1 Introduction

The purpose of this textbook is to introduce undergraduate and graduate students in geophysics, geology, geotechnical engineering, archaeology, and related disciplines to the application of geophysical methods for studying the uppermost tens of meters beneath Earth's surface. This portion of Earth both affects and is impacted by human activities such as building, excavating, tunneling, and storing or accidentally releasing hazardous materials. Many of the planet's mineral and groundwater resources are located in the uppermost subsurface layers. The techniques of near-surface geophysics are being increasingly used to benefit society in activities such as nuclear-waste storage, carbon sequestration, precision agriculture, archaeology, crime-scene investigations, and cultural-resources management. Near-surface geophysicists conduct a huge range of scientific and engineering investigations in service of society (Doll *et al*., 2012). Some of these are shown in Table 1.1.

Moreover, near-surface geophysicists address basic scientific questions relevant to a spectrum of natural processes that include biogeochemistry, coastal processes, climate change, ecology, hydrology, tectonics, volcanology, and glaciology (Slater *et al*., 2006a). Near-surface geophysical data are now routinely used, for example, in basic geoscience investigations such as environmental remediation, natural-hazards risk assessment, water-resource management, gas hydrates and permafrost studies, glacier and ice-sheet mass transport, watershed-scale and coastal hydrology, fault-zone characterization, and the reconstruction of Earth's tectonic, volcanic, and extraterrestrial impact history.

Near-surface geophysicists also develop new instrumentation, data acquisition and processing strategies, and explore fundamental aspects of Earth imaging, forward

Table 1.1 Near-surface applied geophysics in the service of society

Engineering and environmental	Shallow resources	Archaeology, forensics, military	Groundwater
Building foundations	Geological mapping	UXO/landmine detection	Water-well site location
Top of bedrock	Ore body delineation	Historic preservation	Water-table mapping
Non-destructive evaluation	Aggregate prospecting	Cultural-resources management	Fracture-zone delineation
Tunnel detection	Offshore gas hydrates	Gravesite location	Salinization mapping
Underground storage tanks	Coal-seam mapping	Crime-scene investigations	Aquifer characterization
Slope stability	Geothermal mapping	Nautical archaeology	Contaminant mapping

modeling, and inversion. Also of critical interest to near-surface geophysicists is the petrophysical interpretation step which provides the link from the geophysical image to the geological properties of the subsurface. The latter, which include such properties as porosity, salinity, and rock strength, are of broad scientific or engineering concern.

1.1 Workflow

The following list outlines a typical series of activities that a near-surface geophysicist, or a team of geophysicists, or a multi-disciplinary team including one or more geophysicists, might undertake in order to complete a scientific or engineering project. The order and extent of the individual activities varies from project to project.

A. Front-end

- define the scientific or engineering problem to be solved
- gather the available prior information
- formulate possible hypotheses
- initial site reconnaissance
- decide on relevant geophysical techniques
- design the experiment (subject to logistical and budget contraints, etc.)
- purchase/build/modify/test and sequester instrumentation
- assemble field crew and analysis team
- contingency planning/crew scheduling
- safety plan/logistics/shipping/permissions

B. In the field

- prepare daily checklist
- mobilization
- prepare field site for experiment (clear vegetation, etc.)
- determine navigation and acquisition tactics
- survey the site and lay out the grid
- test equipment, perform quality-control procedures
- acquire the data
- store/archive dataset
- demobilization (stow equipment for next use, etc.)

