United States Department of Agriculture	**Natural Resources Conservation Service**	**100 Campus Boulevard Suite 200 Newtown Square, PA 19073**

Subject: Soils -- Geophysical Assistance **Date:** 30 October 2007

To: Bob Graham
State Conservationist
USDA-Natural Resources Conservation Service
1201 NE Lloyd Blvd.
Suite 900
Portland, OR 97232

Ron Reuter
Assistant Professor of Natural Resources
Department of Forest Resources,
Oregon State University Cascades
2600 NW College Way
Bend, OR 99701

Purpose:
Ground-penetrating radar (GPR) was used to characterize near-surface soil and stratigraphic layers in the Deschutes River Basin, Deschutes County, Oregon.

Principal Participants:
Jim Doolittle, Research Soil Scientist, USDA-NRCS-NSSC, Newtown Square, PA
Mike Logan, Undergraduate Student, OSU Cascades, Bend, OR
Ryan Miebach, Soil Scientist, USDA-NRCS, Redmond, OR
Kurt Moffitt, Soil Scientist, USDA-NRCS, Redmond, OR
Ron Rueter, Professor, OSU Cascades, Bend, OR

Activities:
All field activities were completed during the period of 8-11 October 2007.

Summary:

1. In areas of Sunriver and Shanahan soils, GPR provided well-resolved, continuous records of the subsurface to depths of 3 m. Multiple subsurface interfaces were identified on most radar records. The number, reflection patterns, and geometry of these interfaces are considered characteristic of ash and alluvial deposits. On some radar records collected in the La Pine area, a high-amplitude, planar reflector was identified and associated with a medium-textured (about 18 to 25 % clay) layer. This layer can influence the flow of water in the near surface. However, based on limited GPR investigations, this layer does not appear to be continuous over extensive areas. Where present, this layer appears relatively thin and segmented on radar records. In some areas this layer does not exist within depth of 3 m.

2. GPR detects, but does not identify subsurface features. While the presence of a medium-textured stratum was confirmed by auger observations within one study area, similar reflections were not identified in all surveyed areas. In addition, similar reflections can be produced by differences other than clay content alone (abrupt changes in moisture, density, grain-size distributions). Limited and directed ground-truth observations are needed to confirm further radar interpretation made in the La Pine area.

3. At the Camp Polk study area, radar records, though restricted to a signal polygon of Omahaling fine sandy loam, 0 to 5 percent slopes, displayed large differences in signal penetration depth, signal quality and attenuation, and the number of subsurface interfaces. These results suggest that a large number of contrasting soils and soil materials were included in the mapping of this delineation.

It was my pleasure to work in Oregon and to be assistance to your staff and Ron Reuter.

With kind regards,

James A. Doolittle
Research Soil Scientist
National Soil Survey Center

cc:
B. Ahrens, Director, National Soil Survey Center, USDA-NRCS, Federal Building, Room 152, 100 Centennial Mall North, Lincoln, NE 68508-3866
M. Golden, Director of Soils Survey Division, USDA-NRCS, Room 4250 South Building, 14th & Independence Ave. SW, Washington, DC 20250
C. McGrath, MLRA Office Leader, USDA-NRCS, 1201 NE Lloyd Blvd., Suite 900, Portland, OR 97232
W. Tuttle, Soil Scientist (Geophysical), USDA-NRCS-NSSC, P.O. Box 974, Federal Building, Room G08, 207 West Main Street, Wilkesboro, NC 28697

Background:
Since the early 1960s, a rapid development of homes on small lots has occurred in the vicinity of La Pine, Oregon (Hinkle et al., 2007). In the 1980s, high concentrations of NO^3-N (10 mg/l) were recognized in the groundwater beneath La Pine (Hinkle et al., 2007). The source of the NO^3-N is believed to be effluent from improperly functioning septic systems. This effluent is contaminating the region's shallow, sandy aquifer. In the mid-1980s, the Oregon Department of Environmental Quality required the creation of a special sewer district in La Pine. Restrictions have been placed on the installation of septic systems. The US Geological Survey (USGS) has installed several deep monitoring wells in the area and prepared a model of groundwater and nutrient flows from septic systems. Reacting to this model, Deschutes County officials are presently considering new regulations, which would require landowners to retrofit or replace older septic systems that are buried near wells. This proposed measure has stirred a great deal local interests and controversy.

La Pine is located within the Deschutes River drainage basin. The Deschutes River was once blocked by lava flows that emanated from Lava Butte. The lava barrier impounded water and created a large lake, which filled with sediments. Following the establishment of a new river channel, the lake drained and these finer-textured lacustrine deposits were subsequently overlain by ash deposits. Repeated local deposition and erosion associated with river meandering has further complicated the local stratigraphy. Dr Ron Reuter has noted that layers of finer-textured lacustrine deposits can act as aquitards and influence the flow of soil water and nutrients. These layers have been observed within the upper 2 m of soil profiles in the vicinity of La Pine, but were largely overlooked in the USGS model. The purpose of this investigation was to explore the potential of using ground-penetrating radar (GPR) to characterize the thickness, extent, and continuity of these of finer-textured layers.

Study Areas
All study areas are located within the Upper and Little Deschutes drainage basins. Two study areas are located in La Pine, Oregon. One study area is located off of Burgess Road (see Figure 1). The Burgess Road study area is located in a polygon of Sunriver sandy loam, 0 to 3 percent slopes (map unit 144A). The locations of two transect sites within the Burgess Road study area are shown in Figure 1. In Figure 1, these sites are identified with different colored dots (Sites 1 & 2 are colored green and red, respectively). A second study area is located off of 6th Street (see Figure 2). The 6th Street study area is located in a polygon of Shanahan loamy coarse sand, low, 0 to 3 percent slopes (map unit 115A). The locations of the three transect sites within the 6th Street study area are shown in Figure 2. In Figure 2, these sites are identified with different colored dots (Sites 3, 4, & 5 are colored orange, yellow, and magenta, respectively).

