United States Department of Agriculture

Natural Resources Conservation Service

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Subject: SOI -- Geophysical Assistance **Date:** 4 October 2006

To: Joyce A. Swartzendruber
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Purpose:
Ground-penetrating radar (GPR) was used to determine the depths to bedrock and the composition (by soil depth class) of soil map units in Penobscot County. In Aroostook County, a study was conducted of cleavage planes in slate to help clarify radar interpretations.

Participants:
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William Roberts, Soil Scientist, USDA-NRCS, Presque Isle, ME

Activities:
All field activities were completed during the period of 11 to 15 September 2006. GPR investigations were conducted in southern Penobscot and northern Aroostook Counties.

Summary:

1. A total of 58 radar traverses were conducted across areas of nine soil map units in southern Penobscot County. The lengths of these traverses were variable, but with observations spaced at intervals of 3 paces, a total of 763 observations are recorded and summarized in this report. Data from this study may be used by soil scientists to determine map unit composition (based on soil depth criteria) and names. In addition, the data contained in this report may help to confirm mapping concepts used by soil scientists.

2. A study of cleavage planes in low metamorphic grade slates was conducted in northern Aroostook County. While the 400 MHz antenna is a satisfactory tool for the detection of soil/bedrock surfaces, in areas of slate, its wave length is too long to resolve the slaty cleavage.

3. The 400 MHz antenna detected horizontal reflectors that do not mimic the slaty cleavage. These horizontal reflectors may represent bedding planes. Compare to cleavage planes, which are caused by parallelism of constituents, bedding planes consists of parallel layers of different textures and compositions. More work needs to be done to verify this interpretation.

As always, it was my pleasure to work in Maine and with members of your fine staff.

With kind regards,

James A. Doolittle
Research Soil Scientist

cc:
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Equipment:
The radar unit is the TerraSIRch Subsurface Interface Radar (SIR) System-3000 manufactured by Geophysical Survey Systems, Inc. (Salem, New Hampshire)[1] The use and operation of GPR are discussed by Daniels (2004). The SIR System-3000 consists of a digital control unit (DC-3000) with keypad, SVGA video screen, and connector panel. A 10.8-volt lithium-ion rechargeable battery powers the system. The SIR System-3000 weighs about 4.1 kg (9 lbs) and is backpack portable. With an antenna, this system requires two people to operate. The 200 and 400 MHz antenna were used in the reported investigations.

Field Procedures:
Each radar traverse was completed by pulling the antenna by hand. Although, GPR provides a continuous profile of the subsurface, interpretations were restricted to reference points. For each transect, reference points were spaced at a uniform interval of 3 (Penobscot County) and 1 (Aroostook County) pace. At each reference point, the radar operator impressed a mark on the radar record. This mark identified a reference point on the radar record. Each radar traverse was stored as a separate file. Radar records were reviewed and the bedrock surface was identified. At each reference point, the depth to soil horizon, bedrock, or subsurface feature was interpreted from the radar record.

Calibration of GPR:
Ground-penetrating radar is a time scaled system. This system measures the time that it takes electromagnetic energy to travel from the antenna to an interface (e.g., bedrock, 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 (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:

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

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 of water (temperature dependent) have the greatest effect on the E_r and v.

At most sites, hyperbola matching techniques were used to estimate the relative dielectric permittivity and the velocity of propagation. At some sites, these parameters were determined by comparing the interpreted depth to a known, buried metallic reflector whose image appeared on the radar record with the measured depth. Based on the measured depth and the two-way travel time to the reflector, and equation [1], the velocity of propagation was estimated.

The relative dielectric permittivity and velocity of propagation varied with antenna frequency and with soils and landscape positions. In general, there is a tendency for E_r to decrease with increasing frequency. With the 200 MHz antenna, the estimated E_r ranged from 6.4 to 14 (v = 0.118 to 0.080 m/ns). With the 400 MHz antenna, the estimated E_r ranged from 6.9 to 8.4 (v = 0.113 to 0.103 m/ns). Most soils were relatively dry at the time of this investigation. Low soil moisture contents account for the comparatively low E_r and high v. Depending on the soils present, scanning times were adjusted and varied from 40 to 75 ns.