C. In the office

- notebook/data reconciliation
- visualization of raw data
- preliminary data processing (removal of bad data points, etc.)
- prepare initial field report
- advanced data processing (spectral analysis, filtering, etc.)
- modeling and inversion to construct Earth model

- geological interpretation
- formulate tentative conclusions

D. Back-end

- place results in broader context
- prepare presentation/draft report
- get feedback from colleagues
- refine hypotheses/acquire additional data/perform additional analysis
- finalize conclusions
- provide recommendations for further study
- prepare and submit technical report/scientific publication
- rigorous peer review
- acquire additional data/perform additional analysis/refine hypotheses
- prepare and submit revised technical report/scientific publication

There are numerous introductory field guides which describe the various geophysical techniques in simple terms and explain how to select the appropriate equipment, plan and conduct a geophysical experiment, and display and provide a preliminary interpretation of the data. An example is the chapter entitled "Geophysical Techniques" from the Field Sampling Procedures Manual produced by the New Jersey Department of Environmental Remediation and available on the web at www.nj.gov/dep/srp/guidance/fspm/. Practical guidelines for applying geophysics to engineering problems, with a special emphasis on transportation projects, is provided in NCHRP (2006). The American Society for Testing and Materials has produced a standard guide for selecting surface geophysical methods (ASTM, 2011).

1.2 Some applications of near-surface geophysics

Near-surface applied geophysics (NSG) differs from traditional exploration geophysics, as practiced by the oil and gas and mineral industries, in several key respects. First, there is a demand for sub-meter-scale depth and lateral resolution. Second, there often exists an opportunity for confirmation, or ground-truthing, of the geophysical interpretation via excavation or drilling. Third, near-surface geophysics involves certain specialized techniques not found in traditional geophysics such as ground-penetrating radar (GPR), metal detection, surface nuclear magnetic resonance, high-frequency seismology, and microgravity. Finally, a near-surface geophysics project is often motivated and constrained not by profit concerns but by public health and safety concerns, and the work often must be carried out subject to rigorous legal or regulatory requirements (Butler, 2005).

Over the past 30 years, the field of near-surface geophysics has grown rapidly, as indicated by the following analysis. The number of papers in the Science Citation Index (SCI) (www.wokinfo.com) published between 1980 and 2010 that contain the keyword "ground penetrating radar" in the title or abstract is shown in Figure 1.1.

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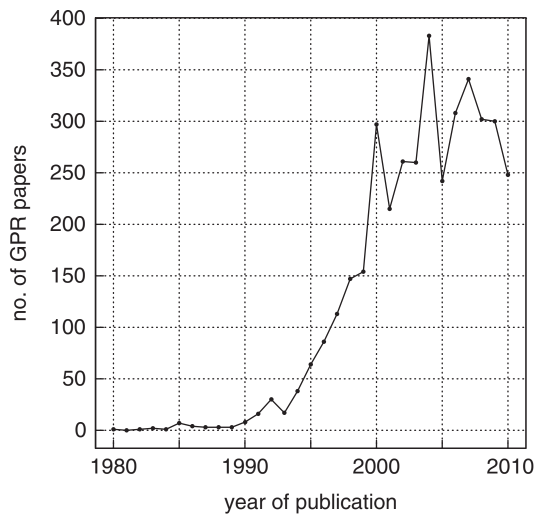

Figure 1.1 Numbers of papers in Science Citation Index between 1980 and 2010 with "ground penetrating radar" as keyword.

The figure shows that GPR literature is virtually non-existent in the SCI database prior to the early 1990s. The activity level in all aspects of NSG prior to 1991 is not well described by these data however since GPR is a relatively new technique compared to electromagnetic (EM), magnetic, seismic, and resistivity techniques. The number of GPR papers grew rapidly in the 1990s and since 2000 it has stabilized at ~ 300 per year. The variation in the number of GPR papers since the early 1990s serves as a rough proxy for the overall level of activity in near-surface applied geophysics over the same period of time.

