Ground-Penetrating Radar as a Means of Quality Control for Soil Surveys

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Ground-penetrating radar (GPR) can be used to chart the presence, depth to, and lateral extent of diagnostic subsurface soil horizons. During the past 7 yr, USDA-Soil Conservation Service and participants in the National Cooperative Soil Survey have tested GPR in diverse physiographic regions on a wide variety of soils. The principal use of GPR has been to estimate the taxonomic composition of soil map units and to determine the accuracy of soil mapping completed by conventional sampling procedures. As the users of soil surveys become more diverse, demands are being made for more detailed and quantitative information, and often to depths greater than are presently being attained in most modern surveys. Ground-penetrating radar techniques have been used to supply more detailed and quantitative analysis of soil variability. Compared with conventional surveying methods, GPR provides continuous spatial data of subsurface features, greater depth and lateral coverage per area sampled, and higher levels of confidence in site evaluations. However, the relative success of GPR investigations remains highly site- and interpreter-dependent.

Soil surveys, the production and interpretation of soil maps, were first conducted in the United States in 1899. Since then, the nature and objectives of soil surveys have changed greatly. Prior to the 1950s, soil surveys were oriented largely toward providing technical assistance for soil conservation and agricultural programs. In the 1950s, information and interpretations in soil survey reports were expanded to include forestry, engineering, urban, and other uses not considered in earlier survey reports. Modern soil surveys provide data useful in estimating soil properties and in planning the general location and construction of highways, power transmission lines, sewers, water and drainage systems, dwellings, and waste disposal systems.

In urbanizing areas where land use is most intense, the need for soil information and interpretation continues to evolve at an unprecedented rate (*1*). Users are requesting more detailed and site-specific information with narrower confidence limits, and to depths greater than are presently attained in modern soil surveys (*2*). As users require more accurate and detailed information concerning the characteristics, composition, and variability of soils within map units, the need for more intense sampling and quantitative description of soil variability is being recognized. To fulfill these needs, different approaches to and methods of observing soils may be required.

Even with the development of soil interpretations for different types of land uses, class differentials used in soil classification do not exceed depths of 2 m. Many nonagricultural uses require information from zones deeper than the limits of modern soil survey investigations. The use of soils for sewage lagoons, sanitary landfills (trench), dwellings with basements, excavated ponds, reservoirs, or as sources of sand, gravel, or roadfill, often requires information on soil properties to depths beyond the limits of soil survey investigations or requires additional information where observations made have been insufficient to establish reliable standards. In some areas, conventional methods of observing soils are becoming inadequate for the needs of more exacting users of soil surveys.

While the uses of soil surveys have evolved greatly, surveying tools have changed little since 1899. Though aided by backhoes and mechanical probes, the spade and auger have remained the primary sampling tools of soil surveyors. While effective in most areas, conventional methods of observing soils are slow and tedious and produce incomplete data as a result of the limited number of observation sites and the small area actually observed. It is estimated that more than 99.9 percent of the area delineated on soil maps is not observed below the surface (*2*). The potential for errors is great. In areas where soils are poorly drained, have high densities, or contain large amounts of coarse fragments, surveying costs increase because of time required for field investigations. Errors resulting from insufficient observations and inadequacy of information from deeper soil depths are more conspicuous in these areas.

The depth of observation, efficiency of sampling, and the quality and quantity of data could be increased in many areas if faster and less labor-intensive methods were available to improve or complement existing soil survey techniques. Since the late 1970s, the USDA-Soil Conservation Service (SCS) has been exploring the potential of GPR technology to assist and improve soil survey operations (*3*).

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Ground-penetrating radar is being used to increase the accuracy and precision of soil surveys by providing continuous spatial records of the subsurface, greater depth and areal coverage per unit sampled, and higher levels of confidence in site evaluations. Advantages of GPR systems are speed of operation, capacity to produce large quantities of continuous subsurface data, and high resolution. Compared with conventional methods of observing soils, ground-penetrating radar techniques are faster, more economical, less likely to overlook subsurface features, and nondestructive.

