients) of the results of noninvasive subsurface characterization are seldom geoscientists or engineers. Results of noninvasive characterization are inherently nonunique and sometimes cannot address certain classes of subsurface characterization requirements (e.g., contaminant concentrations). The users' expectations of unique and definitive answers often make the results of subsurface characterization seem suspect. This suspicion can be reinforced when results are presented with realistic error (accuracy) estimates, statements of nonuniqueness, and assessments of resolution. This problem requires effort from all parties to understand, educate, and communicate effectively.

Geoscientists and engineers performing noninvasive site characterizations should strive to understand the purpose and potential application of the characterization and attempt to present the results in a form that is understandable and applicable by the users. Users likewise should attempt to bridge the gap by being aware of the limitations and uncertainties associated with subsurface characterization.

Because most of today's problems require multidisciplinary solutions, more cross-disciplinary education is necessary. Although research areas have become highly specialized, practitioners require a general knowledge of many disciplines. They also should understand the importance of knowing and using structured design and decision-making processes, and they should be able to codify and defend the thought processes used to arrive at a particular decision. The educational system should meet both needs—the narrow, in-depth focus of the researcher and the general, multidisciplinary need of the practitioner. There is a need to inform regulators, decision makers, and the public about the capabilities and limitations of noninvasive methods.

Efforts are needed to examine the effectiveness of the following in addressing many of the educational concerns: (1) university curricula and research programs; (2) continuing education programs, particularly using distance learning technologies; and (3) public outreach programs.

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7

Realizing Future Capabilities

During the past two decades, advances in computing and microelectronics have stimulated the production of an impressive array of tools and techniques for noninvasive characterization of the shallow subsurface. These advances have made existing tools and techniques faster, cheaper, or more effective. However, there have been relatively few fundamental innovations with regard to the phenomena being observed or the sensing devices that convert those phenomena into electrical signals. Additional research and development (R&D) is needed to enhance and extend current capabilities, to develop fundamentally new measurements, and to close the aforementioned gap between the state of the practice and the state of knowledge.

Some of R&D areas are short-term (e.g., 3 to 5 years) opportunities for advances that can be achieved using existing knowledge and technologies—in other words, enabling the state of the practice to be closer to the state of the art. These include the automation of tools and techniques and the development of methods for monitoring properties, processes, and temporal variations. Others are of a long-term (e.g., 10 to 20 years), high-risk nature, but they offer the potential to enhance significantly our ability to "see into the earth." The long-term needs deal primarily with the discovery of fundamentally new phenomena that can provide information about subsurface conditions and the development of new sensing techniques for making measurements at a distance. In this section, the recommendations for R&D are presented in order from short term to long term.

The resource industries (particularly oil) have invested heavily in R&D because they are profit driven; breakthroughs in exploration can dramatically increase profits. In comparison to the gross expenditures on characterization efforts, the near-surface characterization industry invests relatively little in R&D.

The committee believes that lack of investment results because site characterization activities do not generate revenue for the client but are required in a wide range of environmental and engineering situations. In this situation, R&D is often a cost without commensurate short-term benefits. This is exacerbated by the "low-bid" nature of most specific site characterization efforts (Shuirman and Slosson, 1992), a situation not likely to change. As a result, the private sector usually defers needed R&D in favor of activities that produce more immediate benefits in the form of cost reduction. As such, the committee believes that it is in the interest of the nation to increase the federal government's investment in R&D and to provide incentives and mechanisms for increased private sector investment. Finally, because much of the research is based in universities and federal laboratories, it will be important to provide for effective communications between researchers and industry to ensure that both short-term and long-term R&D products are of great value to the near-surface characterization industry.

> ***Government agencies should be encouraged to increase their investment in near-surface characterization R&D in the areas appropriate to their mission.***

For example, this includes:

- Agencies (e.g., the Department of Defense and the Department of Energy) that are required to deal with near-surface problems (hazardous waste, construction, etc.) at their own sites;
- Agencies (e.g., the Environmental Protection Agency, the Department of the Interior, the Department of Transportation, and the U.S. Army Corps of Engineers) responsible for oversight of the environment, resource development, transportation, and infrastructure where near-surface characterization can be an integral part of their business; and
- Agencies for which basic research either is their primary mission (e.g., the National Science Foundation) or is critical to their mission (e.g., the U.S. Geological Survey).

In addition, research programs supported by federal agencies should take advantage of advisory boards to ensure that R&D expenditures are producing innovations that will be of value to the site characterization process.

The federal government already supports some of the R&D that is needed to deal with proliferating societal issues ranging from land mines to hazardous waste to underground construction. A mechanism should be developed to stimulate private sector investment in R&D in spite of the cost-driven nature of the industry and its size (usually small consulting firms) and application-specific nature.

Government and industry should cooperatively investigate mechanisms for coordination and support of site characterization research.

One possible mechanism is a quasi-governmental entity that could be empowered to collect funds from site characterization contractors and clients. On the other hand, the site characterization industry may have special characteristics that demand an entirely new model. Initially it would be useful to define the needs and characteristics of the industry (particularly the economic structure) prior to designing a solution that optimally meets these needs.

