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Purpose:
The purpose of this investigation was to evaluate the information provided by ground-penetrating radar (GPR) in an area of Kauder soil.

Participants:
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Activities:
All field activities were completed during the period of 21 to 22 September 1998.

Background:
Ground-penetrating radar (GPR) has been used for twenty years to chart the variability of soils and soil properties. In most studies, GPR has proven to be a valuable, noninvasive tool for the detection and accurate depth measurement of features in soils. This geophysical tool has been used to map the spatial variability of spodic horizons (Collins and Doolittle, 1987; Burgoa et al., 1991), the depth to bedrock (Collins et al, 1989; Collins et al., 1990; Doolittle and Collins, 1998), loamy substrata (Farrish et al., 1990), and argillic horizons (Truman et al., 1988); the continuity of ortstein (Mokma et al., 1990); and the thickness of active layers (Doolittle et al., 1990) loess (Rebertus et al., 1989), and peat (Shih and Doolittle, 1984).

Ground-penetrating radar has been used to investigate fragipans (Olson and Doolittle, 1985;Doolittle, 1987; Lyons et al., 1988). In an area of Laidig soils (fine-loamy, siliceous, mesic Typic Fragiudults), variations in the amplitude of the reflected signal were attributed to the abruptness and contrast of materials across the boundary separating the fragipan and overlying horizons (Olson and Doolittle, 1985; Doolittle, 1987). Working in areas of Canfield (fine-loamy, mixed, mesic Aquic Fragiudalfs) and Wooster (fine-loamy, mixed, mesic Oxyaquic Fragiudalfs) soils, Lyons and other (1988) noticed that fragipans produce strong and identifiable reflections. These researchers attributed the strong radar reflections to a significant increase in bulk density, clay and moisture contents across the abrupt upper boundary of fragipans.

In several studies (Collins et al., 1990; Doolittle and Collins, 1998; Truman et al., 1988), GPR was used to chart depths to the argillic horizon. However, in these studies, because of high rates of signal attenuation, the argillic horizon was virtually opaque to GPR and observation depths were restricted to the upper part of the Bt1 horizon. What is surprising in studies of fragipans is the apparent capacity of GPR to penetrate through Bt horizons and discern Btx horizons. Equally surprising in these studies was the inability of GPR to detect the overlying Bt1 and Bt2 horizons. In Laidig, Canfield and Wooster soils, the combined thickness of the Bt1 and Bt2 horizons can be substantial, varying from 6 to 42 inches. Nevertheless, the clay

contents within the argillic horizons did not restrict the detection of underlying fragipans. In addition, it is assumed that clay contents within the upper part of the argillic horizons of these soils were insufficient or too gradual to produce visible reflections on radar profiles.

In most radar studies, the number of observations used to verify radar interpretations is small. This can lead to errors in interpretation and false expectations as to the suitability of GPR to achieve the desired results. In areas of intricate soil patterns, multiple and complex horizons or layers, accurate radar interpretations require a greater number of observations. In several studies interpreted depths to soil features appearing on radar profiles have been compared with measured depths in pits and trenches (Collins et al, 1989; Lyons et al., 1988; Mokma et al., 1990). The purpose of these studies was to evaluate the accuracy of GPR interpretations and measurements. Observations and measurements of soil features within pit are used to verify radar interpretations and too confirm relationships between measured depths and interpreted or scaled depths.

The objectives of this study were to evaluate the suitability of GPR to determine the depth to fragipan, confirm radar interpretations of soil horizons, and evaluate the accuracy GPR-derived depths with independent soil data.

Equipment:

The radar unit used is the Subsurface Interface Radar (SIR) System-2, manufactured by Geophysical Survey Systems, Inc.[1] The SIR System-2 consists of a digital control unit (DC-2) with keypad, VGA video screen, and connector panel. A 12-volt battery powered the system. Morey (1974), Doolittle (1987), and Daniels and others (1988) have discussed the use and operation of GPR. Antennas used included the models 5106 (200 mHz), 3105 (300 mHz), and 5103 (400 mHz).

Study Site:

The study site was located near the town of Weippe, Clearwater County, Idaho. The study site is in an area of Kauder silt loam, 5 to 20 percent slopes. Kauder is a member of the fine-silty, mixed Andic Fragiboralfs family. Kauder is a moderately deep to a fragipan, moderately well drained soil that formed in volcanic ash and loess over silty alluvium. Kauder soil occurs on undulating foothills and plateaus and has slopes of 5 to 20 percent. Permeability is very slow.

