United States Department of Agriculture

Soil Conservation Service

401 SE 1st Avenue, Room 248
Gainesville, Florida
32601

Subject: SOILS - Ground-Penetrating Radar (GPR) Trip Report - Minnesota

Date: February 23, 1984

To: Donald G. Ferron, State Conservationist
SCS, St. Paul, Minnesota

File Code: 430

The ground-penetrating radar (GPR) system was field tested in Minnesota during the period of December 9-17, 1983. The primary purpose of this investigation was to evaluate the systems potential for determining the thickness, degree of decomposition, and stratification of organic soils. The GPR was also scheduled to conduct several studies in mineral soils. The purpose of these studies were to evaluate the GPR´s performance in determining the thickness of surface mantles, depths to water tables, and locating sinkholes and fracture plains in bedrock. A copy of the trip report is attached.

Participants were:

Kip Bolstad, Soil Scientist, MAES, Virginia, Minnesota
Ed Bruns, Assistant State Soil Scientist, SCS, St. Paul, Minnesota
Jim Doolittle, Soil Specialist (GPR), SCS, Gainesville, Florida
Tom Fait, Area Soil Scientist, SCS, Duluth, Minnesota
Brandt Heikel, Soil Scientist, St. Louis County, SCS, Minnesota
Kathy Krupinski, Soil Scientist, SCS, Aitkin, Minnesota
Jeff Lepp, Soil Scientist, SCS, Virginia, Minnesota
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Bob Lueth, Soil Scientist, SCS, Lewiston, Minnesota
Joe Magner, Minnesota Pollution Control Agency, St. Paul, Minnesota
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Mike Oja, Soil Scientist, SCS, Aitkin, Minnesota
George Poch, Soil Scientist, SCS, Rochester, Minnesota
Mary Ryan, Soil Scientist, MAES, Virginia, Minnesota
Charles Saari, Soil Scientist, SCS, Long Prairie, Minnesota
Jerry Sharp, Soil Scientist, Virginia, Minnesota

All commitments scheduled in the itinerary report of November 15, 1983, were met with two exceptions. A snow storm and the inaccessibility of selected areas prompted the cancellation of all geologic investigations scheduled in Olmsted County. A demonstration, scheduled for December 19 in Anoka County, was cancelled because of extremely frigid temperatures.

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A slide presentation on the GPR was given before the state office staff on December 8, 1983, and before the Soil Scientist's Workshop on December 14, 1983. Summary conferences were held on December 19, 1983, before the state office staff, and later before faculty and students of the Soils Department of the University of Minnesota.

The equipment utilized during this field trip was the SIR System-8 with microprocessor and the ADTEK SR-8004H Graphic Recorder. The 80, 120, and 300 MHz antennas were utilized. Generally the equipment operated satisfactorily. The graphic recorder proved to be sensitive to cold temperatures, but operated well when placed in the "heated" cab of the Bombadier. The microprocessor was inoperative during this field investigation due to faulty leads in the control unit. The inability to use the microprocessor did not impair observations or results.

The GPR did not perform well in all investigated organic deposits. Maximum depths of penetration ranged from less than 2.5 meters in the minerotrophic organic soils of Kandiyohi County to 5.7 meters in the ombrotrophic blanket bogs of St. Louis County. Differences in the degree humification or in the internal structure of the organics were not observed on the imagery, not adequately expressed, or not sufficiently correlated to serve as a basis for measurements.

This field study has demonstrated that not all organic deposits are equally suitable for the application of present GPR technology. Although the range of successful GPR applications has been restricted, the potential for using the GPR as a rapid reconnaissance and investigatory tool remains high, especially in the more acid bogs of northern Minnesota.

The GPR provided detailed information which can assist soil survey party leaders characterize map units. Unfortunately, in most moderately fine textured soils in Minnesota, the maximum effective depth of penetration is approximately 1 meter. In coarser textured materials quality imagery was attained from depths as great as 2 to 3 meters.

In an experiment near Fountain, the GPR was used to study the variability in the depth to the limestone bedrock. In the study area the limestone was overlain by 4 to 5 meters of loess. As with other mineral soils, the depth of penetration was restricted. The maximum effective depth of penetration ranged from 1 to 1.3 meters in loess.

All pertinent graphic profiles have been returned to Edward Bruns under a separate letter.

I wish to pass along my personal thanks for the cooperation and enthusiasm that all members of your staff extended to me.

James A. Doolittle

James A. Doolittle
Soil Specialist (GPR)

Attachment

cc: w/attachment
Kenneth C. Hinkley, Assist. Director, Soils Division, SCS, Washington, D.C.
Maurice Stout, Jr., Director, Midwest NTC, SCS, Lincoln, Nebraska
James W. Mitchell, State Conservationist, SCS, Gainesville, Florida
Dr. Richard Rust, University of Minnesota, St. Paul, Minnesota
Tom Malterer, University of Minnesota, St. Paul, Minnesota

ORGANIC SOILS

In recent years increased attention has been focused on the use of ground-penetrating radar (GPR) to investigate organic soils. Engineers, geophysicists, and soil scientists have been using GPR technology in many areas of the world to examine organic soils (Bjelm, 1980; Blom and Nelson, 1980; Geophysical Survey Systems, Incorporated, 1979; Remotec Applications, Incorporated, 1982; Shih and Doolittle, 1984; and Ulriksen, 1980 and 1982).