In addition to traditional forms of R&D support, universities and government labs should be encouraged to form more partnerships with industry to develop tools and techniques that will enhance everyday field applications. This will help effect the transition between the state of knowledge and the state of practice.

To ensure rapid technical transfer from research to practice, research could be carried out by teams that include both practitioners (e.g., geobiologists, geochemists, geophysicists) and clients (e.g., environmental scientists, civil engineers). Such research teams should communicate their results to the scientific, engineering, and user communities in widely available venues and in forms suitable for more immediate adoption.

AUTOMATION OF TECHNIQUES

Research and development efforts applied to automation of data acquisition, data processing, and decision making could produce rapid improvement in all aspects of near-surface characterization and should be given a high priority for research funding.

Automation can be applied to data acquisition (e.g., robotics), data processing, and decision making (e.g., use of expert systems and other decision tools for survey planning and data interpretation). The benefits of automation include ease of use, consistency, quality assurance, and cost reduction. It also could enable more rapid technology transfer of the latest tools and techniques from the research lab to the field, thus enabling the state of the practice to be nearer to the state of the science. Finally, automation could help the site characterization industry deal with periodic shortages of trained professionals in specialized fields.

At present, for example, there is a potential shortage of individuals with advanced education in shallow-exploration geophysics. Low enrollments in university programs for the past decade, coupled with employment opportunities in the oil and mining industries, may make it difficult for site characterization companies to hire enough qualified professionals. However, computers can help design a site survey, automate data acquisition, check the quality of data, process the data, model the data, and provide a rough interpretation. For example, the Geophysics Advisor Expert System (Olhoeft, 1992) can help select appropriate geophysical tools to apply to EPA Superfund site problems (and in the process, educate site managers and contractors). However, such systems are guides and will not replace the need for skilled professionals; the uniqueness of sites makes it difficult to include every possibility in such systems. Another example is a tunnel detection system (Olhoeft, 1993) that automatically tests data quality through 12 consistency tests (and, if necessary, indicates what might be wrong with the data and ways to correct them). The system also processes the data for the normal logistical, operational, and instrumental artifacts; manipulates and models the data; and provides a graphical output of the most likely location for detection of a tunnel. At each step, the program provides quantitative data processing, modeling, and interpretive (uncertainty and confidence) indicators. These types of automation and decision support systems can provide the expertise to complement the skills of practitioners and help alleviate personnel shortages.

Automation also can make an important contribution to work in hazardous environments. Not only can robotic technology make it possible to avoid putting humans in dangerous situations, but expert systems and decision support tools can further enhance the quality of data by making real-time decisions about optimizing acquisition parameters. Ultimately, such systems could improve data quality, lower cost, and enhance safety.

These are only a few examples of automation techniques that could provide expertise, guide the characterization process, and ensure quality control. The necessary capability to develop such techniques exists in universities and government laboratories, and the techniques could be rapidly embedded in systems for broad use. Impediments to broader development and use of these automated systems include the issue of deciding how such systems should be certified, who should be authorized to conduct the certification, and how the systems will be updated.

Automation will not replace skilled practitioners; however, it can significantly increase the knowledge base that practitioners use to accomplish their jobs. By producing a better result, more rapidly and at lower cost, robotics and decision support systems could be the key to more—and more effective—use of site characterization methods. Therefore, automation of site characterization processes should be pursued on two broad fronts simultaneously. Experts in universities and government laboratories should move aggressively to develop techniques and systems for automation of activities and decision-making processes. At the same time, the key regulatory bodies should develop certification policies and procedures using experts from the legal, technical, and political arenas. Research and development should include (but not be limited to) the following:

- Expert systems to provide advice and guidance in designing characterization surveys, optimizing parameters, estimating probability of success, validating decisions, and justifying costs;

- Automated data acquisition instruments to ensure competent use, enable field processing and interpretation, and provide quality control;
- Expert systems, decision trees, and pattern recognition software to guide data processing sequences;
- Decision support systems to assist in interpretation, incorporating effective use of modeling and simulation to validate possible interpretations and provide quantitative estimates of uncertainty;
- Policies and procedures for certifying the validity and effectiveness of automation tools; and
- Guidelines for regulatory adoption of the appropriate and proper use of certified automation tools.

MONITORING TEMPORAL VARIATIONS

Many site characterization problems involve changes with time. Examples include monitoring engineered barriers to confirm containment of contaminants, analyzing changes in soil moisture to assess water fluxes, or surveying an environmental remediation site to characterize the reduction in the extent of subsurface contamination. A single observation or survey at a characterization site may show the distribution of materials in question at that point in time, but it will not provide information about changes from earlier conditions or help predict future evolution.

In many cases, properly designed multiple surveys can detect and monitor small changes in properties with higher resolution than is possible within a single survey. Significant advances can result from the development of exploration strategies (using existing tools) for acquiring, processing, and interpreting time-varying information. In the long term, research also is needed to develop measurement technology that will allow monitoring new processes such as in situ leaching or bioremediation.

Uses for time-varying information include the following:

- The ability to predict changes that may occur in response to human activity (or lack thereof) is essential to design and defend remediation plans.
- Baseline data and historical information often are needed to assess liability or responsibility. Where baseline information does not exist, data from repeated measurements sometimes can be extrapolated backwards to provide insight into history.
- Monitoring the remediation process might either verify that the plan is working or provide a quantitative basis for changing the plan to improve the chances of success.