The very deep Shanahan and Sunriver soils form on pumice mantled terraces. Depth to bedrock is greater than 60 inches. The somewhat excessively drained Shanahan soils are shallow and moderately deep (range is 14 to 40 inches) to buried, loamy soil materials. The ash mantle has an estimated clay content that ranges from 0 to 5 percent. The loamy materials have an estimated clay content that ranges from 10 to 20 percent. The somewhat poorly drained Sunriver soils are moderately deep to buried, loamy soils. The loamy materials have estimated clay content that only range from 5 to10 percent. The taxonomic classifications of these soils are listed in Table 1.

Table 1. Taxonomic classifications of soils

Series	*Taxonomic Classification*
Omahaling	Coarse-loamy, mixed, superactive, frigid Fluvaquentic Haploxerolls
Shanahan	Ashy over loamy, glassy over isotic Xeric Vitricryands
Sunriver	Ashy over loamy, glassy over mixed, superactive Aquic Vitricryands

A third study area is located at Camp Polk along Squaw Creek (see Figure 3) near Sisters, Oregon. This site is part of a wetland restoration project involving the re-establishment of the stream to its original channel. The study area is located principally in a polygon of Omahaling fine sandy loam, 0 to 5 percent slopes (map unit

94A). The very deep, somewhat poorly drained Omahaling soils form in mixed ash and alluvial deposits on flood plains. The locations of the four transect sites within the Camp Polk study area are shown in Figure 3. In Figure 3, these sites are identified with different colored dots (Sites 6, 7, 8, & 9 are colored green, red, blue, and yellowish-orange, respectively).

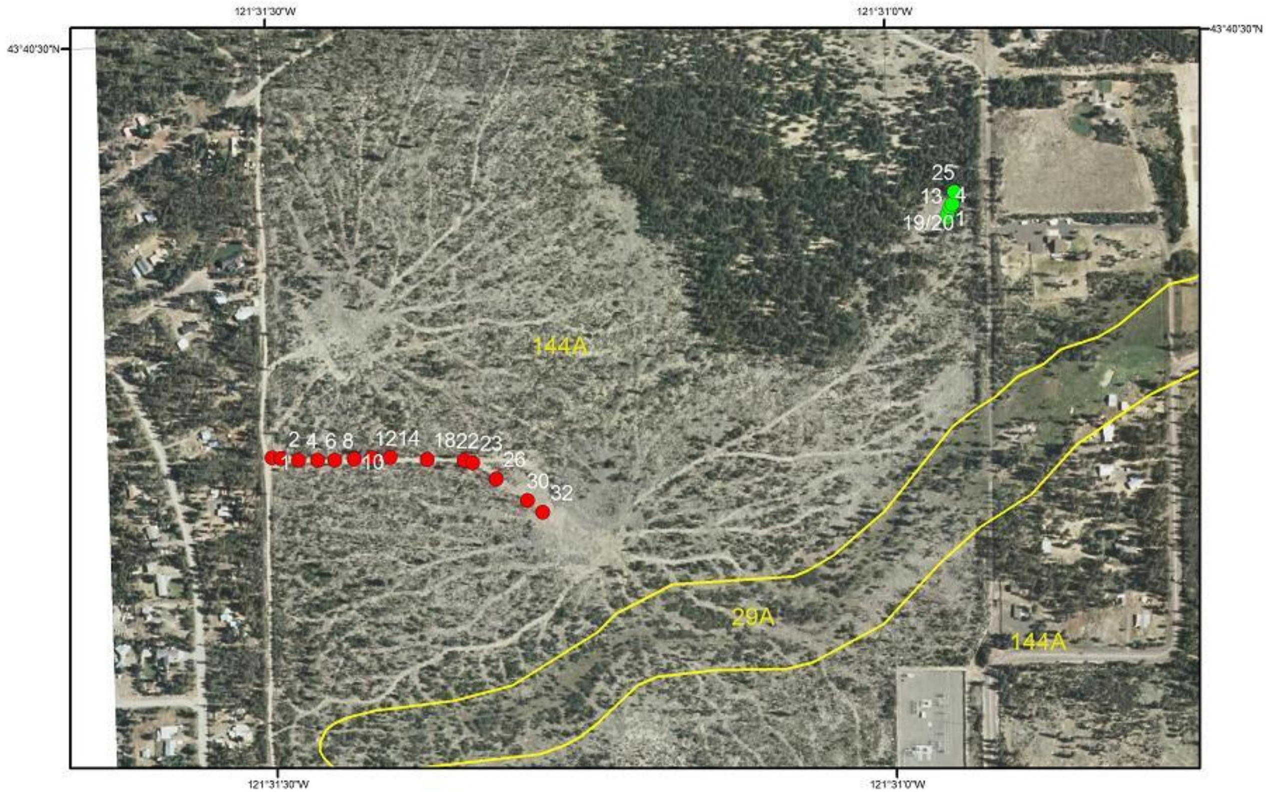

Figure 1. This aerial photograph shows the locations of GPR traverses and soil map units within the Burgess Road study area.