Study Areas in southern Penobscot County:
Multiple transects were conducted in areas of the map units listed in Table 1. Radar traverse lines were located along logging and access roads, in open fields and in wooded areas. Site 1 is located in an area of map unit 308B in Plymouth Township (near 44.80869 N Lat. and 69.25585 W Long.). Site 2 is located in areas of map unit 330D in Dixmont Township (near 44.68069 N Lat. and 69.10016 W Long.). Site 3 is located in an area of map unit 342B in Dixmont Township (near 44.66627 N Lat. and 69.09649 W Long.). Site 5 is located in an area of map unit 318C in Dixmont Township (near 44.73530 N Lat. and 69.11001 W Long.). Site 7 is located in an area of map unit 342B in Etna Township (near 44.73446 N Lat. and 69.10367 W Long.). Site 8 is located in an area of map unit 431C in Exeter Township (near 44.93106 N Lat. and 69.14816 W Long.). Site 9 is located in an area of map unit 57B in Etna Township (near 44.74141 N Lat. and 69.15820 W Long.). Site 10 is located in an area of map unit 14B in Carmel Township (near 44.75353 N Lat. and 69.07636 W Long.). Site 11 is located in an area of map unit 342B in Newburgh Township (near 44.73512 N Lat. and 69.06676 W Long.). Site 12 is located in an

[1] Manufacturer's name is provided for specific information and does not constitute endorsement.

area of map unit 57B in Newburgh Township (near 44.71316 N Lat. and 69.99481 W Long.). Site 13 is located in an area of map unit 36C in Newburgh Township (near 44.70420 N Lat. and 69.03230 W Long.).

Table 1
Names of Soil Map Units traversed with GPR in Penobscot County, Maine

Name	Symbol
Pushaw-Swanville complex, 0 to 8 % slopes	14B
Elliottsville-Chesuncook complex, 8 to 15 % slopes	36C
Nicholville very fine sandy loam, 3 to 8% slopes	57B
Brayton-Colonel Association, 0 to 8 % slopes, very stony	308B
Elliottsville-Monson complex, 5 to 15% slopes, very stony	318C
Monson-Elliottsville-Abrams complex, 10 to 25 % slopes, very stony	330D
Telos-Monarda-Monsoon association, 1 to 8 % slopes, very stony	342B
Corinna-Penobscot complex, 3 to 15 % slopes, very stony	431C

The taxonomic classifications of the soils recognized in the names of the map units traversed with GPR in Penobscot County are listed in Table 2.

Table 2
Soil Series Profiled with GPR in Penobscot County, Maine

Series	Taxonomic Classification
Brayton	Loamy, mixed, active, nonacid, frigid, shallow Aeric Endoaquepts
Abram	Loamy, isotic, frigid Lithic Haplorthods
Chesuncook	Coarse-loamy, isotic, frigid Aquic Haplorthods
Colonel	Loamy, isotic, frigid, shallow Aquic Haplorthods
Corinna[2]	Coarse-loamy, isotic, frigid, Lithic Eutrudepts
Elliottsville	Coarse-loamy, isotic, frigid Typic Haplorthods
Monarda	Loamy, mixed, active, acid, frigid, shallow Aeric Endoaquepts
Monson	Loamy, isotic, frigid Lithic Haplorthods
Nicholville	Coarse-silty, isotic, frigid Aquic Haplorthods
Penobscot[1]	Coarse-loamy, isotic, frigid, Dystric Eutrudepts
Pushaw[1]	Fine-silty, frigid Aeric Epiaquepts
Swanville	Fine-silty, mixed, active, nonacid, frigid Aeric Epiaquepts
Telos	Coarse-loamy, isotic, frigid, shallow Aquic Haplorthods

Results:
Table 3 contains the tabulated depths to the Cd horizon in an area of Brayton-Colonel association, 0 to 8 percent slopes, very stony. Depths are expressed in centimeters.

Table 3

Radar Interpreted Depths to Cd Horizon
(All depths are in cm.)

	Observations													
Map Unit	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	
308B	56	50	63	87	90	81	94	63						
308B		82	81	92	84	96	76	61	46	72	71			
308B		54	47	59	58	66	61	68	65	47	64	61	73	
308B		52	39	86	76	31	55	79	70	63	54	49	68	65

[2] Proposed soil series.

Table 4 contains the tabulated depths to bedrock for radar traverses conducted in several map units. Depths are expressed in centimeters. Where bedrock was exposed at the surface the observation depth is 0.

Table 4
Radar Interpreted Depths to Bedrock
(All depths are in cm.)