THE GPR SYSTEM

The ground-penetrating radar is an impulse radar system designed for shallow subsurface site investigations. Pulses of electromagnetic energy radiate into the ground from a transmitting antenna. Each pulse consists of a spectrum of frequencies distributed around the center frequency of the antenna. Whenever a pulse contacts an interface separating layers of differing electromagnetic properties, a portion of the energy is reflected back to the receiving antenna. The receiving unit amplifies and samples the reflected energy and converts it into a similarly shaped waveform in a lower frequency range. The processed, reflected waveforms are displayed on a graphic recorder or are recorded on magnetic tape for future playback or processing. The graphic recorder uses a variable gray scale to display data. It produces images by recording strong reflections as black and lesser intensity reflections in shades of gray.

The GPR systems used by USDA-SCS are the Subsurface Interface Radar (SIR) System-8 and System-3 manufactured by Geophysical Survey Systems, Inc. The SIR System-8 consists of a control unit, tape recorder, graphic recorder, and power distribution unit. A microprocessor, which has programs to enhance signals, remove background noise, and amplify weak signals obscured by background noise, is available with this unit.

The SIR System-3 consists of a profiling recorder and a power distribution unit. The profiling recorder houses the radar control electronic and graphic recorder in a single unit. Compared with the SIR System-8, the SIR System-3 unit is easier to use, more portable, and less expensive. Both systems can be powered by a motor vehicle battery or by two 12-v marine batteries.

Five antennas (80, 120, 300, 400, and 500 MHz) have been used to investigate earthen materials. Two higher frequency antennas (900 and 1000 MHz) are available, but their use has been limited to the investigation of reinforcing steel, road pavements, and bridge deckings. The lower frequency antennas (80 and 120 MHz) have longer pulse widths and greater radiation powers and emit signals that are less rapidly attenuated by earthen materials. The higher frequency antennas (300, 400, and 500 MHz) have shorter pulse widths and greater powers of resolution, but are limited to shallower depths. For most field work, the 120 MHz antenna has been found to provide the best balance of probing depth and resolution. The 80 MHz antenna is heavy and cumbersome and is difficult to maneuver in rough or forested terrain.

Each of these antennas has a fairly broad radiation pattern. Theoretically, the radiation pattern is conical with the apex of the cone at the center of the antenna. Reflections from an interface are a composite of returns from within the area of radiation.

A vehicular installation of the GPR has proven to be the most practical approach for soil survey operations in nonforested areas. A four-wheel-drive vehicle provides a mobile, weatherproof base for routine field work and is also used for transporting the equipment. The control and recording units are "shock-mounted" on a shelf within the vehicle. An antenna is towed behind the vehicle in a sled at speeds of 3 to 8 km/h for most field work. The sled protects the antenna and smooths surface irregularities. GPRs have also been mounted on all-terrain vehicles, boats, helicopters, skis, and snowmobiles. In forested or rugged terrain, surveys are often conducted by hand-towing the antennas and the electronics.

HISTORICAL DEVELOPMENT

In the early 1970s, soils were considered to be "essentially radar opaque because of their high electrical conductivity" (*4*). However, in 1979, the feasibility of using GPR for soil survey investigations was successfully demonstrated in a study conducted by the National Aeronautics and Space Administration (NASA), USDA-SCS, and Florida Department of Transportation (*5*). Since then, the use of GPR for soil survey investigations has developed slowly. Use of GPR remains restricted for the following reasons:

- Limited awareness of this geophysical technique,
- Results that are dependent on the skill and experience of the operator,
- Initial high costs of equipment,
- Limited knowledge of its performance in various media and geographical areas, and
- Rapid signal attenuation and severe depth restrictions in some media.

In organic soils, GPR has been used to determine the thickness of organic soil materials(*6–12*), estimate the degrees(s) of humification (*9, 11, 13*), classify Histosols (*7, 14*), and profile the topography at the base of the organic materials (*14–16*).

In recent years there has been a notable increase in the number and types of GPR applications on mineral soils. Applications include characterizing soil map unit composition (*3, 17, 18*), determining water table depths in coarse-textured soils (*19*), summarizing microvariability of depths to soil horizons (*20*), characterizing soil properties (*17*), determining the depth to bedrock (*21*), assessing soil-landscape relationships (*22, 23*), and improving soil-salinity management (*24*).