Observing contaminant transport in the subsurface has been done almost exclusively through the use of monitoring wells. However, certain situations may preclude the use of monitoring wells. Even where wells are allowed, they often may not be the most-cost effective solution, and in many cases they provide limited areal coverage. Noninvasive methods could provide an economical means for large-scale, long-term monitoring and also reveal the dynamics of subsurface processes; for example:

- Monitoring of the land surface by remote sensing techniques could provide much information about the subsurface conditions in the top meter or so.
- Changes in moisture conditions at the surface could indicate subsurface heterogeneity. Soil-gas surveys could monitor microbial activity or assess the success of remediation schemes.
- Repeat geophysical surveys could indicate changes in the distribution of subsurface fluids, which is particularly useful in monitoring contaminant movement (e.g., DNAPL remobilization) during site remediation activities.

Noninvasive monitoring for prolonged periods of time should be considered an integral part of site characterization, underground construction, and remediation projects that require monitoring.

Noninvasive techniques could augment traditional invasive monitoring and enhance our ability to test and develop an understanding of subsurface processes. In some cases, noninvasive methods are the only alternative. The following R&D efforts are needed for this to become common practice:

- Geological noise and other factors limit the resolution of a survey method. If the noise does not change with time, then changes in key properties often can be detected with higher resolution than the properties themselves can be mapped. The development of processing and interpretation techniques that take advantage of differential measurements would allow existing tools and survey methods to be used effectively for monitoring.
- As new remediation techniques are developed (in situ leaching, bioremediation, etc.), monitoring properties indicative of the progress of a remediative actions might be difficult using existing characterization tools and survey methods. Fundamentally new tools (such as magnetic resonance imaging and seismic-electric techniques) offer the promise of making measurements previously thought impossible. Monitoring needs for the next decade could require a long-term, sustained program of fundamental research into "exotic" measurement technologies.

PROPERTIES AND PROCESSES

Site characterization historically has focused on mapping the subsurface geometry (e.g., location of anomalies, shapes of boundaries). Physical, chemical, and biological properties and processes (including coupling between processes) are at least as important as geometry; however, there has been limited research into the noninvasive measurement of such properties and processes and their distribution. Developing the ability to observe these properties and processes noninvasively will require long-term research, from the perspective of both understanding the phenomena and developing the methodology to measure and interpret these phenomena.

Until recently, measurements of properties (e.g., the bearing strength of the foundation material at a construction site) usually have been done on samples obtained by drilling or other intrusive means. Today there is a growing demand for nonintrusive surveys that measure in situ properties (chemical and biological as well as mechanical). For example, no longer is it sufficient to find the top of the saturated zone; now it also is necessary to determine water quality or identify contaminants. In the future, solutions to environmental and engineering problems of the shallow subsurface also will depend on understanding and observing in situ chemical and biological processes and the interactions between them.

Characterization methods used to find anomalies or map subsurface geometry actually are detecting variations in properties or mapping boundaries between areas of different properties. However, quantitative relationships between the phenomena being observed and the values of the in situ properties usually are not well defined and often involve ambiguity. Therefore, although the location of the variations or boundaries can be mapped, relatively little information about the properties themselves (such as the specific contaminant being mapped) can be determined. The problem is worse if the target involves a chemical or biological process because, in many cases there is little knowledge about the relationship between the in situ process and the phenomena observable at the surface. An example would be the situation wherein a biological agent was introduced into a region containing a chemical pollutant. We know little about whether the biological process produces any effect that is potentially measurable, let alone how to measure it.

> ***As part of a basic research program, there needs to be a significant effort directed toward quantification of physical and chemical realities of what is being sensed as well as possible interactions between in situ properties and processes.***

Some noninvasive methods for subsurface characterization are well understood. For instance, there is a good correlation between seismic measurements and the elastic properties of the material being sensed. This is not the case for many other measurements. Fundamental studies should be initiated and expanded to include the following:

- Understand subsurface processes and the interactions between them, and identify the measurable properties that might be associated with these processes or combinations of processes.

• Establish theoretical and phenomenological relationships between the properties and processes of interest and the phenomena that could be measured noninvasively at the surface.

• Develop instruments and techniques that will allow these phenomena to be measured with useful resolution and adequate signal-to-noise ratio.

• Produce the interpretive tools and procedures to invert the surface measurements into an accurate description of the properties or processes at depth.

Fundamental studies should be supplemented by variable-scale testing, ranging from laboratory examination of cores to full-scale integrated surveys of standard test sites. The National Geotechnical Test Site Program, supported by the National Science Foundation and the Federal Highway Administration and managed by the National Council for Geo-Engineering and Construction, might serve as a useful model. Other test sites (e.g., those at the University of Arizona, Stanford University, and the Idaho National Environmental Engineering Laboratory) have been established for specific research projects. These test sites can be used to develop new techniques and to validate models.

