E-PHASE SYSTEM FOR DETECTING BURIED GRANULAR DEPOSITS

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In 1968, the Saskatchewan Department of Highways and Transportation began an investigation of airborne geophysical survey methods for mapping buried deposits. Single-frequency E-Phase airborne resistivity surveys were carried out in 1970 and 1971, and multifrequency survey programs began in 1973. The E-Phase airborne resistivity system uses radio wave transmissions to provide the primary field, and it measures the apparent resistivity of the ground at 3 frequencies simultaneously. The measurement of apparent resistivity at 3 frequencies provides information about the subsurface to 3 depths. The correlation between earth materials and resistivities may vary from area to area, but definite limits of resistivity can be assigned for broad ranges of soil classification. The E-Phase survey in the Wadena area of Saskatchewan, where intertill gravel deposits were suspected to exist, resulted in 27 anomalies worthy of follow-up. Fifteen of these were followed up on, and all but 1 contained granular material under till cover. The preliminary ground follow-up results for 1 of the anomalies indicate a minimum of 1 million Mg of gravel that is covered and underlain by till. The test trials and routine surveying to date have shown that the E-Phase system can be used successfully for locating surficial and intertill granular deposits and that the system as it now exists represents a major advance in soil-exploration methods.

•IN MANY areas, including Saskatchewan, all surface deposits of granular material have been exploited, and interest is turning to those covered with a considerable thickness of overburden. Conventional methods of interpretation by aerial photographs are not usually adequate for the location of these buried deposits. Ground geophysical measurements are useful but time consuming and costly unless they are applied to a specific and relatively small area. In 1967, the Department of Highways of Saskatchewan began an investigation of airborne geophysical survey methods for mapping shallow deposits of gravel. In 1968 and 1969, surveys were carried out by using the input airborne electromagnetic system. This system has a number of base-metal discoveries to its credit, but the trials with input indicated that an airborne system with better sensitivity was required to detect granular deposits. An airborne resistivity system called E-Phase was developed in 1970. The trials of the E-Phase system in 1970 and 1971 indicated that this system has the potential to detect buried deposits.

RESISTIVITY OF EARTH MATERIALS

The physical property of electrical resistivity of earth materials forms the basis of the resistivity method of geophysical subsurface investigation. Figure 1 shows a relationship between resistivity and unconsolidated sediments and rocks compiled from a number of sources (1, 2, 3). The resistivity of minerals, ores, rocks, and Pleis-

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tocene materials varies between wide limits. Unconsolidated materials have resistivities that are lower than the resistivities of crystalline rocks but may overlap with resistivities of sedimentary rocks. There are 4 major factors that determine the resistivity of soils: type of soil, water content, soil temperature, and ice content. Type of soil is independent of time over long periods of time. However, water content, soil temperature, and ice content are subject to daily and seasonal variations. A number of less important factors, such as pressure and free-salt content of the pore water, also influence the resistivity of the soil strata (2). Gravel and sand tend to have high resistivity; organic material, silt, clay, and till have low resistivity because clay particles act as charge carriers.

E-PHASE METHOD THEORY

The E-Phase system is a passive system that uses radio wave transmissions to provide the exciting primary electromagnetic field; electrical properties of the ground are derived from measurements of the ground wave of the vertically polarized radio waves.

If the earth is assumed to be perfectly conducting, the measurement of the field components of a vertically polarized radio wave transmission would show that there is an electric field E that is vertical and a magnetic field H that is horizontal and perpendicular to the direction of propagation (Figure 2). If the resistivity of the ground increases from 0, then the electric field will be tilted forward in the direction of the propagation. The magnitude of the forward tilt is a function of the resistivity of the ground and the frequency of the transmission. Over resistive ground at low frequencies, such as 20 kHz, the wave tilt may be as much as 1 degree; however, over conductive ground, the wave tilt may be as little as a few minutes (decimal degrees) of arc. The electric vector, which is tilted because of the resistivity of the ground, has a vertical component E_z and a horizontal component E_x in the direction of propagation (Figure 3). To measure the tilt of the electric vector from an airborne platform is virtually impossible, but an indirect measurement of the tilt can be made by measuring the horizontal and vertical components of the electric field. Local changes in the resistivity of the ground cause variations in the amplitude and phase of the horizontal electric field. Measurements of these variations at or near the ground surface are the basis of the method. Variations in the vertical electric field and in the horizontal magnetic component occur near abrupt lateral changes in resistivity, but no significant variations take place when the resistivities change gradually. However, the horizontal electric field is dependent on the resistivity of a horizontally stratified ground and the measurement of this field is useful in mapping gradual variations in the resistivity and thickness of flat-lying strata (4). In the case of homogeneous half-space, if displacement currents (which are important only at high frequencies and resistivities) are ignored, the ratio of either the in-phase component $E_x(I)$ or the quadrature-phase component of the horizontal electric field $E_x(Q)$ and the vertical electric field E_z can be shown to be proportional to the square root of the resistivity (Figure 4). Because of theoretical and practical considerations, the E-Phase system measures the ratio of $E_x(Q)$ and E_z, and, therefore, the resistivity of the ground at 3 frequencies simultaneously. As a result of the assumption made (homogeneous half space, single uniform layer), the resistivity determined by the system in the case of layered earth is an apparent resistivity. The apparent resistivity is defined as the resistivity of that uniform half space (single homogeneous layer) that would give the same value for ratio $E_x(Q)/E_z$ as that which actually was measured (5, 6).