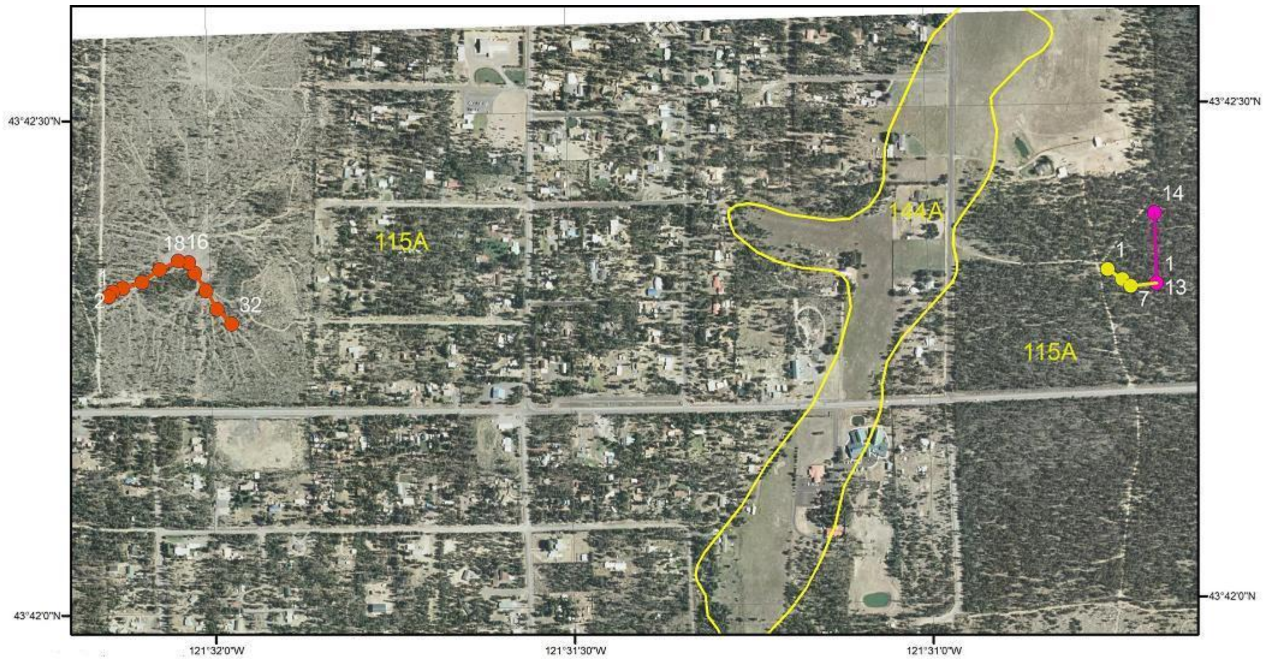

Figure 2. This aerial photograph shows the locations of GPR traverses and soil map units within the 6th Street study area.

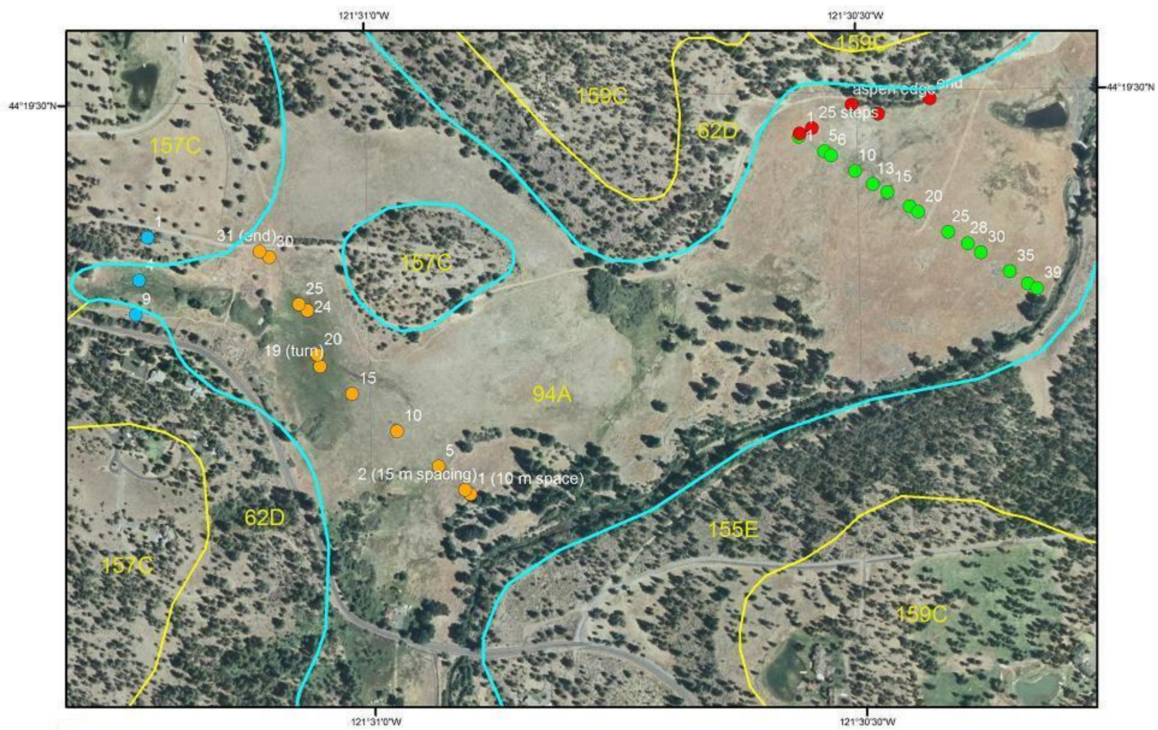

Figure 3. This aerial photograph shows the locations of GPR traverses and soil map units within the Camp Polk study area.

Equipment:
The radar unit is the TerraSIRch Subsurface Interface Radar (SIR) System-3000, manufactured by Geophysical Survey Systems, Inc. (Salem, New Hampshire).[1] Daniels (2004) discusses the use and operation of GPR. The

SIR System-3000 weighs about 9 lbs (4.1 kg) and is backpack portable. With an antenna, the system requires two people to operate. Antennas with center frequencies of 200 and 400 MHz were used in this study.

Radar records contained in this report were processed with the RADAN for Windows (version 5.0) software program (Geophysical Survey Systems, Inc).[1] Processing included setting the initial pulse to time zero, color transformation, marker editing, distance normalization, horizontal stacking, migration, and range gain adjustments. All radar records were migrated to remove hyperbola diffraction patterns and to improve the geometry of inclined soil horizons and stratigraphic layers.

Survey Procedures:
A single traverse lines was established at most sites. At the La Pine sites (Burgess Road and 6th Street study areas), where access was a problem, traverses were conducted across recently harvested (timber) lands managed by the Bureau of Land Reclamation (BLM). Because of the amount of residue, stumps, and tree limbs on the surface, traverses were restricted to cleared access roads and logging trails. At the Camp Polk study area, four random GPR traverse lines were established across areas of forbs and grasses on different portions of the flood plain (see Figure 3). At each site, traverse line lengths varied. Along each line, survey flags were inserted in the ground at a uniform interval (for the La Pine sites, intervals were either 1 or 10 m; for the Camp Polk study area, intervals were either 10 or 15 m) and served as reference points. Auger observations were made at several reference points to confirm interpretations and improve the accuracy of depth scales.