OPPORTUNITIES FOR INNOVATIVE MEASUREMENTS

Most existing technologies measure physical phenomena and are used to interpret physical properties and processes. Few methods exist to monitor the chemical or biological properties and processes that are becoming increasingly important, particularly in areas such as groundwater management and hazardous waste mitigation. The discovery of fundamentally new measurement technologies, the ability to observe fundamentally new phenomena, and better interaction between disciplines are essential for nonintrusive site characterization to meet current and future needs.

Nonintrusive characterization methods inherently rely on "action at a distance." Furthermore, the action at a distance must occur rapidly compared to the time scale of the process in order for the measurement to reflect current conditions. For example, biological agents working on organic pollutants at depth might produce a volatile by-product that can migrate to the surface where it could be mapped with a soil-gas survey. However, if the rate of propagation of the volatile product is slower than the action of the biological agent, the soil-gas survey could be describing conditions that have changed by the time of the survey.

The measurement of physical phenomena on the surface to infer physical properties at depth is relatively well developed. However, many of the challenges in site characterization for environmental applications involve interpreting surface measurements to infer chemical and biological properties and processes at depth. Methods for accomplishing the latter are not as well developed, and in many cases, there are no quantitative measurements that can yield information about such properties or processes.

Some physical phenomena can be interpreted to yield such information (for example, subtle features in a ground penetrating radar signal are linked to the chemistry of certain subsurface pollutants); however the relationships between the phenomena and the properties or processes generally are not well understood. There are a few geochemical measurements that also can provide information about in situ properties (the use of "sniffers" to sample gases emanating from the soil), but again the connection between the source and the observation is not always well understood. Furthermore, in many cases involving geochemical measurements, the time scale of the phenomenon is long relative to the process being monitored (e.g., the soil-gas survey mentioned above), in which case the measurements may be of little practical use.

In the future, the committee expects subsurface biological activity to become a major issue; however, the ability to relate surface observations to biological properties and processes is even more limited. A few physical measurements indirectly involve biological agents (for example, spectral imaging can be used to interpret the health of plants that, in turn, can indicate depth to water table). However, there are few, if any, ways to infer biological agents or activity at depth directly from physical observations on the surface. It may be possible to use geochemical observations to infer geobiological properties or processes, but at the present time the capabilities of most of these methods are limited and their efficacy has not been demonstrated. Such measurements also are subject to the time-delay problems mentioned above.

The committee believes that the lack of progress in these areas is the result of insufficient research directed to the connections between the physical phenomena and the chemical or biological property or process; part of this is probably a lack of understanding or appreciation of the importance of these problems. However, the problem may be more deeply rooted in the lack of communication between geophysicists, geochemists, and geobiologists. Fragmentation in the traditional earth sciences is well documented (there are 32 separate professional societies that are members of the American Geological Institute and even more that do not participate in this organization), but the gap between fields and geochemistry or (especially) geobiology is even greater. Therefore, any increase in support for research in mapping chemical or biological properties must be accompanied by a commitment to truly effective cross-disciplinary interaction.

Long-term research to develop fundamentally new noninvasive tools and techniques should be given a high priority, with emphasis on research done by multidisciplinary teams.

Among the challenges in site characterization technologies in the coming decades will be measurement, both direct and indirect, of geochemical and geobiological properties and processes. Meeting this challenge will require long-term investment in high-risk research leading to

- A better understanding of the relationship between chemical and biological properties and processes and physical phenomena that can be measured with existing instruments;
- The discovery of fundamentally new measurement technologies that can
  1. measure a physical phenomenon that has a causal relationship with subsurface chemistry or biology;
  2. make a direct chemical or biological measurement that is diagnostic of conditions at depth; and
  3. the ability to observe fundamentally-new phenomena; and
- Better data fusion and integrated processing, modeling, and visualization of data from all three specialties.

Development of these innovative techniques and measurements will require the following:

- Research to be done by multidisciplinary teams;
- Cross-disciplinary education of specialists to enhance their ability to work effectively on multidisciplinary teams;
- Facilities such as well-controlled test sites that support multidisciplinary development and validation of measurement, processing, interpretation, and modeling systems; and
- More effective communication and interaction between the biological, chemical, and physical specialists within the site characterization community.

Progress in promoting more effective use of existing tools for noninvasive characterization and improving and developing new techniques should lead to a greater understanding of the shallow subsurface and the applications that depend on this understanding.

