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United States Department of Agriculture

Soil Conservation Service

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

Date: July 17, 1984

To: Rex D. Tracy, State Conservationist
SCS, Massachusetts

File Code: 430-5

JUL 25 1984

Miller
Giuliano
Langlois
Quandt
Rice
Smith
Crosson
Gehlen
Hodges
Noce
File
Waste Basket

During the period of June 11-15, 1984, a field study was made to familiarize field soil scientists with ground-penetrating radar (GPR) technology and to evaluate the system's potential on a variety of soils in Massachusetts. A presentation and field demonstration were given before a biennial meeting of the Northeast Regional National Cooperative Soil Survey at the University of Massachusetts on the afternoon of June 12 and the evening of June 13, respectively.

Participants included:

Carl Gustafson, Engineer, SCS
Peter Fletcher, Soil Survey Party Leader, SCS
Denise Frappier, Soil Scientist, SCS
Tom Peragallo, Soil Survey Party Leader, SCS
Steve Schertzer, Graduate Student, BU
Mike Simmons, Engineering Technician, SCS
Eric Swenson, Soil Survey Party Leader, SCS
William Taylor, Soil Survey Party Leader, SCS

The equipment utilized during this field trip was the SIR System-8 with microprocessor, the ADTEK SR-8004H graphic recorder, and the ADTEK DT 6000 tape recorder. The 80 and 120 MHz antennas were used for field work. The equipment operated well with no noted malfunctions.

The ground-penetrating radar or, as it is known by its manufacturer, the subsurface interface radar, was made commercially available and field tested in northeastern Massachusetts. Early successes in the coarse textured glacial drift and the crystalline bedrock of New England spurred the growth of GPR technology. It was a most rewarding experience to bring the equipment and myself "back home."

Results from GPR field work in Massachusetts are exceptional and comparable with results obtained in Florida, the home of SCS's GPR program. Excluding an areas of Boxford soil which is underlain by silts and clays, good to excellent results were achieved at all sites.

As a rapid reconnaissance tool for site assessments, the GPR offers a highly accurate and reliable alternative method for determining the depth to bedrock in most areas of Massachusetts. Generally, the GPR provided clear and easy to interpret profiles of the bedrock surface in about 50 percent of the areas transected. In the remaining 50 percent, the bedrock surface was less clear and was inferred from characteristics of the graphic signature. Near Buzzard Bay, a water table was profiled in coarse texture outwash and traced from a depth of 6 to about 38 feet across a "furrow" and sloping upland. This is the deepest depth to which a water table has been traced.

The results from Massachusetts are most encouraging. The potential application of the GPR will depend on its need, use, and program development. The enclosed report summarizes the field work and highlights the major factors affecting the GPR's operation and interpretations in Massachusetts. All pertinent graphic profiles have been returned to Gene Grice under a separate cover letter.

Thank you for the opportunity to work in your state and to share a most rewarding experience with members of your staff.

James A. Doolittle
JAMES A. DOOLITTLE
Soil Specialist (GPR)

Enclosure

cc:
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PRINCIPLES OF OPERATION

The GPR is a broad bandwidth, pulse modulated radar system that has been specifically designed to penetrate earthen materials. Relatively high frequency, short duration pulses of energy are transmitted into the ground from a coupled antenna. When a pulse strikes an interface (boundary) separating layers of differing electromagnetic properties, a portion of the pulse's energy is reflected back to the receiving antenna. The reflected pulse is received, amplified, sampled, and converted into a similarly shaped waveform in the audio frequency range. The processed reflected signal is displayed on the graphic recorder or is recorded and stored on magnetic tape.

The graphic recorder uses a variable gray scale to display the data. It 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 difference in electromagnetic properties across the interface, the stronger the reflected signal and the darker the generated image.

The graphic profile is developed as electrosensitive paper moves under the revolving styli of the graphic recorder. Reflections above a preset threshold level are "burned" onto the electrosensitive paper. Each scan of a stylus draws a line across the paper in the direction of increasing signal travel time (depth). The intensity of the images printed along each line is dependent upon the amplitude of the processed signals. A continuous profile of subsurface conditions is "burned" onto the paper by the graphic recorder by towing the antenna along the ground surface.

Figure 1 is an example of a graphic profile. The horizontal scale represents unit of distance traveled along the transect line. This scale is dependent upon the speed of antenna advance along the transect line, the rate

of the paper advance through the graphic recorder, and the playback speed of data recorded on magnetic tape. The vertical scale is a time or depth scale which is based upon the velocity of signal propagation. The dashed vertical lines are event markers inserted on the graphic profile by the field operator to indicate known antenna positions or reference points along the transect line. The evenly spaced horizontal lines are scale lines. Scale lines provide reference planes for relative depth assessments.

Most graphic profiles consist of four basic components: the start of scan image (A), inherent system images (B), surface images (C), and subsurface interface images (D). All of these components, with the exception of the start of scan image, are generally displayed in groups of three dark bands unless limited by high rates of signal attenuation or the proximity of two or more closely spaced interface signals. These bands, which are produced by oscillations in the reflected pulses, limit the ability of the GPR to discriminate shallow or closely spaced interfaces. The dark bands occur at both positive and negative signal amplitudes. The narrow white line(s) separating the bands represent the neutral or zero crossing between the polar amplitudes.

The start of scan image (A) is a result of the direct coupling of the transmit and receive antennas. Though a source of unwanted clutter, the start of scan image is often used as a time reference line.

Reflections inherent in and unique to each of the system's antennas are the first series of multiple bands on graphic profiles. Generally, the number and width of these bands increase with decreasing antenna center carrier frequency. These reflections (B) are a source of unwanted "noise" in graphic profiles.

The surface images (C) represent the first major interface signal. The first zero crossing of the surface images is normally selected as a matter of its convenience and repeatability as the soil surface for depth calibrations and measurements.

Below the images of the surface reflection are the images from subsurface interfaces (D). Interfaces can be categorized as being either plane reflectors or point objects. Most soil horizons and geologic layers will appear as continuous, parallel, multiple bands similar to those appearing in the left-hand portion of Figure 1. Small objects, such as rocks or buried pipes, will appear as point objects and will produce hyperbolic patterns similar to those appearing in the right-hand portion of this figure. Hyperbolic patterns are a function of the radar's conical area of radiation which enables the antenna to receive echoes even though it is not directly over the object.

