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EM31 - MK2

OPERATING MANUAL

OCTOBER 1995

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NOTE TO EM31 AND EM34 USERS:

Through the normal course of operation, it is possible that the battery contacts will become contaminated with dirt and grit. To clean these contacts use fine sand paper (#400 or higher) and wipe several times over the contact.

Ensure that the spring action of the battery holders is maintained. Bend holder sides slightly if necessary.

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EM31-MK2 SPECIFICATIONS

MEASURED QUANTITIES	(1) Apparent conductivity of the ground in millisiemens per meter (mS/m)* (2) Inphase component in parts per thousand (ppt) of the ratio of the secondary to primary magnetic field.
PRIMARY FIELD SOURCE	Self-contained dipole transmitter
SENSOR	Self-contained dipole receiver
INTERCOIL SPACING	3.66 meters
OPERATING FREQUENCY	9.8 kHz
POWER SUPPLY (For Main Console)	8 disposable alkaline "C" cells (approx. 20 hrs. life continuous use)
CONDUCTIVITY RANGES	10, 100, 1000 mS/m
INPHASE RANGE	±20 ppt
DATA LOGGER CAPACITY	a) 8,000 records (two components) b) 6,000 records (two components + GPS)
MEASUREMENT RESOLUTION	0.1% of full scale
MEASUREMENT ACCURACY	+5% at 20 mS/m
NOISE LEVELS	0.1 mS/m, 0.03 ppt
OUTPUT PORT FOR REAL TIME LOGGING	RS-232C, 9,600 baud rate
DIMENSIONS	Boom : 4.0 meters extended : 1.4 meters stored Shipping Case : 144x21.5x36 cm
WEIGHT	Instrument Weight : 12.4 kg Shipping Weight : 24 kg

Millisiemens per meter (mS/m) are the same as millimhos per meter (mmho/m)

1.0 INTRODUCTION

Measurement of ground resistivity is one of the oldest geophysical techniques. Table 1, taken directly from Heiland*, lists typical values of resistivity for a variety of geological materials (pages 4-8). The values given are in ohm-centimeters and must be divided by one hundred to give ohm-meters.

It will be observed that in most cases the actual resistivity itself is not diagnostic and a knowledge of the way in which the resistivity varies laterally and with depth is of great importance, since this permits us to "see" features as a result of their shape rather than their actual resistivity values. There is thus a requirement for instrumentation which permits the rapid and accurate measurement of terrain resistivity. Since the EM31 does not require electrical contact with the ground it fulfils this objective.

The basic principle of operation of the EM31 is simple. With reference to Figure 1 a transmitter coil located at one end of the instrument induces circular eddy current loops in the earth. Under certain conditions fulfilled in the design of the EM31 the magnitude of any one of these current loops is directly proportional to the terrain conductivity in the vicinity of that loop. Each one of the current loops generates a magnetic field which is proportional to the value of the current flowing within that loop. A part of the magnetic field from each loop is intercepted by the receiver coil and results in an output voltage which is therefore also linearly related to the terrain conductivity.