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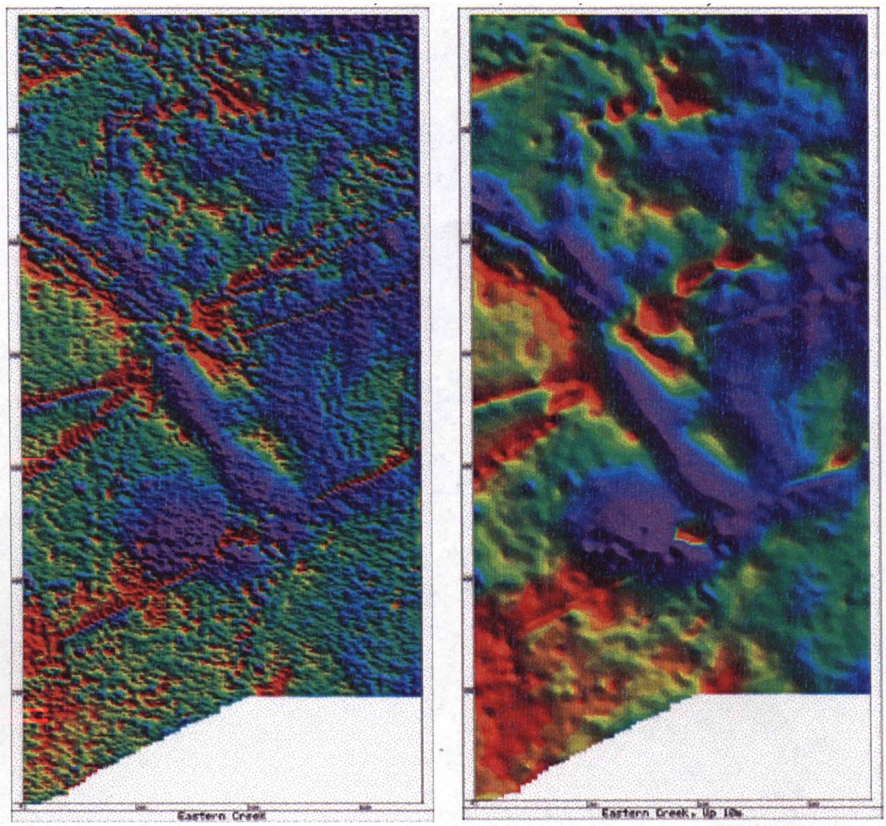
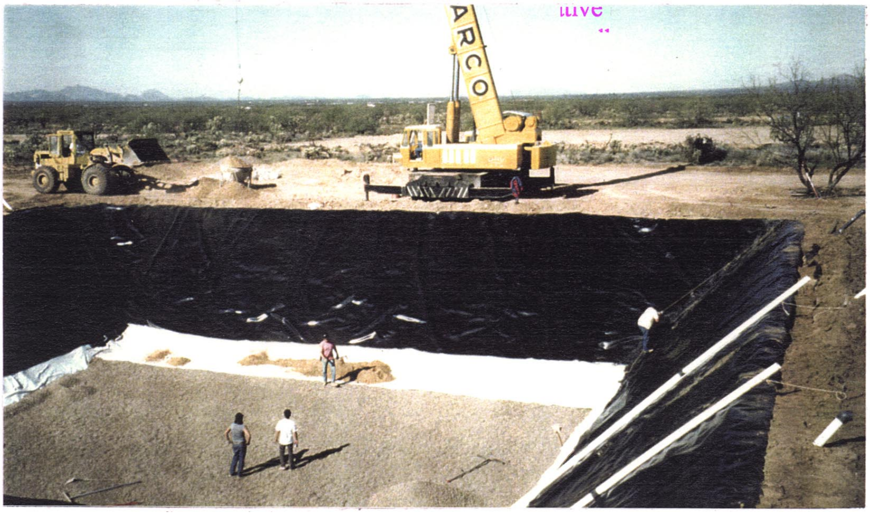


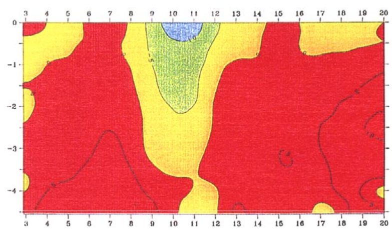
Magnetic data collected with a hand-held total-field magnetometer with resolution of 0.02 nT on traverses recorded with the sensor 1 m above ground with a sample interval of 0.5 m and a line spacing of 10 m, over an area 700 m by 1400 m. The data show a wealth of geological detail, containing shear zones, very thin dikes (<1 m), and a reverse magnetized plug.

Same area, with data collected at an elevation of 10 m from a helicopter-borne, dual-sensor system with laser elevation meter. The sensors are transverse to the aircraft, giving a 10-m data line spacing with two survey lines per flight line. This helimag system closely meets the ground specifications, but the thinnest of the dikes have slipped out of view. The helimag data cost about one-quarter to one-third as much as the hand-held data.

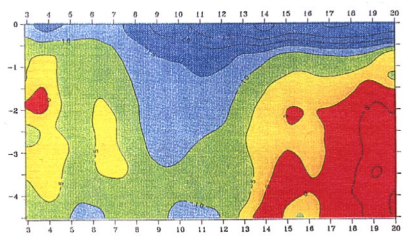
PLATE 1 An application of high-resolution magnetics in coal exploration is shown below. The inherent resolution of potential field geophysical techniques such as magnetics depends on the distance from the sensor to the causative source. (Data courtesy of Newlands Coal and Geophysical Research Institute, Armidale, NSW, Australia.)



This photograph shows a lined basin constructed at the University of Arizona's Avra Valley Geophysical Test Site. The basin is 30 m by 30 m by 5 m deep. The entire basin was lined with high-density polyethelene; drain pipes were placed in the bottom and the basin refilled with native soil. This test site allows a closed system for injection and retrieval of fluids. During the summer of 1992, 24,170 liters of water were injected along a 1-m by 25-m strip at the center of the basin.