In the layered situation, which is the case under most geologic conditions, some information is lost by not measuring the in-phase component of the horizontal electric field, but this can be overcome to a large degree by measuring the quadrature-phase component at several well-separated frequencies. The depth penetration of the radio waves is dependent on the resistivity of the ground and the frequency of the transmission. The behavior of the skin depth (a measure of depth penetration) as a function of frequency is shown in Figure 5, which illustrates that the effective depth of investigation can be altered by changing the frequency. In Figure 5, ρ = resistivity in ohm-meters, f = frequency in hertz, and μ = permeability in henries per meter (12.57 ×

Figure 1. Resistivity of earth materials.

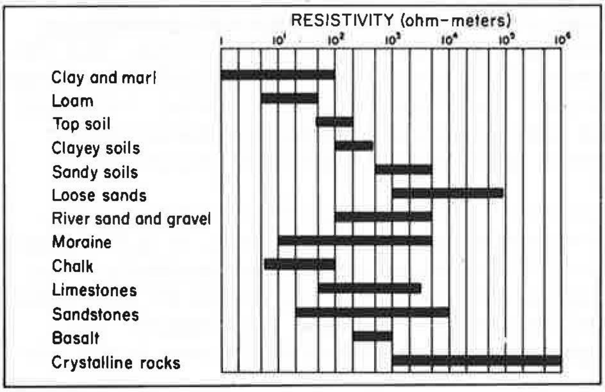


Figure 2. Field vectors for perfectly conducting earth, $\rho = 0$.

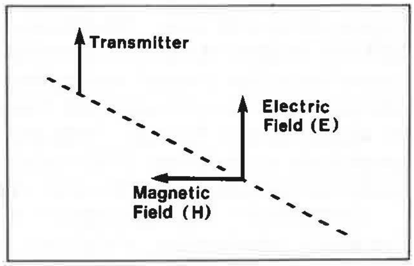


Figure 3. Field vectors for resistive earth $\rho = \rho_1$.

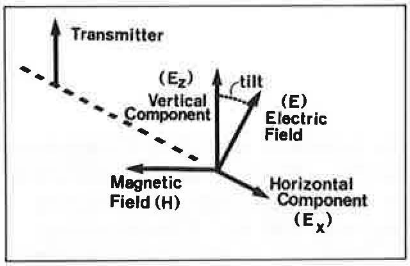


Figure 4. Relationship between electric field components and resistivity assuming uniform half space and ignoring displacement currents.

$$\frac{E_x}{E_z} = (i\omega\epsilon_0\rho_1)^{\frac{1}{2}}$$

$$\frac{E_x\,(\text{In-phase})}{E_z} = \frac{E_x\,(\text{Quad-phase})}{E_z} = \left(\frac{\omega\epsilon_0\rho_1}{2}\right)^{\frac{1}{2}}$$

$i = (-1)^{\frac{1}{2}}$

$\omega = 2\pi f$ (f – frequency – Hz)

ϵ_0 = permittivity of free space (8·854 x 10^{-12} Farad/meters)

ρ_1 = ground resistivity (ohm-meters)