SOILS INVESTIGATIONS

In Massachusetts, the field study with the ground-penetrating radar (GPR) included a wide geographic area and variety of soil. Representative soils were profiled with the GPR in areas of Hampshire, Worcester, Middlesex, Norfolk, and Barnstable Counties. Soil profiled included: Amostown (coarse-loamy, mixed, mesic Typic Dystrochrepts), Boxford (fine, mixed, mesic Aquic Dystric Eutrochrepts), Carver (mixed, mesic Typic Udipsamments), Charlton (coarse-loamy, mixed, mesic Typic Dystrochrepts), Enfield (coarse-silty over sandy or sandy-skeletal, mixed, mesic Typic Dystrochrepts), Hollis (loamy, mixed, mesic Lithic Dystrochrepts), Holyoke (loamy, mixed, mesic Lithic Dystrochrepts), Narragansett (coarse-loamy, mixed, mesic Lithic Dystrochrepts), and Paxton (coarse-loamy, mixed, mesic Typic Dystrochrepts).

Though having a wide range of particle-size classes, these soils belong to only two suborders: Ochrepts and Psamments. As a result of the shortness of time since the last glaciation, evidence of alteration is weakly expressed in these soils. All have ochric epipedons and most have cambic horizons. Unfortunately, these diagnostic features are weakly expressed or gradational and are not normally discerned by the GPR.

The GPR is a subsurface interface radar. It has been specially designed to provide information concerning subsurface conditions. Some surface conditions or features, such as the presence or absence of an organic root mat, barren soil, or shallow puddles of water, have been inferred from the graphic imagery. In some areas, ochric epipedons have been distinguished from umbric or mollic epipedons. But generally, surface and near surface features are masked by the strong amplitude of the surface reflection and its reverberated signals.

The shallowest depth at which an interface can be detected is controlled by the type and condition of the soil material and by the length of the

transmitted pulse. With the 120 MHz antenna, the shallowest depth at which an argillic horizon has been discerned in moderately-fine textured soils is approximately 7 to 10 inches.

As a general rule, the more abrupt an interface and the greater the electromagnetic gradient across an interface, the stronger the reflected signals. In the soils examined, the boundary of the surface or subsurface layers within the subsoil was too gradual and lacked sufficient contrast for the radar to detect. Cambic horizons are altered horizons, but the degree of alteration is generally too slight and the electromagnetic gradient too gradual for the radar to detect.

Though the pedogenetic features were weakly expressed, geologic features were strikingly apparent and provided the basis for the identification and separation of the soils. In Massachusetts, geologic and soil/geologic interfaces were excellent reflectors of the radars energy and provided the imagery on most graphic profiles.

In any GPR field study, the first step is antenna selection. Four antennas (80, 120, 300 and 500 MHz) were available for this study. Generally, the most suitable antenna is the one having the highest possible frequency and able to penetrate to the desired depth. Provided sufficient energy is available to penetrate to the desired depth, a higher frequency antenna will provide better resolution of subsurface features.

In the soils examined, the 120 MHz antenna provided ample depth of penetration and good resolution of most soil and geologic features. The 80 MHz antenna was tested at several sites. Though the 80 MHz antenna displayed a greater potential to probe to deeper depths than the 120 MHz antenna, depth was not a critical factor when comparing the utility of these antennas for soil investigations. With the 80 MHz antenna, near surface or closely spaced interfaces were poorly resolved and many appeared to have been "averaged" together by its broader bandwidths. As the 120 MHz antenna provided good

resolution of subsurface features, no attempts were made in this study to use the 300 or 500 MHz antennas.

The depth scale on all graphic profiles is a time scale. This time scale can be converted into a depth scale once the average rate of signal propagation through the soil has been determined or the depth to an interface is confirmed by auger borings.

Generally, the depth scales are accurate within each map unit provided the soils are similar and are on similar positions in the landscape. When extended across soil boundaries, drainage classes, or slope positions, depth scales can only be close approximations and should not be relied upon for highly precise measurements unless the number of ground-truth observations is increased.

The second step in all field operations is the calibration of the control and recording units to achieve optimal signal returns. This procedure is relatively simple in areas of uniform soils and soil conditions. In areas of similar soils, once the optimal settings have been achieved, readjustments are generally unnecessary. As the complexity of soils and soilscapes increase, readjustments are required to maintain optimal settings.

The control and recording units are adjusted to achieve the most optimal settings at the beginning of each transect. No single combination of range gain or filtration settings is suitable for the diverse soil conditions encountered along transect conducted in areas of complex soilscapes. Along several transects, the lack of or the reduction in the quality of subsurface interfaces can be attributed to wetter soil conditions or higher clay content, and the radar being temporarily out of optimal adjustment or pressed beyond its limits.

The SIR 4800 control unit was designed to satisfy the need for variable range gain and filtration settings in areas having dissimilar soils or soil conditions. Transects recorded on magnetic tapes can be played back with

range gain and/or filtration settings being continuously adjusted to cope with variations in soil conditions. Though time consuming, this procedure enhances the imagery on most graphic profiles.

The first soil profiled with the GPR was Boxford silt loam. Boxford soils (Figure 2) formed in glacio-lacustrine deposits. In the study area, profiles were silt loam in the upper part and varved silts and clays in the lower part. Regardless of whether the 80 or 120 MHz antennas were utilized, depth of penetration were restricted to the contact with the varved sediments.

The clays were responsible for the rapid and complete dissipation of the radar's signals. In many medium, the maximum depth of signal penetration is inversely related to the rate of signal attenuation. The attenuation coefficient for saturated clays is approximately 20 decibels per meter (db.m). This value is relatively high when compared with similar values for saturated sands (2.3 db.m $^{-1}$) or dry sand (0.14 db.m $^{-1}$).

In Figure 2, the boundary separating the moderately fine textured and the fine textured deposits is apparent at "A." Near "B," this boundary is faint and almost indistinguishable. This change in the expression of the boundary has been caused by soil erosion and the mixing of the varved sediments into the plowed layer.

Lateral changes in electromagnetic properties along an interface can be inferred from the resulting changes in the width of the white and dark bands on graphic profiles. As a general rule: the more abrupt or contrasting an interface, the stronger the amplitude of the reflected signal, the blacker and wider the dark bands, and the narrower the width of the white bands (see A). If the Boxford soil has been eroded and the upper part of the fine-textured varved sediments has been mixed with the plow layer, the contrast between the surface layers and the varved sediments will be reduced and the width of the white bands should increase (see B). In this areas of Boxford soils, erosion can be measured with the GPR on the basis of the depth to the varved layers,

and the relative strength (lightness or darkness) of the black bands and the width (to the exclusion of the dark bands) of the white bands.