	Observations																				
MU	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**
330D	102	119	146	147	135	166	162	132	123	108	158	124	121	138							
330D	151	209	205	102	155	170	119	181	164	192	155	119	119								
330D	107	153	154	132	170	94	124	112	126	93	120	154	151	150							
330D	147	157	158	159	132	118	99	103	130	156	144	156	144								
330D	130	157	160	102	151	157	203	151	151	174	182	162									
330D	132	140	163	134	147	140	180	178	196	215	139	177	124								
330D	63	30	50	108	118	132	96	128	110	145	198	220	220	209	170						
330D	68	53	35	30	48	30	135	143	155	134	65	36	39								
330D	47	61	46	73	94	54	92	104	109	124	117	99	136	181							
318C	92	57	79	46	70	76	68	66	170	10	36	58	147	200	144						
318C	72	88	135	64	150	105	58	97	122	62	105	84	57	54	48	62					
318C	95	72	53	50	0	0	31	64	55	69	58	52	115	50	42						
318C	99	76	55	13	17	70	78	95	78	126	78										
342B	121	94	77	53	30	0	0	40	24	68	94	77	189	155	170						
342B	28	41	81	185	122	141	133	127	78	116	106	64	29	29	111	66					
342B	29	70	111	112	62	0	78	141	65	0	46	76	107	99	39	0	35				
342B	30	69	81	49	25	0	0	25	0	61	28	15	0	18	18	28	12				
342B	31	16	15	64	115	118	119	111	11	63	80	64	116	148	137	167	98				
342B	32	59	0	33	14	33	28	57	0	0	0	0	41	0	0	0	0	0	28	13	46
342B	38	51	94	108	68	77	44	76	106	110	108	65	84	50	26	0	0	41	42	0	0
431C	75	57	74	85	88	107	61	51	48	55	29	29	39	35	95	49	79	0			
431C	95	129	101	188	155	130	95	61	51	30	74	84	57	55	40	30					
57B	170	135	162	174	114	160	148	142	138	129	155	166									
57B	158	142	164	167	201	148	158	136	156	160	128	160	156								
57B	129	135	162	139	152	157	105	124	145	163	188	170									
57B	152	143	129	132	105	113	133	148	121	123	147										
57B	86	86	78	63	78	71	105	93	80	89	106	114									
57B	111	126	136	158	175	144	138	123	98	111	104	99									
14B	253	258	245	235	270	253	250	254	248	247	235	253									
14B	249	236	234	238	229	213	223	233	232	247											
14B	223	210	164	112	36	21															
14B	74	147	182	206	160	163	155	160	186	172											
14B	177	184	190	246	229	272	255	242	189	148	209	217	225								
14B	241	189	241	274	281	294	293	310	334	343	352	354	311								
342B	101	139	123	125	90	92	133	58	68	93	76	176									
342B	103	9	126	103	37	29	63	66	49	110	60	63	68								
342B	130	88	84	122	27	90	86	104	108	115	93	128	107								
342B	114	107	116	106	140	114	116	125	143	109	135	158	116								
342B	99	93	133	134	158	105	131	132	89	97	99	101	128								
57B	101	139	123	125	90	92	133	58	68	93	76	176									
57B	265	277	291	297	296	283	272	302	292	305	302	320									
57B	290	211	255	236	248	258	243	254	241	218	124	111	146								
57B	172	170	150	128	83	113	109	133	114	85	134	145									
57B	122	125	124	147	131	157	201	167	192	243	234	244	266								
57B	134	130	89	94	97	85	53	136	129	105	120	122									
57B	120	122	121	127	131	254	75	68	82	71	77	94	73								
57B	84	80	77	62	71	116	90	101	107	98	86										

Table 4 (continued)
Radar Interpreted Depths to Bedrock
(All depths are in cm.)

	Observations																				
MU	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**
36C	231	179	125	220	232	224	186	217	188	139	56	48									
36C	201	185	200	244	208	189	218	209	190	226	227	191	124								
36C	141	133	194	156	168	110	141	133	160	160	157	139	162								
36C	109	134	103	91	86	93	95	86	135	127	152	182	181								
36C	76	133	159	147	164	216	167	150	162	157	177	126	124								
36C	104	86	24	4	37	52	50	48	41	39	36	53	35								
36C	232	215	167	162	190	190	223	194	205	63	49	48	58								

Table 5 summarizes for each GPR transect the frequency distributions of observations based on soil depth classes (depth to bedrock). For Site 1, the depth to Cd horizon was grouped into two soil depth classes. Depth classes are shallow (0 to 50 cm), moderately deep (50 to 100 cm), deep (100 to 150 cm) and very deep (>150 cm). Where bedrock was exposed at the surface the observation depth was 0 and the depth class was "Outcrop."

Table 5

Summary of GPR Transect Data collected in Penobscot County
Frequency (%) by Soil Depth Class

Day 1:

Site 1 Map Unit 308B "Brayton-Colonel Association, 0 to 8 % slopes, very stony"

Depth to Cd horizon.