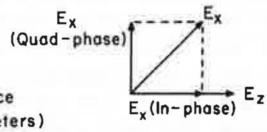
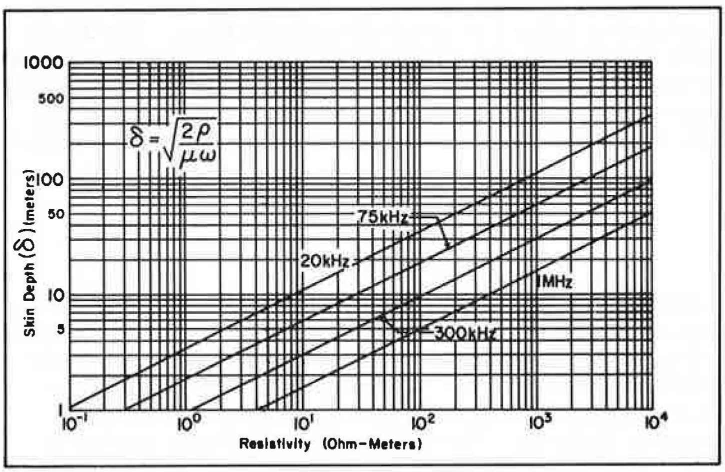


Figure 5. Skin depth as a function of resistivity assuming uniform half space and ignoring displacement currents.



15^7 H/m). $\omega = 2\pi f$.

The deepest penetrating radio waves are in the very low frequency (VLF) range between 10 and 30 kHz. VLF transmissions provide communications with submarines, and the transmitters are operated by government agencies around the world. The frequencies in the second range, low frequency (LF), are between 200 and 400 kHz. These are aircraft navigational aid frequencies, and the transmitters are located at airfields or along airline routes. The shallowest penetrating radio waves are transmitted by amplitude modulation (AM) ratio stations in the broadcast band (BCB) range of frequencies between 550 kHz and 1100 kHz.

Because the VLF frequency is approximately 50 times that of the BCB frequency, the depth penetration, which varies as the square root of the frequency, is at VLF frequency approximately 7 times that at the BCB frequency for a given resistivity. One frequency of each of the 3 frequency bands is used for surveying and the electric fields are monitored simultaneously. In effect, results from 3 depths are obtained. By virtue of using 3 frequencies, the geologic section is described as 3 layers having distinct electrical properties.

Instrumentation can be installed in fixed-wing aircraft or in helicopters; the sensors will be located in a nose boom in both cases. The flight path of the aircraft is recorded by using a 35-mm camera. Fiducial marks are made automatically at 1-sec intervals on the flight path film, the analogue chart recorder, and the digital magnetic tape recording, which provides the means to relate the airborne records to the ground.

CASE HISTORIES

Kindersley Area

The application of the E-Phase method to locate granular material and map Pleistocene geology is illustrated by a survey in the Kindersley area (7). The survey was carried out in 1971, and only 1 frequency in the BCB range was used (540 kHz). The flying height was 75 m above ground, and the flight-line interval was 300 m. The direction of the flight lines was north-south. The main geological features of the area are shown in Figure 6 (8). The northeast-striking interlobate moraine, the ground moraine in the southeast, and the northwest-striking meltwater channel are the promising areas for occurrence of gravel deposits. The rest of the survey area is covered by glacial lake basin material of till and clay.

The BCB-apparent resistivity contour map shown in Figure 7 illustrates the striking correlation between the known geology and the apparent resistivity contours. The interlobate moraine, ground moraine, and meltwater channel are outlined by resistivities ranging up to 1000 $\Omega \cdot m$. The glacial lake basin material correlates with the low apparent resistivities. Note the higher resistivity area in the northwest corner of the area that may indicate a buried moraine hitherto unknown. Two areas were selected for a ground follow-up that consisted of holes 8 m apart along flight lines. The depth of the holes was 8 m. A definite correlation was found between the resistivity and soil texture: The higher the resistivity was, the coarser the soil was. Although an apparent resistivity that is characteristic of the type of soil in an area may not be appropriate for another area, definite limits of resistivity can be assigned for broad ranges of soil classification (7).

Wadena Area

The 1971 trials with E-Phase led to a full-scale gravel-search program in 1973. The search concentrated on intertill deposits (layers of sand or gravel sandwiched between 2 till sheets). A wide area is known to contain these deposits running in a northwest-southeast direction through southern Saskatchewan. Because of the thickness of the overburden or upper till sheet, the deposits are effectively masked to conventional aerial-photograph or ground-search methods. The ability of the E-Phase method to

Figure 6. Surficial geology of Kindersley area.