Researchers have learned that present GPR technology can provide meaningful data on organic soils. Observations have been made concerning the ability of GPR systems to determine the thickness of organic layers, estimate the degree(s) of humification, and profile the variations in "topography" at the base of the organic soils. The principal use of the GPR has been in depth and volume calculations. Compared with conventional methods, the GPR is generally accepted as being faster and slightly more accurate.

The enthusiasm for the GPR must be tempered with an understanding of the incompleteness of our current knowledge and interpretive skills, and the systems limited field applications. The GPR has not been applied to a wide range of organic soils, nor do the studies address their diverse geographic and geomorphic settings. As there is no universally accepted classification or terminology for organic soils, it is often difficult and perhaps misleading to compare results from different areas of the world, let alone from different researchers having varied skills and backgrounds. The examples presented in the literature are mostly from situations in which the GPR has worked exceptionally well. It is uncertain whether many of the depths reported in the literature were consistently achieved and of good and usable quality. Some reported depths may represent the lone and most significant exception to an otherwise more restricted trend in observable depths.

This report contains the findings from field investigations conducted in Minnesota during the period of December 9 to 17, 1983. The primary purpose of this investigation was to determine the thickness, degree of decomposition, and internal stratification of organic soils. Mineral soils were also investigated and the results have been summarized in this report.

The equipment utilized during this field trip was the Subsurface Interface Radar (SIR) System-8, manufactured by Geophysical Survey Systems, Incorporated. The components of the SIR System-8 used in this study consisted of a control unit, a power distribution unit, an ADTEK SR-8004H graphic recorder, and a microprocessor.* Three antennas (80, 120, and 300 MHz) were also utilized. The system was powered from the 12 volt battery of the Bombadier.

An antenna was placed in a wooden sled and towed behind the Bombadier (Figure 1). The sled protected the antenna from obstructions protruding through the snow. The control unit and graphic recorder were placed next to the driver's seat in the Bombadier's cab. The Bombadier provided a highly mobile "heated," "weatherproof" base for routine field work in snow. The snow ranged in depth from 6 to 36 inches. With the exception of the graphic recorder the system performed well in subzero temperatures. The graphic recorder's stylus belt would not turn freely in the open air, but when placed in the "heated" cab performed satisfactorily.

The GPR is a broad-band width, pulse modulated radar system that has been specifically designed to penetrate earthen materials. Electromagnetic waves are emitted at low frequencies to enhance the radar's effective depth

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*Trade names have been used to provide specific information. Their mention does not constitute endorsement by the Federal Government.

of penetration. The eléctromagnetic energy is emitted in pulses of only a few nanoseconds (a billionth of a second) duration. The extremely brief duration of each pulse is essential to achieve maximum discrimination between closely spaced interfaces.

Radar pulses are directed into the soil from the transmitting antenna. When a pulse strikes an interface separating layers of differing electromagnetic properties, a portion of the pulses energy is reflected back to the receiving antenna. The reflected pulse is received by the antenna, amplified, and converted into a similarly shaped waveform in the audio frequency range. The processed reflected signal is displayed on the graphic recorder. By towing the antenna along the ground surface, a continuous profile of subsurface conditions is generated on the graphic recorder.

The graphic recorder produces images by recording strong signals as black, intermediate signals in shades of gray, and weak signals as white. As a general rule, the more abrupt the interface and the greater the differences in electromagnetic properties across the interface, the stronger the reflected signal and the darker the image generated.

Three study areas were selected in Minnesota to field test the GPR on organic soils. The sites were located in Kandiyohi, Aitkin, and St. Louis Counties. Initially, transects were conducted using the 80, 120, and 300 MHz antennas. The 120 and 300 MHz antennas were exceedingly depth restricted and produced poor imagery when used at the sites in Kandiyohi and Aitkin Counties. Due to the poor quality of the graphic profiles, these antennas were not used at the St. Louis County site. The 80 MHz antenna provided the greatest effective depth of penetration through organic soils. The lower frequency 80 MHz antenna has greater average and peak powers of radiation, and emits signals that are less rapidly attenuated than signals emitted from the higher frequency antenna.

The transects displayed in the enclosed figures represent the "best" examples from the numerous transects that were taken at each study area. Each of these transects was conducted with the 80 MHz antenna. Transects were conducted at an average ground speed of approximately two miles per hour.

Depths to the organic/mineral interface and the characteristics of the organics and underlying mineral layers were determined at several reference points with the aid of a Macauley peat sampler. This ground-truth data was used to depth scale and characterize the imagery on the graphic profiles. Without ground-truth data, GPR imagery provides only relative depths. After correlating the ground-truth data with the images on the graphic profiles, depth scales were calculated for each transect with a high degree of confidence.

The first study site was located near Willmar in Kandiyohi County. Here the organics had formed in a lake filled depression on a collapsed and highly pitted glacial outwash plain. The organics are minerotrophic and are strongly contaminated by lime enriched groundwater from the surrounding slopes (rheophilous). The organic layers in this deposit are highly enriched with calcium carbonates. The organics are underlain by limnic materials, principally marl. The dominant soil in the study area is Lena (euic Typic Medisaprists).

The 80 MHz antenna consistently provided not only the greatest depth of penetration but also the clearest and most detailed imagery at this site (Figure 2). Unfortunately, the rate of signal attenuation was so severe in the organics that the imagery is difficult to follow even after improvements in signal amplification.

With the GPR, a natural tendency is to "squeak-up" the signal gain on the control unit in order to amplify deeper and weaker subsurface reflections. High gain settings often result in multiple, parallel lines of reverberations. These reverberations are inherent in the radar system and become prominent at high gain settings making interpretations exceedingly difficult.