In Figure 2, the broad black band, "C," is a reverberated signal from the interface of the varved sediments with the surface layers.

Amostown soil formed in glacio-fluvial deposits on outwash plains, terraces, and deltas. In Figure 3, a lithologic discontinuity (A) separating the moderately-coarse and the coarse textured sediments of Amostown soil is evident. In this portion of the transect, the depth to this discontinuity ranges from 52 to 89 inches. Below this discontinuity, multiple, interfingering interfaces suggest stratification within the coarser texture sediments.

In Figure 3, as in all figures, the vertical scale is exaggerated. In Figure 3, the ratio of horizontal scale to vertical scale is approximately 20:1. The vertically exaggerated scale creates the impression that the contact between the moderately-coarse and coarse textured sediments is more steeply inclined in some areas than it is in reality.

Though not investigated in the field, a strata of dissimilar material is evident at "B." This strata appears discontinuous on the graphic profile, suggesting lenses of dissimilar materials that vary laterally in expression. The water table is weakly expressed at "C." It becomes indistinguishable in the right hand portion of this figure where it has been masked within the images from the strata of dissimilar materials.

An area of Enfield soils was examined with the GPR. The Enfield soil consisted of very fine sandy loam or silt loam eolian deposits overlying coarse sand outwash. In Figure 4, this contact is apparent at "A." It ranges in depth from 19 to about 37 inches. The outwash is stratified; the underlying dark band represents a second, lower-lying strata. The second strata appears to be more irregular and segmented in expression.

Water tables often appear on graphic profiles taken from areas of coarse textured soils. In coarse textured soils, the capillary fringe is abrupt and produces a strong image on most graphic profiles. As textures become finer, the capillary fringe becomes increasingly more gradual and the water table becomes more indistinct on graphic profiles. In all soils, as the number of subsurface interfaces increase, images of the water table are often superimposed on other images making identification difficult.

In Figure 5, the water table produces a distinct image which is the inverse of the topographic expression. The water table is deeper and "appears" to lie at a lower elevation in the left-hand portion of this figure. In this portion of the transect a higher-lying knoll was crossed. It must be remembered that regardless of slope, the ground surface on all graphic profiles is always horizontal. For correct interpretations, slopes and slope positions should be noted on graphic profiles.

The probing depth of the radar was later extended and a second transect was conducted to trace the depth to the water table in an area of Carver-Enfield soils. In Figure 6, the radar profiled the water table (A) to a depth of approximately 39 feet. The transect was conducted perpendicular to the slope from a concave toe-slope area (left-hand portion) to a convex summit position (right-hand portion). Along the toeslope area, layers of colluvium are apparent at "B." The outwash is stratified and many beds appear to interfinger producing white out areas (C). The whiteout areas are believed to represent patterns of signal interference and cancellation. Along the summit and upper shoulder slope positions, the lithologic discontinuity of Enfield soil is apparent (D). On the upper sideslope this contact is lost as the eolian déposits thin in response to erosion.

Figure 7 is from a steeply sloping area of Paxton soils. The complexity of soils along this slope is clearly expressed. Most interface appear variable and segmented. No single interface could be traced for more than

fifty feet. As all interfaces appear on graphic profiles in shades of gray to black, and are closely similar in expression, their identification is problematic and requires a greater number of ground-truth observation sites.

But several observations can be made about this areas of Paxton soil. Changes in the texture or consistency across the contact between ablation till and basal till appear as prominent black lines on most graphic profiles (A). Non-sorted accumulations of boulders and cobbles can be inferred from the mottled appearance of till (B) on most graphic profiles. With increasing soil depth, the radar will discern only the increasingly larger reflectors. The apparent absence of boulders or cobbles in the lower part of the till is a result, in part, of these rock fragments passing below a critical size to depth ratio.

In many areas of the Appalachian Highalnds, it is exceedingly difficult to examine soil profiles with conventional soil surveying tools. Numerous rock fragments limit the effectiveness of spades, bucket augers, and hand or mechanical probes. Soil scientist are frustrated and tired, and work is slowed by having their tools repeatedly being stopped by cobbles and boulders. Often an observation site consists of several holes with each hole being restricted by bedrock or rock fragments. At most sites it is uncertain whether penetration was halted by a rock fragment or bedrock. In many areas inferences and broad assumptions must be made concerning the composition of map units and the depth to bedrock.

A more comprehensive, faster, and less labor intense method is needed to determine the depth to bedrock and its variability within map units. The ground-penetrating radar appears to have the potential to rapidly assess the depth to bedrock in many areas of the Appalachian Highlands.

In Figure 8, the till/bedrock interface (A) is apparent between depths of 0.75 and 1.75 meters. Other than near "A," the depth to the till/bedrock

interface is obscured by concentrations of boulders and cobbles (B) or a deeply weathered zone of saprolite (C).

Surfaces of igneous and metamorphic are highly irregular and are often difficult to interpret. The irregular bedrock surfaces scattered and waste more energy than they reflect. In places (B) where a large number of detached boulders immediately overlie the bedrock surface, interpretations become more difficult. Images from the detached boulders are short, segmented and randomly spaced. Images from the bedrock surface (A) are more closely spaced and sub-parallel.

In areas of highly weathered bedrock, saprolite, the upper boundary of the bedrock is gradational. Often, as at "C," the upper part of the saprolite is indistinct from the moderately coarse textured till. But even saprolite displays a unique and identifiable graphic signature. Though its upper boundary is slightly obscured, zones of saprolite are identified by dispersed signals having decidedly vertical rather than horizontal expressions.

The bedrock surface (A) is more apparent in Figure 9. Disjointed boulders and cobbles (B) are more numerous in the right hand portion of this figure, but generally do not obscure the definition of the bedrock surface. In the lower part of the graphic profile, a steeply inclined plane (C), possibly a fracture plane, is evident.

In about one-half of the areas transected with the GPR in Massachusetts, the bedrock surface was clear and easy to interpret. Interpretations were more difficult in the remaining one-half as a result of (1) the equipment being out of optimum adjustment for a particular site; (2) the equipment being pushed beyond its limits; or (3) unfavorable ground conditions.

A déltaic deposit was studied in Middlesex County. In Figure 10, the topset, foreset, and bottomset beds cane be distinguished. Noteworthy is the GPR discrimination capabilities. Although individual foreset layers cannot be picked out of the data, their general characteristics is apparent. The system

has also discriminated between both thick and thin deposits as well as cross-bedding (white-out areas) situations.