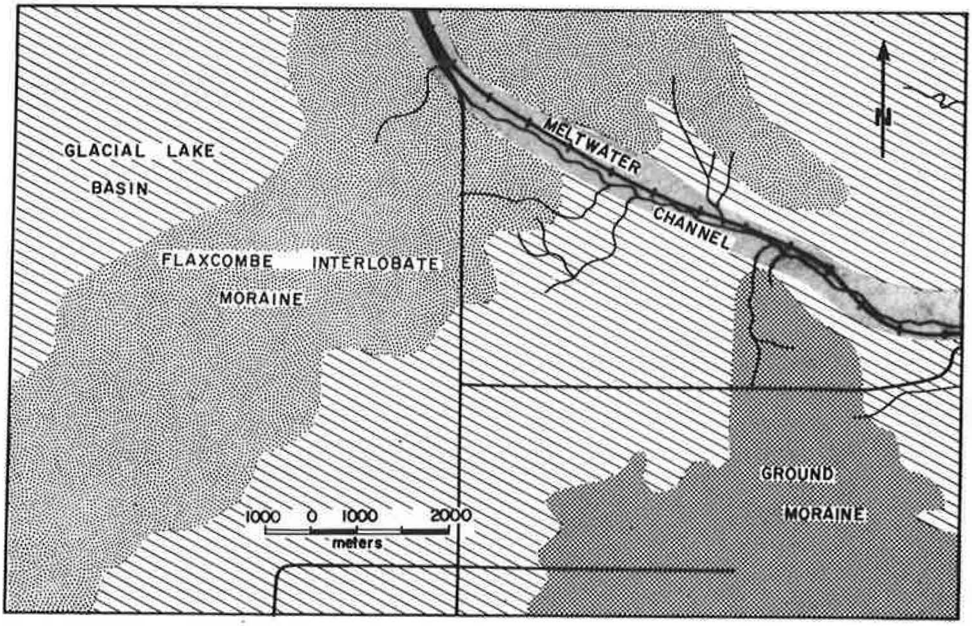
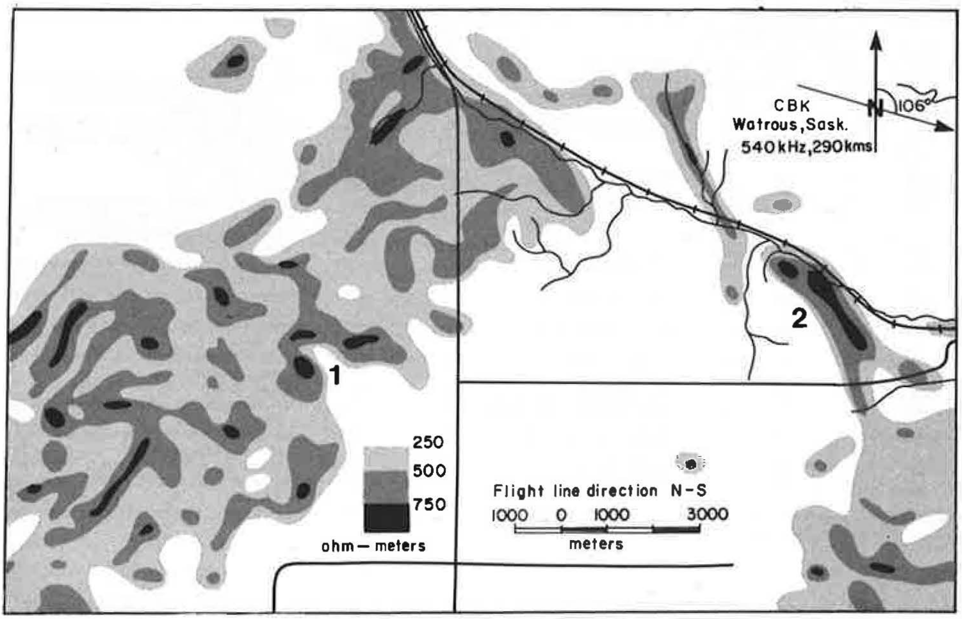


Figure 7. Broadcast-band-apparent resistivity contour map for Kindersley area.



cover a wide area in a short time and sense through a significant depth makes these deposits available for exploration.

The area surveyed in this case is near Wadena and covers about 464 km^2. The flight-line spacing was 400 m; the aircraft kept a constant altitude of 75 m; and 966 line km were required to cover the area. The 3-frequency system was used, and apparent resistivities at 3 frequencies were obtained simultaneously. An initial check

Figure 8. Low-frequency-apparent resistivity contour map for Wadena area.