Transect #	**2**	**3**	**4**	**5**
Soil Depth Class				
Shallow	0.12	0.10	0.29	0.23
Moderately deep	0.88	0.90	0.71	0.77

Site 2 Map Unit 330D "Monson-Elliottsville-Abrams complex, 10 to 30% slopes, very stony"

Depth to Bedrock

Transect #	**9**	**10**	**11**	**12**	**12b**	**13**	**14**	**16**	**17**
Soil Depth Class									
Outcrop	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Shallow	0.00	0.00	0.00	0.00	0.00	0.00	0.13	0.46	0.14
Moderately deep	0.00	0.00	0.14	0.08	0.00	0.00	0.13	0.23	0.43
Deep	0.79	0.31	0.50	0.54	0.17	0.54	0.40	0.23	0.36
Very deep	0.21	0.69	0.36	0.38	0.83	0.46	0.33	0.08	0.07

Site 5 Map Unit 318C "Elliottsville-Monson complex, 5 to 15% slopes, very stony"

Depth to Bedrock

Transect #	**22**	**23**	**24**	**25**
Soil Depth Class				
Outcrop	0.00	0.00	0.00	0.00
Shallow	0.00	0.00	0.00	0.00
Moderately deep	0.00	0.00	0.14	0.08
Deep	0.79	0.31	0.50	0.54
Very deep	0.21	0.69	0.36	0.38

Site 7 Map Unit 342B "Telos-Monarda-Monson Association, 1 to 8 % slopes, very stony"

Depth to Bedrock

Transect #	**27**	**28**	**29**	**30**	**31**	**32**	**32B**
Soil Depth Class							
Outcrop	0.13	0.00	0.19	0.25	0.00	0.48	0.19
Shallow	0.20	0.20	0.19	0.56	0.19	0.38	0.29
Moderately deep	0.40	0.27	0.38	0.19	0.31	0.14	0.33
Deep	0.07	0.47	0.25	0.00	0.44	0.00	0.19
Very deep	0.20	0.07	0.00	0.00	0.06	0.00	0.00

Site 8 Map Unit 431C "Corinna-Penobscot complex, 3 to 15 % slopes, very stony"

Depth to Bedrock

Transect #	**33**	**34**
Soil Depth Class		
Outcrop	0.06	0.00
Shallow	0.33	0.19
Moderately deep	0.56	0.50
Deep	0.06	0.19
Very deep	0.00	0.13

Day 2:

Site 9 Map Unit 57B "Nicholville very fine sandy loam, 3 to 8 % slopes"

Depth to Bedrock

Transect #	**2**	**3**	**4**	**5**	**6**	**7**
Soil Depth Class						
Outcrop	0.00	0.00	0.00	0.00	0.00	0.00
Shallow	0.00	0.00	0.00	0.00	0.00	0.00
Moderately deep	0.00	0.00	0.00	0.00	0.75	0.17
Deep	0.50	0.31	0.50	0.91	0.25	0.67
Very deep	0.50	0.69	0.50	0.09	0.00	0.17

Site 10 Map Unit 14B "Pushaw-Swanville complex, 0 to 8 % slopes"

Depth to Bedrock

Transect #	**9**	**10**	**11**	**12**	**13**	**14**
Soil Depth Class						
Outcrop	0.00	0.00	0.00	0.00	0.00	0.00
Shallow	0.00	0.00	0.33	0.00	0.00	0.00
Moderately deep	0.00	0.00	0.00	0.10	0.00	0.00
Deep	0.00	0.00	0.17	0.10	0.08	0.00
Very deep	1.00	1.00	0.50	0.80	0.92	1.00

Site 11 Map Unit 342B "Telos-Monarda-Monson Association, 1 to 8 % slopes, very stony"

Depth to Bedrock

Transect #	**16**	**17**	**18**	**19**	**20**
Soil Depth Class					
Outcrop	0.00	0.00	0.00	0.00	0.00
Shallow	0.00	0.21	0.08	0.00	0.00
Moderately deep	0.50	0.43	0.38	0.00	0.38
Deep	0.42	0.29	0.54	0.92	0.54
Very deep	0.08	0.07	0.00	0.08	0.08

Site 12 Map Unit 57B "Nicholville very fine sandy loam, 3 to 8 % slopes"

Depth to Bedrock

Transect #	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**
Soil Depth Class								
Outcrop	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Shallow	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Moderately deep	0.50	0.00	0.00	0.17	0.00	0.42	0.54	0.73
Deep	0.42	0.00	0.23	0.67	0.38	0.58	0.38	0.27
Very deep	0.08	1.00	0.77	0.17	0.62	0.00	0.08	0.00