The GPR was briefly and unsuccessfully used to locate buried utility lines in Walpole. The poor response of the GPR was attributed to its inability to differentiate cobbles and boulders in the till from a buried utility lines. Though large concrete pipes were apparent on graphic profiles, the utility lines were to small, they did not return a strong reflection, or both.

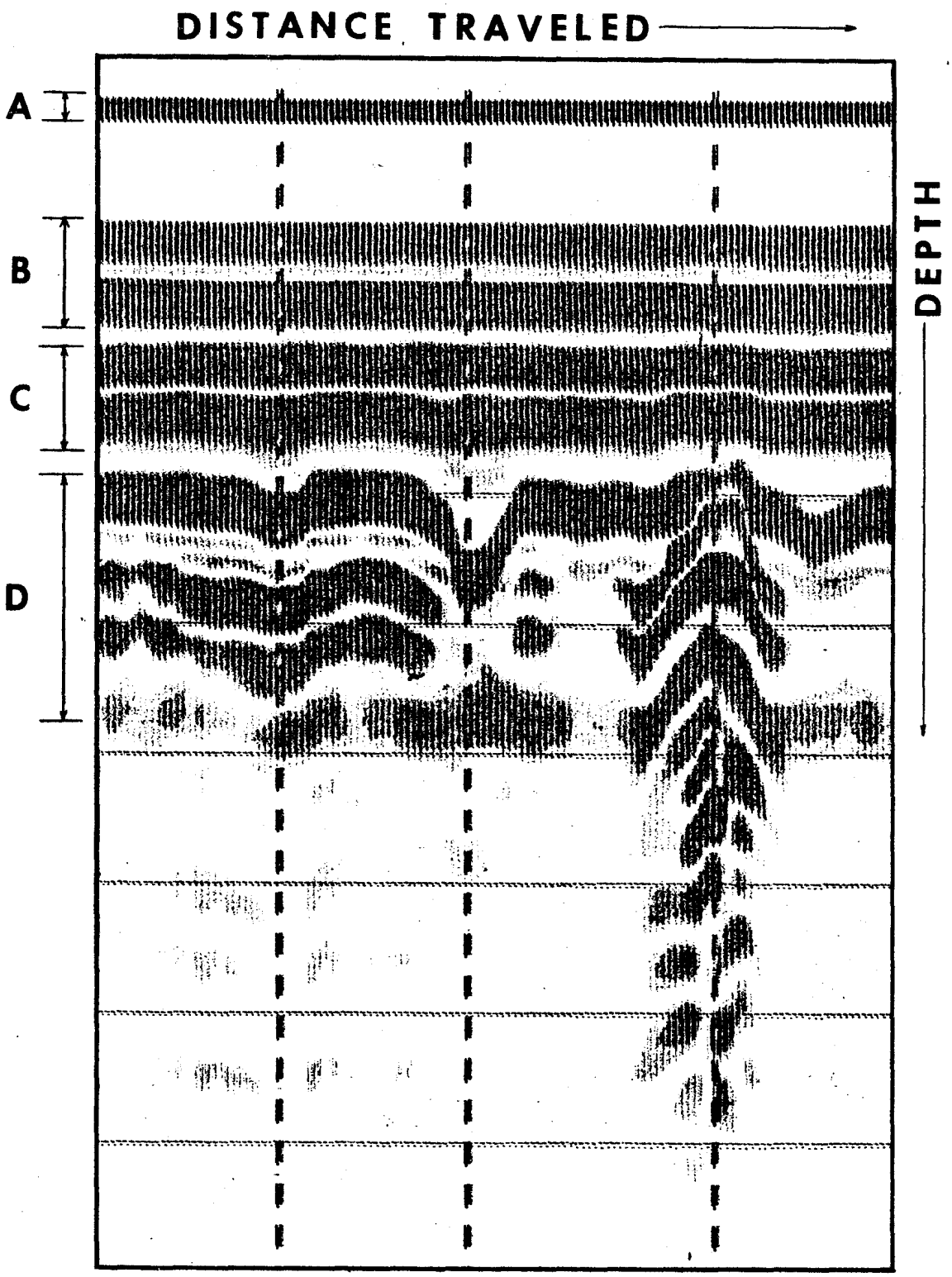
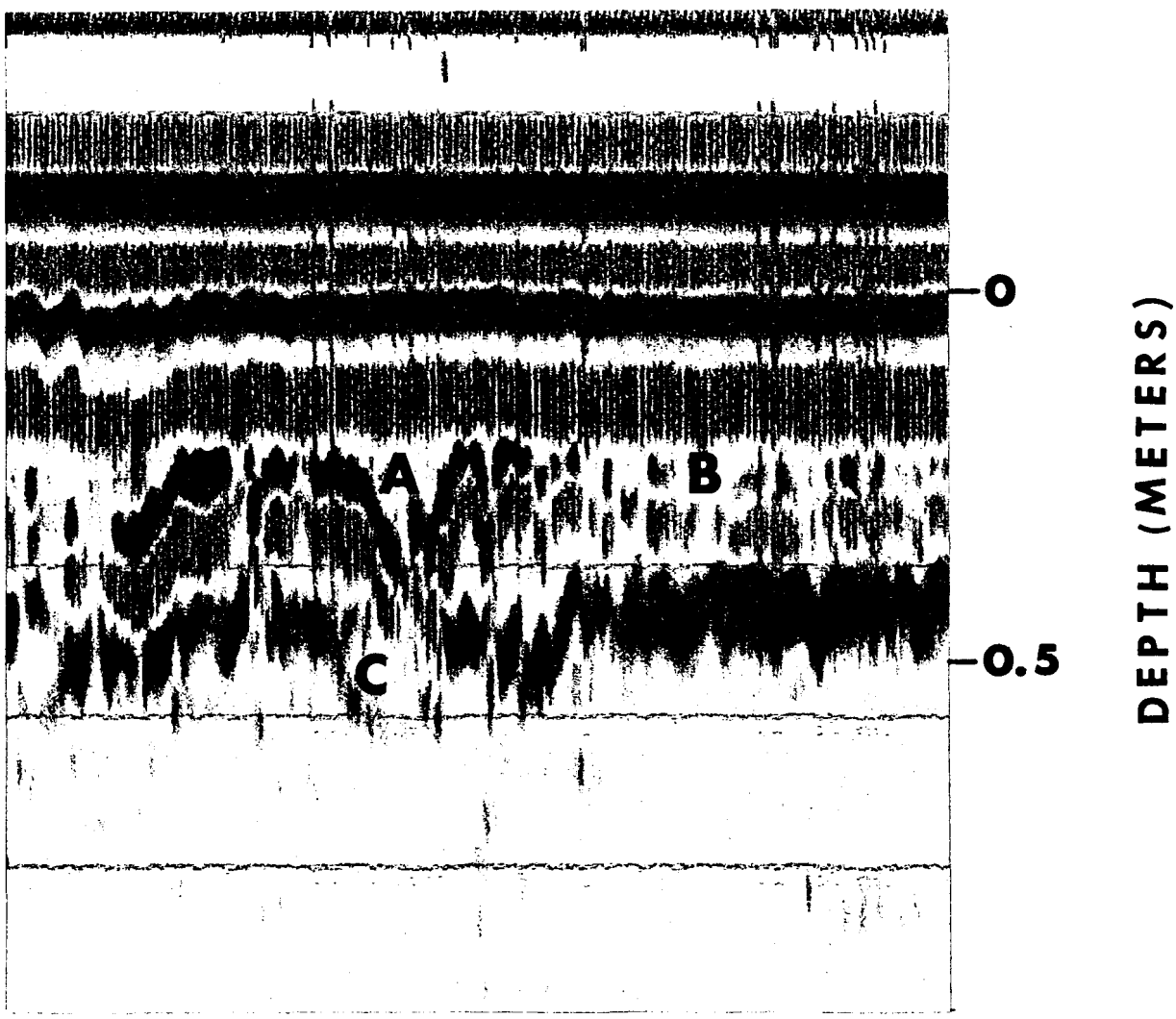