After 1 day



After 17 days

Difference in electrical resistivity of the ground between the beginning (1 day) of the injection of a fluid and after 17 days. The small blue region (more negative than 10 ohm-m) in the left panel shows the location of the plume of injected water. After 17 days (right panel), the blue area has increased in depth and spread out. These data were collected with an electromagnetic sounding system. A long-line source was oriented parallel and offset 10 ohm-m from the injection region. The receiver line was perpendicular to the line source and the injection region. The scales are in meters. There was a close correspondence between these images and those based on 25 electric well-log and neutron probe measurements within the test basin. Such measurements make it possible to monitor and map the flow of fluids over time. From Sternberg (1993).

PLATE 2 Monitoring an underground plume with electromagnetic methods.

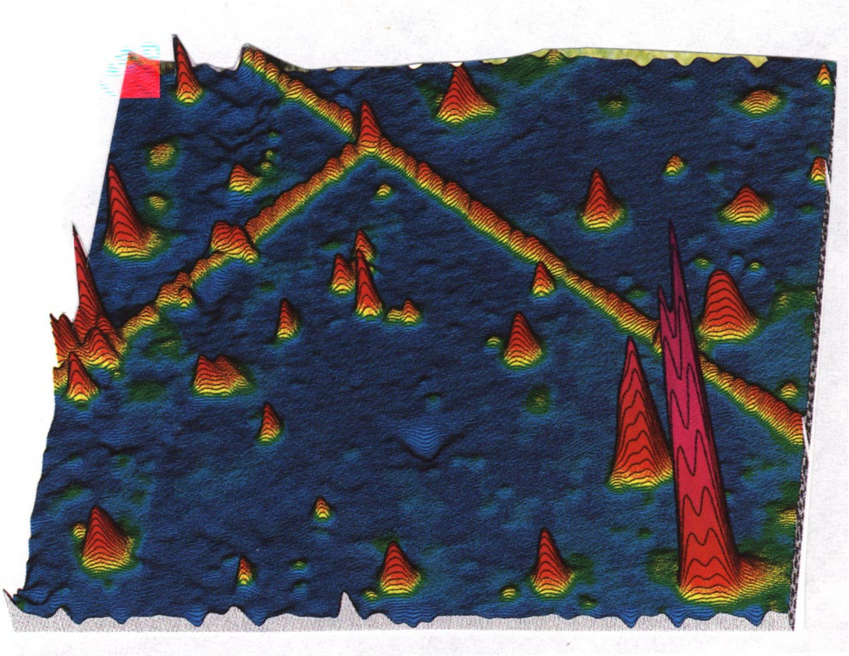
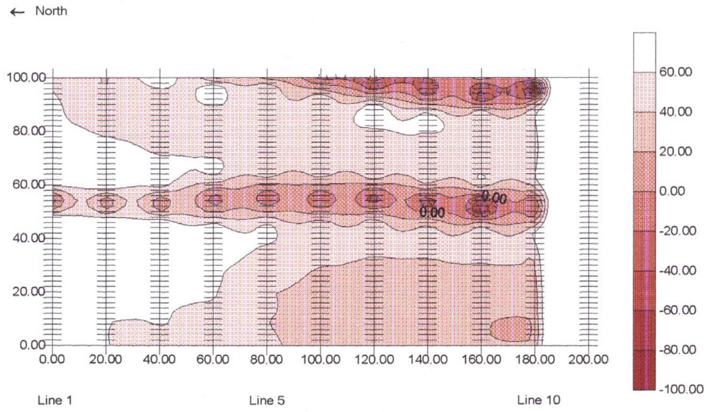
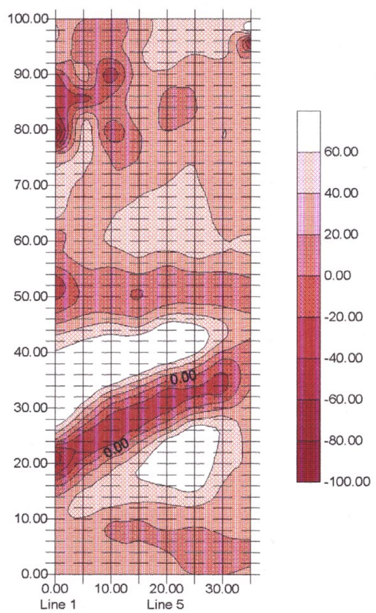


PLATE 3 Time-domain electromagnetics at Stanford Test Site. Several new time-domain electromagnetic (TEM) instruments have been developed to satisfy requirements of the environmental market. These instruments are based on techniques developed for the mineral exploration industry over the past two decades, specifically designed to discriminate between moderately conductive earth materials and more conductive metallic targets and, perhaps more importantly, to be more portable and less expensive than their exploration counterparts. The instrument is optimized to detect moderate-sized metallic conductors at depths of 1 m. Newer instruments are being designed to discriminate between ferrous and nonferrous materials, with better depth resolution.

The example below is from data gathered with a trolley-mounted TEM gradiometer system (Geonics EM 61) at Stanford University's environmental test site, which simulates many of the buried waste situations encountered in environmental assessments. The TEM instrument detected all of the known buried metallic objects as well as several unknown objects and clearly shows two buried pipes. A void is detected in the lower center of the image, evidenced by a subtle depression in the background. (Example courtesy of Geonics Limited, Missisauga, Canada.)



