United States Department of Agriculture | **Natural Resources Conservation Service** | **5 Radnor Corporate Center, Suite 200, Radnor, PA 19087-4585**

Subject: SOI -- Geophysical Assistance **Date:** 9 September 1996

To: Scott Hoag
State Conservationist
USDA-NRCS,
P. O. Box 1458
Bismarck, North Dakota
58502-1458

Purpose:
The purpose of this investigation was to explore further applications of electromagnetic induction (EMI) techniques in North Dakota.

Participants:
Jim Doolittle, Research Soil Scientist, USDA-NRCS, Radnor, PA
Mary Doolittle, Earth Team Volunteer, USDA-NRCS, Radnor, PA
Joe Freidlander, Environmental Manager, Coteau Properties Company, Beulah, ND
Tim Hendrick, Conservational Engineer Technician, USDA-NRCS, Grand Forks, ND
Ernie Jensen, Party Leader, USDA-NRCS, Devils Lake, ND
Jeff Lewis, Soil Conservation Technician, USDA-NRCS, Park River, ND
Bob LiSanta, Area Resource Soil Scientist, USDA-NRCS, Devils Lake, ND
Dean Moos, Environmental Scientist, North Dakota Public Service Commission, Bismarck, ND
Jon Nesreoss, Design Engineer, USDA-NRCS, Bismarck, ND
Carol Reed, Geologist, USDA-NRCS, Bismarck, ND
David Reeves, Soil Scientist, USDA-NRCS, Devils Lake, ND
Steve Seiler, Soil Scientist, USDA-NRCS, Bismarck, ND
Cindy Steele, Environmental Engineer, USDA-NRCS, Huron, SD
John Sucher, Conservational Engineer Technician, USDA-NRCS, Grand Forks, ND
Roger Thompson, Project Engineer, USDA-NRCS, Grand Forks, ND
Mike Ulmer, Soil Scientist, USDA-NRCS, Bismarck, ND
Hal Weiser, Area Resource Soil Scientist, USDA-NRCS, Jamestown, ND

Activities:
Field studies closely followed the objectives and itinerary established in Mike Ulmer's letter to Jim Doolittle of 13 June 1996. All field activities were completed during the period of 5 to 9 August 1996.

Electromagnetic Induction Methods:
Electromagnetic induction has been used to identify, map, and monitor soil salinity (Cook and Walker, 1992; Corwin and Rhoades, 1982, 1984, and 1990; Rhoades and Corwin, 1981; Rhoades et al., 1989; Slavich and Petterson, 1990; Williams and Baker, 1982; and Wollenhaupt et al., 1986). The North

Dakota Soil Staff has used the EMI-38 meter extensively for both site investigations and production surveys of saline areas. The purpose of this study was to explore expanded uses for EMI techniques in North Dakota. Recently, the use of this technology has been expanded to include the assessment and mapping of soils and soil map units (Ammons et al., 1989; Doolittle et al., 1996; Jaynes et al., 1993; and Nettleton et al., 1994).

Electromagnetic induction techniques use electromagnetic energy to measure the apparent conductivity of earthen materials. Apparent conductivity is a weighted, average conductivity measurement for a column of earthen materials to a specific observation depth. Variations in apparent conductivity are produced by changes in the electrical conductivity of earthen materials. The electrical conductivity of soils is influenced by the (i) volumetric water content, (ii) type and concentration of ions in solution, (iii) temperature and phase of the soil water, and (iv) amount and type of clays in the soil matrix, (McNeill, 1980a). The apparent conductivity of soils increases with increases in the exchange capacity, water content, and clay content.

Values of apparent conductivity are seldom diagnostic in themselves, but lateral and vertical variations in these measurements can be used to infer changes in soils and other earthen materials. Interpretations of EMI data are based on the identification of spatial patterns within data sets. Electromagnetic induction techniques are not suitable for use in all investigations. Generally, the use of EMI techniques has been most successful in areas where subsurface properties are reasonably homogeneous and the effects of one property (e.g., clay, water, or salt content) dominate over the other properties. In these areas, variations in EMI response can be related to changes in the dominant property or feature (Cook et al., 1989).

Advantages of EMI methods include speed of operation, flexible observation depths (with commercially available systems from about 1 to 60 meters), and moderate resolution of subsurface features. Results of EMI surveys are interpretable in the field. These techniques can quickly provide the large number of observations needed for the characterization and assessments of sites. Maps prepared from correctly interpreted EMI data provide the basis for assessing site conditions and for planning further investigations.

Equipment:

The EM38, EM31, and EM34-3 meters used in this study. These meters are manufactured by Geonics Limited of Mississauga, Ontario, Canada[1]. These meters are portable and require either one or two persons to operate. Principles of operation have been described by McNeill (1980b, 1986). No ground contact is required with these meters. Each meter provides limited resolution and depth information. For each meter, resolution is approximately equal to the intercoil spacing. The observation depth of an EMI meter is dependent upon intercoil spacing, transmission frequency, and coil orientation. Table 1 lists the theoretical observation depths for the meters. Observation depths can be varied by changing coil orientation, intercoil spacing, and/or frequency.

The EM38 meter has a fixed intercoil spacing of about 1.0 meter. It operates at a frequency of 13.2 kHz. The EM38 meter has theoretical observation depths of about 0.75 and 1.5 m in the horizontal and vertical dipole orientations, respectively (McNeill, 1986). The EM31 meter has a fixed intercoil spacing of about 3.6 m. It operates at a frequency of 9.8 kHz. The EM31 meter has theoretical observation depths of about 3 and 6 m in the horizontal and vertical dipole orientations, respectively (McNeill, 1980b). The EM34-3 meter consists of two coils and three reference cables with lengths of about 10, 20, and 40 m. One of the coils serves as the transmitter, the other as the receiver. Observation depths

[1] Trade names are provide for specific information. Their use does not constitute endorsement.

range from about 7.5 to 60 m. With all meters, values of apparent conductivity are expressed in milliSiemens per meter (mS/m).