FIG. 1

A GRAPHIC PROFILE

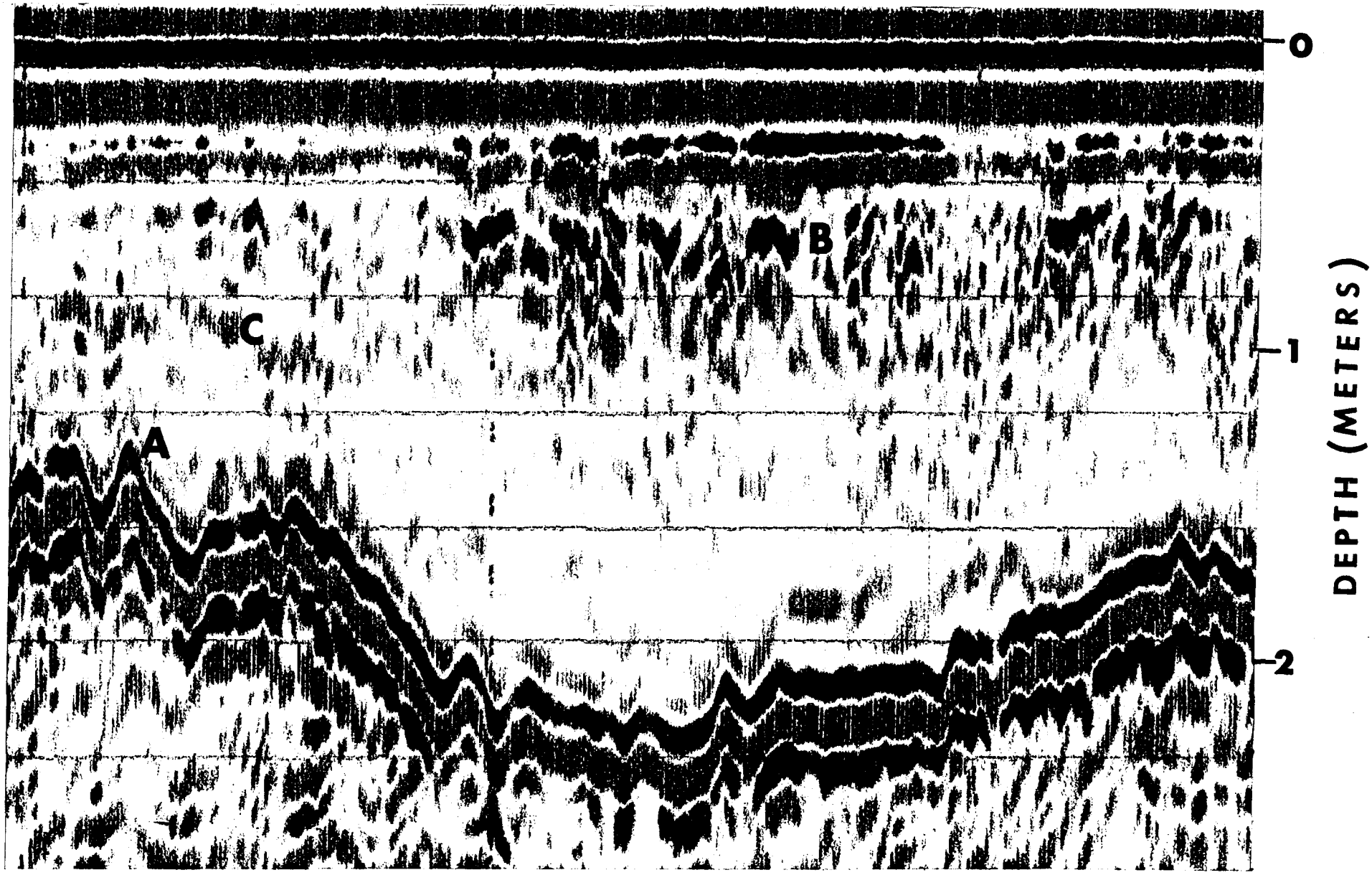
FIG. 2



DEPTH TO VARVED SILTS AND CLAYS

BOXFORD SILT LOAM

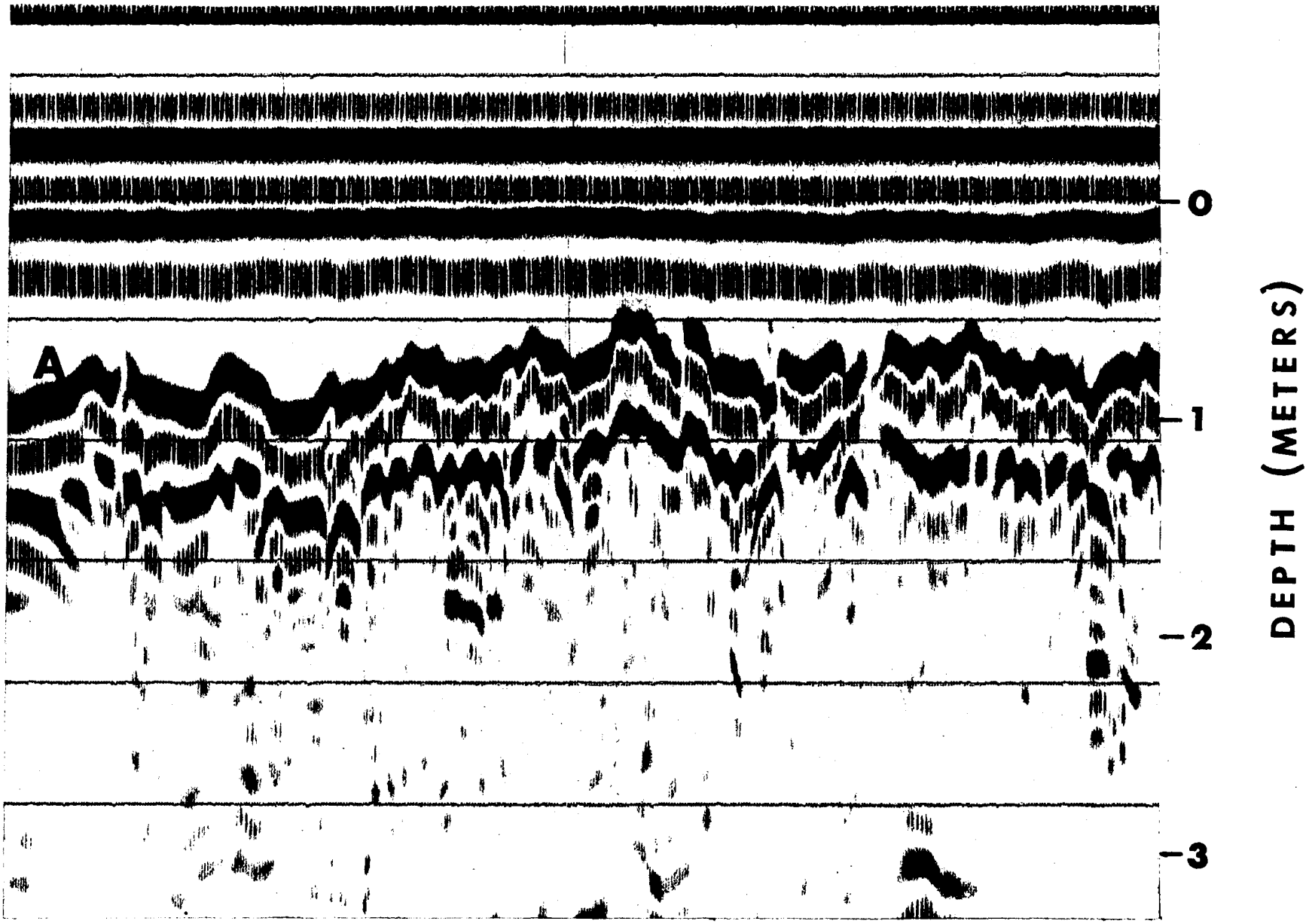
FIG. 3