It is difficult to discern the lateral extent of the organic/mineral interface along this transect. Severe rates of signal attenuation limit the effective depth of penetration to less than 2.5 meters (8.3 ft). Below this depth, the reflected signals from the organic/mineral interface are too weak to be recognized on the graphic profile even after signal amplification.

The restricted depth of penetration was most disappointing to the participants. Earlier studies had described detailed profiles of organics to depths in excess of 10 to 15 meters (Bjelm, 1980; and Ulriksen, 1980). In most of the reported studies, a determination of the maximum effective depth of penetration was restricted by limitations in the thicknesses of the organics rather than by limitations in the capabilities of the GPR. The organics were simply too shallow to evaluate the maximum depth of GPR penetration. In these studies, the organics provided favorable mediums for the application of GPR.

The dashed vertical lines in Figure 2, were impressed on the graphic profile by the operator as the antenna was towed passed "flagged" reference points along the transect line. The reference points are spaced at intervals of approximately 15.2 meters.

Interface signals are generally displayed in groups of three continuous bands. Each group of bands represent signal oscillations from the same interface. Along the left margin of Figure 2: "A" represents oscillations inherent in the design of the 80 MHz antenna; "B" includes interface signals and oscillations caused by superimposed surface and near surface features; "C" includes system noise induced on the graphic profile by high gain settings.

In Figure 2, the image of the organic/mineral interface is denoted by "D." The image is generally clear and complete above a depth of approximately 1.5 meters. The image becomes discontinuous between depths of 1.5 and 2.5 meters, and is indistinct below depths of 2.5 meters.

Within the upper 2.5 meters of the organic soils, the GPR did not distinguish layers having different degrees of humification, moisture content, or density. Several studies (Bjelm, 1980; Remotec Applications, Incorporated, 1982; and Ulriksen, 1982) have inferred the potential of the GPR to identify different layers within organics. Further investigations and the development of interpretive skills are necessary in order to begin to exploit this potential.

In order for the radar to discern the reflected signal, Ulriksen (1982) stipulated that the interfaces must be abrupt and the difference in the degree of decomposition between two layers must be at least 2 to 3 units in the Von-Post method. Lateral shifts from sapric material to either hemic or limnic materials are not distinguishable in Figure 2. Possibly, the transitions were too gradual or the high calcium carbonate content of the groundwater diluted the electromagnetic gradient across the layers.

Ground-truth measurements provide the basic data on which radar imagery is scaled and compared. This data can and often does contain an inherent degree of measurement error. Measurement error can be attributed to the habit of rounding off numbers, nonvertical probing, and slight spatial discrepancies between the site of measurement and the track of the radar scan.

The antenna has a fairly broad radiation pattern within the ground and "averages" the depth to an interface across the area of radiation. Theoretically, the radiation pattern is conical in shape with the apex of the cone at the center of the antenna.

TABLE 1

Deviation Between Measured Depths and the Scaled Radar Imagery

Method of Measurement	Reference Points				
	50	100	150	200	250
Depth to mineral layer	12.0"	16.0"	26.0"	30.0"	60.0"
Scaled depth	11.5"	17.8"	28.3"	29.4"	53.0"
Absolute deviation	-0.5"	+1.8"	+2.3"	-0.6"	-7.0"

Average deviation - 2.44"

Slight discrepancies often exist between soil boring data and the depths scaled on the graphic profile. In order to document the accuracy of the GPR system at this site, a study was conducted comparing scaled radar imagery with ground-truth auger data.

The measured depth to the organic/mineral interface, the scaled depths of the radar imagery, and the difference between these measurements are listed in Table 1. The average deviation between soil boring depths and scaled radar imagery is 6.2 cm. The deviations between the scaled radar imagery and the ground-truth auger data are as follows: within 18 cm at all sites; within 5.8 cm in 80 percent of all sites; within 4.6 cm in 60 percent of all sites; and within 1.5 cm in 40 percent of all sites. The match between the ground-truth data and the scaled radar imagery, with the exception of the deepest site, is considered remarkable. Changes in the velocity of signal propagation with increasing depth may have caused the wider disparity between the data and the imagery at the deepest site.

The second study site was located near Aitkin in Aitkin County. The site was located on the level plain of Glacial Lake Aitkin. The organics had formed in the lowest part of the landscape principally through the process of paludification. The organics are generally less contaminated by groundwater seeping from surrounding slopes than the Kandiyohi site. The organics are underlain by limnic materials, principally coprogenous earths. The dominant soils in the study area are Seelyeville (euic Typic Borosaprists) and Cathro (loamy, mixed, euic Terric Borosaprists).

After several trial runs, the graphic profile shown in Figure 3 was produced. Compared to the Kandiyohi site, the Aitkin profile was clearer, more continuous, and less depth restricted. High rates of signal attenuation continued to frustrate investigations, but the effective depth of penetration was extended to 3.2 meters (10.4 ft) as a result of more favorable ground conditions.

In Figure 3, the unevenness of the surface reflection and reverberations is believed to have been caused by variations in the thickness and degree of compaction of the snow cover. The thick snow cover insulated the organics and retarded the development of a frozen layer near the surface. Greater penetration can be achieved at this site with a thinner mantle of snow and the deeper development of a frozen layer (Sellmann, Arcone, and Delaney, 1983).