TABLE 1

Depth of Measurement
(All measurements are in meters)

	Intercoil	**Depth of Measurement**		
Meter	**Spacing**	**Horizontal**	**Vertical**	EM38
1.0	0.8	1.5		
EM31	3.7	3.0	6.0	
EM34-3	10.0	7.5	15.0	
	20.0	15.0	30.0	
	40.0	30.0	60.0	

To help summarize the results, the SURFER for Windows software program was used to construct two-dimensional simulations. Grids were created using kriging methods with an octant search. All grids were smoothed using a cubic spline interpolation. In each of the enclosed plots, shading and filled isolines have been used. These options were selected to help emphasize spatial patterns. Other than showing trends and patterns in values of apparent conductivity (i.e., zones of higher or lower electrical conductivity), no significance should be attached to the colors themselves.

Discussion:
***McIntosh County*:**
The site was located near Ashley, North Dakota (see Figure 1). Three transects were established in areas of Wabek and Lehr soils. Wabek soils are members of the sandy-skeletal, mixed Entic Haploborolls family. Lehr soils are members of the fine-loamy over sandy or sandy-skeletal, mixed Typic Haploborolls family. This investigation assessed the use of EMI techniques to determine depths to sands and gravels and to distinguish soils in areas of collapsed tills.

At this site, the thickness, composition, and sequences of soil horizons were highly variable. Electromagnetic induction techniques are highly sensitive to changes in clay, moisture, and salt contents. At the Ashley site, these parameters were highly variable and varied jointly within and among soil types. In this highly complicated soil landscape, no strong relationship was found between EMI response and depth to sand and gravels. Interpretations of the depth to sands and gravels based on EMI responses were weak and ambiguous. If was felt that correlations could be improved, if soil scientists restricted measurements to only one soil type or partitioned the data by landscape components. However, such partitioning of soils and landscape is considered impractical for present soil survey operations. Considering the results of this study, in areas of collapsed till, electromagnetic induction methods do not provide a reasonably reliable estimate of the depth to sand and gravel. This technique is considered inappropriate for determining the depths to sand and gravels on similar area of collapse till in North Dakota.

Variations in the electromagnetic response have been attributed to the arrangement and the physical and chemical properties of soil horizons. Many soil properties affect EMI responses. These properties included variations in the depth and texture of diagnostic surface and subsurface horizons (mollic epipedon, argillic, natric, and calcic horizons), disparities in the concentration of carbonates within Bk horizons or soluble salts in soil horizons, and/or differences in the degree of water saturation or depth to water table within the soil profile.

Within the Ashley site, a large number of soil types were observed. As EMI measurements integrate the bulk physical and chemical properties of soils into a single value, responses can be associated with changes in soils and soil map units (Hoekstra et al., 1992; Jaynes et al., 1993, Doolittle et al., 1996). During the course of this investigation, soils were identified with a soil auger at 30 observation points. Table 2 lists the soils identified at these observation points and some basis statistics for the observed values of apparent conductivity.

Table 2

EM38 TRANSECT DATA
Some Basic Statistic for Selected Soils
(In mS/m)

						Averaged	
Soil	**# Observations**	**Min.**	**Max.**	**Min.**	**Max.**	**EMH**	**EMV**
Appam	1					12.3	14.5
Arrogard	3	27.7	28.0	34.4	39.7	27.8	37.3
Badger	1					39.9	55.2
Bearpaw	1					44.4	60.4
Bowbells	3	13.5	34.9	17.0	50.2	24.2	33.3
Cresbard	1					38.7	47.0
Divide	1					16.2	21.2
Hamerly	1					33.1	35.9
Lehr	4	12.9	15.4	13.4	19.2	14.0	16.0
Niobell	2	29.2	32.2	40.9	45.4	30.7	43.2
Schaller	2	10.4	18.7	14.9	24.8	14.6	19.8
Shambo	1					16.1	22.0
Stady	3	14.0	18.3	15.6	23.2	16.5	19.4
Vallers	3	26.7	43.0	33.3	48.7	32.9	39.3
Wabek	3	10.6	17.8	14.8	28.5	13.4	19.7
Zahl	3	28.4	45.4	42.0	56.0	39.1	51.0

In Table 2, albeit the sample size is exceedingly small, each soil appears to have a fairly unique EMI response. Some soils, because of greater inherent or acknowledged variations in physical and chemical properties (clay, moisture, or soluble salt contents), are more variable than others. Within areas of Wabek and Lehr soils, and probably within a broader geographic area (till plains of the Dakotas), most similar soils will share comparable EMI responses. (In Table 2, as an example, note the similarity in EMI responses between Hamerly and Vallers soils.) Many dissimilar soils will have disparate EMI responses. (In Table 2, as an example, note the differences in EMI responses among Arrogard, Lehr, and Niobell soils.) However, the electrical conductivity of some similar and dissimilar soils will overlap. (In Table 2, as an example, note the similarity in EMI responses among Cresbard, Zahl, and Vallers soils.) This last example occurs where contrasts in EMI responses caused by differences in one property (clay, moisture, or soluble salt contents) are offset by differences in another property. Some soil properties and soils can be inferred and mapped with EMI techniques. This application will require careful attention to changes in parent materials, topography, drainage, and vegetation.

Observations from the Ashley sites demonstrated that EMI techniques were inappropriate for determining and mapping the depths to sands and gravels in areas of collapsed tills. These areas have complex properties that influence EMI responses and foster ambiguous interpretations of the depth to sand and gravel. However, these results do not depreciate the potential value of using EMI techniques to chart distributions of some soils or soil properties, to clarify some spatial patterns, and to select sampling or monitoring sites.

***Mercer County*:**

Mine Spoil

The site was located on reclaimed mine spoil of the Coteau Properties Company near Beulah, North Dakota (see Figure 1). The purpose of this investigation was to assess the potential of using EMI techniques to determine the thickness of the "topsoil" and the depth to mine spoil on a reclaimed area. In related studies, electromagnetic induction techniques have been used to map the depths to claypans (Sudduth and Kitchen, 1993; Stroh et al., 1993; and Doolittle et al., 1994). These studies indicate that EMI responses will change with the amount and density of clay in the subsoil.