Both the 400 and 200 MHz provide ample penetration depths (>3 m) in areas of Shanahan and Sunriver soils. A greater number of closely-spaced subsurface interfaces were resolved with the higher-frequency 400 MHz than with the 200 MHz antenna. Base on results at the Burgess Road calibration site (colored green in Figure 1), image quality and the continuity of a medium textured subsurface layer were considered more striking, clearly expressed, and interpretable with the 200 MHz antenna. As a consequence, all subsequent radar surveys were completed with the 200 MHz antenna.

Calibration:
Ground-penetrating radar is a time scaled system. This system measures the time 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 (after Daniels, 2004):

$$v = 2D/T \qquad [1]$$

The velocity of propagation is principally affected by the relative dielectric permittivity (E_r) of the profiled material(s) according to the equation (after Daniels, 2004):

$$E_r = (C/v)^2 \qquad [2]$$

where C is the velocity of propagation in a vacuum (0.298 m/ns). Velocity is expressed in meters per nanosecond (ns). In soils, the amount and physical state (temperature dependent) of water have the greatest effect on the E_r and v.

Soils were relatively dry in the upper part and moist in the lower part at the time of this investigation. Based on measured depths (ranged from about 1.5 to 2 m) and the two-way pulse travel times to a contrasting, fine-loamy layer, and equations [1] and [2], the velocity of propagation and the relative dielectric permittivity through the upper part of the Sunriver soil profile were estimated. The estimated E_r was about 6.0 and 6.1 for the 400 and 200 MHz antennas, respectively. These E_r result in propagation velocities of 0.1217 and 0.1207 m/ns for the 400 and 200 MHz antennas, respectively. This information was used to depth scale the radar records. The Sunriver and Shanahan soils form in similar parent materials and have similar moisture contents and

[1] Manufacturer's names are provided for specific information; use does not constitute endorsement.

distributions at the time of this investigation. As a consequence, the same E_r and v were used for each soil. As the velocity of propagation varies spatially and with soil depth, depth scales are close approximations, but should not be considered exact.

Vertical resolution is dependent on the propagated wavelength (λ). In general vertical resolution is assumed to be about 1/2 λ. If two interfaces are separated in time by less than this amount they will be indistinguishable and interpreted as one interface. The wavelength is determined by dividing the propagation velocity (v) by the antenna frequency (f).

$$\lambda = v/f \qquad [3]$$

Using equation [3] and propagation velocities of 0.1217 (for 400 MHz antenna) and 0.1207 (for 200 MHz antenna), the estimated wavelengths were 30 and 60 cm. Therefore, the estimated vertical resolution of the 400 and 200 MHz antennas in areas of Sunriver and Shanahan soils (at the time of this investigation) are about 15 and 30 cm, respectively. In general, the detection limit of sedimentary layers is considerably lower than the estimated vertical resolution (Moorman and Michel, 1997).

Results:

Burgess Road study area:

Figures 4 and 5 are representative radar records that were collected with the 200 and 400 MHz antenna at the calibration site within the Burgess Road study area (see Figure 1). The depth and distance scales on both records are expressed in meters. The same color scale and color transform have been used to display the radar data on both radar records.

On both radar records, the pumice mantle appears relatively free of reflections. However, beginning at a depth of about 60 cm on each record, horizontal to slightly wavy, discontinuous bands with varying signal amplitudes are evident. These bands represent stratigraphic layers. Auger observations confirmed the presence of strata that varied in particle-size distributions, clay contents, moisture contents, and colors. On the radar records (Figures 4 and 5), reflector signatures and patterns suggest that these strata have complex and variable compositions (judged by variations in signal amplitudes) and geometries. These characteristics are considered typical of fluvial sediments. The reflectors are not laterally continuous, but appear segmented, with noticeable breaks appearing on the radar record. On radar records, segmentation is caused by truncation of layers, lateral gradation in the of degree contrast between reflectors, and/or superposition and cancellation of closely-spaced reflected signals. Segmentation can be caused by the erosion and deposition of alluvial materials on flood plains.

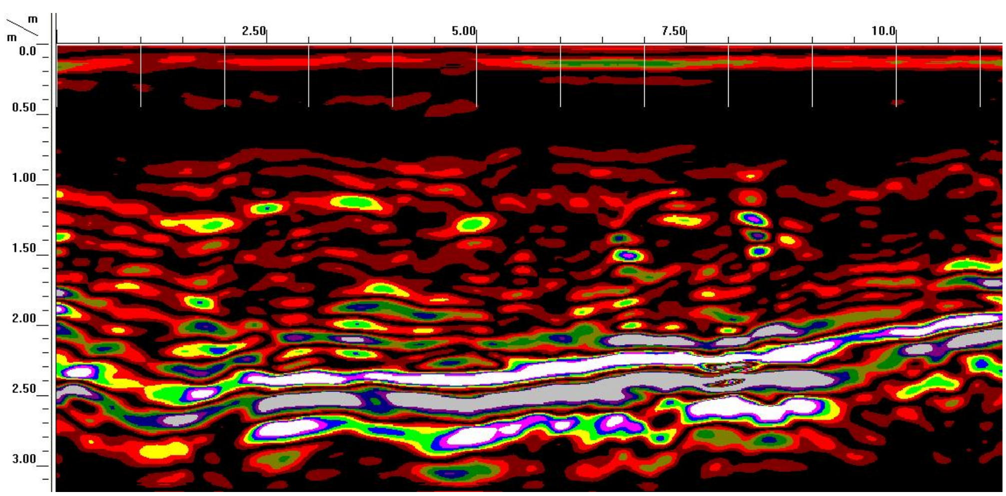

Figure 4. This radar record that was collected with the 200 MHz antenna in an area of Shanahan *soils.*