Site 13 Map Unit 36C "Elliottsville-Chesuncook complex, 8 to 15 % slopes"

Depth to Bedrock

Transect #	**29**	**30**	**31**	**32**	**33**	**34**	**35**
Soil Depth Class							
Outcrop	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Shallow	0.08	0.00	0.00	0.00	0.00	0.69	0.15
Moderately deep	0.08	0.00	0.00	0.38	0.08	0.23	0.15
Deep	0.17	0.08	0.46	0.38	0.38	0.08	0.00
Very deep	0.67	0.92	0.54	0.23	0.54	0.00	0.69

Study of cleavage planes in low grade metamorphic slate in Aroostook County:
Traveling through northern Maine on my way to Fort Kent, I was impressed by the large number of road cuts with vertical exposures of parent rock. In most of these exposures, the parent rock is highly deformed with steeply inclined to near vertical fractures and cleavage planes. With the consent of Mary Jo Kimble, a study was conducted to better understand and interpret the internal structure of this parent rock as recorded on radar records.

The first bedrock exposure was located in an area of Elliottsville (coarse-loamy, isotic, frigid Typic Haplorthods) soil. The well drained Elliottsville soil formed in a moderately deep mantle of glacial till derived mainly from slate, meta-sandstone, phyllite or schist. In Elliottsville soil, the depth to bedrock ranges from 50 to 100 cm. The selected exposure bordered a logging road (47.180 N Latitude, 68.9706 W Longitude) (Figure 1). The bedrock is slate, probably of the Devonian Seboomook formation (Caldwell, 1998). The slate was formed by low grade metamorphism at relatively low temperatures and pressures. Rock cleavage (fissility) is clearly evident in the exposure. This foliated rock has cleavages that allow it to split into thin sheets. The flat surfaces along which slate cleaves or breaks are shear surfaces along which the rock broke and shifted in response to deformation pressures. The technical term for this flow cleavage is *slaty cleavage*.

The slate has numerous, closely spaced cleavage planes that are not root restricting (Cr horizon). This low metamorphic grade slate is so pliable that it is considered by some soil scientists as saprolite. In the exposure, the plates of slate between the closely-spaced cleavage planes are very thin (0.1 to 1.3 cm) (Figure 2). In this exposure, cleavage planes are mostly vertical. In places the slaty cleavage is deformed with curved and convoluted forms. Cleavage planes are parallel but are refracted generally at boundaries separating layers of different composition and resistance (Lahee, 1952).