A rectangular grid was established across an area of reclaimed mine spoil. The survey area was 0.92 acre. The dimensions of the grid were 200 feet by 200 feet. The grid interval was about 25 feet. At each of the eighty-one grid intersections, a survey flag was inserted in the ground and served as an observation point. At each observation point, measurements were taken with an EM38 meter placed on the ground surface in both the horizontal and vertical dipole orientations.

Table 3

Basic Statistics
EMI Survey
Reclaimed Spoil Site, Coteau Properties Company near Beulah
(All values are in mS/m)

				Quartiles			
Meter	**Orientation**	**Minimum**	**Maximum**	**1st**	**Median**	**3rd**	**Average**
EM38	Horizontal	30.6	99.4	50.1	56.1	64.3	57.0
EM38	Vertical	44.6	99.3	67.3	77.5	82.4	74.9

Basic statistics for the EMI data collected within the site are displayed in Table 3. In general, values of apparent conductivity increased, but became slightly less variable with increasing depth of observation. Measurements averaged 57.0 mS/m and 74.9 mS/m in the horizontal and vertical dipole orientations, respectively. In the shallower-sensing horizontal dipole orientation, one-half of the observations had values between 50.1 and 64.3 mS/m. In the deeper-sensing vertical dipole orientation, one-half of the observations had values between 67.3 and 82.4 mS/m. The increase in apparent conductivity with increasing soil depth was attributed to the higher clay and sodium salts (relatively conductive materials) contents and the increased compaction of the spoil materials.

At each observation point, relationships between horizontal and vertical measurements conformed to tentative assumptions made concerning the site. It was assumed that a less conductive layer of topsoil overlaid the spoil materials. The more compact spoil materials had higher clay, shale, and sodium contents and were assumed to be more conductive than the topsoil.

Figures 1 and 2 are two-dimensional plots of data collected with the EM38 meter in the horizontal and vertical dipole orientations, respectively. In each of these plots, the isoline interval is 5 mS/m. Spatial patterns and trends are evident in both plots. Based on limited ground-truth auger observations, these spatial patterns do not appear to reflect the depth to spoil materials alone. Patterns seem to correspond more closely with variations in clay content and soil compaction. In general, apparent conductivity increased toward the southeast corner of the site. This area was lower-lying and had experienced greater compaction. In this portion of the site, the underlying mine spoil materials appeared to have greater clay contents. Values of apparent conductivity decreased toward the northwest corner of the site. This area was higher-lying and appeared to have had experienced less compaction.

Collapsed mine features

This study evaluated the use of EMI techniques for the detection and delineation of abandoned mine tunnels. Electromagnetic induction techniques have been used to locate and map subsurface cavities and unstable ground. These techniques have been used principally in areas of karst to identify and map subsurface cavities and zones of higher permeability within carbonate bedrock (Canace and Dalton, 1984; Pazuniak, 1989; Robinson-Poteet, 1989; Rumbens, 1990). In a study conducted in Kansas, electromagnetic induction techniques provided ancillary information concerning the location and extent of abandoned mine workings (Friedel et al., 1990).

The detection of air-filled voids, such as abandoned mines, requires a favorable size-to-depth ratio, and often demanding survey techniques and complex interpretations. Detection of air-filled voids is facilitated where the surrounding materials are electrically conductive.

The site was located to the northeast of Beulah, North Dakota. Signs, posted in the area, warned of the risk of surface collapse over the abandoned mines. A portion of the site was selected for investigation with EMI techniques. The selected area was accessible to a road and contained two, opened, collapsed features (see spot symbols in figures 4 and 5).

A rectangular grid was established across the selected area. The survey area was 0.92 acre. The dimensions of the grid were 200 feet by 200 feet. The grid interval was about 50 feet. At each of the twenty-five grid intersections, a survey flag was inserted in the ground and served as an observation point. At each observation point, measurements were taken with an EM31 and an EM34-3 meter in both the horizontal and vertical dipole orientations. A 10 m intercoil spacing was used with the EM34-3 meter. For each measurement, the meters were placed on the ground surface.

Two-dimensional isarithmic maps of apparent conductivity values measured with the EM31 and EM34-3 meters are shown in Figure 3. Figures 3A and 3B represent the data collected with the EM31 meter in the horizontal and the vertical dipole orientations, respectively. Theoretically, the horizontal orientation integrates values of apparent conductivity within depths of 0 to about 3 meters; the vertical orientation integrates these values within depths of 0 to about 6 meters. Figures 3C and 3D represent the data collected with the EM34-3 meter in the horizontal and the vertical dipole orientations, respectively. Theoretically, the horizontal orientation integrates values of apparent conductivity within depths of 0 to about 7.5 meters; the vertical orientation integrates these values within depths of 0 to about 15 meters. In each plot, the approximate locations of two open mine cavities have been noted with spot symbols. It was inferred that an abandoned mine tunnel extended between these two openings.

Comparing figures 3A and 3B, values of apparent conductivity increase with increasing soil depth (horizontal dipole measurements < vertical dipole orientation). This relationship was assumed to reflect higher clay and volumetric water contents at greater soil depths. Comparing figures 3B with figures 3C and 3C, values of apparent conductivity decrease with increasing depth (EM31 measurements less than EM34-3 measurements; and for the EM34-3 meter, horizontal dipole measurements > vertical dipole orientation). This relationship was assumed to reflect the presence of more resistive strata or possibly air-filled cavities in the lower part of the profiled materials. In addition, the orientation of the spatial patterns changes from essentially east-west with the EM31 (see Figure 3, A and B) meter to predominantly north-south with the EM34-3 meter (see Figure 3, C and D). The north-south patterns conform with the alignment of the collapsed structures and the suspected orientation of the abandoned mine tunnel.

The observation depth (0 to 6 meters) of the EM31 meter was too shallow to adequately sense and detect the abandoned mine tunnel. The patterns appearing in the plots of the EM31 data (Figure 3, A and B) appear to reflect variations in soils and soil properties. The observation depth (0 to 15 meters) of the EM34-3 meter (with a 10 m intercoil spacing) was considered adequate to detect the abandoned mine tunnel. The spatial patterns appearing in the simulated plots (Figures 3, C and D) support the presence of an abandoned mine tunnel. These patterns appear to correspond with the presumed orientation of the mine tunnel. This orientation was presumed to be aligned with the two collapsed cavities. However, in each plot (Figures 3, C and D) values of apparent conductivity were higher along this line. These higher values suggested that the tunnel, if present, was filled with conductive materials. This was considered unlikely.