Several white "blobs" are contained within the imagery of the organic/mineral interface near sites 1 and 3 in Figure 3. These "blobs" probably have resulted from the superimposition of reflection from point sources distributed along the interface. Possible point source include buried logs or boulders. The narrow, sweeping lines in the lower part of the graphic profile below sites 1 and 4 were caused by folds in the graphic paper.

The graphic profile contains no apparent evidence of internal stratification within the organics.

The graphic profile in Figure 3 is plagued by system noise that has been induced on the graphic profile by high gain settings. The prominent, continuous lines that appear on the graphic profile at a depth of approximately 2 meters are believed to be double return echoes from the surface reflection (a form of unwanted noise).

The last organic deposit studied during this field trip was located near Meadowland in St. Louis County. The site is known as the Toivola Bog. This is the site of an earlier GPR investigation by Harding-Lawson Associates and the Minnesota Department of Natural Resources (Blom and Nelson, 1980).

The Toivola bog, having developed upslope from a depression, is believed to be ombrotrophic. It is a "blanket bog" characterized by lower levels or values of pH, lime, and nutrients. The dominant soil in the study area is Rifle (euic Typic Borohemists) with inclusions of a sandy, euic Terric Borohemists.

The organics are dominated by hemic material and range in thickness from 18 to 210 cm. The organics are underlain by a thin veneer of silt loam which varied in thickness from 3 to 20 cm. The underlying material is stratified fine and very fine sands.

The maximum depth of organics in Figure 4 is approximately 2 meters. As no deeper deposits were located along the transect route, the maximum detectable depth through these organics remains speculative. Excellent subbottom reflections were obtained from depths as great as 5.7 meters, but no attempts were made to determine the systems maximum depth of penetration in this area.

In Figure 4, the reflection from the organic/mineral interface (A) is readily apparent. Some indication of layering within the organics is also evident on the graphic profile (B). The layering appears intermittently along the transect, but is consistent in pattern, strength, and location. The layering could not be identified or verified because of insufficient ground-truth data. Distinct subbottom stratifications, presumably within the sands, are evident at "C." A strong, continuous subbottom reflection (D) is apparent on the graphic profile. A possible source of this reflection could be the underlying finer textured drift.

The 80 MHz antenna is unshielded and some radiation is emitted upwards from the unit. At "E," the antenna was towed beneath overhanging limbs from a tamarack tree. The imagery recorded on the graphic profile at "E" represents the false echoes from the overhanging tree limbs.

Figure 5 is a nonreduced copy of a portion of a transect conducted at a lower range setting. The intricacies of the organic/mineral interface imagery are more apparent in this figure than in Figure 4. The apparent irregularities in the near surface and surface reflections between reference points 100 and 270 were produced by uneven snow compaction and the presence of varying thicknesses of water in the compressed tracks of the Bombadier. The indications of possible layering within the organics is again apparent at "B."

Figure 5 provides an excellent profile to once again compare the measured depth to the organic/mineral interface with the scaled depths of the radar imagery, and to observe the difference between these measurements (Table 2).

In this example, the average deviation between soil boring depths and the scaled radar imagery is 3.7 cm. The deviation between the scaled radar imagery and the ground-truth auger data are as follows: within 12 cm at all sites; within 5 cm in 83 percent of all sites; and within 2.3 cm in 50 percent of all sites.

This investigation has demonstrated the need for cautious site assessment prior to recommending the use of ground-penetrating radar techniques for making surveys of organic soils. The study sites examined in Kandiyohi, Aitkin, and St. Louis Counties are each unique in terms of their physical and chemical compositions. Not all of these sites were suitable for the application of GPR. The sites investigated in Aitkin and St. Louis Counties provide suitable environments for the use of GPR technology to determine the depth and volume of organics.

MINERAL SOILS

The GPR system was used to help characterize several map units composed of mineral soils in Kandiyohi, Aitkin, St. Louis, and Olmsted Counties. With the exception of studies conducted in Olmsted County, these transects were adjuncts to the investigation of organic soils.

Interpretations from these investigations are limited by the lack of adequate ground-truth data. Ground-truth data was not collected in Kandiyohi, Aitkin, and St. Louis Counties. Without ground-truth reference data, it is impossible to accurately identify the imagery, and the time based measurements of the GPR can only provide relative depths. In the absence of adequate ground-truth data, depth scales were constructed on the graphic profiles based on standard "tabled" values for the assumed average relative dielectric constant of the medium. This method is sufficient for preliminary surveys which test the applicability of the GPR.

At all of the sites investigated, the 80 MHz antenna provided detailed information to depths of 1 meter. In coarser textured materials, good quality imagery was attained from depths as great as 2 to 3 meters.

The presence of 15 to 90 cm of snow did not inhibit the reception of subsurface signals, but did introduce errors into the interpretations. Variations in snow depths and densities, and the superimposing of the surface reflections from the snow and the soil created havoc.

The GPR is not only site specific, but is weather dependent. The cold, snowy Minnesota weather was responsible for increasing the number of near surface reflections which complicated the interpretations of the graphic profiles. Consider the interfaces that were weather induced and added to the confusion within the graphic profiles: snow, frozen soil layers, unfrozen soil layers. The signals from these features were completely or partially superimposed upon the diagnostic soil horizons and confused the near surface interpretations.

Figure 6 is an example of a transect from which adequate ground-truth data was collected. The transect was conducted in an area of Dakota (fine-loamy over sandy or sandy skeletal, mixed, mesic Typic Argiudolls) and Chelsea (mixed, mesic Alfic Udipsamment) soils near Rochester. The spacing between each reference point (numbered across the top of each profile) is approximately 30 meters.