FACTORS INFLUENCING AREAS OF APPLICATION

Ground-penetrating radar does not perform equally well in all soils. The maximum probing depth of GPR is, to a large degree, determined by the conductivity of the soil. Soils having high conductivities rapidly dissipate the radar's energy and restrict the probing depth. The principal factors influencing the conductivity of soils to electromagnetic radiation are degree of water saturation, amount and type of salts in solution, and the amount and type of clay.

Moisture content is the primary determinant of soil conductivity. Electromagnetic conductivity is essentially an electrolytic process that takes place through moisture-filled pores. As water-filled porosity increases, the rate of signal attenuation increases and the probing depth of the radar is restricted.

Electrical conductivity is directly related to the concentration of dissolved salts in the soil solution. In unirrigated areas, the concentration of dissolved salts in the soil profile and the probing depth of the GPR are influenced by parent material and climatic parameters. Soils formed in regolith weathered from shale or limestone generally contain more ions in solution than soils developed from felsic crystalline rocks. In general, most soluble salts are leached in humid regions. In semi-arid and arid regions, soluble salts of potassium and sodium and the less soluble carbonates of calcium and magnesium are likely to accumulate in soil profiles, the depth of accumulation being a function of precipitation, soil textures, and bulk densities.

Ions absorbed to clay particles can undergo exchange reactions with ions in the soil solution and thereby contribute to the electrical conductivity of the soil. The concentration of ions in the soil solution is dependent on the clay minerals present, the pH of the soil solution, the degree of water-filled porosity, the nature of the ions in solution, and the relative proportion of ions on exchange sites. Smectitic and vermiculitic clays have higher cation-exchange capacities than kaolinitic and oxidic (e.g., gibbsite and goethite) clays, and, under similar soil-moisture conditions, are more conductive (Table 1). Table 2 illustrates how the maximum probing depth of electromagnetic radiation increases as clay content decreases and the proportion of low-activity clays increases.

Soil texture influences the performance of GPR. Generally probing depths are 5–25 m in coarse-textured materials, 2–5 m in moderately coarse-textured materials, 1–2 m in moderately fine-textured materials, and less than 0.5–1.5 m in fine-textured soils. As discussed earlier, these probing depths become less as the concentration of soluble salts in solution and the exchange activities of clays increase.

Acknowledging these limitations, geographic generalizations can be made as to the areas in the United States in which GPR techniques are likely to produce satisfactory results (17). Figure 1 is a map of the United States summarizing the suitability of different geographic areas for GPR investigations of soils. This map is very generalized and ignores the site-specific nature of the radar.

The potential for utilizing GPR techniques for soil investigations is high in areas of coarse- or moderately coarse-textured soil materials, areas of highly weathered soils having low proportions of 2:1 type clays or concentrations of soluble salts, and uplands underlain by felsic crystalline bedrock.

GPR APPLICATIONS TO SOIL SURVEYS

Increasing the Quantity of Soil Data

Within USDA-SCS, GPR has been used as a reconnaissance, investigatory, and quality control tool. The principal use of GPR has been to estimate the taxonomic com-

TABLE 1 CATION-EXCHANGE CAPACITY OF CLAY MINERALS (*25*)

Clay Mineral	Capacity (meq/100 g)
Vermiculite	100–150
Montmorillonite	80–150
Chlorite	10–40
Illite	10–40
Kaolinite	3–15

TABLE 2 PROBING DEPTH OF GPR IN RELATION TO MINERALOGY CLASS AND CLAY CONTENT

Soil	Mineralogy Class	Percent Clay	Probing Depth
Vaiden	Montmorillonitic	>60	15 cm
Rhinebeck	Illitic	35–60	40 cm
Kirvin	Mixed	35–60	2 m
Sites	Oxidic	35–60	5 m