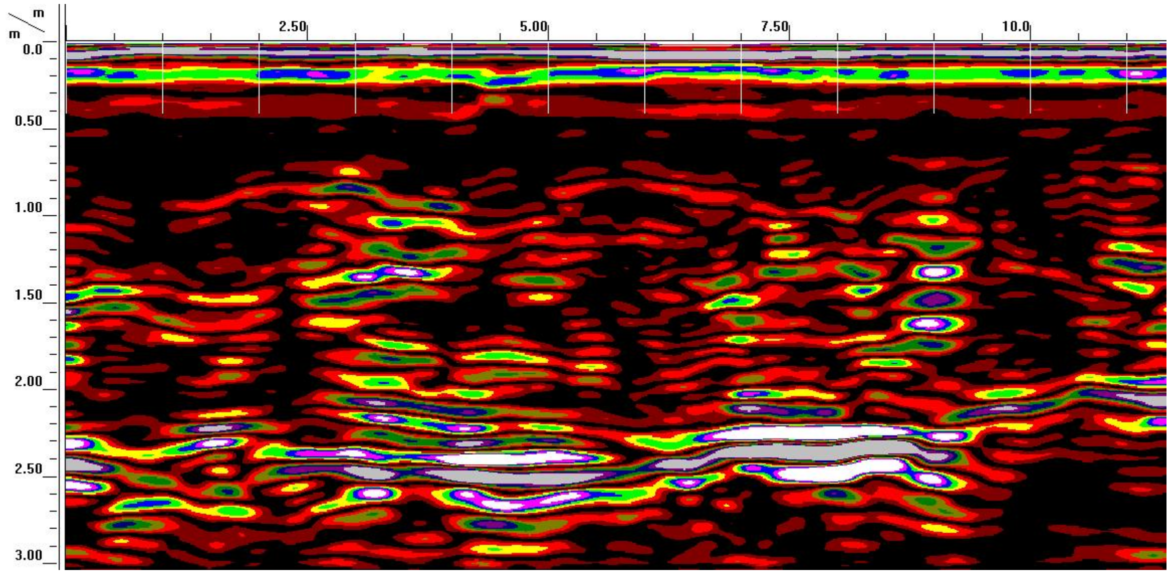

Figure 5. This radar record was collected with the 400 MHz antenna in an area of Shanahan *soils.*

On both of the radar records shown in Figures 4 and 5, a conspicuous, high-amplitude (colored white, grey, purple and blue) slightly inclined, planar reflector is evident at depths ranging from about 190 to 240 cm. Field observations confirmed that this reflector represents a medium-textured (heavy sandy loam to sandy clay loam) layer with clay contents varying laterally between about 18 and 25 %. Because of the large number of closely spaced and contrasting strata, superposition and cancellation of reflected signals are unavoidable. Because of signal superpositioning, the identification and actual interpreted depth to this interface are ambiguous and imprecise. Based on multiple auger observations, differences between the measured and interpreted depths to this interface ranged from 0 to 28 cm. While the depth to this interface will be imprecisely interpreted, the presence of this interface is undeniable. This very deep, medium textured layer should act as an aquitard to the downward flow of soil moisture.

It needs to be noted that all layers of contrasting materials separated by abrupt boundaries have the potential to produce high-amplitude radar reflections. At the Burgess Road study area, the presence of a medium-textured stratum was confirmed by auger observations within. In other areas, similar reflections can be caused by abrupt and contrasting differences in other soil properties (moisture, density, grain-size distributions). All radar interpretations must be confirmed by a limited number of directed ground-truth observations.

Figure 6 is a portion of a radar record that was collected along the southeastern traverse line (see Figure 1, red dots) within the Burgess Road study area. Compared with the radar records shown in Figure 4, a similar sequence of stratigraphic layers are evident, but a greater number of closely-spaced, high-amplitude, planar reflectors are evident in the lower part of this radar record. These high-amplitude planar reflectors represent multiple, closely spaced interfaces that have abrupt boundaries and separate thin, contrasting layers of lacustrine and/or alluvial deposits. Contrast is principally attributed to differences in particle-size distributions and water contents. The broader, more continuous, high-amplitude, planar reflectors are assumed to represent stratigraphic layers with higher clay and/or moisture contents. Greater signal attenuation and loss of high-frequency signal components are inferred from the broader widths of these reflected signals. These losses are attributed to soil and stratigraphic layers with higher clay and moisture contents. Because of the large number of closely-spaced interfaces, identification of individual layers is impractical and ill-advised. These planar interfaces appear more numerous and segmented than at the calibration site. They undoubtedly separate relatively thin layers of contrasting fluvial deposits.

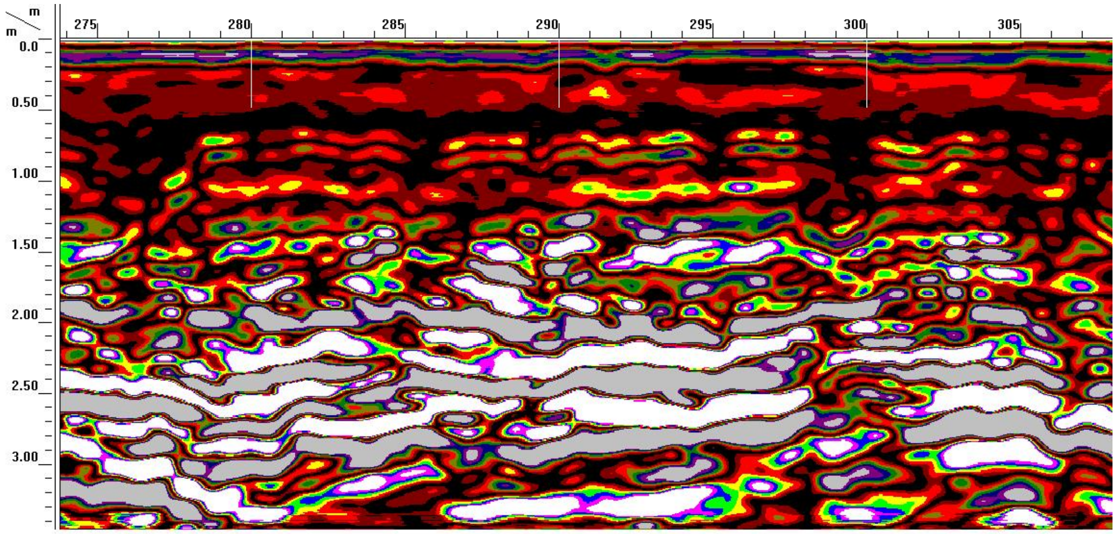

Figure 6. This portion of the radar record that was collected within the Burgess Road study area shows a number of high-amplitude planar reflectors in the lower part.