** Heiland, C.A. Geophysical Exploration. Hafner Publishing Co., New York 1968*

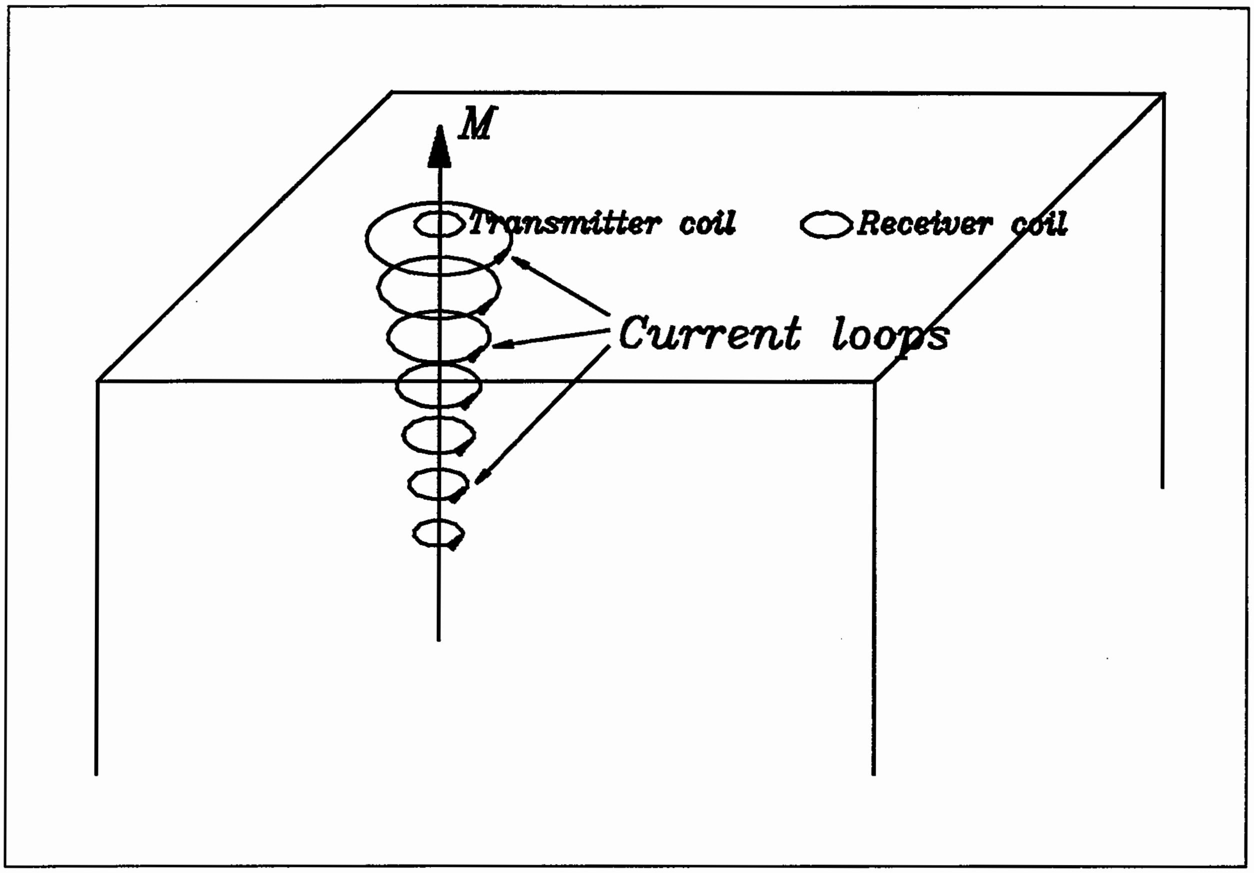


Figure 1: Induced Current Flow in Ground

This instrument is calibrated to read the correct conductivity when the earth is uniform. In the event that the earth is layered, with each layer of different conductivity, the instrument will read an intermediate value as discussed in more detail in Section 5.2.

The unit of conductivity used is the millimho per meter (the same as millisiemens per meter). To obtain resistivity in ohm-meters the instrument reading is divided into 1000 - i.e., a reading of four millimhos per meter divided into 1000 gives two hundred and fifty ohm-meters.

1.0 **INTRODUCTION** (Cont'd)

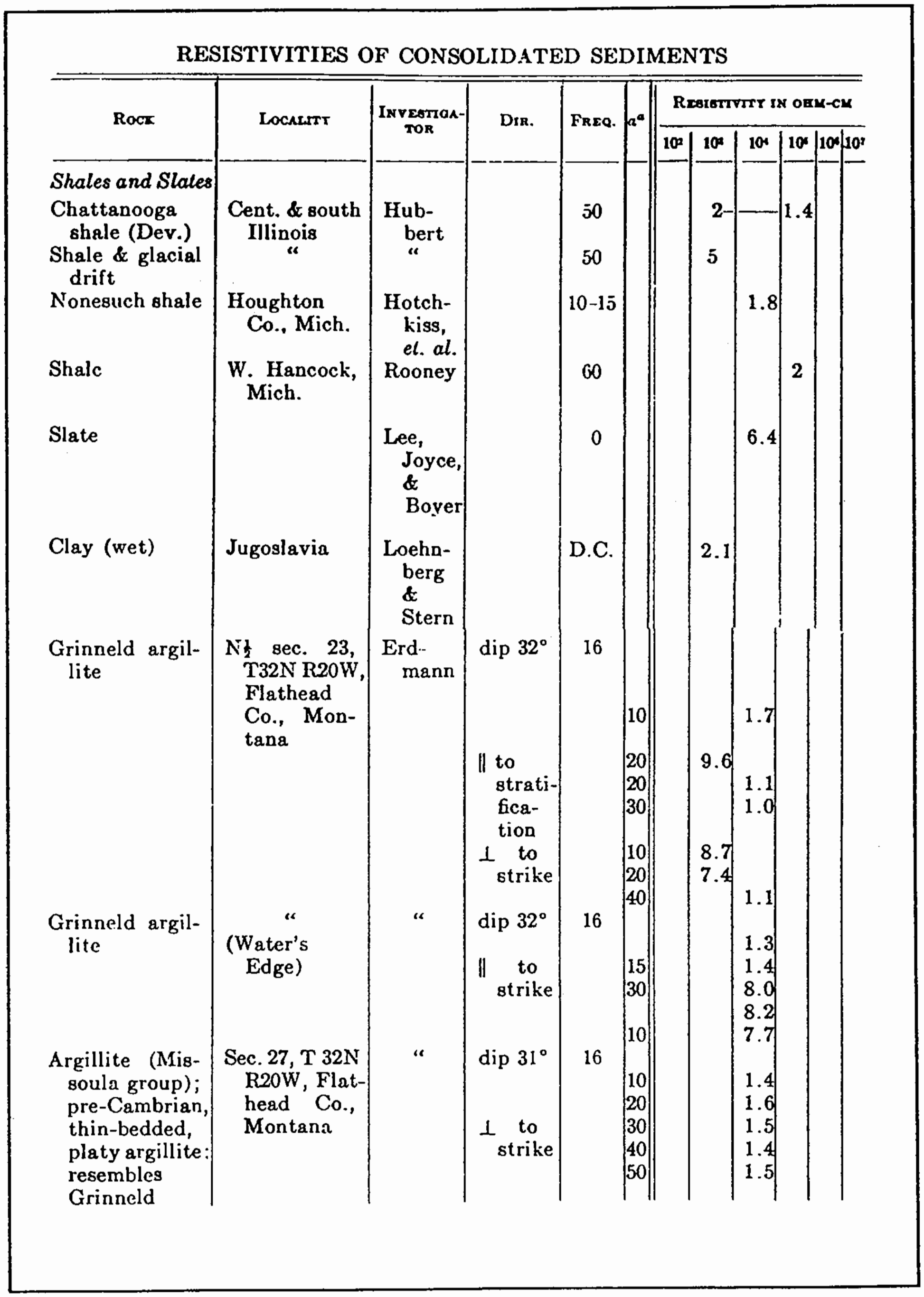
Theoretical calculations show, as will be quickly evident to the operator, that the reading obtained is essentially independent of the orientation of the instrument with respect to the earth. There is, however, a small dependence on the height above the ground; lifting the instrument from the surface of a uniform earth to the normal operating height of about one meter results in a reduction in the reading of 12%. The calibration has been adjusted at the factory so that the instrument reads correctly over a uniform half-space when worn as shown on page 13. If the earth is layered, raising the instrument from the surface of the earth to the normal operating position can result in a reading which stays constant or even increases slightly with height. In general readings made with the instrument at hip height will be sufficiently accurate, but for maximum accuracy the instrument can be laid on the ground as will be discussed in Section 5.2.