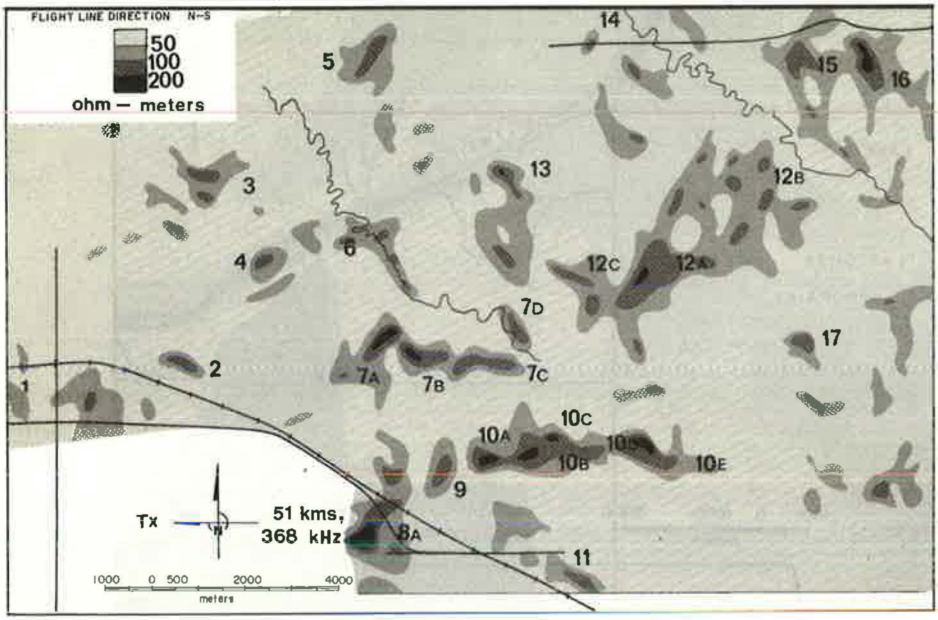


Table 1. Summary of ground follow-up for Wadena area.

Anomaly	Drill Holes	Total Meters	Percentage of Materials: Gravel	Sand	Other	Photogeology	Flight Lines Crossed	Max. LF Anomaly (Ω·m)	Remarks
2	10	73	30	44	26	Likely old beach ridge	1	<150	Anomalous on 3 frequencies; 1 hole bottoms in gravel.
5	32	237	43	4	53	Small area of surfical sand	2	125	Gravel and coarse gravel: approximately 10" Mg; water table: ~4m; number of holes bottom in gravel.
7A	18	110	3	43	54	Surficial granulars	3	>150	Water table: ~2m.
7C	18	110	3	43	54	Surficial granulars	3	>150	Water table: ~2m.
8A	9	55	—	7	93	No indications	1	350	Resistivity may have been affected by topography. Could not be tested along flight line because of topography.
9	12	67	33	6	61	Terrace and outwash	1	200	Water table: >5m.
10C	32	192	—	64	36	Surficial granulars	2	200	Water table: 7m; number of holes bottom in sand.
10D	32	192	—	64	36	Surficial granulars	1	200	Water table: 7m; number of holes bottom in sand.
10E	32	192	—	64	36	Surficial granulars	3	275	Water table: 7m; number of holes bottom in sand.
11	6	34	—	21	79	No indications	1	225	Peak of anomaly could not be checked because of access.
12A	36	272	51	19	30	No indications	4	200	Mostly fine gravel; water table: ~6m.
12B	26	186	26	54	20	Small area of surficial sand	1	175	1 hole bottoms in sand; 1 hole bottoms in gravel.
13	6	37	—	2	98	Surficial sand in vicinity	1	175	Anomaly is not fully explained; source may possibly be deeper.
14	7	46	21	39	40	Old beach ridge	1	125	Fine gravel and sand; water table: ~2m.
15	8	41	—	15	85	No indications	1	150	Poorly defined anomaly; water table: ~4.5m.

Note: Other materials include till, silt, sandy silt, and topsoil.

of the computed apparent resistivities indicated that the most diagnostic information is contained in the LF-apparent resistivity data. A contour map was prepared for this frequency (Figure 8), but all 3 apparent resistivities were used for interpreting the data (9). (Anomaly 5 in Figure 8 is recommended for follow-up.)