In order to provide a rough estimate of how often the various techniques of near-surface applied geophysics are used, the abstracts of articles from the European Association of Geoscientists and Engineers (EAGE) journal *Near Surface Geophysics* during the years 2002–2010 were analyzed. The result of an analysis of the 299 articles is shown in Figure 1.2. Clearly, GPR and resistivity are the two most widely used techniques in this database, being mentioned in more than 50% of all abstracts. The next most prominent methods are the various EM and seismic techniques, the latter including surface-wave, reflection, and refraction analysis. Following these, in order of popularity, are magnetics, magnetic resonance, gravity, borehole seismic/radar, self-potential (SP), and induced-polarization (IP) methods. The "other" category includes specialized techniques such as seismoelectrics, ultrasonics, infrared imaging, microwave tomography, γ-ray spectrometry, cone-penetration testing, microseismic and ambient seismic noise studies, time-domain reflectometry, acoustics, and temperature mapping.

A number of case histories are now briefly described to provide the reader with an early glimpse of the range of science and engineering problems that can be addressed using the techniques of near-surface geophysics.

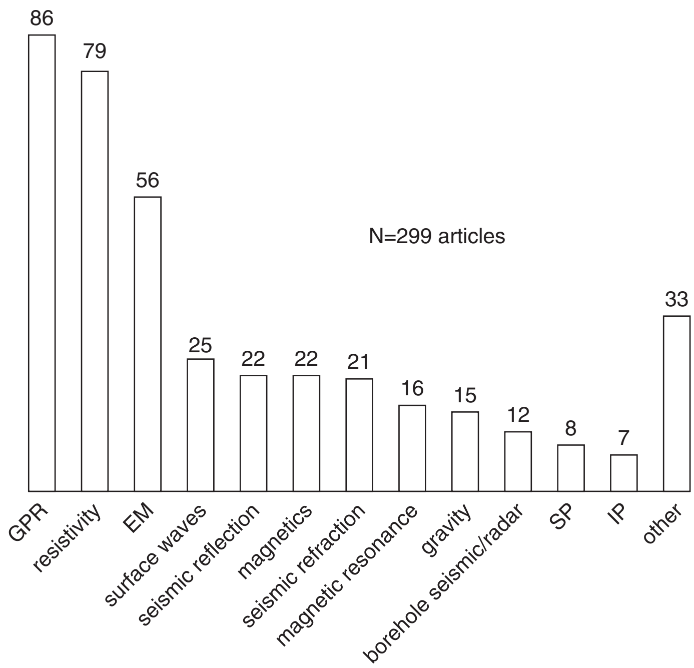

Figure 1.2 Number of times that the use of a specific technique is mentioned in articles published in *Near Surface Geophysics*, 2002–2010.

Example. UXO clearance.

An excellent example of the special characteristics of near-surface geophysics is provided by the problem of unexploded ordnance (UXO) clearance. The US Congress periodically directs the Department of Defense to close military bases that are no longer needed to fulfill mission requirements (MacDonald *et al.*, 2004). A major impediment to the transfer of these lands to civilian purposes is the environmental clean-up of potentially dangerous UXO resulting from military training and weapons testing. The primary technology used for UXO detection and its discrimination from harmless metal clutter is electromagnetic induction geophysics.

Two sample UXO electromagnetic induction geophysics datasets are shown in Figure 1.3. The quantity plotted is Q_{SUM} [ppm], the quadrature response summed over multiple frequencies, which for the present purpose may be regarded simply as a measure of the metal content in the ground. Figure 1.3a shows anomalies due to purposely buried metal objects, namely steel, copper, and aluminum pipes, at a test site in North Carolina. Figure 1.3b shows anomalies due to putative UXO at a live site in Kaho'olawe, Hawaii. The background response is noisy at the Hawaii site due to the high magnetic mineral content of the basaltic soils.