There are two components of the induced magnetic field measured by the EM31. The first is the quadrature-phase component which gives the ground conductivity measurement as described. The second is the inphase component used primarily in the EM31 for calibration purposes. The inphase component, however, is significantly more sensitive to large metallic objects and hence, very useful when looking for buried metal drums (see Section 2.2).

RESISTIVITIES OF IGNEOUS & METAMORPHIC ROCKS

Rock	Locality	Investigator	Dir.	Freq.	Resistivity in ohm-cm							
					Intermediate Conductors							
					10^3	10^4	10^5	10^6	10^7	10^8	10^9	10^{10}
Specimens												
Diabase	Idaho	Sundberg	3				3.1					
Granite	Bavaria	Hunkel	3							1		
Devonian slate	Harz	Ebert					2					
" "	"	"						6.5				
Porphyry, schistose	S. Australia	Edge & Laby		100			3					
Serpentine		Eve & Keys					3-	-2				
Diorite	Bavaria	Hunkel	3					1				
Gabbro	Mineville	Lee & Boyer		D.C.					1.0	—	1.4	
Garnet gneiss	Bavaria	Hunkel	3						2			
Hornblende gneiss	Mineville	Lee		D.C.						1–6		
Gray biotite gneiss	"	Lee & Boyer		D.C.						4		
Syenite	Bavaria	Hunkel	3							1		
In Situ												
Graphitic schist	Normandy	Schlumberger		16	1–	1						
Schists	Missouri	Poldini			2–	6						
Hard calc. schist	Belgian Congo	Geoffroy & Charrin				2–	1.1					
Mica schist (hard packed)	Washington, D. C.	Gish & Rooney		16			1.3					
Quartz porphyry (slightly altered)	Newfoundland	Kihlstedt				3.4						
Keweenawan lavas	Michigan	Hotchkiss, *et. al.*		10–15		1.2	—	4.4				
Greenstone	"	Rooney		16			1.1					
Porous traprock	"	"		16		1.6						
Pre-Cambrian	Sweden	Sundberg					3–6					
Granite	Washington, D. C.	Gish & Rooney		16			5					
Slightly altered syenite	Ontario	Kihlstedt		200			2.4 3.7					
Massive vein quartz	"	"		200				2				
Diabase	Michigan	Rooney		16		4.5						
Serpentine	Ontario	Kihlstedt		200		2.1 5.3						

Table 1A: Resistivities of Igneous and Metamorphic Rocks



RESISTIVITIES OF CONSOLIDATED SEDIMENTS

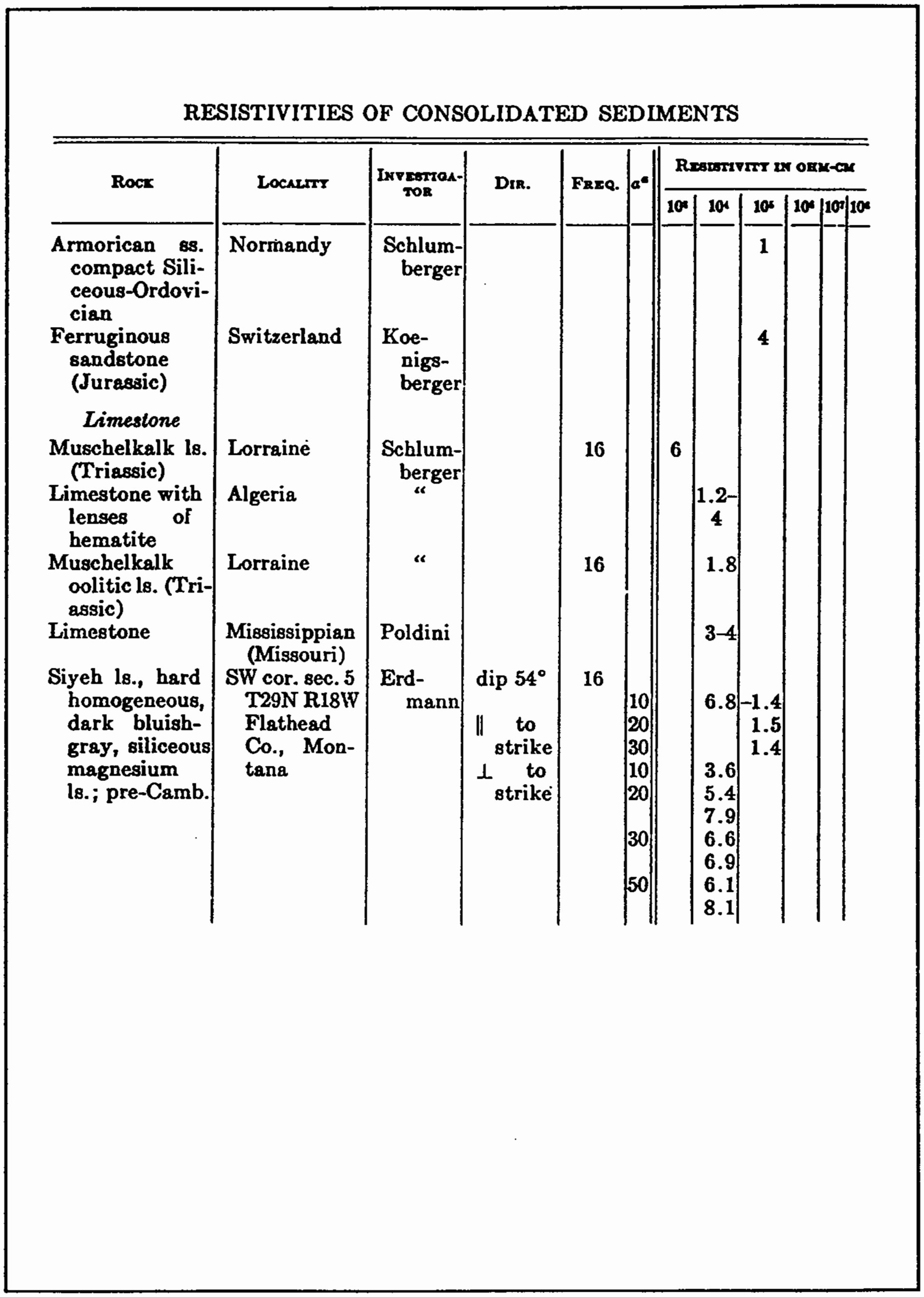
Rock	Locality	Investigator	Dir.	Freq.	a[a]	Resistivity in ohm-cm					
						10^2	10^3	10^4	10^5	10^6	10^7
Shales and Slates											
Chattanooga shale (Dev.)	Cent. & south Illinois	Hubbert		50			2–	—	1.4		
Shale & glacial drift	“	“		50			5				
Nonesuch shale	Houghton Co., Mich.	Hotchkiss, *et. al.*		10-15				1.8			
Shale	W. Hancock, Mich.	Rooney		60					2		
Slate		Lee, Joyce, & Boyer		0				6.4			
Clay (wet)	Jugoslavia	Loehnberg & Stern		D.C.			2.1				
Grinneld argillite	N½ sec. 23, T32N R20W, Flathead Co., Montana	Erdmann	dip 32°	16							
					10			1.7			
			‖ to stratification		20		9.6				
					20			1.1			
					30			1.0			
			⊥ to strike		10		8.7				
					20		7.4				
					40			1.1			
Grinneld argillite	“ (Water's Edge)	“	dip 32°	16							
								1.3			
			‖ to strike		15			1.4			
					30			8.0			
								8.2			
					10			7.7			
Argillite (Missoula group); pre-Cambrian, thin-bedded, platy argillite: resembles Grinneld	Sec. 27, T 32N R20W, Flathead Co., Montana	“	dip 31°	16							
					10			1.4			
					20			1.6			
			⊥ to strike		30			1.5			
					40			1.4			
					50			1.5			