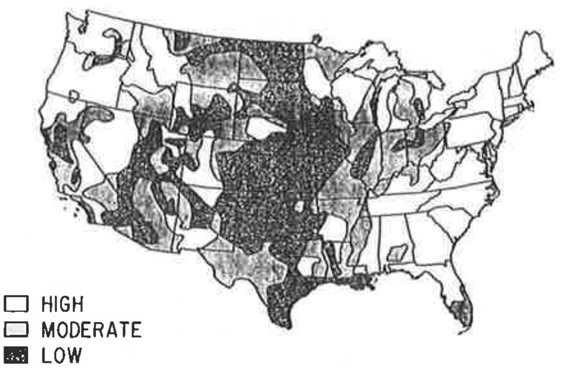

FIGURE 1 Potential for ground-penetrating radar soils interpretations.

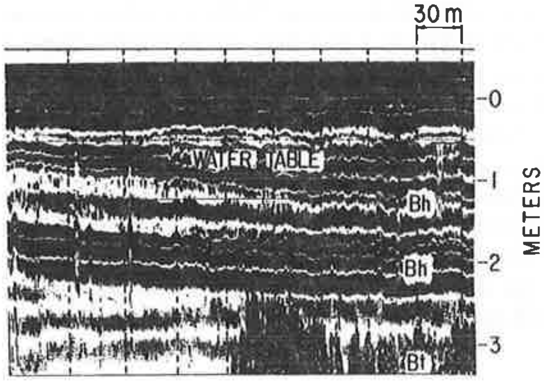

FIGURE 2 A GPR profile charting the water table, and the Bh and Bt horizons.

position and variability of soils within map units obtained with traditional survey procedures. Many of the diagnostic subsurface horizons described in Soil Taxonomy (*26*) can be identified and traced using GPR.

Abrupt changes in texture, density, moisture, or organic carbon content will generally produce strong reflections and distinct GPR imagery. Distinct radar images that are produced by abrupt changes in moisture (water table), organic carbon content (Bh horizons), and texture (Bt horizon) are illustrated in Figure 2. This graphic profile was recorded within an area of sandy, siliceous, hyperthermic Arenic Haplaquods (Immokalee series) in Florida. Dark lines have been drawn to highlight the upper boundary of the water table and the major subsurface diagnostic horizons. The presence and depth to diagnostic soil horizons and soil features are used to classify soils. Knowledge of the lateral extent and depth of these horizons, obtained with GPR, can be used to determine their spatial variability within mapping delineations and thereby document map unit composition.

Ground-truth boring and test data are needed to calibrate radar imagery and to confirm interpretations. To scale the radar data, the dielectric constant of the medium, the propagation velocity of the radar pulse in the medium, or the depth to an interface must be known. Generally, for most soil investigations, one soil boring will suffice to establish a depth scale and to identify soil horizons. In areas of complex soil patterns, more than one boring is often required to properly identify images appearing on the graphic profiles.

The precision of GPR for determining the depth to subsurface features has been well documented. For soil features occurring within depths of 2 m, the difference in measurements between the scaled radar images and the auger boring data is generally within 2.5 to 5.0 cm (*3*).

The precision of data collected using GPR decreases with increasing depth and with soil variability. In an area of loamy, mixed, mesic Arenic Hapludalfs and mixed, mesic Typic Udipsamments (Matea and Plainfield series) in Michigan, the difference in measurements between the scaled radar imagery and the auger boring data were less than 10 cm in 71 percent of the observation sites and less than 5 cm in 43 percent of sites. Differences between the two methods of measurement are attributed to the wide range in water table depths (0.68–4.2 m) and the presence of discontinuous finer-textured strata in these predominantly coarse-textured soils.

In soils having horizons with irregular or broken boundaries, the agreement between the scaled radar imagery and the auger boring measurements will be less. During field investigations of cultivated Histosols within the Florida Everglades, the lack of concurrence between soil auger data and the scaled radar imagery was attributed to the highly pitted nature of the underlying limestone bedrock. Variations in the depth to bedrock as great as 43 cm were observed within a 25-cm radius of observation sites (*19*). At each observation site, it was possible for the soil auger to have contacted a residual microhigh or entered a solution cavity. Soil auger measurements often reflect the extreme rather than the average depth to an underlying interface. GPR profiles, based on a composite of scans that have been averaged across the area of radiation beneath the antenna, are influenced less by an irregular subsurface microtopography.