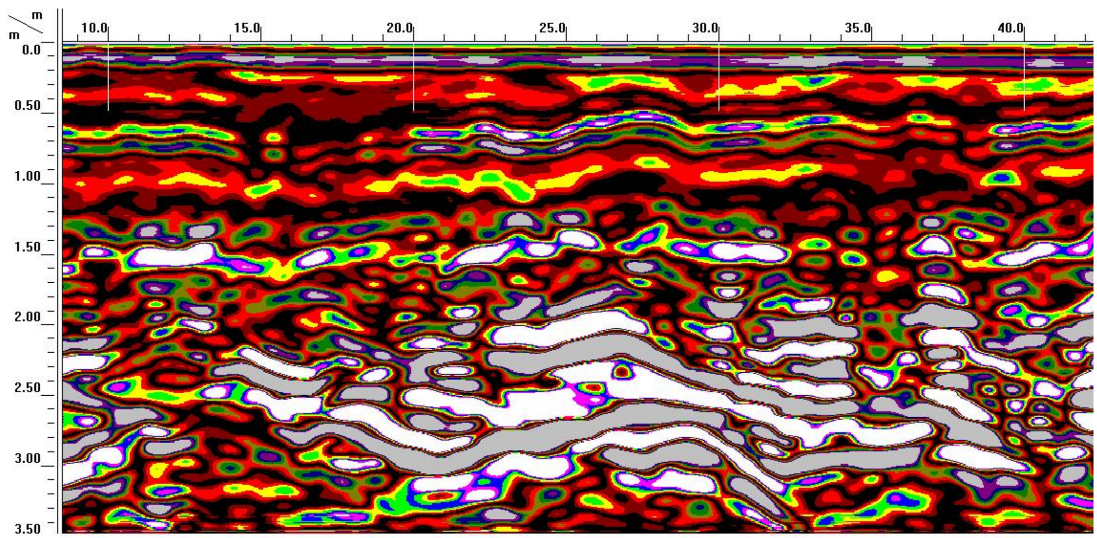

Figure 7 Portion of the radar record from the 310 m traverse line within the Burgess Road study area.

Figure 7 is another portion of the radar that was collected along the long traverse line within the Burgess Road study area. The same sequence of soil and stratigraphic layers that are evident on the radar record shown in Figure 6 are evident on this radar record. However, the interfaces are less continuous and more noticeably inclined and segmented. These forms suggest a high-energy environment. These layers will redirect the downward flow of soil water, but should not perch the water as effectively as the more level and continuous interfaces shown on the radar record in Figure 6.

<u>6th Street study area</u>

In general, radar records collected at the three transect sites (Sites 3, 4 and 5) within the 6th Street study area lacked well defined and continuous reflectors that could be identified as a loamy aquitard. On several radar records from this study area, high pass filtration was needed to remove background noise and improve interpretations. Even after advance signal processing techniques were used, the presence of a continuous high-amplitude reflector, which could be associated with a loamy aquitard, was indistinguishable. While multiple subsurface interfaces were distinguishable on most portions of the radar records collected within this study area, reflectors ranged from inclined and highly segmented (see Figure 8), to blurred and weakly expressed (see Figure 9). In areas with inclined and segmented interfaces, signal amplitudes varied in intensity, suggesting variability along and across stratigraphic boundaries.

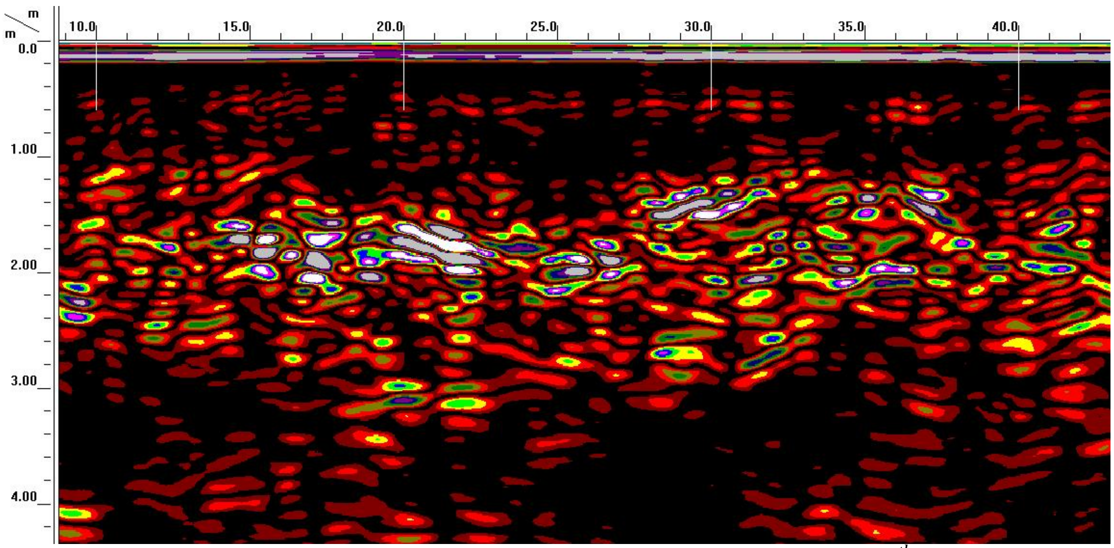

Figure 8 Portion of the radar record from the 310 m traverse line within the 6th Street study area.