Table 1B: Resistivities of Consolidated Sediments

RESISTIVITIES OF CONSOLIDATED SEDIMENTS

Rock	Locality	Investigator	Dir.	Freq.	a^c	Resistivity in ohm-cm					
						10^2	10^3	10^4	10^5	10^6	10^7
Conglomerates											
Great conglomerate outcrop	Eagle Harbor, Mich.	Hotchkiss, *et. al.*		10–15					1.1		
Calumet & Hecla conglomerates	Michigan	Rooney		60					2	1.3	
Sandstone											
Eastern sandstone	Michigan	Hotchkiss, *et. al.*		10–15			3.5	-1.2			
Eastern sandstone	"	Rooney		16			4.3				
Muschelkalk ss. (Triassic)	Lorraine	Schlumberger		16			7				
Sandstone (Tertiary Oligocene); soft, friable; extremely fine grained ss.; pale green to yellowish and buff; contains thin beds of lignite	Coal Creek Road, Flat head Co., Montana	Erdmann	dip = almost 0	16	10 20 30		8.8 9.8 6.2 6.7 4.8				

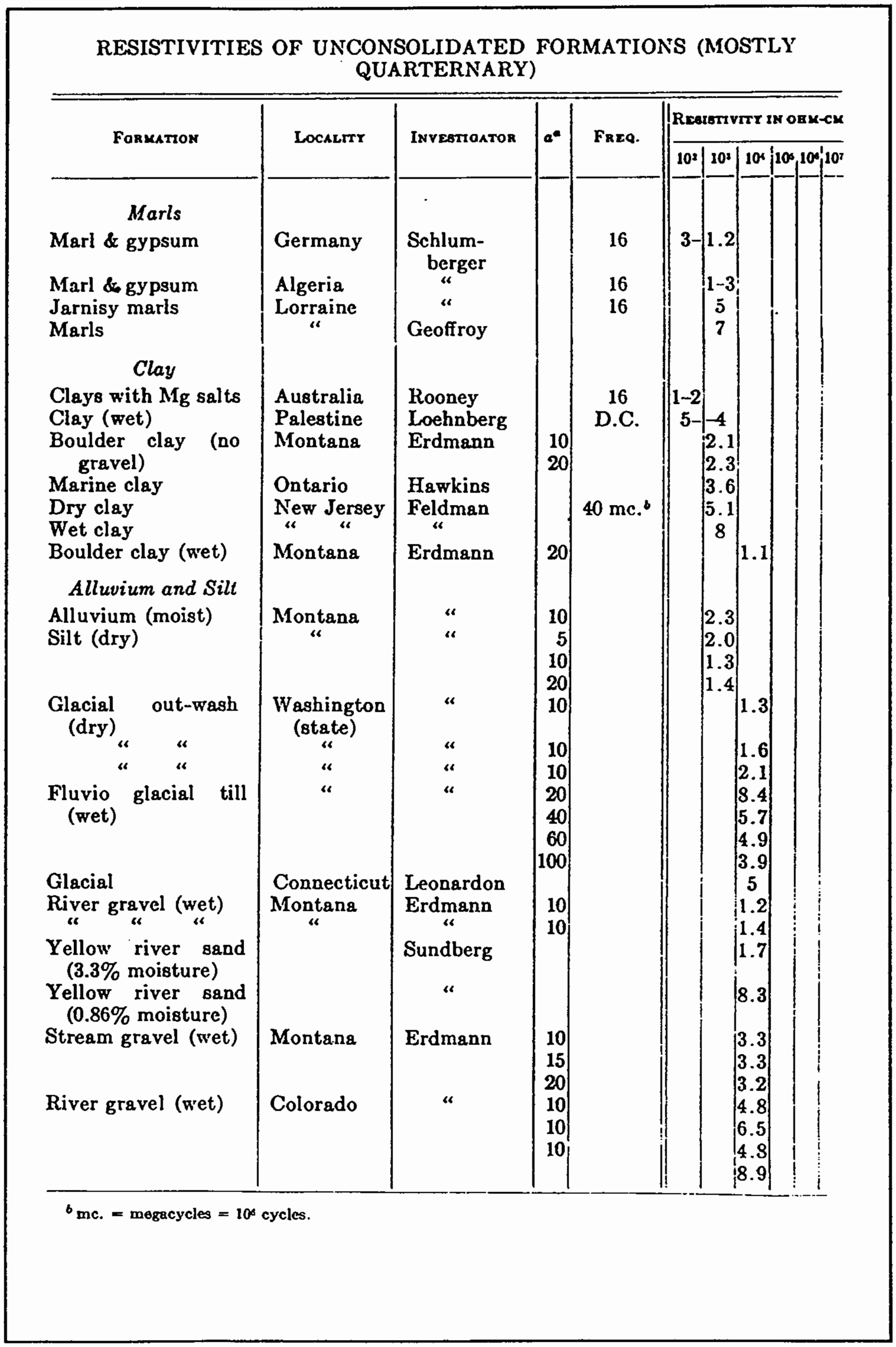
Table 1B (cont'd): Resistivities of Consolidated Sediments