Abandoned mine tunnels and cavities are air-filled. These features are electrically resistive and, if large enough, should contrast with the enclosing more conductive till and bedrock lithologies. It was hypothesized that abandoned mine tunnels and cavities were more likely to occur beneath areas where values of apparent conductivity decreased with increasing observation depths. In addition, it was assumed that the greater the difference between horizontal and vertical dipole measurements, the larger or nearer the surface would be the abandoned tunnel cavity.

The data collected with the EM34-3 meter were manipulated to improve interpretations. For each observation point, the measurement collected in the vertical orientation was subtracted from the measurement collected in the horizontal orientation. Observation points having positive values indicate areas with reductions in conductivity with increasing depth. The higher the value, the greater the reduction in apparent conductivity with depth and the larger the disparity in materials. This transformed data has been plotted in Figure 4. In Figure 4, areas with higher values were more likely to be underlain by air-filled, abandoned mine tunnels. The spatial patterns appearing in Figure 4 match the presumed alignment of the abandoned tunnel. Areas with greater contrast in apparent conductivity are presumed to reflect larger and shallower air-filled cavities. These areas have thinner layers of overburden are considered more susceptible to collapse.

Eddy County:

Two sites were selected in Eddy County (see Figure 1). At both sites, EMI techniques were used to estimate depths to contrasting materials. One site was located in an area that had been mapped as Renshaw loam, 0 to 3 percent slopes. Renshaw soils are members of the fine-loamy over sandy or sandy-skeletal, mixed Udic Haploborolls family. The purpose of this investigation was to use EMI techniques to determine the depth to sands and gravels. One site was located in an area that had been mapped as Towner-Dickey sandy loams, 0 to 3 percent slopes. Towner and Dickey soils are members of the sandy over loamy, mixed Udorthentic Haploborolls family. The purpose of this investigation was to use EMI techniques to determine the depth to till and the thickness of overlying, coarse-textured materials.

Renshaw Site

A transect line was established at the Renshaw site. Along this line, the depth to sand and gravel was measured with a hydraulic probe at four observation points. The depth to sand and gravel averaged 23 inches and ranged from 11 to 34 inches. A comparison of soil probe and EMI data collected at the four observation points revealed strong positive relationships between the observed depths to sand and gravel and the EMI data.

The observed depths were compared with EMI data and used to develop a predictive equation. This equation was used to predict the depths to sand and gravel from values of apparent conductivity. Data collected with the EM38 meter in the horizontal dipole orientations had the strongest correlation with the depth to sand and gravel ($r^2 = 0.970459$) and were used to develop the following predictive equation:

$$D = -8.93705 + (3.217839 * EM38H) \qquad [1]$$

In this equation, "D" is depth to sand and gravel (inches); "EM38H" is apparent conductivity (mS/m) measured with the EM38 meter in the horizontal dipole orientation.

Based on the EMI measurement (horizontal dipole orientation) and Equation [1], the depth to sand and gravel was predicted at each of the five probed sites. The predicted depth to sand and gravel was compared with the observed depth at each of the four probed points. The average difference between observed and predicted depths to sand and gravel was 1.45 inches. All predicted depths were within 3 inches of the observed depths.

Equation [1] was used to estimate the depth to sand and gravel at each of the thirteen observation points along the transect line. Based on thirteen EMI measurements and the predictive equation [1], the average depth to sand and gravel was estimated to be 20.8 inches with a range of 10.7 to 40.6 inches. One-half of the observations had depths to sand and gravel between 12.8 and 21.8 inches. Within the Renshaw site, depths to sand and gravel were shallow (0 to 20 inches) at 54 percent, moderately deep (20 to 40 inches) at 38 percent, and deep (40 to 60 inches) at 8 percent of the observation points.

Towner-Dickey Site

A transect line was established at the Towner-Dickey site. Along this line, the depth to till and the thickness of overlying, coarse-textured materials were measured with a hydraulic probe at seven observation points. The depth to till averaged 31.7 inches and ranged from 0 to greater than 52 inches (extensions were not available to probe beyond 52 inches). A comparison of soil probe and EMI data collected at the seven observation points revealed positive relationships between the observed depths to till and the EMI data.

The observed depths were compared with EMI data and used to develop a regression equation to predict depths to till from values of apparent conductivity. Data collected with the EM38 meter in the vertical dipole orientations had a strong correlation with the depth to till (r^2 = 0.851195) and were used to develop a predictive equation:

$$D = -8.93705 + (3.217839 * EM38V) \qquad [2]$$

In this equation, "D" is depth to till (inches); "EM38V" is apparent conductivity (mS/m) measured with the EM38 meter in the vertical dipole orientation.

Based on the EMI measurement (vertical dipole orientation) and Equation [2], the depth to till was predicted at each of the seven probed points. The predicted depths to till were compared with the observed depths. The average difference between observed and predicted depths to till was 6.4 inches. Eighty-six percent of the predicted depths were within 10 inches of the observed depths.

Equation [2] was used to estimate the depths to till at nineteen observation points along the transect line. Based on EMI measurements and predictive equation [2], the average depth to till was 33.8 inches with a range of 0.5 to 46.2 inches. One-half of the observations had depths to till between 32.8 and 41.0 inches. Within the site, depths to till were shallow at 16 percent of the observation points, moderately deep at 47 percent, and deep at 37 percent.

Walsh County:

Dam #5, Middle Branch of the Park River-

Dam Site # 5 is located along the Middle Branch of the Park River. The site is near the town of Park River, North Dakota. Figure 1 shows the approximate location of Park River in Walsh County. Shale bedrock had been detected in one coring observation made along the proposed spillway of the dam. This bedrock anomaly occurred at relatively shallow depths in only one core. Knowledge of the depth and distribution of bedrock is critical to design considerations.