DEPTH TO COARSE SANDS

AMOSTOWN SOIL

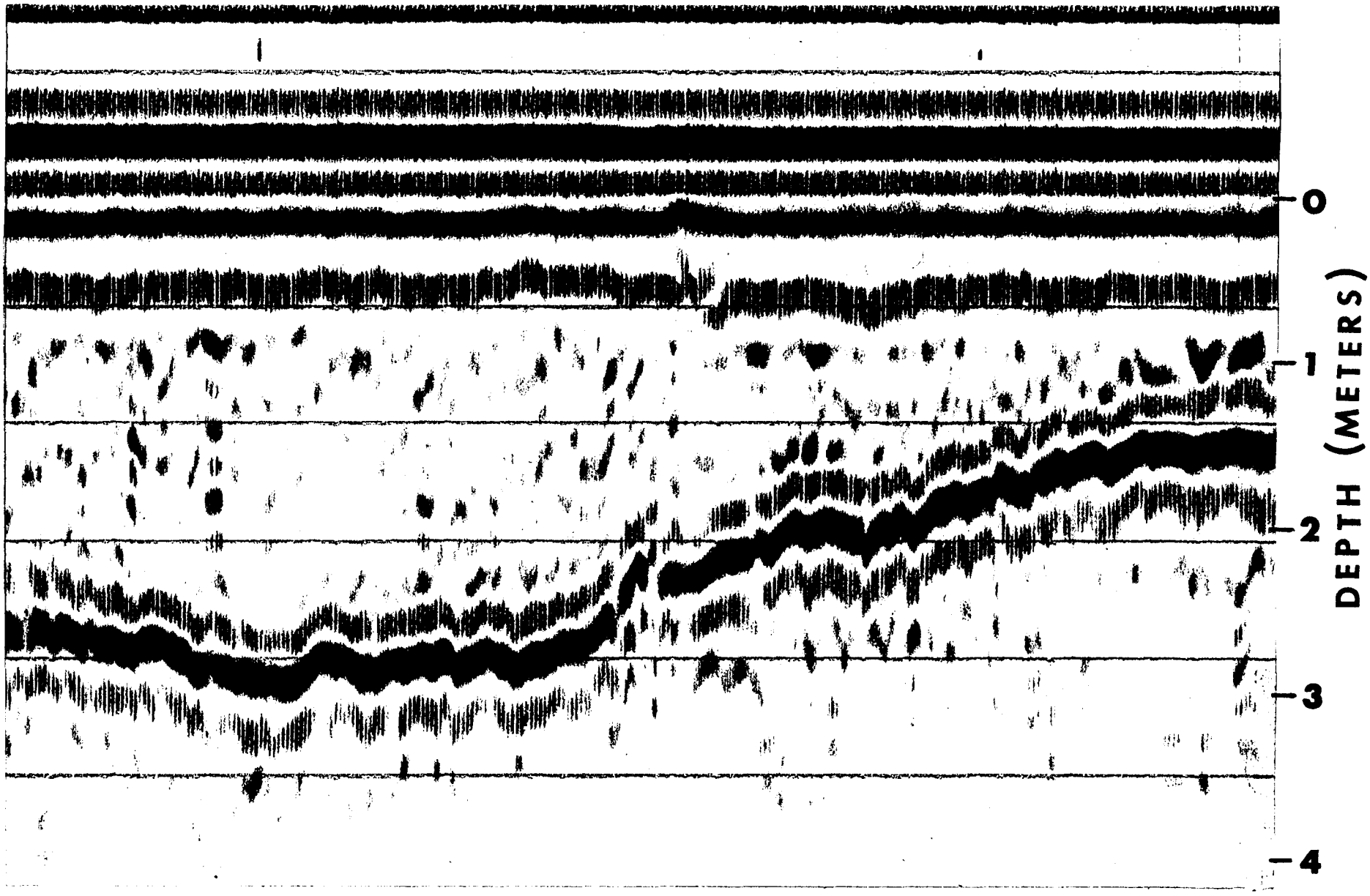
FIG. 4



DEPTH TO OUTWASH DEPOSITS

ENFIELD SOILS

FIG. 5



DEPTH TO WATER TABLE