Map view of the route of a buried pipeline as indicated by data collected with an induction-type, ground conductivity meter (Geonics EM 61). The pipeline, of steel construction, is buried about 5 feet. The anomalous conductivity at the upper right of the figure is due to reinforced concrete at the surface. The horizontal contouring in the center of the plot is an example of poor practice. The "bulls-eyes" that coincide with measurement points (to a lesser extent the same applies to the contours at the right near surface) are artifacts of an inadequate contouring software package. Line spacing 20 feet; station spacing 2 feet; conductivity millisiemens per meter; and contour interval is 20 mS/m. North is to the left.



Map view of a different location showing a previously unknown pipeline (lower left to upper right) at an angle to the main pipeline as above (horizontally across the top). It was found to be another pipeline of a previous vintage and purpose that had not been removed. Line spacing is 5 feet; all other details are the same as the top figure. North is to the left.

PLATE 4 Using ground conductivity in locating buried pipelines.

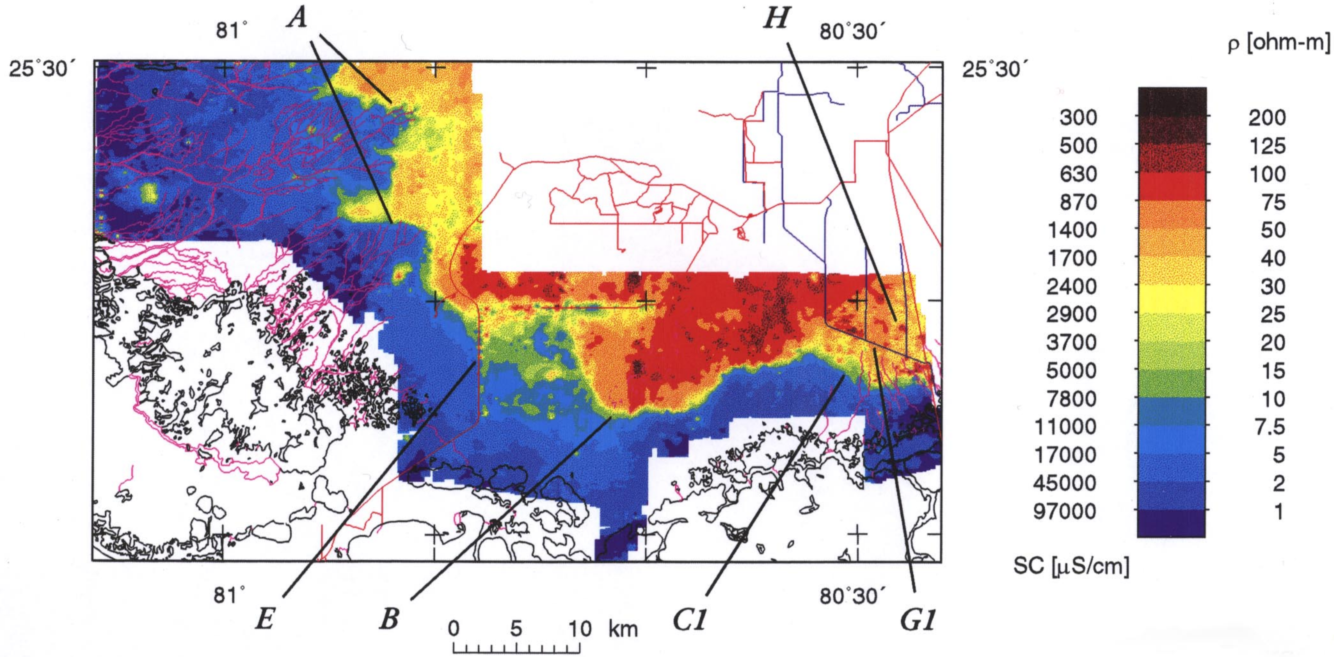
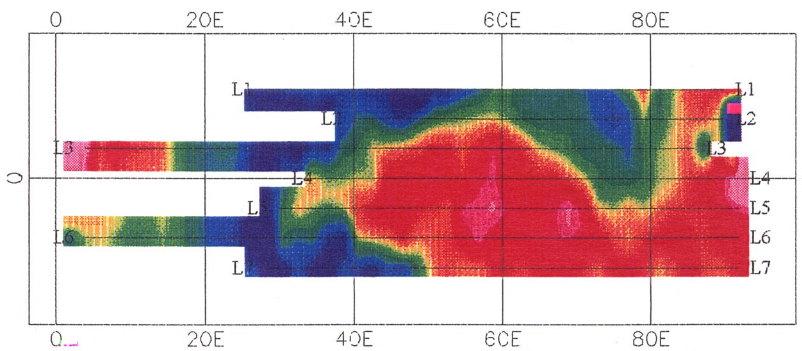


PLATE 5 Resistivity values at 1-m depth interpreted from a helicopter electromagnetic survey in the Everglades National Park, Florida; area covered was 1036 km^2. Coastlines and shores (black), rivers (magenta), canals (blue), and roads (red) are shown. The color bar shows interpreted formation resistivity on the right and estimated water quality (specific conductance) on the left, based on well-log correlations. Features shown are (A) diffuse freshwater-saltwater interface in Shark River Slough caused by tidal flow in drainages; (B) sharp interface in Taylor Slough; (C1) effect of near surface, freshwater recharge; (E) resistivity contrast produced by roadway blocking surface water flow; (G1) elevated near-surface resistivity due to flow from C-111 canal. Figure courtesy of D. V. Fitterman; see also Fitterman and Deszcz-Pan, 1998.