Procedures:

Calibration trials were conducted to obtain the appropriate control settings, select the most suitable antenna, and determine the velocity of signal propagation through the soil. In a nearby area, a 100-ft transect line was established. Observation flags were inserted in the ground at 5-ft intervals along this line. Following calibration trials, a radar traverse was completed by pulling the 200 mHz antenna along the line. The radar profile was reviewed in the field. A conspicuous subsurface layer was observed on the radar profile and was initially interpreted to be either the Bt/E or Btx/E horizon. At each observation point on the radar profile, the travel time to this interface was measured and converted into a depth scale using the estimated velocity of propagation. Although, GPR provides a continuous profile of subsurface conditions, interpretations were restricted to the twenty-one, flagged observation points. Next, the area traversed by the radar antenna was excavated to a depth of about 5-ft with a backhoe. At each observation point, soil scientists described brief profile descriptions. The interpreted depths to the subsurface interface appearing on radar profiles were compared with measured depths to soil horizons described in the trench.

Kauder Soils:

Figure 1 is a graph showing zones of similar soil features observed in the exposed trench wall. This graph was prepared from twenty-one brief profile descriptions that were taken at intervals of 5 feet along the trench wall. In Figure 1, the vertical scale is exaggerated about 10 to 1. The cross-section has been subdivided into three “zones.” Zone 1 is about 4 to 28 inches thick and includes the A, E, EB, E/B, BE, Bw horizons. This zone includes the ochric epipedon and layers of volcanic ash. The dominant texture within this zone is silt loam. Zone 2 represents a transitional zone of increasing clay content and is comprised of combination horizons. Combination horizons have recognizable properties of two master horizons (Soil Survey Division Staff, 1993). Within the combination horizon, discrete parts of each component are intermingled with the other component. The combination horizons include the E/Bt, Bt/E, and Btx/E horizons. The average thickness of the combination horizons is 18.2 inches with a range of 8.5 to 28.5 inches. The texture of the combination horizon is silt loam and/or silty clay loam. Within the combination horizons, columns of any one component were irregularly shaped and highly variable in dimensions. Boundaries separating the intermingled bodies of E and B materials are abrupt with an irregular or broken topography. The placement of many boundary lines was subjective. Often during soil descriptions, boundary placement changed as the side of the trench was shaved back.

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[1] Trade names have been used in this report to provide specific information. Their use does not constitute endorsement.

In Figure 1, the fragipan (Btx1) is where tongues of E material constituted less than 15 percent of a horizon. Fingers and pockets of E material extended throughout the Btx1 horizon. A noticeable increase in brittleness and clay content occurs within the upper part of the fragipan. Along the trench wall, the fragipan ranged in depth from 31 to 51 inches. The average depth to the fragipan is 37.3 inches. The fragipan is silty clay loam. It was very hard and brittle.

The Kauder soil profile did not favor GPR interpretations. Radar interpretations are eased in soils having a minimum number of layers or horizons consisting of highly contrasting materials and separated by abrupt and smooth boundaries. These interfaces produce strong reflections that appear as strong amplitudes on radar profiles. In this area of Kauder soil, the fragipan is overlain by a sequence of horizons having discrete, intermingled bodies of B and E materials. Nearer the surface, E materials dominate, and some profiles have an E horizon. Nearer to the fragipan, bodies of Bt or Btx materials dominate. Within this complex and ill-defined transition zone, the amount of E material thins while Bt or Btx materials and the clay content gradually increases with increasing depth. This produces a complex pattern of intermingled components having irregularly shapes, variable dimensions, and irregular or broken boundaries. These patterns do not favor unique and clearly defined radar reflections.