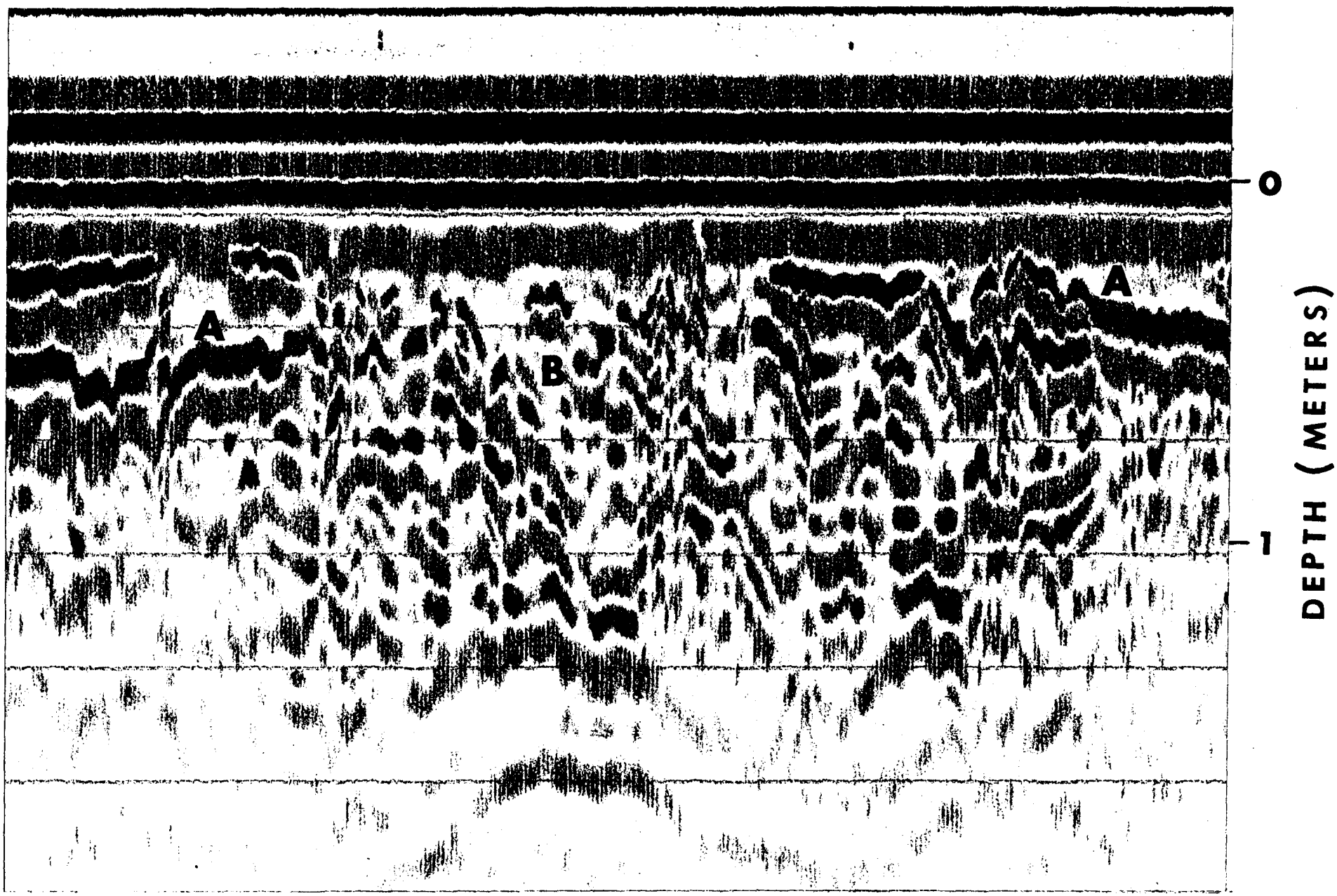
CARVER SOILS

FIG. 6

DEPTH TO WATER TABLE

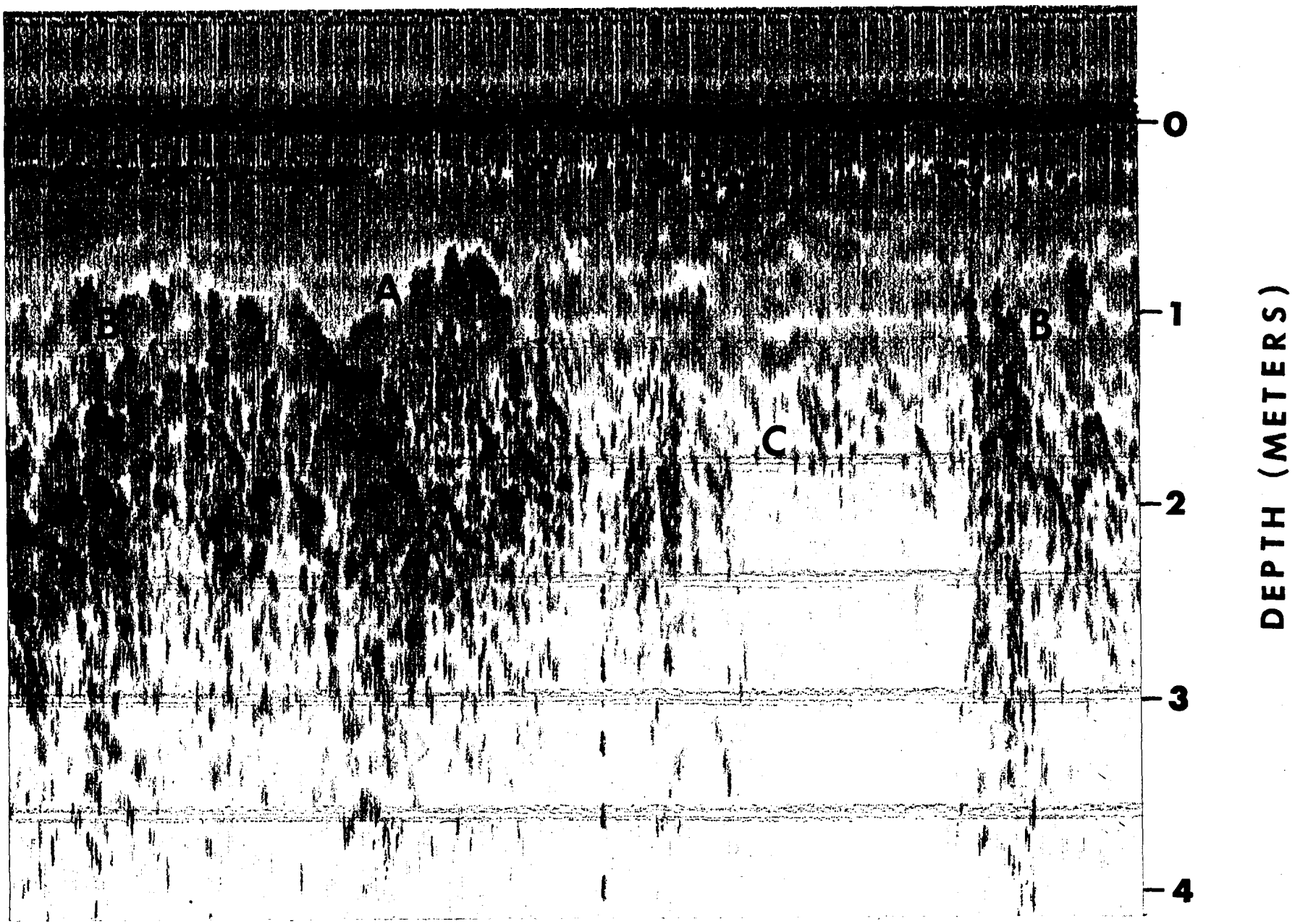
CARVER-ENFIELD SOILS

FIG. 7



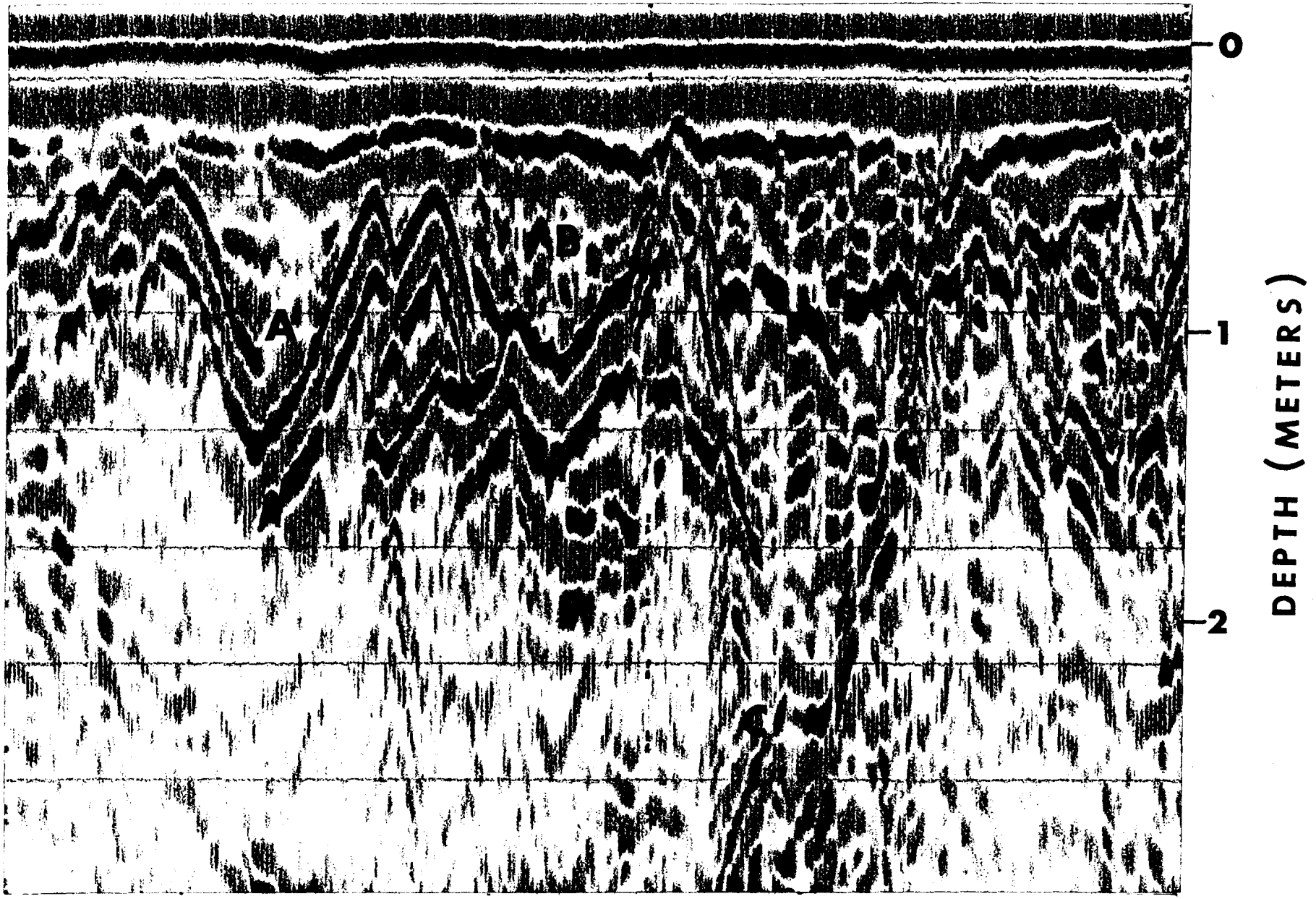
AN AREA OF PAXTON SOIL

FIG. 8



DEPTH TO BEDROCK
NARRAGANSETT-HOLYOKE-ROCK OUTCROP

FIG. 9



DEPTH TO BEDROCK

CHARLTON-HOLLIS-ROCK OUTCROP

FIG. 10

DELTAIC DEPOSITS