Areas of Dakota soil are identified by the weakness and relative paucity of subsurface reflections. The clay loam argillic horizons dissipated the radar signal and restricted the depth of effective signal penetration. Depending upon the clay content and thickness of the argillic horizon, the reflection from the underlying sandy outwash sediment (dashed line) is weak or nonexistent.

Areas of Chelsea soil (A) are identified by the relative strength and number of subsurface reflections. The soil is stratified. At reference point 5, Chelsea soil consisted of 91 cm of loamy sands overlying an 8 cm strata of sandy loam. The underlying material is coarse sand.

The transect is approximately 85 percent Dakota and similar soils, and 15 percent Chelsea and similar soils.

General trends are apparent on all graphic profiles. These trends or groupings relate to variations in soil type or subsurface conditions. The graphs are useful as a preliminary guide to segment the landscape and locate "typical" sites for more detailed soil characterization.

TABLE 2

Deviation Between Measured Depths and the Scaled Radar Imagery

Method of Measurement	Reference Points					
	0	100	170	270	370	470
Depth to mineral layer	54.0"	12.0"	7.0"	24.0"	54.0"	72.0"
Scaled depth	54.0"	11.1"	6.2"	20.5"	52.1"	73.6"
Absolute deviation	0	-0.9"	-0.8"	-4.5"	-1.9"	+1.6"

Average deviation - 1.45"

References

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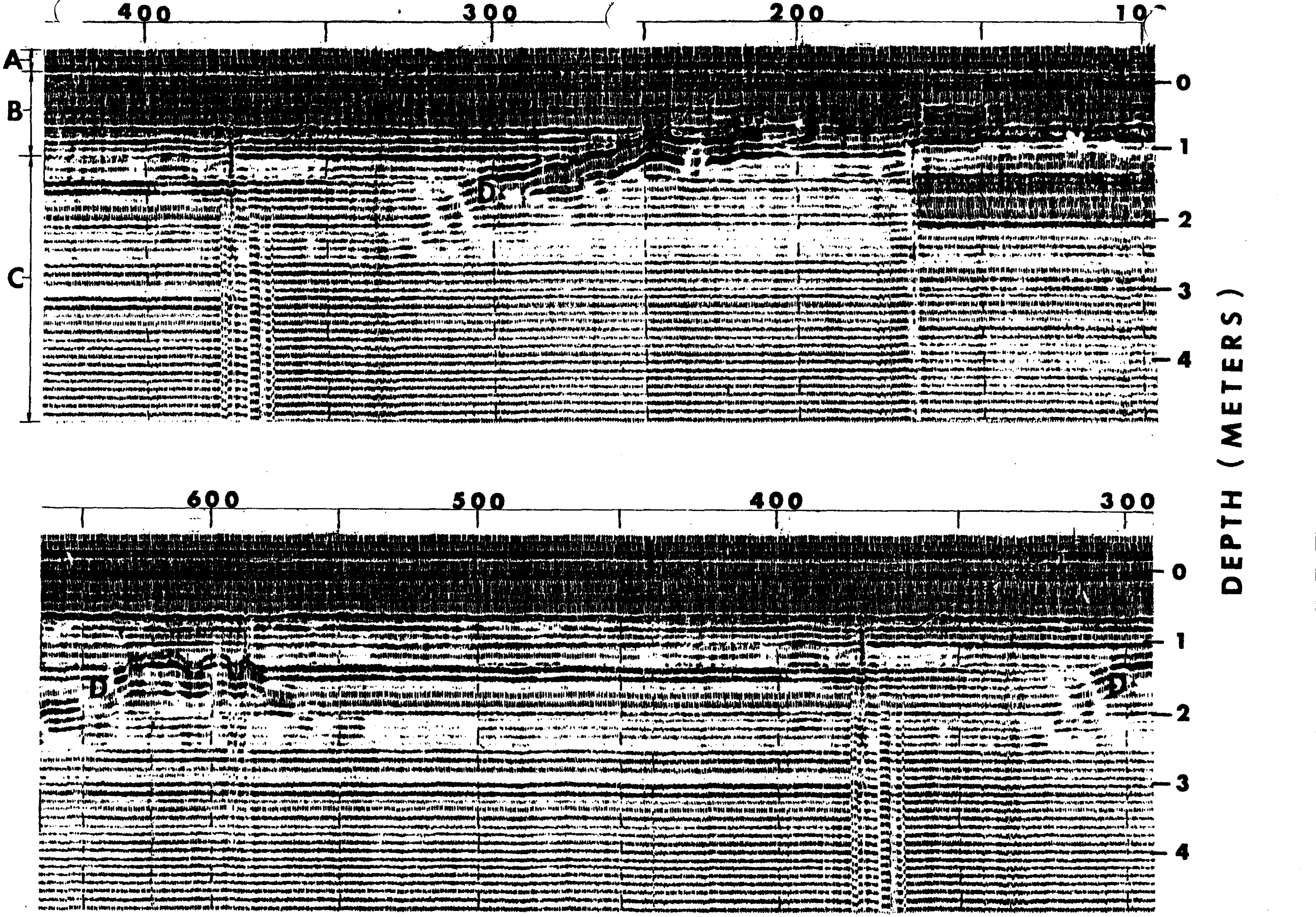
Ulriksen, C. P., (1980). Investigation of Peat Thickness with Radar. Prof. paper Lund Institute of Technology, Department of Engineering, Geology, Lund Sweden.