Data in UXO or landmine surveys are routinely acquired at 10 cm station spacing and 25 cm line spacing, both of which are a factor of ~ 1000 times less than the corresponding spacings in traditional oil and gas exploration geophysical surveys. The goal of a UXO/landmine geophysical survey is to maximize the probability of detection (no misses) while

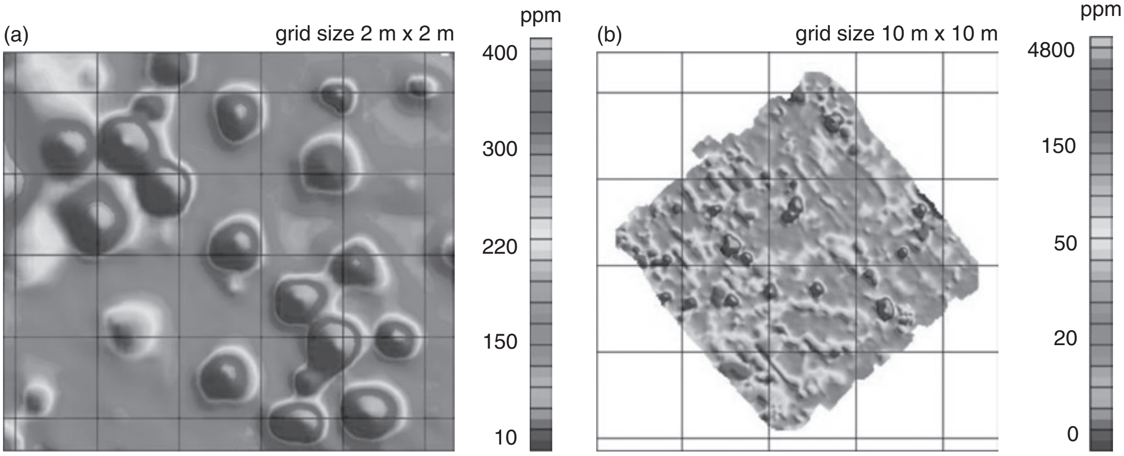

Figure 1.3 (a) EM induction response of metal pipes buried at a test site. (b) EM induction response of unexploded ordnance (UXO) at a live site with highly magnetic soil, Kaho'olawe, Hawaii. From Huang and Won (2003). See plate section for color version.

minimizing the false-alarm rate (no costly false positives) and to generate a reliable dig/no-dig decision for each anomaly. For the clearance operation, a priority dig list is constructed by the geophysicist and ground-truthing is performed by the site operator.

Example. GPR stratigraphy.

An example of a near-surface geophysics survey that uses GPR is shown in Figure 1.4. In this example, a GPR image is presented of the stratigraphy of an active dune on Parengarenga sandspit in New Zealand. The spit is an important source of high-quality (~ 94% quartz) fine sand used for glass manufacture. Besides economic factors, the possible environmental effects on the Parengarenga harbor and the regional coastal hydraulics of continued sand extraction has motivated the GPR investigation. The 200 MHz GPR section reveals the lateral continuity of the underlying "coffee rock," a semi-consolidated Quaternary paleosol. Cross-bedding within the dune can also be seen in the GPR section. The internal structure revealed by the GPR data provides valuable constraints on long-term evolution of the spit at this important coastal site.

Example. Mars radar sounding.

Shallow subsurface radar is finding new and exciting applications in planetary science. Recently, data from onboard the Mars Reconnaissance Orbiter has returned high-resolution images of the Martian north polar layered deposits (NPLD) and the underlying basal unit (BU), as shown in Figure 1.5. The orbiting SHARAD instrument is an 85-μs chirp radar with a central frequency of 20 MHz and a bandwidth of 10 MHz. The depth