Where sandy soils with low electrical conductivity predominate, conditions are optimum for the use of GPR. To date, the use of GPR has been most successful in Florida. Data obtained with the GPR in Florida have been used to update the soil surveys for Hardee, Hillsborough, Manatee, Orange, Sarasota, and Seminole counties. GPR data were used to statistically document the proportion of soils within map units. This information was presented in both tabular and descriptive formats in soil survey reports to inform users about soil variability.

Ground-penetrating radar techniques, while not used as fully elsewhere as in Florida, have been used successfully in many other states to increase the efficiency of data collection and to improve the quality of soil interpretations.

Extending the Depth of Observation

Ground-penetrating radar can extend the depth of soil characterization and improve the quality of soil information at lower depths. The examination of soil profiles with conventional surveying tools is restricted by the presence of coarse fragments (cobbles, stones, and boulders). Field time and cost increase as conventional surveying tools (augers and shovels) are repeatedly stopped by coarse fragments. In areas containing large amounts of coarse fragments, decisions are often based on a few widely spaced exposures or on assumed soil-landscape relationships.

Overcoming Restrictive Features in Soils

On many uplands, the depth to bedrock is underestimated as a result of coarse fragments. The probability of encountering a rock fragment with a soil auger increases with soil depth and thereby reduces the probability of observing deep (100–150 cm) or very deep (150 cm) soils. At most sites, it is uncertain whether auger penetration was halted by a rock fragment or by bedrock. In an unpublished study of tills in Maine containing large amounts of coarse fragments, conventional surveying tools could not effectively and consistently probe beyond depths of 75–100 cm. GPR was not restricted by coarse fragments and provided exceptionally high-quality profiles of the underlying bedrock surface (Figure 3). The bedrock contact (highlighted with dark line) is irregular and varies in depth from 30 to 175 cm. In the lower right hand corner of this figure, a vein of dissimilar material or a fracture plane, is apparent within the bedrock. While less pronounced, the contact of ablation till with basal till is evident between depths of 68 and 84 cm.

Very gravelly, stony, or bouldery layers can form restrictive barriers that thwart conventional tools. In a Michigan study, a thin (50 cm), very gravelly (35–60-percent-rock fragments) layer limited the number and depth of auger observations in an area of sandy-skeletal, mixed udorthentic Haploborolls (Alpena series). The time spent excavating this very gravelly layer with a soil auger and pry bar exceeded reasonable limits. Because of time constraints, the inferences made were based on a small number of observations about the underlying materials within the survey area.

To improve the understanding of materials underlying the very gravelly layer, a GPR investigation was conducted. Unlike conventional surveying tools, the GPR provided a continuous record of subsurface conditions and was not restricted by the layers of coarse fragments. In Figure 4, the very gravelly layer is apparent immediately below the surface. Strata within the coarse-textured glacio-lacustrine deposits are evident between depths of 1 to 2 m. The GPR charted the mean and range of thicknesses of sand and gravel deposits, the depth to loamy till, and the occurrence of limestone bedrock.

Determining the Thickness of Sand and Gravel Deposits

Although it may be possible to determine the potential location of sources of sand or gravel from soil survey reports, little information is available concerning the range or average thickness of these deposits. Soils are rated as probable sources of sand and gravel based on properties occurring between depths of 0.25 to 1.5 m.

In many areas, as sand and gravel resources are depleted and the cost of excavation increases, knowledge of the average depth and range in thickness of suitable material will become increasingly important. GPR can be used effectively in coarse-textured materials to determine their potential as sources for sand and gravel.

Estimating Volume of Organic Materials in Peatlands

Soil survey reports provide information concerning the classification and areal extent of organic soil materials. However, these reports do not contain sufficient data for estimating peat volume. To estimate the volume of organic materials, a larger number of measurements to depths beyond the current limits of soil survey investigations may be required. Procedures for estimating the thickness of peat deposits have been established (*27*). However, established methods are time consuming and costly. The speed and continuous subsurface profiling by GPR reduce the cost of data collection and permit sampling of a greater area. With GPR it is possible to quickly assess the volume of peat reserves, estimate the thickness of layers varying in degrees of humification, and profile the topography at the base of the organic materials.