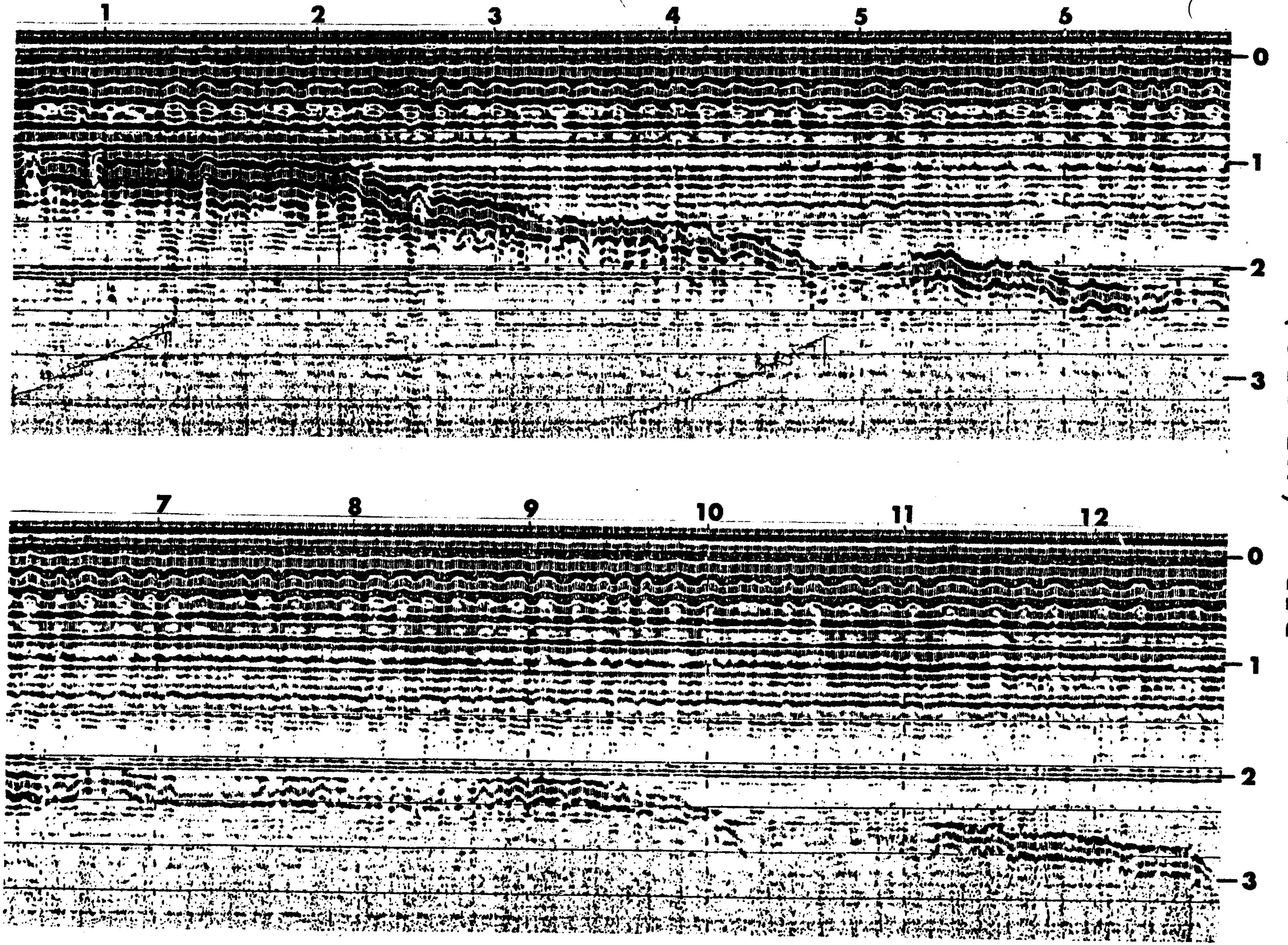
Ulriksen, C. P.,(1982). Application of Impulse Radar to Civil Engineering Doctoral Thesis, Lund University of Technology, Department of Engineering, Geology, Lund, Sweden.

FIG. 2



GPR TRANSECT IN AN AREA OF MEDISAPRISTS
KANDIYOHI COUNTY, MINN.