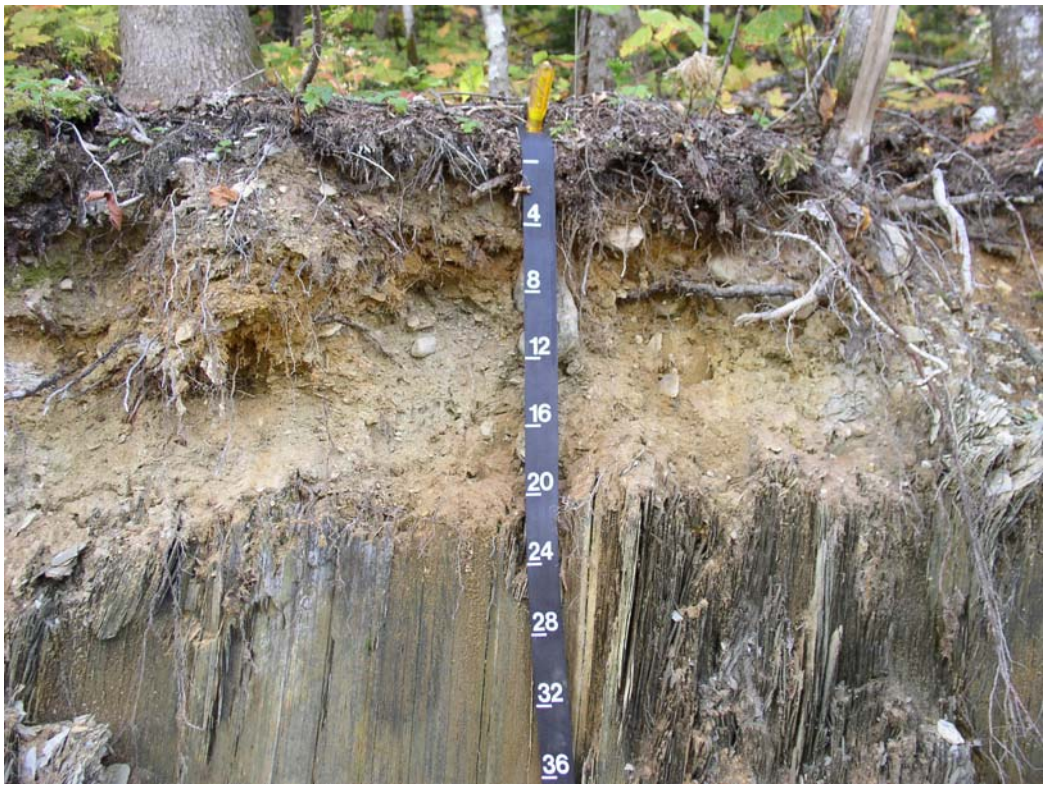

Figure 1. Site 1 is an exposure of Elliottsville soil that is underlain by vertical beds of pliable slate.

A radar traverse was conducted with the 400 MHz antenna. The traverse line was along the top of the exposure with reference points spaced at 1 meter intervals. This traverse line was orthogonal to both the strike and dip of the cleavage planes (see Figure 1).

Ground-penetrating radar radiates and receives electromagnetic energy in a complex 3D cone (Neal, 2004). Resolution is dependent on antenna frequency as well as the relative dielectric permittivity (E_r) and velocity of signal propagation (v)

through the medium. Vertical resolution is dependent upon antenna frequency and the wave length (λ). The λ is governed by the antenna frequency (f) and velocity of propagation (*v*) according to the formula (after Neal, 2004):

$$\lambda = v/f \qquad [1]$$

In this study, an antenna with a center frequency of 400 MHz was used. The dielectric permittivity of the shale was 8 and the velocity of propagation was 0.105 m/ns. According to equation [1], the λ is 0.26 m. Under ideal conditions, resolution is theoretically equal to one quarter of the input wave length (λ /4). Interfaces separated by less than λ /4 will produce constructive and destructive interference (Lane et al., 2000). The result of this interference is often the formation of a single, reflection. In most situations, background noise, velocity and wave form variations limit resolution to about third (λ /3) to one-half (λ /2) of the input wave length (Beres and Haeni, 1991). Based on this principle, the vertical resolution of the 400 MHz antenna at this exposure ranges from 8. 8 to 13.2 cm. In our exposure, the closely-spaced cleavage planes are very thin (0.1 to 1.3 cm) and are below the resolution of the 400 MHz antenna.

Horizontal resolution depends on the frequency used, depth to the reflecting surface and the dielectric permittivity of the material. The use of higher frequency (and shorter wave length) antennas increase the horizontal resolution. In general, the higher the E_r of the profiled material, the more focused is the radar beam and the greater the horizontal resolution. The equation for estimating the approximate size of the footprint area scanned beneath the radar is (after Neal, 2004):

$$A = \lambda/4 + D/\sqrt{E_r}-1 \qquad [2]$$

Where A is the radius of the footprint area, λ is wave length, D is the depth to the reflector, and E_r is the relative dielectric permittivity. Horizontal resolution decreases as the footprint area expands with increasing depth. According to equation [2], fracture, cleavage planes, and other discontinuities will be more poorly imaged and positioned in the lower part than in the upper part of radar records.

While the wave length of the 400 MHz is too wide to resolve the closely spaced cleavage planes, it was hoped that cleavage planes filled with moisture would be detectable. Fracture and bedding plane detection depends on the thickness and the material filling the discontinuity. High amplitude radar reflections have been associated with abrupt changes in water content that occur in filled joints, fractures, and structural planes (Lane et al., 2000; Buursink and Lane, 1999; Olhoeft, 1998; Grasmueck, 1996).

Figure 2. At the first exposure, cleavage planes are paper thin.

As the cleavage planes are vertically inclined, they reflect little energy back to the antenna and therefore provide poor reflecting surfaces. High scattering losses are known to occur in highly fractured rocks. These losses limit the penetration depth and effectiveness of high frequency antennas. For all antennas, scattering losses are greater for reflectors with large dip-angles. These reflectors reflect less energy back to the radar antenna. Fractures and structural planes with dip-angles greater than about 45° are affected by spatial aliasing distortion and are not accurately imaged with GPR (Buursink and Lane 1999; Ulriksen, 1982). Spatial aliasing restricts the dip-angles that are detectable with GPR (Lane et al., 2000). Vertical interfaces reflect very little energy back towards the radar antenna. As a consequence, these reflectors often appear on radar records as low-amplitude diffractions whose alignment reflects the orientation of the steeply inclined fracture (Grasmueck et al., 2004).