RESISTIVITIES OF CONSOLIDATED SEDIMENTS

Rock	Locality	Investigator	Dir.	Freq.	a°	Resistivity in ohm-cm 10^3	10^4	10^5	10^6	10^7	10^8
Armorican ss. compact Siliceous-Ordovician	Normandy	Schlumberger						1			
Ferruginous sandstone (Jurassic)	Switzerland	Koenigsberger						4			
Limestone											
Muschelkalk ls. (Triassic)	Lorraine	Schlumberger		16		6					
Limestone with lenses of hematite	Algeria	"					1.2–4				
Muschelkalk oolitic ls. (Triassic)	Lorraine	"		16			1.8				
Limestone	Mississippian (Missouri)	Poldini					3–4				
Siyeh ls., hard homogeneous, dark bluish-gray, siliceous magnesium ls.; pre-Camb.	SW cor. sec. 5 T29N R18W Flathead Co., Montana	Erdmann	dip 54°	16							
					10		6.8	-1.4			
			‖ to strike		20			1.5			
					30			1.4			
			⊥ to strike		10		3.6				
					20		5.4				
							7.9				
					30		6.6				
							6.9				
					50		6.1				
							8.1				

Table 1B (cont'd): Resistivities of Consolidated Sediments

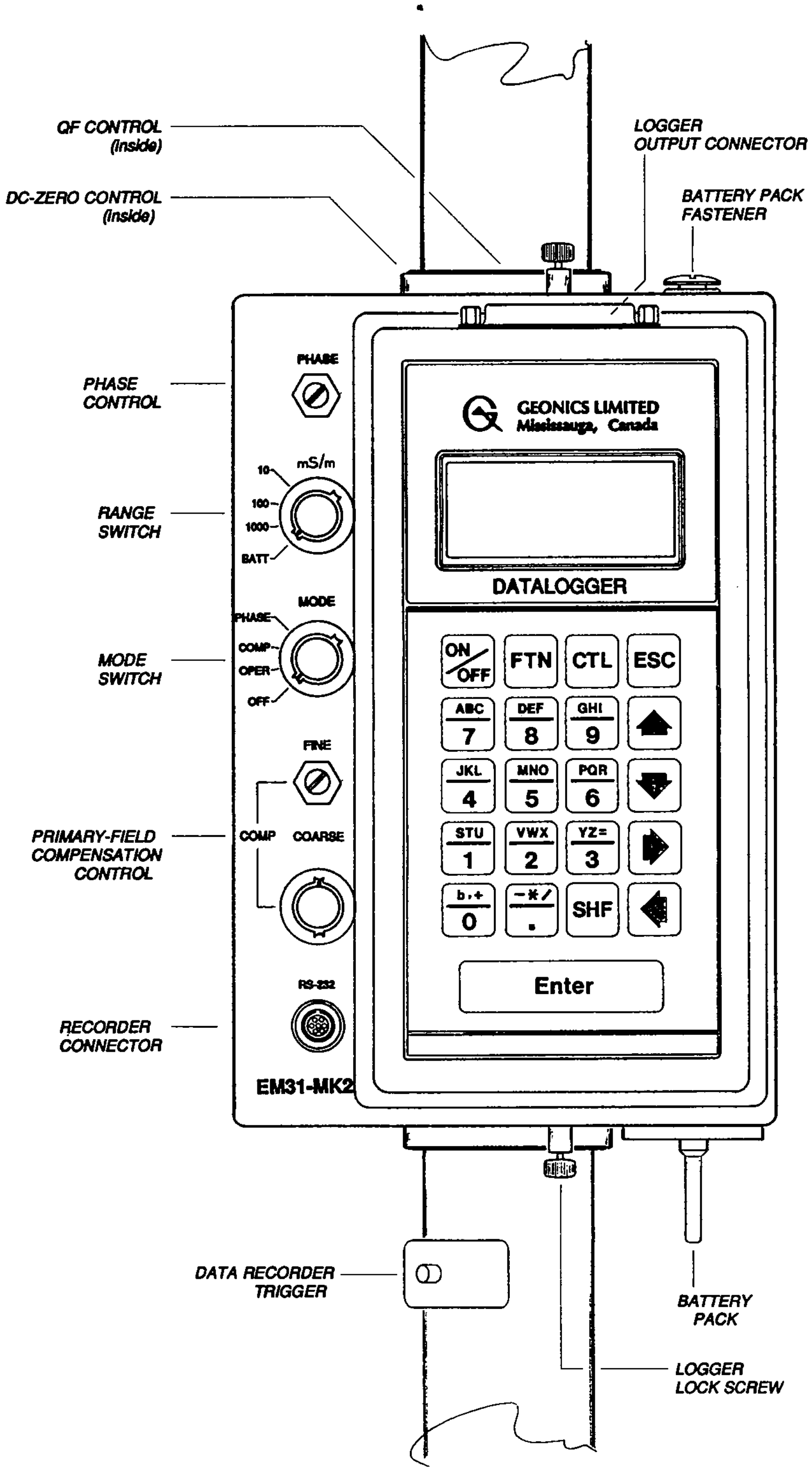


RESISTIVITIES OF UNCONSOLIDATED FORMATIONS (MOSTLY QUARTERNARY)

FORMATION	LOCALITY	INVESTIGATOR	*a*[a]	FREQ.	RESISTIVITY IN OHM-CM					
					10^2	10^3	10^4	10^5	10^6	10^7
Marls										
Marl & gypsum	Germany	Schlumberger		16	3-	1.2				
Marl & gypsum	Algeria	"		16		1-3				
Jarnisy marls	Lorraine	"		16		5				
Marls	"	Geoffroy				7				
Clay										
Clays with Mg salts	Australia	Rooney		16	1-2					
Clay (wet)	Palestine	Loehnberg		D.C.	5-	-4				
Boulder clay (no gravel)	Montana	Erdmann	10			2.1				
			20			2.3				
Marine clay	Ontario	Hawkins				3.6				
Dry clay	New Jersey	Feldman		40 mc.[b]		5.1				
Wet clay	" "	"				8				
Boulder clay (wet)	Montana	Erdmann	20				1.1			
Alluvium and Silt										
Alluvium (moist)	Montana	"	10			2.3				
Silt (dry)	"	"	5			2.0				
			10			1.3				
			20			1.4				
Glacial out-wash (dry)	Washington (state)	"	10				1.3			
" "	"	"	10				1.6			
" "	"	"	10				2.1			
Fluvio glacial till (wet)	"	"	20				8.4			
			40				5.7			
			60				4.9			
			100				3.9			
Glacial	Connecticut	Leonardon					5			
River gravel (wet)	Montana	Erdmann	10				1.2			
" " "	"	"	10				1.4			
Yellow river sand (3.3% moisture)		Sundberg					1.7			
Yellow river sand (0.86% moisture)		"					8.3			
Stream gravel (wet)	Montana	Erdmann	10				3.3			
			15				3.3			
			20				3.2			
River gravel (wet)	Colorado	"	10				4.8			
			10				6.5			
			10				4.8			
							8.9			

[b] mc. = megacycles = 10^6 cycles.

Table 1C: Resistivities of Unconsolidated Formations



EM31-MK2 FRONT PANEL FEATURES

2.0 OPERATING INSTRUCTIONS

The EM31 can be used both to measure the electrical conductivity of the ground and to detect buried metal objects. Section 2.1 describes the procedure for measuring ground conductivity and Section 2.2 for buried metal detection.

2.1 GROUND CONDUCTIVITY MEASUREMENTS

2.1.1 Initial Set-up Procedure