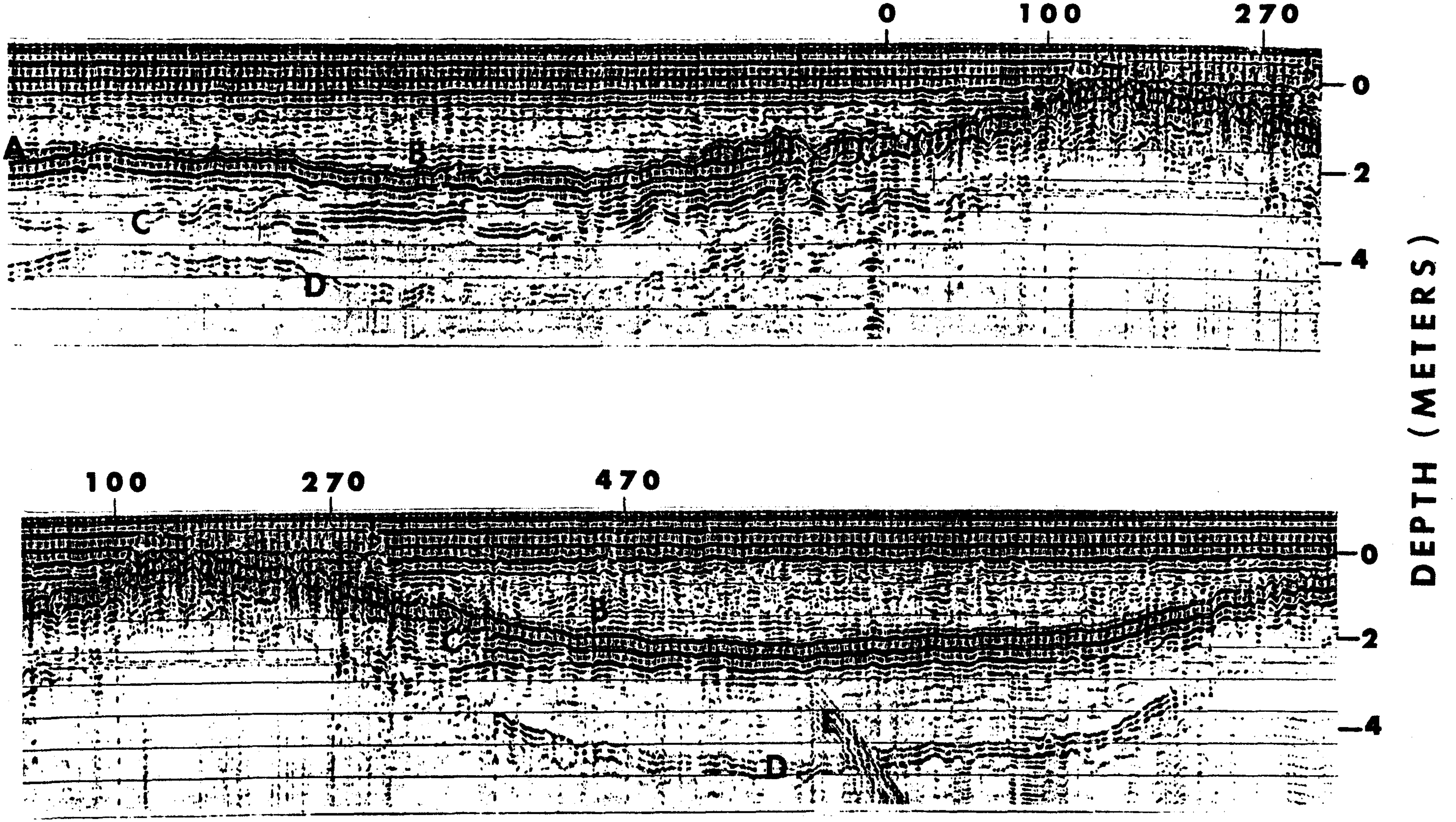
FIG 3



GPR TRANSECT IN AN AREA OF BOROSAPRISTS

AITKIN COUNTY, MINN.