Traditionally, coring observations have been used to characterize dam sites. However, this method is relatively expense and information is restricted to the point of observation. Subsurface properties can be highly variable over short distances and the implied lateral assumptions made from coring data may be poor. In some instances, alternative techniques are needed to improve the assessments of these sites.

A wide array of geophysical methods has been used to assess dam sites. These techniques include electrical resistivity, electromagnetic induction, gravity, ground-penetrating radar, magnetic, and seismic. Each of these techniques has advantages and disadvantages. No single geophysical method works well in all geologic environments. Each technique has been demonstrated to be feasible and appropriate for locating anomalies under certain conditions. However, under different conditions, they all have failed. No one single method will solve all detection problems. The use of multiple geophysical methods can improve results. Geophysical methods do not stand alone. Interpretations derived from geophysical methods must be supported with sound understandings of existing soil and geologic conditions. In addition, interpretative results of geophysical investigations should be verified with ground truth observations.

Electromagnetic induction techniques have been used to determine depths to bedrock (Palacky and Stephens, 1990; Zalasiewicz et al., 1985) and to locate water-bearing fracture zones in bedrock (McNeill, 1991; Olayinka, 1990). These studies have documented that this technique can provide a large number of observations in a relatively short time. In these studies, maps prepared from correctly interpreted EMI data provided the basis for assessing site conditions and planning additional investigations.

The EMI survey was designed to help characterize the site, identify areas with anomalous electrical conductivity, and suggest possible location(s) of shallow bedrock. A survey grid was established across the site. The grid interval was 20 m. At each of the fifty-two grid intersections, a survey stake or flag was inserted in the ground. These markers served as observation points. Measurements were taken at each observation point with an EM34-3 meter. Because of the required depth of observation (30 to 40 m), a 40 m intercoil spacing was used in this investigation. This spacing provides observation depths of 30 and 60 m in the horizontal and vertical dipole orientations, respectively. Measurements were taken with the meter placed on the ground surface in both the horizontal and vertical dipole orientations.

Table 4

Basic Statistics
EMI Survey
Middle Branch Park River, Site #5
(All values are in mS/m)

				Quartiles			
Meter	**Orientation**	**Min.**	**Max**	**1st**	**Median**	**3rd**	**Average**
EM34-3	Horizontal	33.0	54.0	42.0	45.0	48.0	44.7
EM34-3	Vertical	23.0	48.0	34.0	39.0	40.0	37.5

Basic statistics for the EMI data are displayed in Table 4. In general, values of apparent conductivity decreased with increasing observation depths. Measurements averaged 44.7 and 37.5 mS/m in the horizontal and vertical dipole orientations, respectively. For the shallower-sensing (0 to 30 m) horizontal dipole orientation, one-half of the observations had values between 42 and 48 mS/m. For the deeper-sensing (0 to 60 m) vertical dipole orientation, one-half of the observations had values between 34 and 40 mS/m. These vertical trends support the occurrence of stratified and more conductive layers within the upper 30 m. Higher concentrations of soluble salts or clays could explain the higher values of these layers. With an increasing depth of observation, values of apparent conductivity decreased. This suggests the presence of more resistive materials (i.e., sandier alluvial layers or coarser-textured till) and/or a lower concentration of soluble salts and/or water.

An essential assumption of this investigation was that areas with shallow depths to bedrock would appear as anomalies on plots of apparent conductivity measurements. It was assumed that positive (higher values) anomalies would indicate areas with shallower depths to shale bedrock. However, at the time of this investigation, the electrical properties of the overburden and shale bedrock were unknown.

Figures 6 and 7 are two-dimensional plots of the data collected with the EM34-3 meter in the horizontal and vertical dipole orientations, respectively. In each plot, the isoline interval is 5 mS/m. The numbering scheme (see left and bottom borders of each plot) is identical to the one used in the field and helps to identify the base lines. The stream channel is located next to the western boundary of the site. The flood plain of this stream is located in the left-hand portion of each plot. Higher-lying, upland areas are located in the right-hand portions of each plot.

The patterns appearing in figures 6 and 7 are ambiguous and, in themselves, provide little information. In Figure 6, spatial patterns appear uniform and agree with the general trend in the landforms. Values are lowest on the better drained uplands in the northern portion of the site (right-hand portion of Figure 6). These areas have deeper depths to the water table. Values are higher on the lower-lying and more poorly drained flood plain (left-hand portion of Figure 6). A conspicuous anomaly occurs near the center of the site (lines: x = 20, y = -20). Coring records should be checked to see if this anomaly can be identified.

The spatial patterns appearing in Figure 7 are more complex. These patterns could reflect the greater volume of earthen material profiled, more heterogeneous and irregular strata in the lower part, or coil alignment errors. In Figure 7, noticeable anomalies occur in the southern and western portions of the site. These isolated anomalies could indicate areas underlain by bedrock pinnacles or thrusted blocks of shale.

The data collected with the EM34-3 meter were manipulated to provide an alternative interpretation. For each observation point, the measurement collected in the vertical orientation was subtracted from the measurement collected in the horizontal orientation. Observation points having positive values indicate areas with reductions in conductivity with increasing depth. The higher the value, the greater the reduction in apparent conductivity with depth and the variable the materials. This transformed data has been plotted in Figure 8. In Figure 8, the differences in conductivity with depth are slight. However, conspicuous bands occur across the plot. These bands conform to the general orientations of the landforms (flood plain and upland). The significance of these bands, however, cannot be determined without further supporting information.

Several observable patterns have been identified on the enclosed plots. These patterns may allow engineers and geologist familiar with the site to render opinions as to the nature and extent of the problem. These patterns can provide the rationale for locating further borehole observation sites. The products of this survey can be used to identify areas with anomalous electrical conductivity, suggest possible location(s) of subsurface bedrock pinnacles, and guide and reduce the number of further exploratory borehole observations. Interpretations are considered preliminary estimates of site conditions. The results of this investigation do not substitute for direct observations, but rather reduce their number, direct their placement, and supplement their interpretations. Interpretations should be verified by ground-truth observations.