a)1 Before undoing the bottom holder and releasing the transmitter and receiver coil booms, check the battery condition, plus and minus, by setting the Mode switch to the OPER position and rotate the Range switch counter-clockwise to the BATT position. Turn data logger on and run polycorder program EM31-MK2, as per EM31-MK2 data logger manual. If the display reads above ±4.4 the batteries are in good condition, otherwise replace the batteries with a fresh set of C size alkaline batteries. To get access to batteries, undo the battery pack fastener and pull the pack out of the console.

a)2 Digital Recorder (Polycorder) Batteries

- Main Batteries

The Polycorder is shipped with a special battery pack that contains six standard "AA" nickel-cadmium rechargeable batteries.

- Backup Batteries

The backup battery is a half-sized AA lithium cell. This long life "non-replaceable" battery will maintain the Polycorder's memory for at least five years. It can be replaced if necessary, but that must be done at the factory.

- Battery Life

Ni-cad battery life with the Polycorder on the shelf is about 18 months. Depending on the program and how efficient the operator is, battery life for fully charged batteries can be anywhere from 30 to 50 hours.

The Polycorder's operating system completely protects you from losing data because the battery has run down. Here's how it works: as the Polycorder operates, drawing from the main supply, it monitors the batteries so that it can warn you when they need to be charged. Once battery voltage drops below a certain threshold, you will see a flashing message:

```
LOW BATTERIES
```

each time you press ESC, and each time you press ENTER while executing a program. CHARGE YOUR POLYCORDER BATTERIES AS SOON AS YOU CAN if you see this message.

If you fail to charge the batteries and voltage drops below a second threshold, the Polycorder displays the message:

```
CHARGE BATTERIES
CHARGE BATTERIES
CHARGE BATTERIES
CHARGE BATTERIES
```

Then it turns itself off and begins drawing from the backup. The polycorder "knows" not to operate on the backup battery alone. If you try to turn it on again, the polycorder immediately displays CHARGE BATTERIES and shuts down again. Hence the only demand on the backup cell is the small current required to maintain memory, which the battery can deliver for several years.

- Charging Batteries

Contrary to what you might think, it's good practice to let the main batteries discharge just short of seeing the battery messages. If you habitually recharge Ni-cad batteries when they are only slightly discharged, you will get less and less use out of each recharging. Obviously you will need to balance this with the risk of being forced to suspend data collection because the Polycorder has shut down.

The Polycorder comes <u>with a 120 VAC battery charger</u>. To charge the batteries, plug the charger into the Serial I/O Connector. Fully discharged batteries require 14 hours to recharge. Ni-cad batteries cannot be overcharged.