The background resistivity is about 50 Ω · m or less, which indicates the upper till cover. In anomalous zones, the apparent resistivities may exceed 300 Ω · m. Twenty-seven specific resistivity anomalies were recommended for ground checking, but only 15 anomalies were actually checked. Two hundred and two holes were dug to an average depth of 10 m (10). A summary of the results of the ground follow-up is given in Table 1. In all cases except one (anomaly 13), gravel or sand or both were found overlain by till or silt and underlain by till. A number of the anomalies can be correlated with photogeological indications (anomalies 5 and 12B). In most of the cases the LF-apparent resistivity was the most anomalous; the BCB-apparent resistivity was somewhat lower. The VLF-apparent resistivities are the least anomalous of the 3 apparent resistivities. The depth to the water table varied considerably throughout the area and no definite conclusions can be made of its effect on apparent resistivity. For anomaly 13, only a minor amount of sand was found, which does not sufficiently explain the anomaly. Increased resistivity of the covering material or a more resistive material at depth or both may explain the anomaly. Anomaly 8A, in which only minor sands were found, could not be checked at the peak of the anomaly because of access problems. Steep topography may also have affected the apparent resistivities at this location.

Anomaly 5 is of particular interest (Figure 9). Photogeological study indicated a small area of surficial sand southeast of the main peak of the anomaly. Thirty-two test holes were drilled and the results are given in Table 2. The resistivity contours suggest that the intertill deposit may extend to the south of holes 4 and 5 and to the northeast of holes 1, 3, and 4. The bulk of the deposit is located between flight lines; however, sufficient granular material is located along flight line 31 to give an indication of a possible deposit (Figure 10). The LF-apparent resistivity is much higher along the flight line, which indicates a change in the composition of surface and near surface materials. The LF-apparent resistivity contours by no means map out exactly the area of the intertill deposit, but they at least give an indication of where it is located. This deposit would not have been located by the usual location methods used previously in Saskatchewan. Preliminary checking indicates that a minimum of 1 million Mg of gravel may exist in this deposit. This will probably pay for the cost of surveying (10).

Anomaly 12A is also of interest (Figure 11). Aerial-photograph interpretation indicated no surficial sand or gravel. Thirty-six holes were drilled over the anomaly, and granular material was located in each hole. The granular material (fine gravel and sand) is covered by an average of 1.25 m of top soil and till, and the deposit is underlain by till. The profiles of apparent resistivity and drilling results shown in Figure 12 for flight line 47 clearly indicate the usefulness and necessity of using 3 frequencies. The BCB resistivity is lower than the LF-apparent resistivity because of the much lower true resistivity of the upper till. The BCB waves apparently just penetrated into the gravel. VLF waves penetrate much deeper and show the effect of the high-conductivity substratum till; the combined effect of the low resistivity of the upper and bottom till counteracts the higher resistivity of the intertill gravel, which results in the low VLF-apparent resistivities. LF radio waves penetrate into the gravel, and the high apparent resistivities obtained at the LF frequency diagnostically describe the intertill deposit in this geologic environment. The gravel deposit could have been missed by using the VLF frequency only.

Computer programs and 3-layer interpretation curves were developed to model the 3-layer resistivity distribution (11). The method was applied to the data along flight line 47 at 2 locations. The apparent resistivities computed from the assumed true resistivities and thicknesses agree with the observed apparent resistivities at both locations. The northerly location is close to hole 2, and the thicknesses of the layers used in the computation of apparent resistivities are in good agreement with the observed thicknesses in hole 2. The computer model located south of hole 32 indicates an extension of the granular deposit that has not yet been drilled. A true resistivity of 40 $\Omega \cdot m$ for the upper till and 10 $\Omega \cdot m$ for the bottom till is within the range of resistivities of tills. The 1000 $\Omega \cdot m$ true resistivity of the intertill deposit complex provides a good resistivity contrast between it and the surrounding, covering, and underlying till (Figure 12).