Conclusions:

1. The results from the various studies conducted during this brief field trip are generally positive and encouraging. At each study site and for each application, EMI techniques provided some basic information. The following summarizes the results of the various studies:

A. At the Ashley site, soils and soil properties were highly variable. Several properties concurrently influenced EMI responses and fostered ambiguous interpretations. As a consequence, in this and similar areas of collapse till, EMI techniques are considered inappropriate for determining depths to sand and gravel or contrasting materials. However, these results do not lessen the potential for using EMI techniques in similar settings to chart distributions of some soils, clarify some spatial patterns, or select sampling or monitoring sites.

B. At the reclaimed mine spoil site near Beulah, EMI techniques were ineffectual for determining the thickness of the "topsoil" and the depth to mine spoil in a reclaimed area. However, spatial patterns appearing on plots prepared from the EMI data seem to correspond with variations in clay content and soil compaction. Further research is recommended.

C. At the abandoned mine site, and in the words of Mike Ulmer, a "*qualified success*" was obtained in detecting a shallow (0 to 15 m) abandoned, air-filled mine tunnel. If so stirred by this unique application, Mike and Dean Moos are encouraged to write a brief paper for Soil Survey Horizons.

D. At two sites in Eddy County, EMI techniques were used to estimate depths to contrasting materials. Correlations between observed (soil probe or auger) and interpreted (EMI) depths to contrasting materials were strong (r^2 of 0.8512 to 0.9705). Although interpretations were not rigorously examined nor supported by adequate ground truth verifications, this technique appears suited to soil investigations on some glacial fluvial deposits.

E. Electromagnetic induction techniques provided inconclusive results at Dam Site #5, Middle Branch Park River. However, patterns may allow engineers and geologist familiar with the site to render opinions as to the nature and extent of the problem. These patterns can provide the rationale for locating further borehole observation sites.

2. Electromagnetic induction techniques are interpretative. Because they are interpretative, many will find these techniques unacceptable. Direct observations and measurement are preferred by many. However, direct measurements are slow, tedious, and often limited in number and areal coverage. To make inferences across large parcels of land; faster, less tedious, and more comprehensive methods are needed. Compared with traditional survey methods, EMI techniques are faster and provide greater numbers of observations per unit time. These techniques are therefore more efficient and provide more comprehensive coverage. On some terrains, electromagnetic induction can be used to assess large areas at comparatively low costs. Electromagnetic induction techniques can be used to aid interpolation and extrapolation of the data obtain with traditional coring methods.

3. The studies discussed in this report have demonstrated several applications for electromagnetic induction techniques. Electromagnetic induction appears suitable as a reconnaissance or ancillary tool for some pedological investigations in North Dakota. This tool has been used successfully in North Dakota to assess salinity. This tool can also be used to assess sodium-affect soils, estimate the depths to contrasting layers, and to characterize spatial patterns in soil landscapes.

It was my pleasure to work with members of your find staff. Mike Ulmer is commended for the excellent preparation of this study. In a short time, several applications for EMI techniques were examined in different portions of the state.

With kind regards,

James A. Doolittle
Research Soil Scientist

cc:
J. Culver, Supervisory Soil Scientist, USDA-NRCS, National Soil Survey Center,
Federal Building, Room 152,100 Centennial Mall North, Lincoln,
NE 68508-3866
D. Heil, State Soil Scientist/MO Leader, USDA-NRCS, P. O. Box 1458, Bismarck, North Dakota 58502-1458
S. Holzhey, Supervisory Soil Scientist, USDA-NRCS, National Soil Survey Center, Federal Building, Room 152, 100 Centennial Mall North, Lincoln, NE 68508-3866
C. Reed, Geologist, USDA-NRCS, P. O. Box 1458, Bismarck, North Dakota 58502-1458
M. Ulmer, Soil Scientist, USDA-NRCS, P. O. Box 1458, Bismarck, North Dakota 58502-1458

References

Ammons, J. T., M. E. Timpson, and D. L. Newton. 1989. Application of aboveground electromagnetic conductivity meter to separate Natraqualfs and Ochraqualfs in Gibson County, Tennessee. Soil Survey Horizons 30(3):66-70.

Canace, R. and R. Dalton. 1984. A geological survey's cooperative approach to analyzing and remedying a sinkhole related disaster in an urban environment. pp. 342-348. IN: Proceedings of the First Multidisciplinary Conference on Sinkholes. Orlando, Florida. 15 to 17 October 1984.

Cook, P. G., M. W. Hughes, G. R. Walker, and G. B. Allison. 1989. The calibration of frequency-domain electromagnetic induction meters and their possible use in recharge studies. Journal of Hydrology 107:251-265.

Cook, P. G. and G. R. Walker. 1992. Depth profiles of electrical conductivity from linear combinations of electromagnetic induction measurements. Soil Sci. Soc. Am. J. 56:1015-1022.

Corwin, D. L., and J. D. Rhoades. 1982. An improved technique for determining soil electrical conductivity-depth relations from above-ground electromagnetic measurements. Soil Sci. Soc. Am. J. 46:517-520.

Corwin, D. L., and J. D. Rhoades. 1984. Measurements of inverted electrical conductivity profiles using electromagnetic induction. Soil Sci. Soc. Am. J. 48:288-291.

Corwin, D. L., and J. D. Rhoades. 1990. Establishing soil electrical conductivity - depth relations from electromagnetic induction measurements. Communications in Soil Sci. Plant Anal. 21(11&12):861-901.

Doolittle, J., R. Murphy, G. Parks, and J. Warner. 1996. Electromagnetic induction investigations of a soil delineation in Reno County, Kansas. Soil Survey Horizons 37:11-20.

Doolittle, J. A., K. A. Sudduth, N. R. Kitchen, and S. J. Indorante. 1994. Estimating depth to claypans using electromagnetic inductive methods. J. Soil and Water Conservation 49(6):552-555.

Friedel, M. J., J. A. Jessop, R. E. Thill, and D. L. Veith. 1990. Electromagnetic investigations of abandoned mines in the Galena, KS, area. Report of Investigation 9309. United States Department of the Interior, Bureau of Mines, Minneapolis, MN pp. 28.

Hoekstra, P., R. Lahti. J. Hild, R. Bates, and D. Phillips. 1992. Case histories of shallow time domain electromagnetics in environmental site assessments. Ground Water Monitoring Review. 12(4):110-117.