See mod. April/96 CK

Note that the logger can be removed from the console for charging and data dumping by releasing two logger lock screws on each side of the console and pulling the logger straight out.

- Replacing Batteries

Ni-cad batteries can be recharged several hundred times, but effective working life continually decreases. Eventually the batteries need to be replaced. It is a good practice to replace the battery pack annually.

You can change batteries without losing memory.

To replace the battery pack, turn the Polycorder off and lay it face down on a desk or table top. Loosen the six screws, pull the case bottom straight up, and lay it aside for the moment. Do <u>not</u> loosen or remove the six hex standoffs. Remove the bracket from around the battery pack. Unplug the battery connector. Remove the battery pack. Place the new battery pack in the same position as the old one. Plug in the two-pin connector. Place the bracket around the battery pack and align the six holes with the holes in the case. Drop the six outer screws in place and tighten them down. Reload program if necessary, see section II of Data Logger Operating Manual for further information on loading of the program.

b) Using the identifying labels on the tubes, select the transmitter coil tube, align it with respect to the main tube, insert it and fix it with the clamp.

c) Turn the instrument ON by setting the Mode switch to the OPER position and check the zero reading. The Range switch should be set to the least sensitive position 1,000 mS/m (this minimizes any external noise interference while checking the zero position). Tolerance for this check is ±1 mS/m on the conductivity meter. If a zero adjustment is required adjust the DC

ZERO CONTROL by using a small flat-head screwdriver to obtain a zero reading. The control could be accessed through the small hole on the side of the console box. Do not adjust Q/F control at this point.

d) Turn the instrument OFF using the MODE switch, before connecting the receiver coil, then align and connect the receiver coil tube to the main frame tube. The instrument is now ready to proceed with the functional checks.

2.1.2 **Equipment Functional Checks**

The Range switch should be set at 100 mS/m position for all the following tests. (If the conductivity reading is over full scale i.e., greater than 100 mS/m, see note at end of this section).

a) Set the Mode switch to the OPER position and adjust the inphase (I) reading to zero using the COARSE and FINE COMPENSATION controls. Tolerance ±0.1 ppt.

b) To check the phase of the instrument set the Mode switch to the PHASE position. Note the conductivity (Q) reading and rotate the COARSE control one step clockwise. If the conductivity reading remained the same (tolerance ±0.2), the phase is already correct; return the COARSE control to its original position (one step counter clockwise) and no further adjustment is necessary.

If there is a difference in the conductivity readings taken before and after the COARSE control was rotated one step clockwise then a phase adjustment is required. With the COARSE control in its original position adjust the PHASE potentiometer about 1/4 turn clockwise and note the new conductivity reading. Rotate the COARSE control one step clockwise, take a reading, and return the COARSE control to its original position. If the difference in readings has <u>decreased</u>, repeat the procedure using a further <u>clockwise</u> adjustment, until rotating the COARSE control the one step clockwise produces no change in the reading. Tolerance ±0.2 mS/m.

If, on the other hand, the difference in readings has <u>increased</u>, the PHASE potentiometer should be rotated in a <u>counter clockwise</u> direction instead and the procedure described above repeated until there is no change in the readings. Always remember to set the COARSE control back to its original position. This can be confirmed by checking that the inphase (I) reads zero with the mode switch set to OPER mode. If it does not read zero, use the coarse and fine compensation controls to obtain zero on the inphase reading.

c) To check the sensitivity of the instrument, set the Mode switch to the COMP position and rotate the COARSE control clockwise one step. The conductivity reading should change between 22 to 26 mS/m. It is unlikely that the sensitivity of the instrument will vary, however, it may be useful to record the actual reading for comparison at a later date.

Return the COARSE switch to its original setting and set the mode switch to OPER. The EM31-MK2 is now ready to make ground conductivity measurements.

NOTE: a) When conducting the functional tests over ground of conductivity greater than 100 mS/m, the Range switch should be set at the 1000 mS/m range. At whatever level the Range switch is in, the reading taken in (c) should still be between 22 and 26 mS/m.

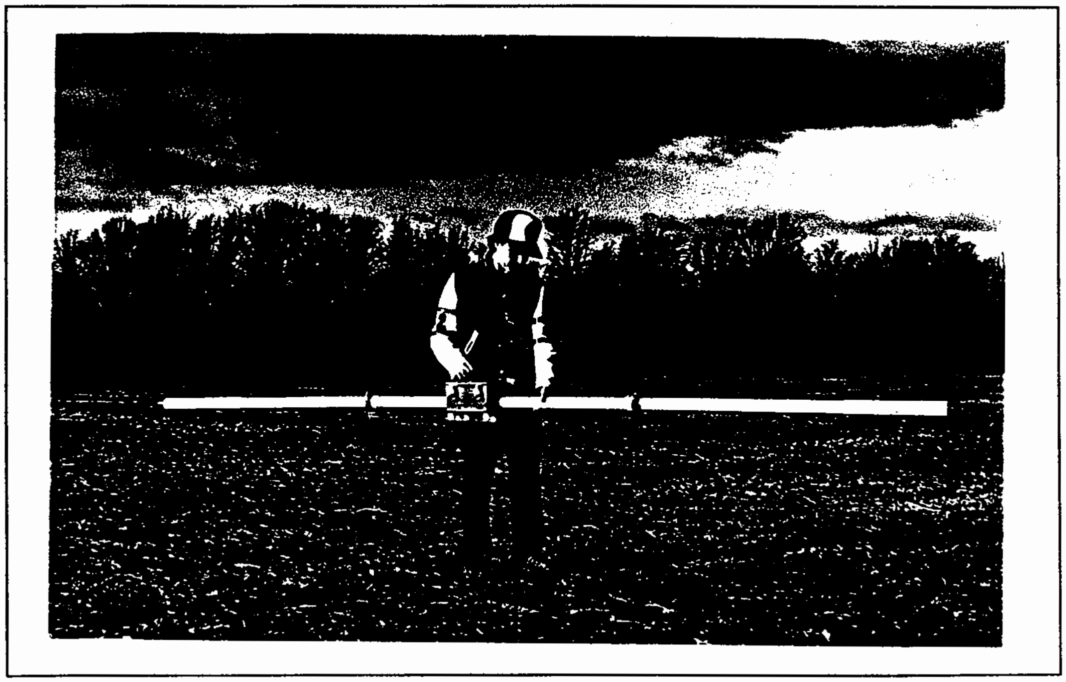
b) The maximum output range of the instrument is 20 mS/m or 200 mS/m, or 2,000 mS/m for conductivity component, and