Figure 5 was constructed from data collected from a bog in Wisconsin. Images from the organic-mineral contact

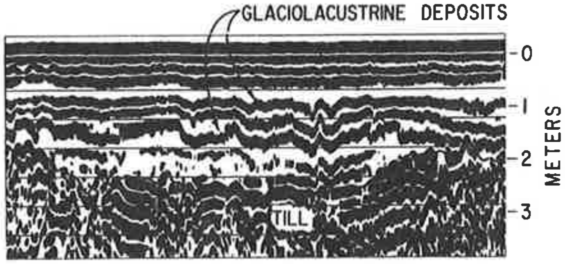

FIGURE 4 A GPR profile of stratified glacio-lacustrine sediments overlying till.

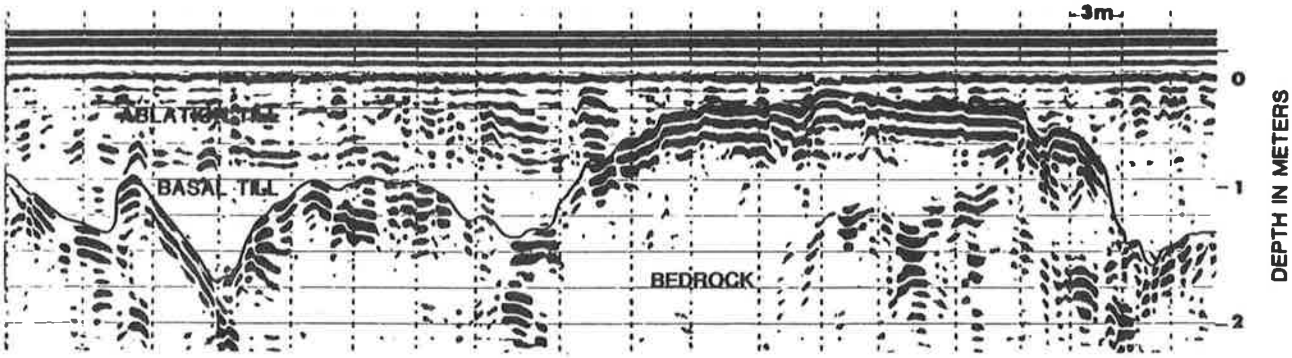

FIGURE 3 A GPR profile of the depth to bedrock.