Jaynes, D. B., T. S. Colvin, J. Ambuel. 1993. Soil Type and crop yield determination from ground conductivity surveys. 1993 International Meeting of American Society of Agricultural Engineers. Paper No. 933552. ASAE, St. Joseph, MI. pp. 6.

McNeill, J. D. 1980a. Electrical conductivity of soils and rocks. Technical Note TN-5. Geonics Ltd., Mississauga, Ontario. pp. 22.

McNeill, J. D. 1980b. Electromagnetic terrain conductivity measurement at low induction numbers. Technical Note TN-6. Geonics Limited, Mississauga, Ontario. pp. 15.

McNeill, J. D. 1986. Geonics EM38 ground conductivity meter operating instructions and survey interpretation techniques. Technical Note TN-21. Geonics Ltd., Mississauga, Ontario. pp. 16.

McNeill, J. D. 1991. Advance in electromagnetic methods for groundwater studies. Geoexplorations 27:65-80.

Nettleton, W. D., L. Bushue, J. A. Doolittle, T. J. Endres, and S. J. Indorante. 1994. Sodium-affected soil identification in south-central Illinois by electromagnetic induction. Soil Sci. Soc. Am. J. 58:1190-1193.

Olayinka, A. I. 1990. Electromagnetic profiling for groundwater in Precambrian basement complex areas of Nigeria. Nordic Hydrology 21:205-216.

Palacky, G. J. and L. E. Stephens. 1990. Mapping of Quaternary sediments in northeastern Ontario using ground electromagnetic methods. Geophysics 55:1596-1604.

Pazuniak, B. L. 1989. Subsurface investigation response to sinkhole activity at an eastern Pennsylvania site. pp. 263-269. IN: Proceedings of the 3rd Multidisciplinary Conference on Sinkholes. St. Petersburg Beach, Florida. 2 to 4 October 1989.

Rhoades, J. D. and D. L. Corwin. 1981. Determining soil electrical conductivity-depth relations using an inductive electromagnetic soil conductivity meter. Soil Sci. Soc. Am. J. 45:255-260.

Rhoades, J. D., N. A. Manteghi, P. J. Shouse, and W. J. Alves. 1989. Soil Electrical conductivity and soil salinity: new formulation and calibrations. Soil Sci. Soc. Am. J. 53:433-439.

Rhoades, J. D., P. A. Raats, and R. J. Prather. 1976. Effects of liquid-phase electrical conductivity, water content, and surface conductivity on bulk soil electrical conductivity. Soil Sci. Soc. Am. J. 40:651-655.

Robinson-Poteet, D. 1989. Using terrain conductivity to detect subsurface voids and caves in a limestone formation. pp. 271-279. IN: Proceedings of the 3rd Multidisciplinary Conference on Sinkholes. St. Petersburg Beach, Florida. 2 to 4 October 1989.

Rumbens, A. J. 1990. Detection of cavities in karstic terrain: road subsidence - Snowy Mountains Highway near Yarrangobilly, state of New South Wales - Australia. Exploration Geophysics 21:121-24.

Slavich, P. G. and G. H. Petterson. 1990. Estimating average rootzone salinity from electromagnetic induction (EMI-38) measurements. Australian J. Soil Res. 28:453-463.

Stroh, J., S. R. Archer, L. P. Wilding, and J. Doolittle. 1993. Assessing the influence of subsoil heterogeneity on vegetation patterns in the Rio Grande Plains of south Texas using electromagnetic induction and geographical information system. College Station, Texas. The Station (Mar 93): 39-42.

Sudduth, K. A. and N. R. Kitchen, 1993. Electromagnetic induction sensing of claypan depth. Paper No. 93-1550. Presented at the December 1993, Winter Meetings of the American Society of Agricultural Engineers. St. Joseph, Michigan. pp. 18.

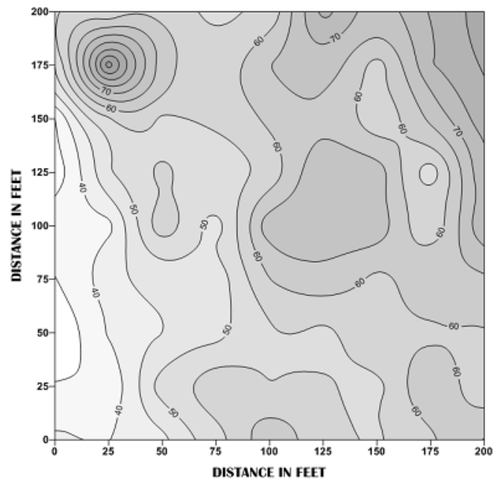
Williams, B. G. and G. C. Baker. 1982. An electromagnetic induction technique for reconnaissance surveys of soil salinity hazards. Australian J. Soil Res. 20:107-118.

Wollenhaupt, N. C., J. L. Richardson, J. E. Foss, and E. C. Doll. 1986. A rapid method for estimating weighted soil salinity from apparent soil electrical conductivity measured with an aboveground electromagnetic induction meter. Can J. Soil Sci. 66:315-321.

Zalasiewicz, J. A., S. J. Mathers, and J. D. Cornwell. 1985. The application of ground conductivity measurements to geological mapping. Q. J. English Geol. London 18:139-148.