The radar record shown in Figure 3 is from the first exposure (see Figure 1). The soil/bedrock contact was detected with the 400 MHz antenna. This interface (see green-colored line in Figure 3) was traced laterally across the radar record with ease and little ambiguity. The 400 MHz antenna, while well suited to soil/bedrock investigations in Maine, lacks sufficient vertical resolution to detect the cleavage planes in low metamorphic grade slates. In the radar record shown in Figure 3, the 400 MHz antenna detected horizontal reflectors that do not mimic the apparent structure. These horizontal reflectors displayed spatially variable amplitudes.

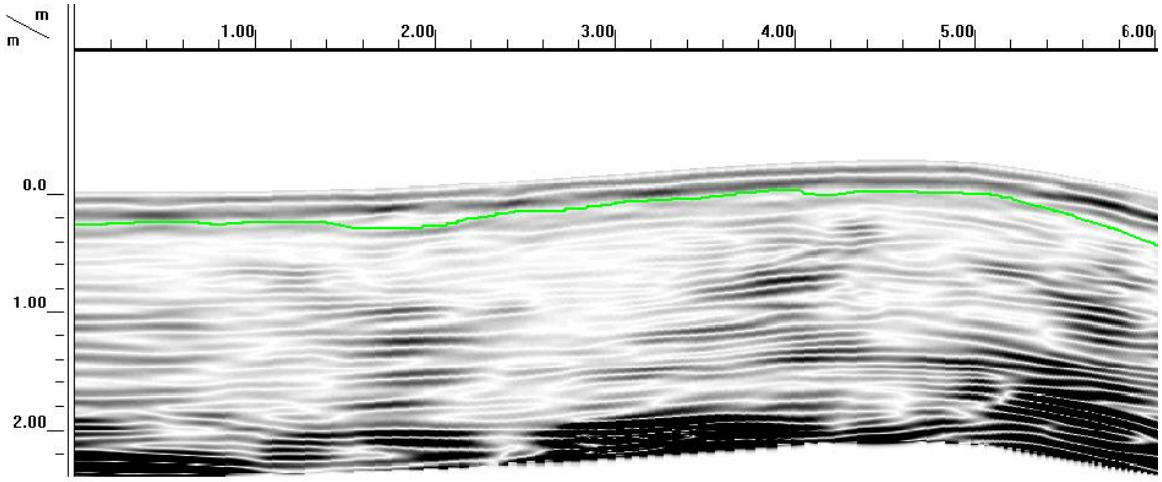

Figure 3. Radar record collected with the 400 MHz antenna at the first exposure.

Parent rock was exposed to the surface along a quarry wall at the second site (46.8933 N Latitude, 68.8177 W Longitude) (see Figure 4). Once again, the bedrock is low metamorphic grade slate, probably of the Devonian Seboomook formation (Caldwell, 1998). *Slaty cleavage* is evident in this exposure, but the slate appears more deformed at this site than at the first studied exposure.

The slate has numerous, closely spaced cleavage planes that are not root restricting (Cr horizon). In this exposure, the thin (0.32 to 2.54 cm) plates of slate (Figure 5) are highly deformed. An abrupt boundary separating cleavage planes with different orientations is evident at depths of 1.2 to 2.0 meters along the face of this exposure. Because of the conspicuousness and abruptness of this interface, it was suggested that the slate in the upper 1.2 to 2.0 m of the exposure had been deformed and moved by glaciers. Cleavage planes in the upper 1.2 to 2.0 m are inclined at angles of 30 to 45 degrees and slope towards the north. Beneath this possible *glacially folded* layer, the cleavage planes are nearly vertical (see Figure 5).

The radar record shown in Figure 6 is from the second exposure. Here, the bedrock extends to the soil surface. In Figure 4, the flags used as reference points along the radar traverse line can be seen above the face of the quarry wall. The contact separating the two layers of slate with distinctly different orientations is evident on the radar record. Obvious differences in the graphic signature allowed this interface (see green-colored line in Figure 6) and the two layers to be identified with little ambiguity. The 400 MHz antenna can detect zones in low metamorphic grade slates with noticeably different internal structure and geometry.