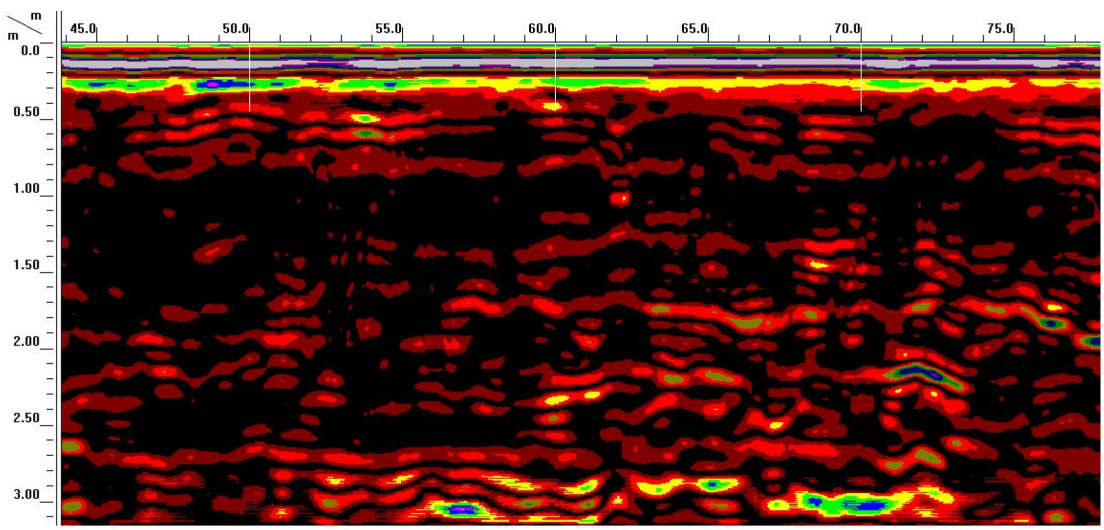

Figure 9. Portion of the radar record from the last traverse line within the 6th Street study area.

<u>Camp Polk:</u>

Radar traverses were largely restricted to a signal polygon of Omahaling fine sandy loam, 0 to 5 percent slopes (see Figure 3). Though restricted to a signal map unit, large differences in soils and soil properties are inferred from the radar records. Based on differences in signal attenuation and penetration depths, soils are believed to range from coarse- to medium-textured. This interpretation is based on the penetration depth, signal quality and attenuation, and the number of interfaces. Figure 10 is a representative radar record that was collected over a point-bar deposit along traverse line #6 (see Figure 3; green). Here penetration depths exceed 4 m. The large number of closely-spaced, high-amplitude, inclined interfaces suggests a succession of coarse-textured alluvial sediments that contrast principally in grain-size that were deposited in a relatively high energy environment. This radar record contrasts greatly with the radar record that was collected along traverse line #9 in an area of finer-textured alluvial deposits. Here radar energy losses are higher and other than multiples of near-surface reflections, no contrasting sediments are distinguishable. The absence of returns from deeper depth is the result of signal attenuation rather than the lack of stratifications.

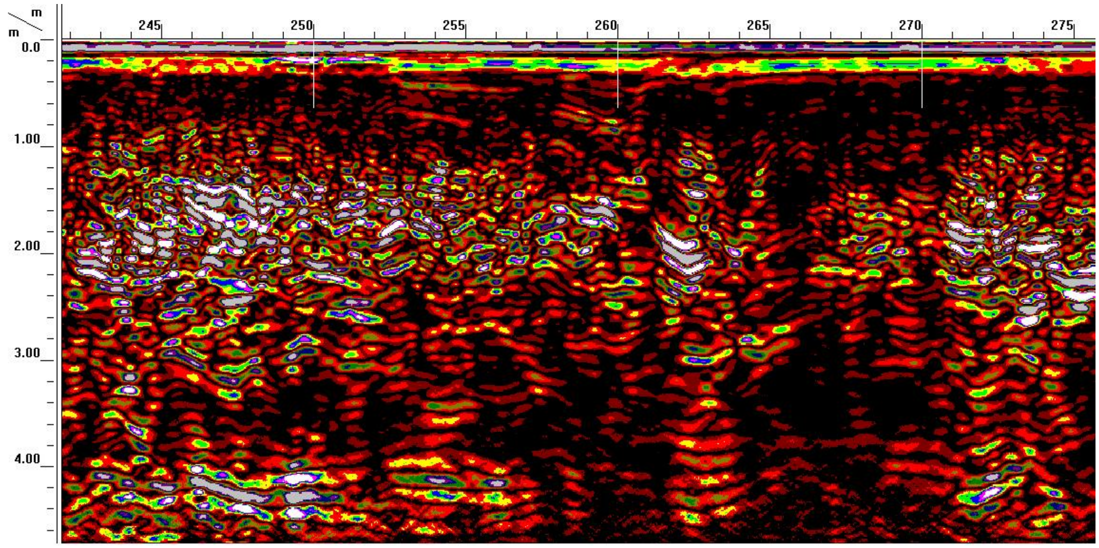

Figure 10. Portion of the radar record collected over a sand bar within the Camp Polk study area.