COTEAU RECLAIM SITE
BEAULAH, ND 8/96

EM 38 METER
HORIZONTAL DIPOLE ORIENTATION

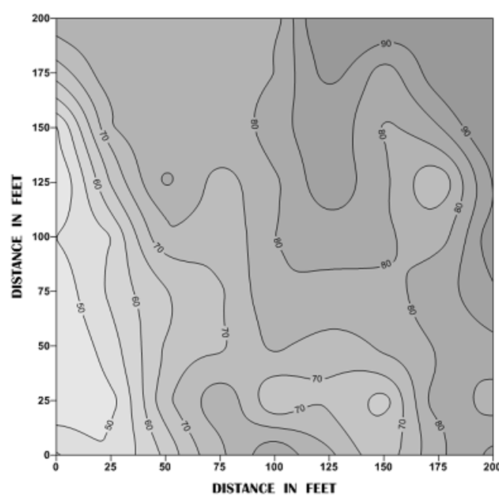


N
←

Figure 2

COTEAU RECLAIM SITE
BEAULAH, ND 8/96

EM 38 METER
VERTICAL DIPOLE ORIENTATION



N
←

Figure 3

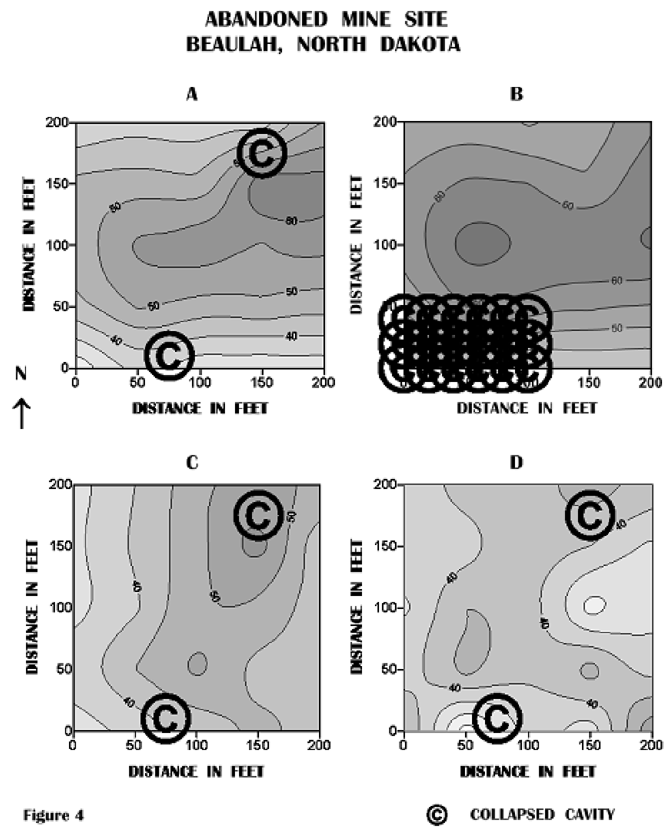


Figure 4

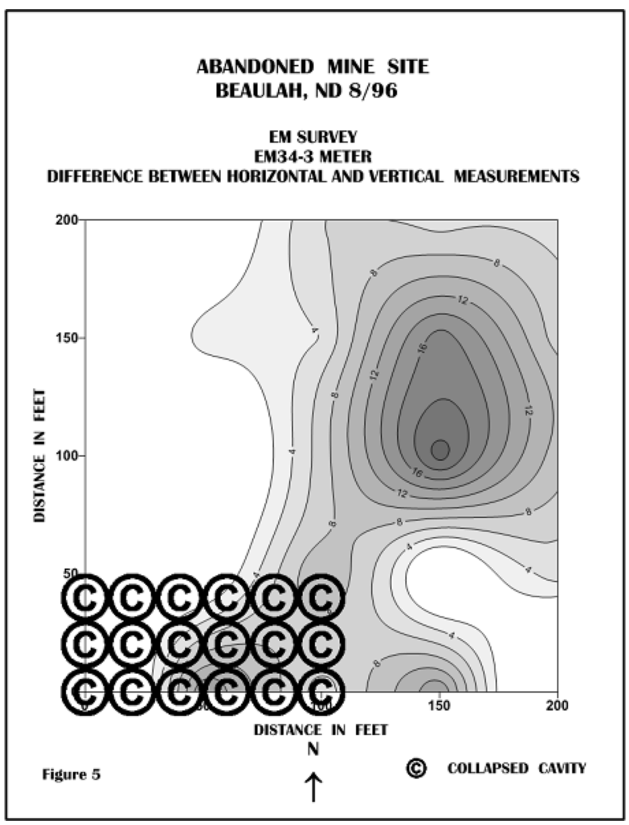


Figure 5

EM SURVEY
MIDDLE BRANCH PARK RIVER
DAM SITE # 5

EM34-3 METER
HORIZONTAL DIPOLE ORIENTATION
40 M INTERCOIL SPACING

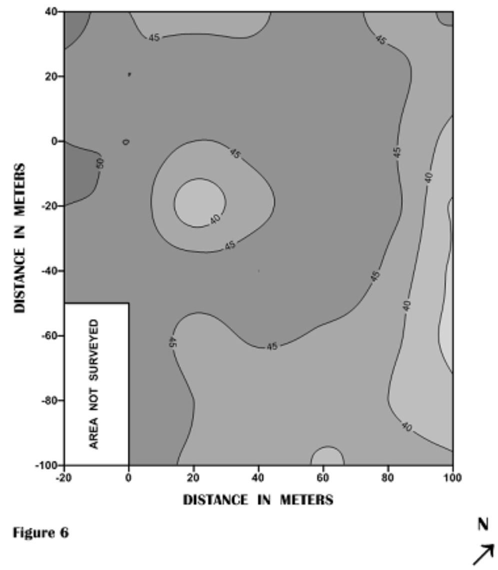


Figure 6

EM SURVEY
MIDDLE BRANCH PARK RIVER
DAM SITE # 5

EM34-3 METER
VERTICAL DIPOLE ORIENTATION
40 M INTERCOIL SPACING

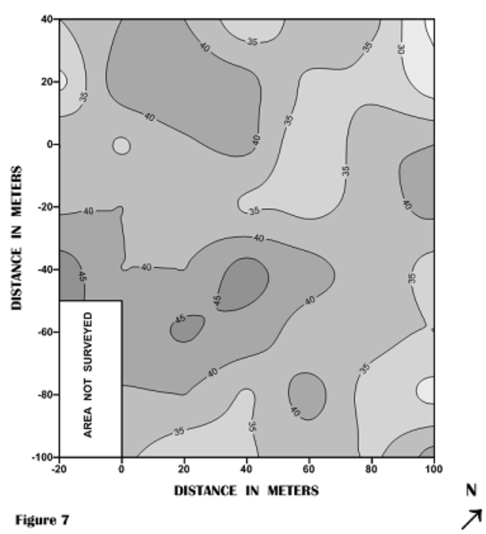


Figure 7