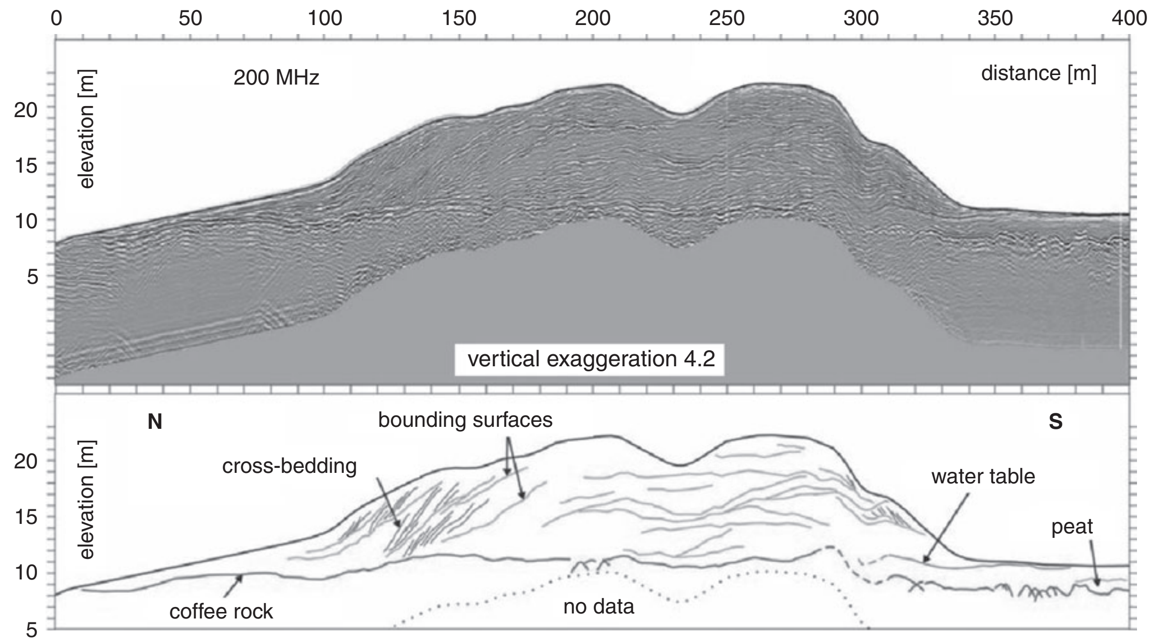

Figure 1.4 GPR stratigraphy of an active dune, Parengarenga sandspit, New Zealand. From van Dam *et al.* (2003).

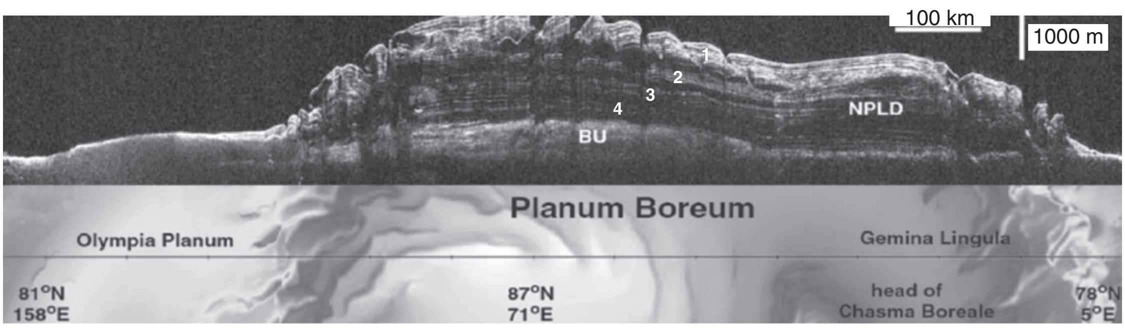

Figure 1.5 Orbiting 85-μs chirp radar image of stratigraphy at the Mars north polar ice cap. From Phillips *et al.* (2008). See plate section for color version.

resolution is ~ 15 m and the along-track horizontal resolution, after data processing, is ~ 1 km. The radar imagery indicates a laterally continuous deposition of high-reflectivity ice, dust, and lava underlain by a basal interbedded sequence of lower reflectivity. The NPLD vertical structure consists of distinct sediment packages characterized by different ice/dust fractions (see Figure 1.5). The stratigraphy may be explained in terms of Mars climatic variations that are governed by the ~ 10^6-year periodicities in planetary obliquity and orbital eccentricity (Phillips *et al.*, 2008). Reprinted with permission from AAAS.