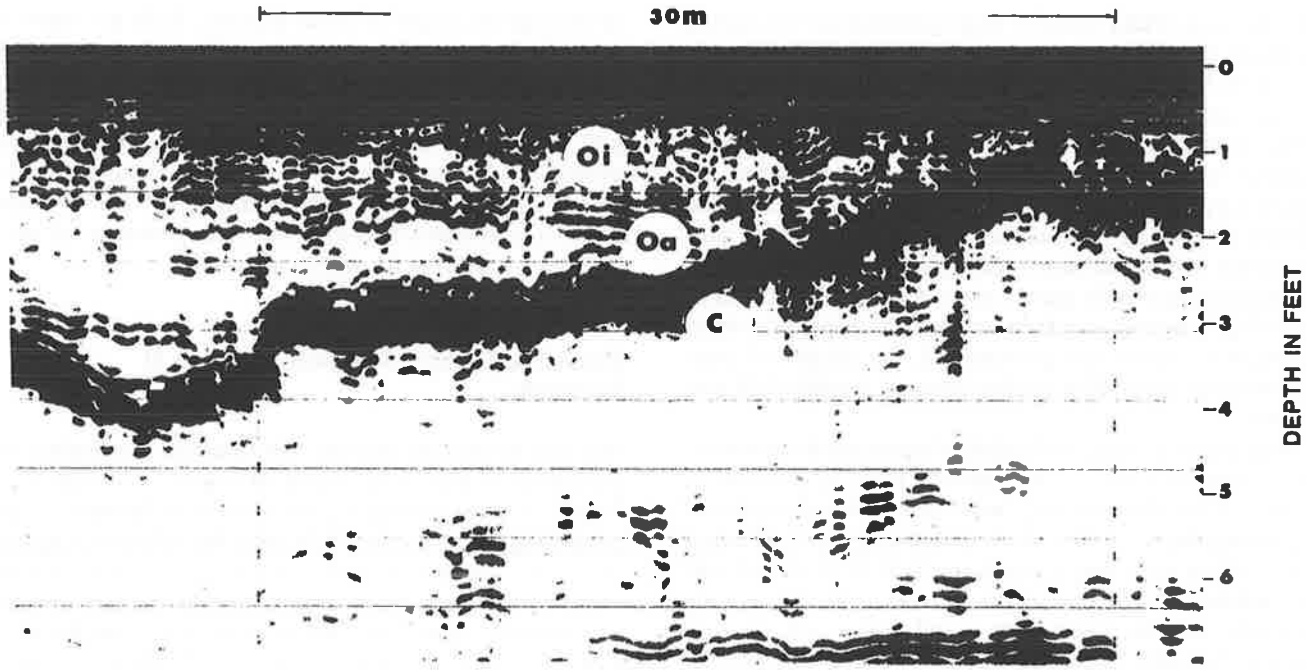

FIGURE 5 A GPR profile of fibric (Oi) and sapric (Oa) organic soil materials and the organic-mineral soil interface (C).

are conspicuous. A contact separating fibric (Oi) from sapric (Oa) organic materials is evident at a depth of 0.5 m. This contact represents a significant change in humification, bulk density, and water content. In the lower part of this figure, strata within the underlying Eau Claire Formation can be seen.

Developing Improved Soil-Landscape Models

As a result of cost and time constraints, soil scientists can not observe profiles from every acre. Observation sites are selected on the basis of soil-landscape relationships and models of soil genesis. Predicting the occurrence and distribution of soils is often based primarily on associations made between soil properties and soil landforms, landscape position, and steepness of slopes. Observation points from which these association models are formulated tend to be limited in number and biased toward the most prominent soils and landscape features (*28*). Unfortunately, as noted by Cline, the predictive value of soil-landscape models is not perfect.

Ground-penetrating radar and computer graphic techniques have been used to produce economical and detailed two- and three-dimensional plots of subsurface conditions. Computer-generated grip maps constructed from data collected by GPR have been used to display soil-landscape relationships (*22, 23*), to characterize the composition of soil map units, and to chart the variability of subsurface horizons and properties (*20*).

In Figure 6, three-dimensional block diagrams of the loess surface and the paleosurface (top of the Pensauken formation) within a 2.52 ha study area in northern Delaware are shown (*23*). Using GPR and computer graphic techniques, it was learned that loess thickness is highly irregular and largely controlled by the underlying paleosurface and cannot be predicted from relief or landform. Documentation of the variability of loess thickness disclosed that the mapping unit names do not properly reflect the composition of the map units. Results from this and other studies underscore the importance of evaluating and improving soil-landscape models and the need for measuring variability in soil properties.

CONCLUSION

Users of soil survey reports are becoming more numerous and diversified. They are requiring more detailed and site-specific information with narrower confidence limits and soil information to depths greater than are presently attained in most modern soil surveys. Ground-penetrating radar has been used to provide accurate and detailed information concerning the characteristics, composition, and variability of soils within map units and to cope with the needs for more intense sampling and detailed and quantitative descriptions of soil variability.

Ground-penetrating radar has been used to increase the accuracy and precision of soil surveys. Compared with conventional surveying methods, GPR techniques provide continuous spatial records of subsurface features, greater depth and areal coverage per unit sampled, and higher levels of confidence in site evaluations. Ground-penetrating radar techniques are also faster, more economical, less likely to overlook subsurface features, and nondestructive.