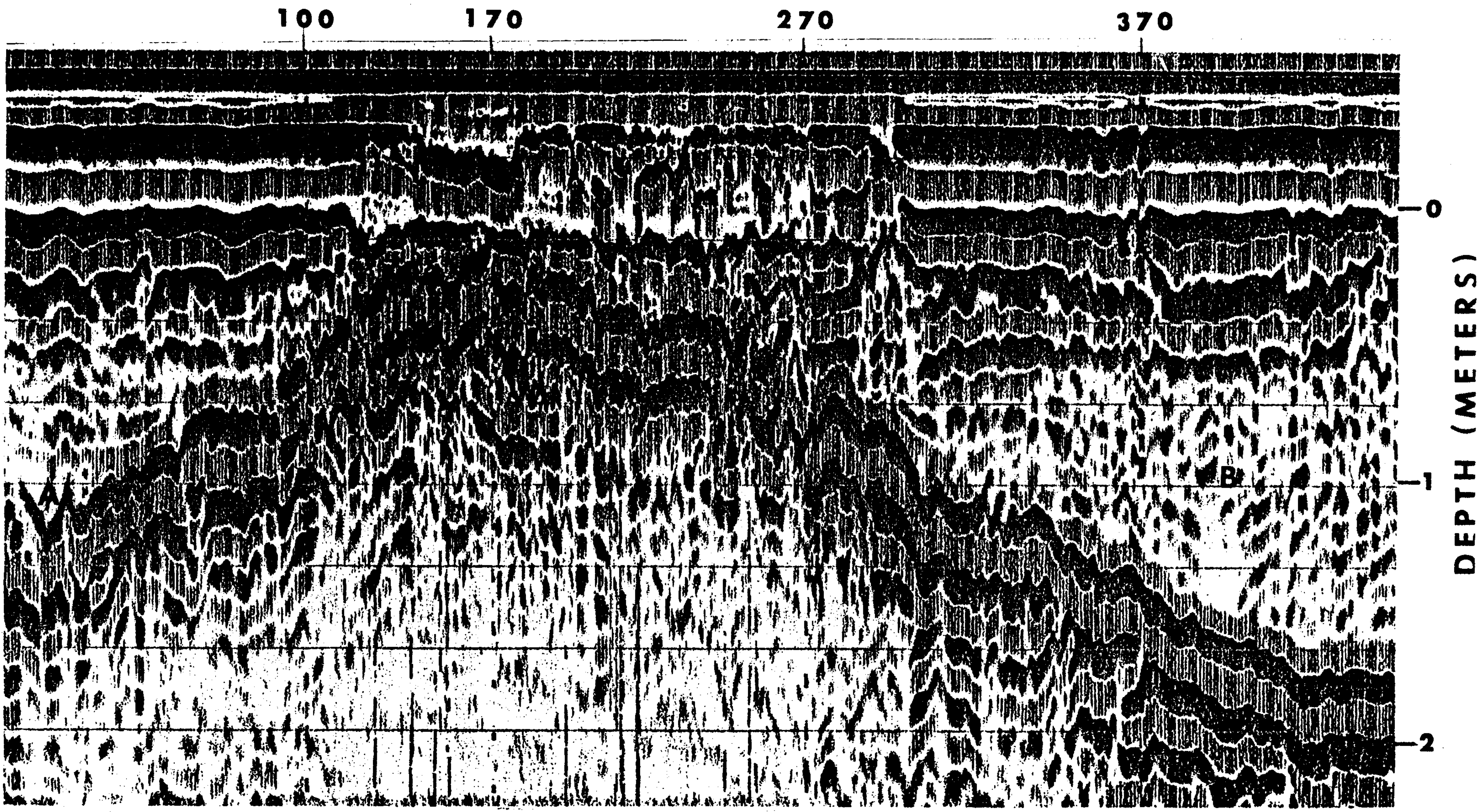
FIG. 4



GPR TRANSECT IN AN AREA OF BOROHEMISTS

ST. LOUIS COUNTY, MINN.

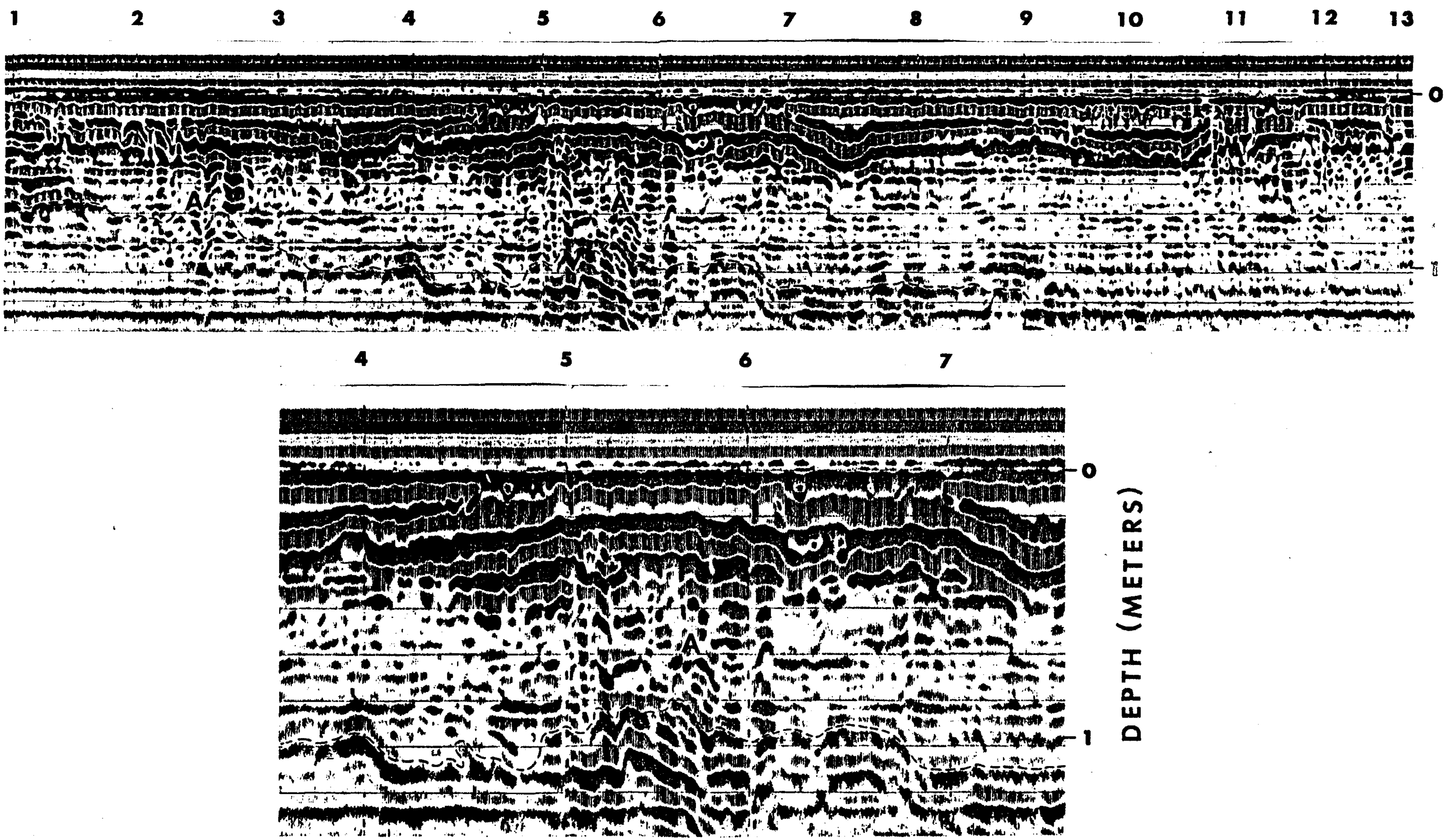
FIG. 5



GPR TRANSECT IN AN AREA OF BOROHEMISTS

ST. LOUIS COUNTY, MINN.

FIG. 6



GPR TRANSECT IN AN AREA OF DAKOTA AND CHELSEA SOILS