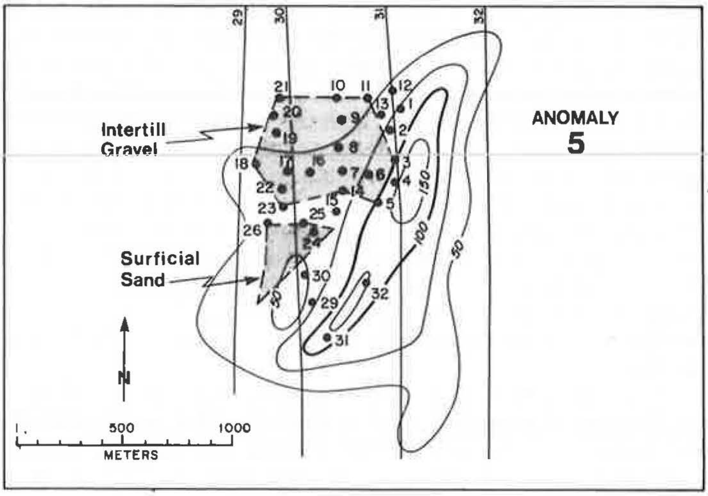


Figure 9. Low-frequency-apparent resistivity contours and drill-hole locations for anomaly 5 in Wadena area.

Table 2. Drilling results for anomaly 5 in Wadena area.

Hole Number	Stratigraphy Thickness (m)	Type	Thickness (m)	Type	Thickness (m)	Type	Thickness (m)	Type	Water Table (m)	Remarks
1	0.3	Sand	4.9	Till	3.3	Gravel	0.3	Till	5.5	
2	4.3	Till							–	Rock? at 4.6 m
3	3.0	Till	4.0	Gravel	0.3	Till			3.6	
4	2.9	Till	6.9	Gravel	0.6	Till			3.6	
5	4.6	Till	4.3	Sand					4.9	Bottom sand
6	0.6	Sand	1.8	Till	5.8	Gravel	0.6	Till	3.0	
7	0.6	Silty sand	1.5	Till	6.7	Gravel			3.0	Bottom gravel
8	2.1	Till	6.1	Gravel	0.3	Till			2.4	
9	2.4	Till	6.7	Coarse gravel					3.0	Bottom gravel
10	2.4	Till	6.1	Coarse gravel					3.0	Bottom gravel
11	3.6	Till	1.8	Gravel	2.1	Till			3.7	
12	5.8	Till							–	
13	5.8	Till							–	
14	2.1	Till	6.7	Fine gravel					3.0	Bottom gravel
15	5.2	Till							–	
16	2.1	Till	4.6	Fine gravel	0.6	Till			3.0	
17	1.0	Till	4.6	Gravel	0.3	Till			3.0	
18	1.5	Till	0.6	Gravel	3.6	Till			2.1	
19	1.2	Till	0.9	Sand	4.6	Gravel	0.6	Till	3.0	
20	1.2	Till	6.1	Fine gravel					3.0	Bottom gravel
21	3.0	Till	4.3	Fine gravel					3.0	Bottom gravel
22	1.2	Till	5.8	Fine gravel					3.0	Bottom gravel
23	3.0	Till	4.3	Sand					3.0	Bottom gravel
24	1.8	Sand	5.5	Till					–	
25	0.9	Gravel	4.9	Till					–	
26	0.6	Gravel	5.2	Till					–	
27	0.9	Gravel	4.9	Till					–	
28	2.4	Till	4.6	Gravel	0.3	Till			5.2	
29	2.7	Till	4.6	Gravel						Bottom gravel
30	3.7	Till	1.5	Sand	5.2	Fine gravel			4.9	Bottom gravel
31	5.2	Till								
32	5.8	Till								

Note: Thickness of topsoil is 0.3 m in each hole.

CONCLUSIONS

The earlier surveys indicated that the E-Phase system could be used for location of surficial granular deposits. Recent surveys show that the system can be used with confidence to locate buried intertill deposits. This is a significant step forward in locating these important deposits.

The E-Phase airborne resistivity system appears to be a unique method that has many potential applications such as locating permafrost, outlining areas of shallow bedrock, exploring groundwater, and locating granular material. The test trials and routine surveying to date have shown that the E-Phase airborne resistivity system can be used successfully for locating surficial and intertill granular deposits. More

Figure 10. Very-low-frequency-, low-frequency-, and broadcast-band-apparent resistivity profiles and drilling results for anomaly 5 in Wadena area.