Photograph shows a survey being conducted at a site at a radioactive waste management acid pit at the Idaho National Engineering Laboratory. The site had been used for dumping acid that contained radioactive wastes and other contaminants. This was an operational survey to provide information for remediation of the site, and the precise location of the wastes were not well known.



Plan map showing the distribution of subsurface resistivities based on ellipticity measurement at a frequency of 62 kHz, which corresponds with a depth of about 2 to 2.5 ohm-m (line spacing was 4 m; measurement spacing along each line was 2 m). Data were collected with a coil spacing of 8 m. The red color (corresponding to low electrical resistivities, of the order of 25(ohm-m) in the center of the map shows the location of the most heavily contaminated soil. The blue color (of the order of 40 m) shows background soil response. The red color on the far left shows the location of solid waste in an adjacent disposal cell. The red color on the far right shows the location of buried utilities beneath a road. Other frequencies were used to map the contaminant concentration at various depths. The soils at this site are far too conductive for ground penetrating (GPR) methods to be effectively used.

PLATE 6 Mapping contaminated soils (from Sternberg, 1997).

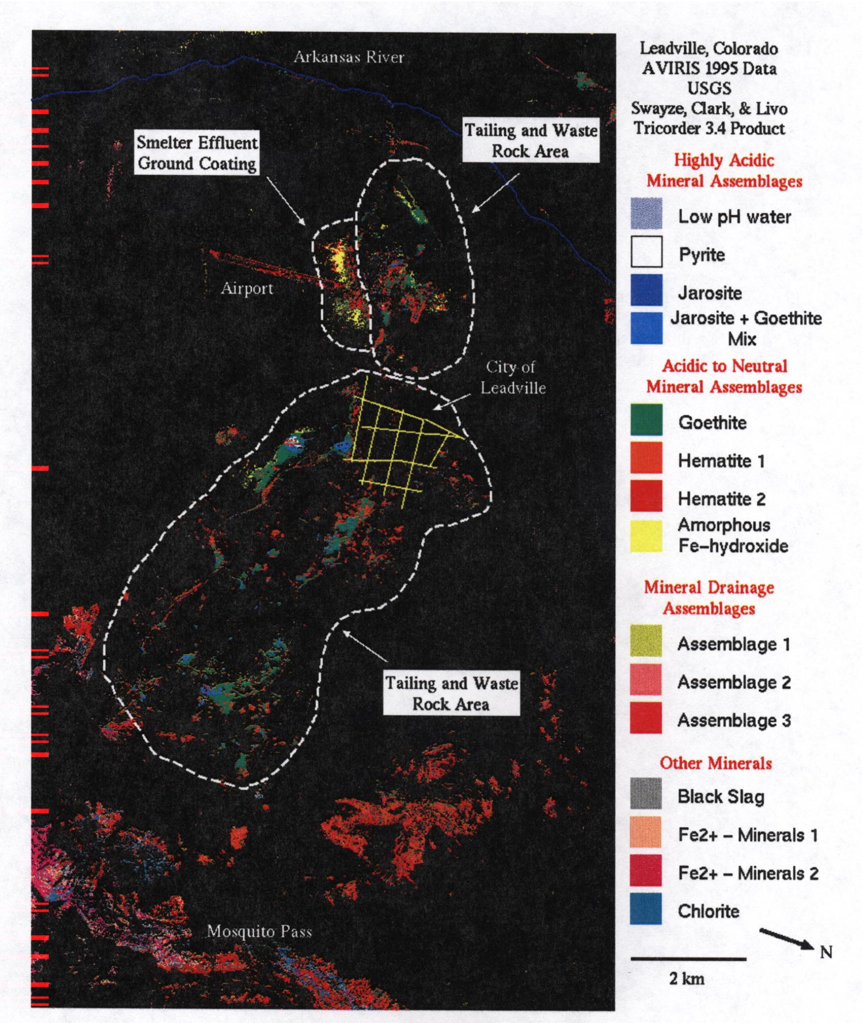


PLATE 7 Leadville iron-bearing mineral map. Map of the mineral distribution of the waste rock and tailings piles at the California Gulch Superfund site near Leadville, Colorado (130 km southwest of Denver). This map was produced by the U.S. Geological Survey for the U.S. Bureau of Reclamation and U.S. Environmental protection Agency using the NASA Jet Propulsion Laboratory Airborne Visible/Infrared Imaging Spectrometer (AVIRIS). Each color identifies iron-bearing minerals in each $17 \times 17\ m^2$ area pixel on the ground. Blue colors show minerals that cause acid mine drainage high in dissolved metals such as cadmium, zinc, and lead. Areas in green have minerals that are more neutral but still of concern. Other colors represent minerals not contributing to water contamination. No iron-bearing minerals were found in areas shown in black. Area shown is 10.5 km wide by 17 km long. North is toward the lower right of the image.