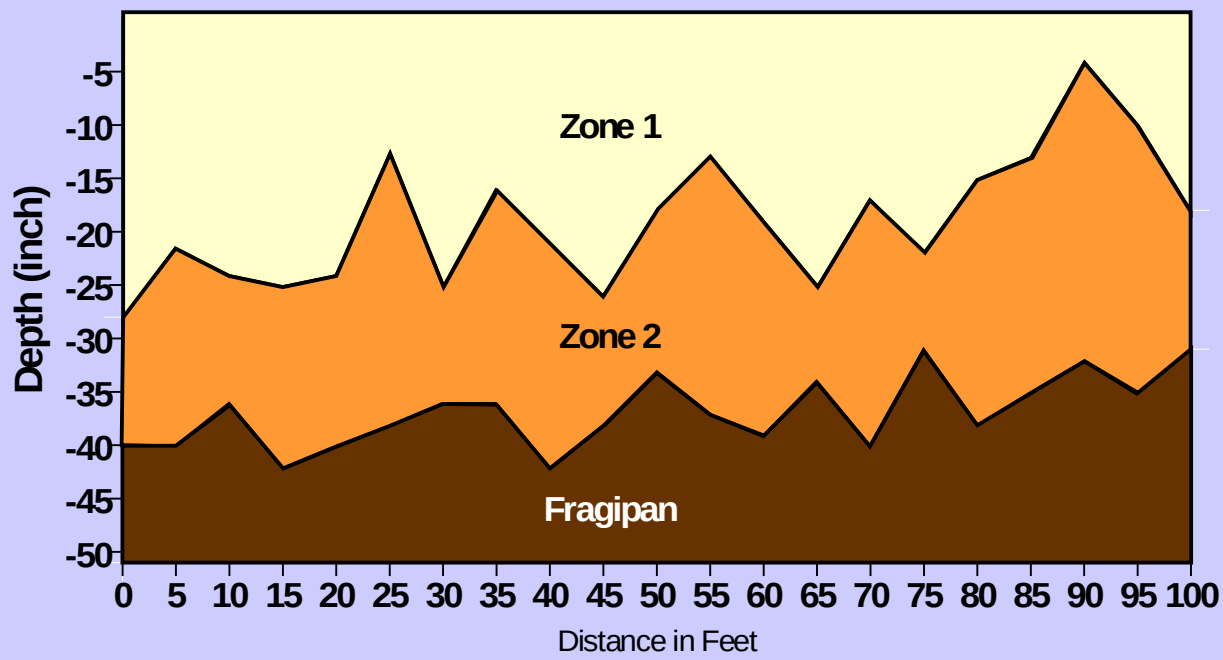

Figure 1 - Depths to major diagnostic horizons and features of Kauder soil recognized in trench wall.

Calibration of GPR:

Ground-penetrating radar is a time scaled system. This system measures the time that it takes electromagnetic energy to travel from an antenna to an interface (e.g., soil horizon, stratigraphic layer) and back. To convert the travel time into a depth scale, either the velocity of pulse propagation or the depth to a reflector must be known. The relationships among depth (d), two-way pulse travel time (t), and velocity of propagation (v) are described in the following equation (Morey, 1974):

$$v = 2d/t$$

The velocity of propagation is principally affected by the dielectric permittivity (e) of the profiled earthen material(s) according to the equation:

$$e = (c/v)^2$$

Where c is the velocity of propagation in a vacuum (0.98 ft/nanosecond). The amount and physical state of water (temperature dependent) have the greatest effect on the dielectric permittivity of earthen materials.

Calibration trials were conducted at the site. The purposes of these trials were to optimize control, select the most appropriate antenna, determine the velocity of propagation through the soil materials, and establish a crude depth scale. A shovel blade was buried in the soil at a depth of 19 inches. The depth to this buried feature was used to estimate the velocity of propagation through the upper soil horizons. Based on the round-trip travel time to this reflector, the velocity of propagation through the upper part of the soil was estimated to be 0.2755 ft/ns with the 200 mHz antenna. The dielectric permittivity was estimated to be 12.8. With a scanning time of 50 ns, the maximum depth of observation was about 6.9 ft.

Results:

Radar Profile:

The 200 mHz antenna provided the best balance of observation depth and resolution. This antenna also provided the most easily interpretable profile of Kauder soil. A portion of this profile is shown in Figure 2. This profile has been processed through the WINRAD software package.[2] Processing was limited to signal stacking, horizontal scaling, color transforms and table customizing. Color transformation and table customization were used to reduce signal amplitudes and background noise. In Figure 2, the horizontal and vertical scale are expressed in feet. The numbers appearing at the top of this figure represent observation points. Observations are spaced at an interval of 5 ft. The vertical scale is a depth scale, which is based on the estimated velocity of signal propagation