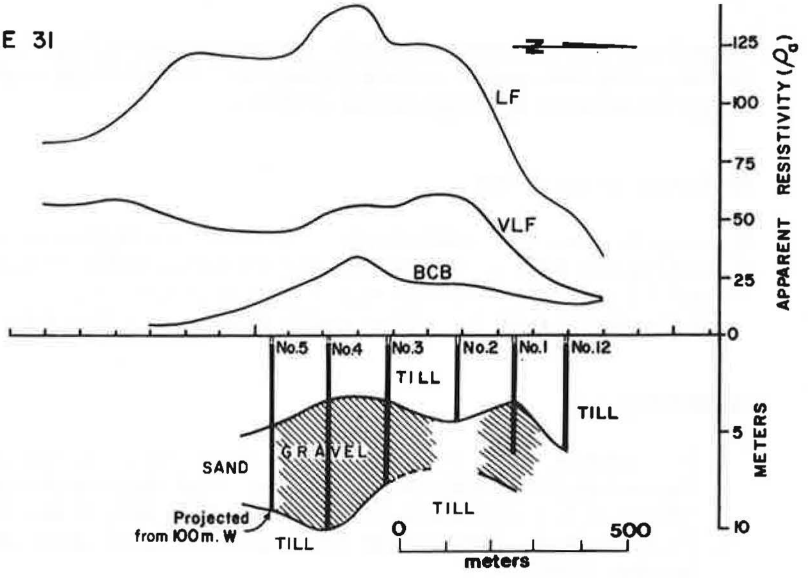


Figure 11. Low-frequency-apparent resistivity contours and drill-hole locations for anomaly 12A in Wadena area.

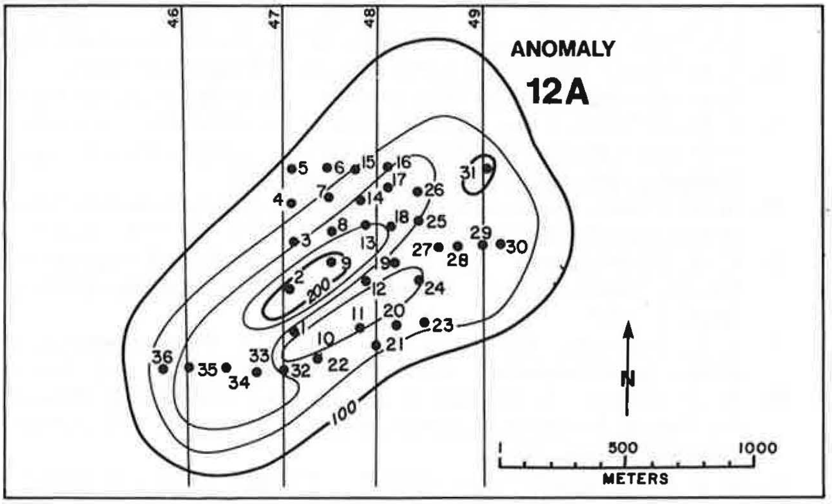
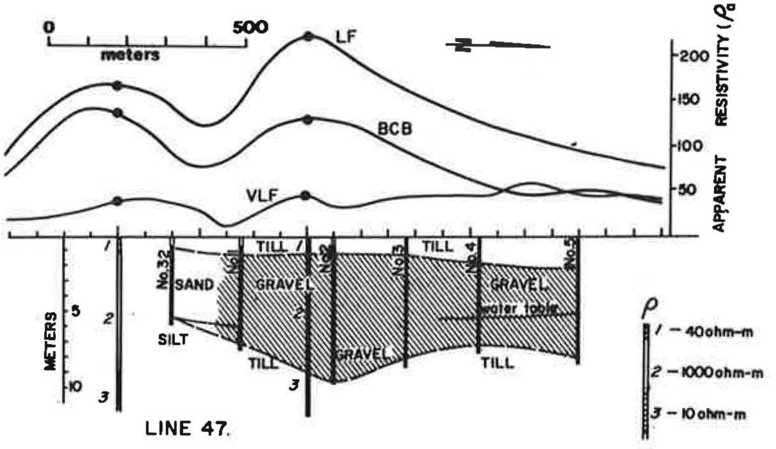


Figure 12. Very-low-frequency-, low-frequency-, and broadcast-band-apparent resistivity profiles, and drilling and computer modeling results for anomaly 12A in Wadena area.



experience and data are required to refine operational specifications for given areas and to refine interpretation techniques, but the system as it now exists represents a major advance in soil exploration methods.

ACKNOWLEDGMENTS

We wish to thank the Saskatchewan Department of Highways and Transportation for permitting the data to be published and for the department's offer to make Technical Report 21 available to anyone who wishes to receive it.

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