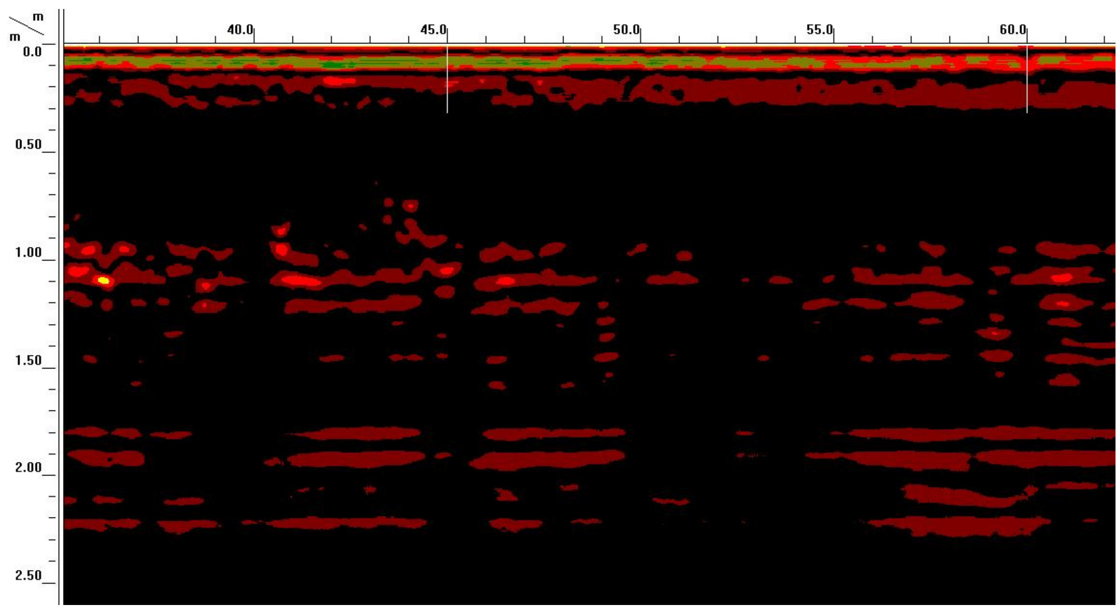

Figure 11. Portion of the radar record collected over an area of finer-textured alluvium within the Camp Polk study area.

Two areas of wetter, depressional soils were traversed with GPR. These depressional areas were traversed at sites #8 and 9 (see Figure 3, blue and yellowish-orange colored dots, respectively). These soils were noticeably wetter, and, as a consequence, had a higher estimated E_r of 14 and slower v of 0.0796 m/ns. In both depressions, high-amplitude subsurface reflections were identified and associated with a stratum of sandy alluvium (see Figure 12).

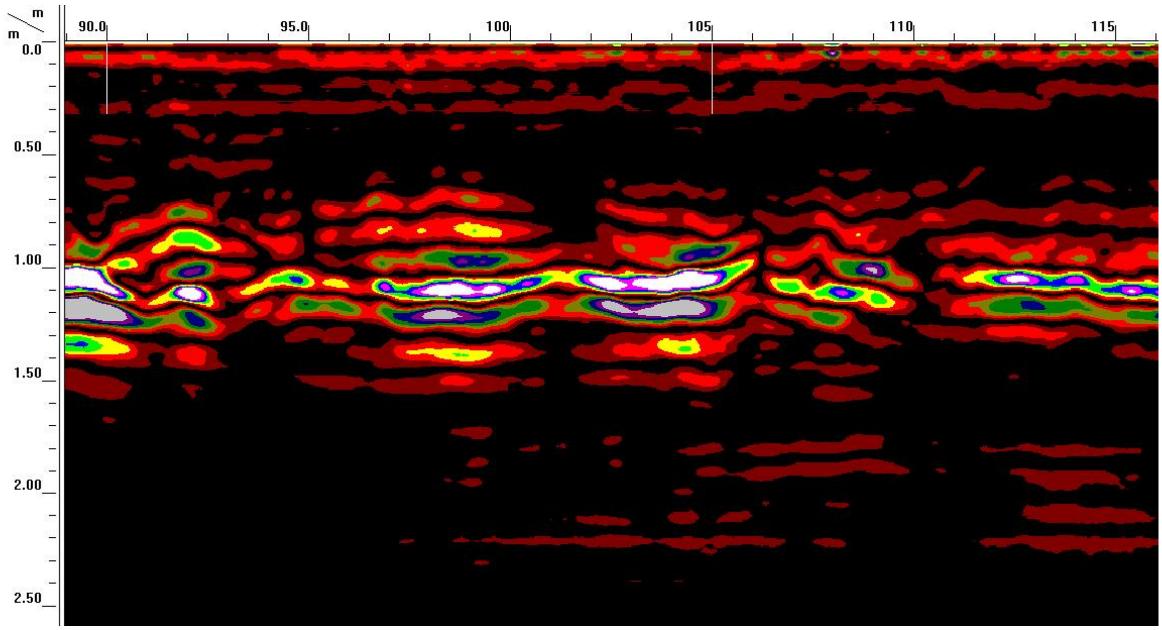

Figure 11. Portion of the radar record collected over at traverse site #8 within the Camp Polk study area. Though surface layers are fine-silty, reflections from a stratum of sandy sediments are evident between depths of about 70 to 150 cm.

Other than the included depressions and point-bar deposits, radar records from the Camp Polk study area were exceedingly depth restricted and provided little or no subsurface information. While the cause of this rapid signal attenuation and limited depth of penetration is suspected to be higher clay and soluble salt contents, this hypothesis is unconfirmed.

Bitmap Images:
Using the RADAN to Bitmap Conversion Utility developed by GSSI, Bitmap images were made of most radar records. The radar traverses for which bitmap images have been prepared are identified in Table 2 by their site number and the general direction in which the traverse was conducted. The maximum depth (in cm) profiled in each bitmap images is also provided. These bitmap images have been forwarded to Dr Reuter under a separate cover letter.

Site	*Direction*	*Scale (cm)*
1	E to W	484
1	W to E	394
2	E to W	484
2	W to E	364
3	W to E	317
3	E to W	364
6	S to N	720
8	E to W	187
9	E to W	239

References

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Hinkle, S. R., J.K. Böhlke, J. H. Duff, D. S. Morgan, and R. J. Weick, 2007. Aquifer-scale controls on the distribution of nitrate and ammonium in ground water near La Pine, Oregon, USA. Journal of Hydrology 333: 486-503.

Moorman, B. J., and F. A. Michel, 1997. Bathymetric mapping and sub-bottom profiling through lake ice with ground-penetrating radar. Journal of Paleolimnology 18: 61-73.