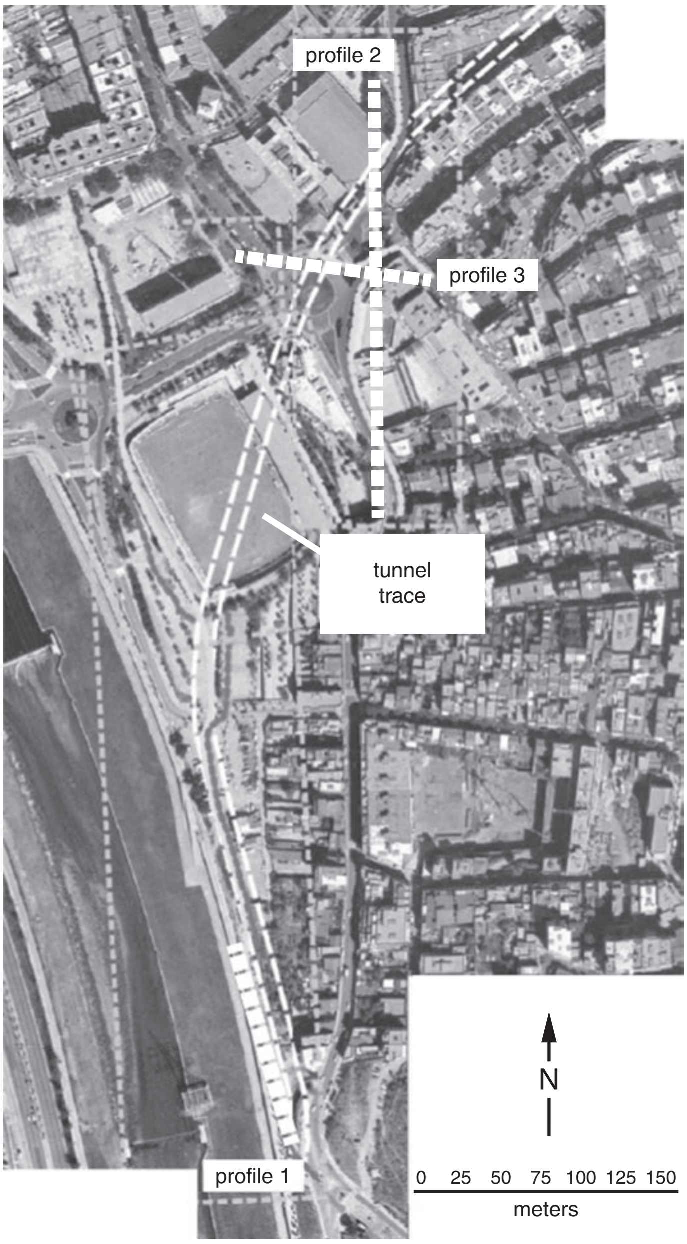

Figure 1.6 Approximate locations of three seismic reflection profiles in the city of Barcelona, Spain (after Martí *et al*. 2008). The route of the proposed subway tunnel is also shown. Only the southernmost ~150 m of profile 1 is indicated in this figure; it continues for an additional ~300 m in the north-northwest direction.

Example. High-resolution urban seismic reflection.

Performing a geophysical survey within an urbanized area is challenging due to the presence of abundant cultural noise and above-ground obstacles. Geophysicists are