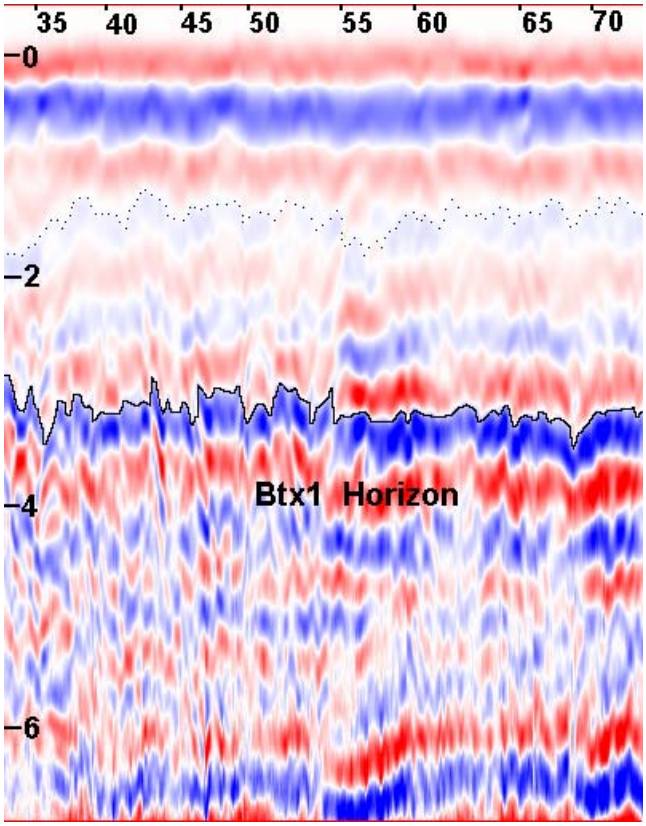

Figure 2 – Portion of the radar traverse in an area of Kauder Soils

In Figure 2, a conspicuously high amplitude, subsurface reflection has been highlighted with a dark line. This interface has a highly irregular topography, which is attributed to the intermingled components and tongues of E material. The interface is continuous across the profile but varies slightly in amplitude and expression. It is presumed that these variations are caused

[2] Trade names are provided for the benefit of the reader and do not imply endorsement.

principally by differences in density and moisture and clay contents across this interface. This interface occurs at an average depth of about 38 inches and has an irregular boundary. The identity of this interface was not known prior to the excavation of the trench. It was presumed to be either the Bt/E or the Btx/E horizon. Several weakly expressed and more discontinuous soil features are detectable in Figure 2 above and below this conspicuous interface. The identities of these interfaces were also unknown prior to excavation.

Comparison of Data on the Depth to Fragipan:

The interpreted depths to the interface most closely approximated the observed depths to the Btx1 horizon. The average depth to the Btx1 horizon measured within the trench was 37.3 inches with a range of 31 to 51 inches. The average depth to the interpreted interface was 38.5 inches with a range of 35.4 to 46.7 inches. Table 1 compares the observed and interpreted depth measurements.

Table 1

Depths to Btx1 horizon observed in trench wall and interpreted from GPR profile.

Station	Observed	Interpreted	Difference
0	51	46.7	-4.3
5	40	43.6	3.6
10	36	36.9	0.9
15	42	35.4	-6.6
20	40	36.4	-3.6
25	38	35.9	-2.1
30	36	41.1	5.1
35	36	36.9	0.9
40	42	38.5	-3.5
45	38	37.2	-0.8
50	33	38.1	5.1
55	37	38.9	1.9
60	39	38.1	-0.9
65	34	38.9	4.9
70	40	38.5	-1.5
75	31	39.0	8.0
80	38	39.0	1.0
85	35	38.0	3.0
90	32	35.0	3.0
95	35	38.0	3.0
100	31	38.5	7.5

Comparatively large differences exist between observed and predicted depths to the Btx1 horizon. The average difference between the observed and interpreted depth to the Btx1 horizon was 3.39 inches with a range of –6.6 to 8.0 inches. One half of the scaled radar imagery was within –1.95 to 3.45 inches of the actual depth to the Btx1 horizon. In addition, the correlation between observed and interpreted measurements was exceedingly low for GPR ($r = 0.5043$). Differences in these measurements and the low correlation can be attributed to the complexity of soil materials, highly irregular boundaries, mismatch between the track of the antenna and the actual point of measurement on the trench wall, and observation and interpretation errors.

Conclusions:

Ground-penetrating radar was used to predict the depth to fragipan (Btx1 horizon) in Kauder soil. The fragipan appeared as a conspicuously high amplitude, continuous subsurface reflector on the radar profile. This reflector was initially believed to be the interface separating the E/B from the Bt/E or Btx/E horizons because of observed soil features and differences in soil density, brittleness, and clay content. However, the interpreted depths to this interface most closely approximated the observed depths to the Btx1 horizon. The average difference between the observed and predicted depths to the Btx1 horizon was 3.39 inches. Differences in measurements ranged from –6.6 to 8.0 inches. A comparatively low correlation ($r = 0.5043$) was found between observed and predicted depths to the Btx1 horizon. The low correlation and the differences in these two sets of measurements were attributed to the complexity of soil materials, highly irregular boundaries, mismatch between the track of the antenna and the actual point of measurement on the trench wall, and observation and interpretation errors. Correlations

should be higher and differences between observed and predicted depths to the Btx1 horizon should be less in soils that lack combination horizons (E/Bt, Bt/E, and Btx/E).

This study confirms the value of *ground-truth* verifications of radar interpretations. Ground-truth verification was required to help confirm the identity of a subsurface reflector.

It was my pleasure to work again in Idaho and with members of your fine staff.

With kind regards,

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