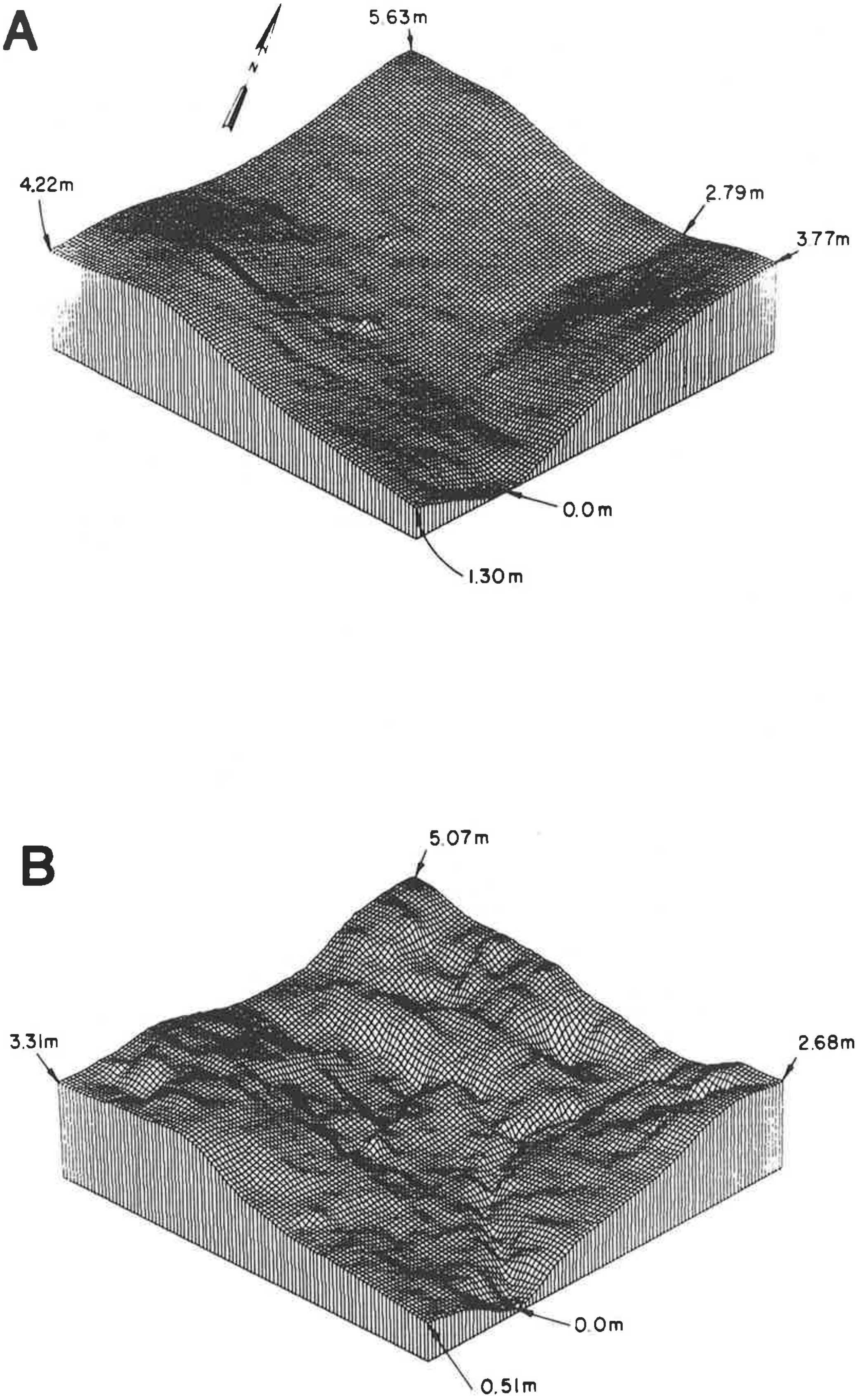

FIGURE 6 Surface net diagrams from GPR profiles showing relative (A) elevation of modern surface and (B) elevation of paleosurface.

Results remain highly site-specific and interpreter-dependent. While it is neither a magic black box nor the panacea to all soil-surveying needs, GPR is a complementary tool that can be used in many areas to increase the quality and quantity of soil data, the depth of observation, and our understanding of soil-landscape relationships.

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