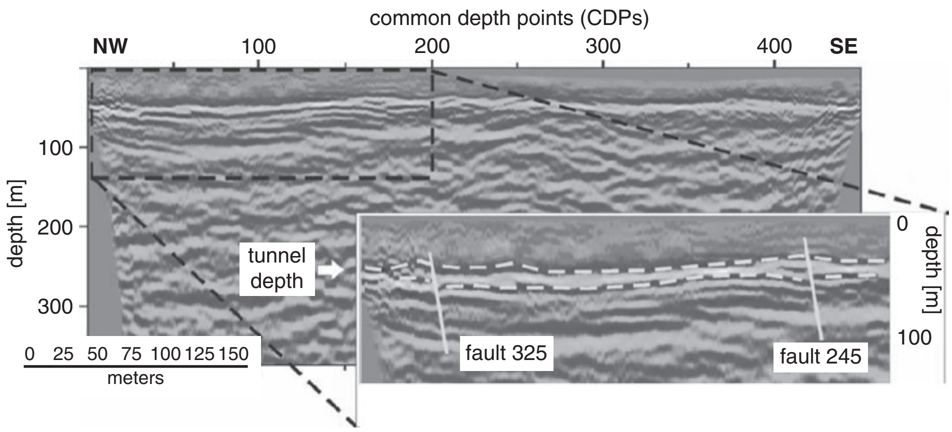

Figure 1.7 Seismic depth section from Martí *et al*. (2008), profile no.1 shown in the previous figure. The inset shows two mapped faults and the contact zone between the near-surface weathered layer and underlying intact bedrock.

increasingly tasked to work in urban settings, industrial brownfields, or other built-up areas since these locations contain a disproportionate number of the world's environmental hazards or require site characterization for further development or land reclamation. A high-resolution seismic-reflection survey was recently carried out within the city limits of Barcelona, Spain to support the overall engineering design for a new subway transportation tunnel. Due to abrupt lateral changes in hydraulic and mechanical rock properties, tunnel-boring conditions often become problematic or hazardous at intersections with subsurface permeable fracture zones. A series of seismic-reflection profiles, shown in Figure 1.6, were acquired along city streets during the relatively quiet overnight hours using a vibroseis truck with a frequency sweep of 14–120 Hz as the source (Martí *et al*., 2008). The stacked seismic section from profile 1 is shown in Figure 1.7. Two previously mapped faults, labeled 245 and 325, have been identified. These faults may be associated with subsurface fracture zones and could cause engineering difficulties during the tunnel construction.

1.3 Communication of uncertainties

It is well known that geophysical data are insufficient to uniquely determine the distribution of subsurface properties, to any level of precision. There are always ambiguities in the interpretation of geophysical data. A major challenge for the near-surface geophysicist is to decide how the uncertainty associated with a given subsurface image should be communicated to stakeholders. Clearly, in all cases it is important that the geophysicist should understand the stakeholders' objectives. Given that, the geophysicist should explain how

Figure 1.8 Excavation of a leaking 30 kL steel tank from a former retail petroleum site. Photo courtesy of Joshua Gowan.

the geophysical result is relevant to the problem objectives, and carefully describe the limitations inherent in the geophysical interpretation.

If the geophysicist is acting purely in a scientific role, this might be the extent of the geophysicist's contribution. A scientist acts primarily as a provider of facts, an interpreter of evidence, or as an advisor and is not obliged, nor oftentimes expected, to contribute in a direct way to decision-making either in the public or a corporation's best interest.

On the other hand, if the geophysicist is acting in a professional role, an expert opinion is normally required. The professional geophysicist bears the responsibility to provide stakeholders with a definite statement in the face of many unknowns. The stakeholder, who has employed the geophysicist, is prepared to tolerate only a certain amount of uncertainty. The professional geophysicist must carefully state the inherent uncertainty in the interpretation, but then provide a definite professional opinion that contains *as much uncertainty as the stakeholder is willing to tolerate*. The professional geophysicist should always strive to act in the best interest of the stakeholders without any compromise of scientific integrity.

Example. Superfund.

A primary example of US federal legislation that has driven near-surface geophysical investigations is the 1980 Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), commonly known as Superfund (www.epa.gov/superfund/policy/cercla.htm). This law created a tax on the chemical and petroleum industries in order to maintain a public trust fund managed by the Environmental Protection Agency (EPA). The fund is used to enable a response to releases of hazardous substances that may endanger public health or the environment and to clean up waste sites. Near-surface geophysics is often used for subsurface characterization and remediation (Figure 1.8), and to perform tasks such as monitoring the subsurface transport and fate of a contamination plume.