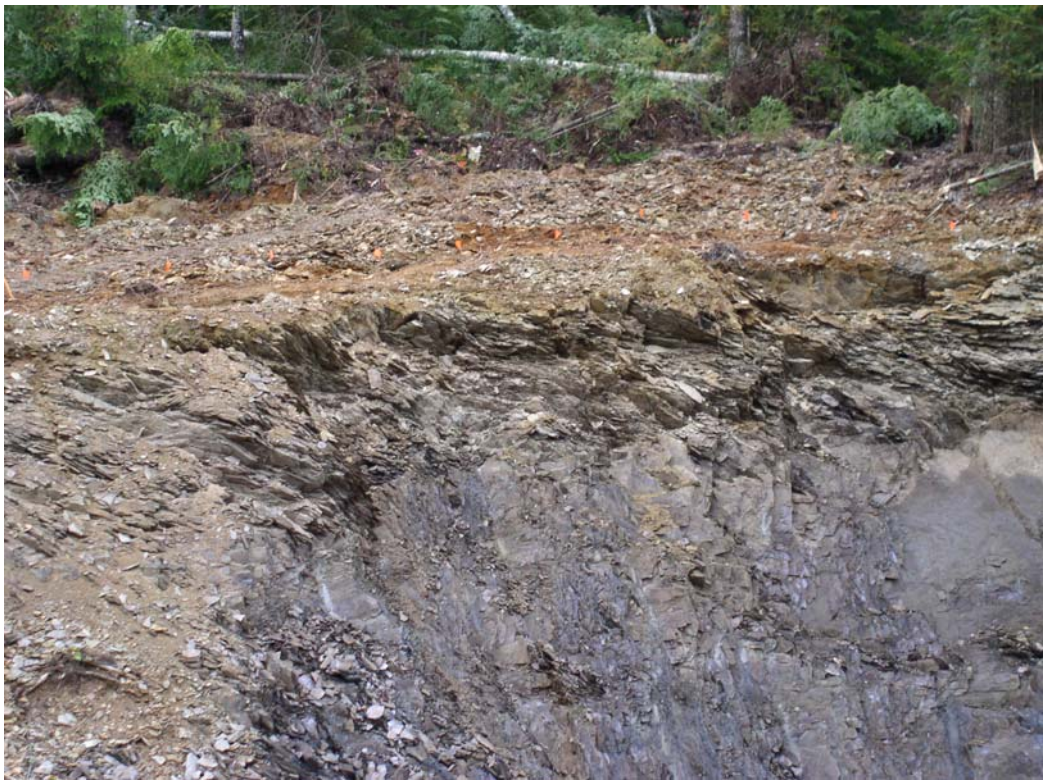

Figure 4. The slate at exposure 2 has cleavage planes with highly contrasting orientations.

Figure 5. A close-up of the highly deformed slates at the second exposure.

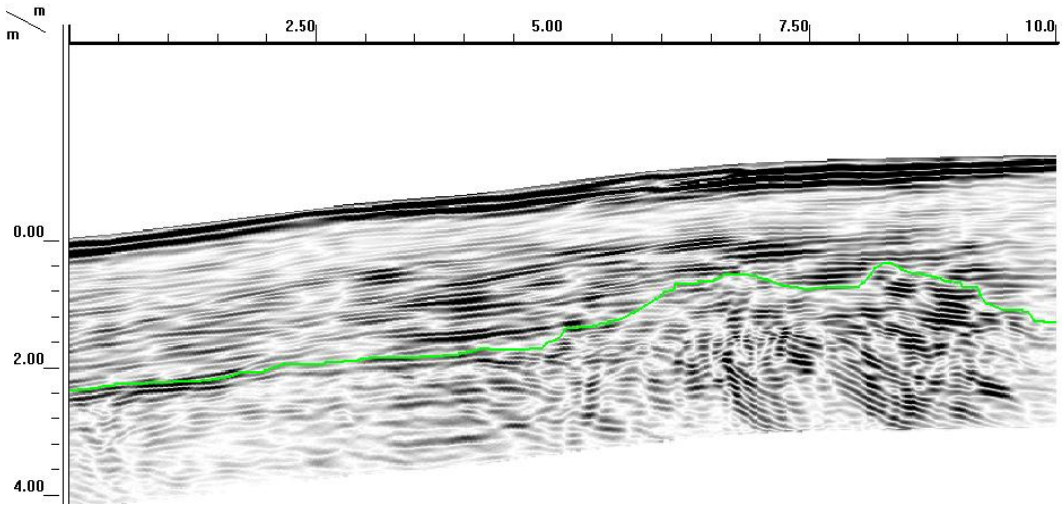

Figure 6. Radar record collected with the 400 MHz antenna at the second exposure.

As at both sites, the 400 MHz antenna detected horizontal reflectors that do not mimic the apparent structure. These horizontal reflectors displayed spatially variable amplitudes. While the 400 MHz antenna lacks sufficient resolution to resolve the cleavage planes, the horizontal layers may represent bedding planes. Compare to cleavage planes, bedding planes consists of parallel layers of different textures and compositions. Cleavage planes are due to parallelism of constituents rather than parallelism of adjacent layers with different grain-size distributions and compositions. More work needs to be done to verify this interpretation.

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