20 ppt for inphase component.

c) At the end of the survey always remember to turn off both data logger and main console.

2.1.3 Operating Procedure

a) Positioning the instrument with the shoulder strap adjusted so that the instrument rests comfortably on the hip as shown, turn the Mode switch to the OPER position and rotate the Range switch so that the conductivity reads in the upper two-thirds of the full range. The conductivity display is now reading ground conductivity directly in mS/m and full scale deflection is indicated by the Range switch.



Normal Operating Position - Vertical Dipoles

b) The instrument can be operated in either of two dipole modes - vertical or horizontal (see also Section 5.3). The instrument response, as a function of depth, varies significantly between the two modes. It is important to recognize that the vertical dipole mode provides twice the effective depth of exploration as the horizontal dipole mode - 6 m and 3 m, respectively. (A complete discussion of the vertical and horizontal dipole modes is provided in Geonics Technical Note TN-6).

When taking horizontal measurements only or both horizontal and vertical dipole measurements together the measurements should be taken at ground level.

To take the horizontal dipole measurements rotate the EM31 90° about the long axis so that the console is facing horizontally and the battery pack is on the up side.

c) When collecting discreet data points the operator can extend battery life by turning the instrument off between stations. In this case, the operator will notice a slight initial overshoot of the display at turn on. This is normal, and at least two seconds should be allowed after initial turn on before the measurement is recorded.

Alternatively, the operator may choose to leave the instrument on and watch for anomalous readings between data points. The instrument, however, has a time constant of about one second for which the operator should adjust his walking speed to obtain greatest accuracy.

Again, the effect of the instrument time constant should be recognized while logging. Fiducial marks can be placed within the data as fixed points of reference.

The orange button on the transmitter boom is used only in conjunction with the data recording systems.

It is also possible to collect data with the use of computer, by connecting the computer directly to the RS-232 output port on the EM31-MK2 front panel (with optional RS-232 interconnect cable). See DAT31-MK2 computer program manual, section 7, Real Time Logging.

2.2 BURIED METAL DETECTION

2.2.1 Set-up and Operating Procedure

The inphase component of the induced magnetic field is significantly more sensitive to large metallic objects than the quadrature phase (quad-phase) component used for ground conductivity measurements.

Typically, the EM31 inphase component will detect a single 55 gallon drum to depths of about 2 meters to the top of the drum. Under certain circumstances, however, single drums have been detected to depths of about 3.5 meters.

a) The inphase component is measured directly on the inphase (I) display with the mode switch in OPER position.

Inphase measurements are the ratio of the induced secondary magnetic field to the primary magnetic field in parts per thousand (ppt). The inphase display reads directly in ppt and it has same sensitivity regardless of the range switch position.

b) Experience has shown that the 100 mS/m range provides the optimum range setting and sensitivity for most geological backgrounds.

To carry out a survey measuring the inphase component set the Mode switch to the OPER postion and adjust the COARSE and FINE COMPENSATION controls so that the inphase components read zero (±0.1 ppt). (It should be noted that a sudden jar to the instrument can result in a small positive or negative change in the reference level).

The lack of a true zero reference should not cause any serious difficulty or confusion with interpretation since metal targets are generally recognized by anomaly signatures in the data.

As an example, Figure 3 shows typical inphase or quad-phase response when the instrument is carried over a metallic pipeline. Variabilty in the shape, depth and orientation of the target will alter the shape of the anomaly. These anomalies can be characterized by increasing or decreasing, and possibly negative values or some combination of each.

NOTE: It is always advisable, when surveying for buried metal to record both the inphase and quad-phase components. While the inphase, in general, is a better detector of metal, the quad-phase is more sensitive to long, extended targets (eg. pipelines) which are, at least partially, in electrical contact with the ground.

3.0 INSTRUMENT CALIBRATION

Prior to shipping, the instrument is calibrated in the factory to read properly. If necessary, calibration procedures are easily carried out as described below. **IMPORTANT** - The most critical adjustment is the QF (quadrature fine) potentiometer which has been precisely adjusted at the factory.

Before any adjustments are made it is strongly recommended that the instrument first be set up at a fixed height over a known location and the ground conductivity carefully noted. If this adjustment is misaligned the instrument will have to be recalibrated over ground of known conductivity.

3.1 Null Calibration

The zero setting of the EM31 can be readily set by following the procedure described in Section 2.1.1 (c).

3.2 Absolute Calibration

Absolute instrument calibration is easily achieved if any area of ground is available of known and constant conductivity down to the depth of penetration of the instrument. The procedure is simple; the instrument is located over the known area at ground level and the QF compensation control is adjusted until the meter reads 1.12 times the correct terrain conductivity. If the ground conductivity is high, Figure 2 must be used to correctly set the instrument reading.

It is wise to maintain such an area as a calibration check area even if the variation of the conductivity with depth at that area is not accurately known. This is useful for cross checking with future measurements.

NOTE: The QF and NULL controls are located under the front panel. Battery pack must be removed to gain access.

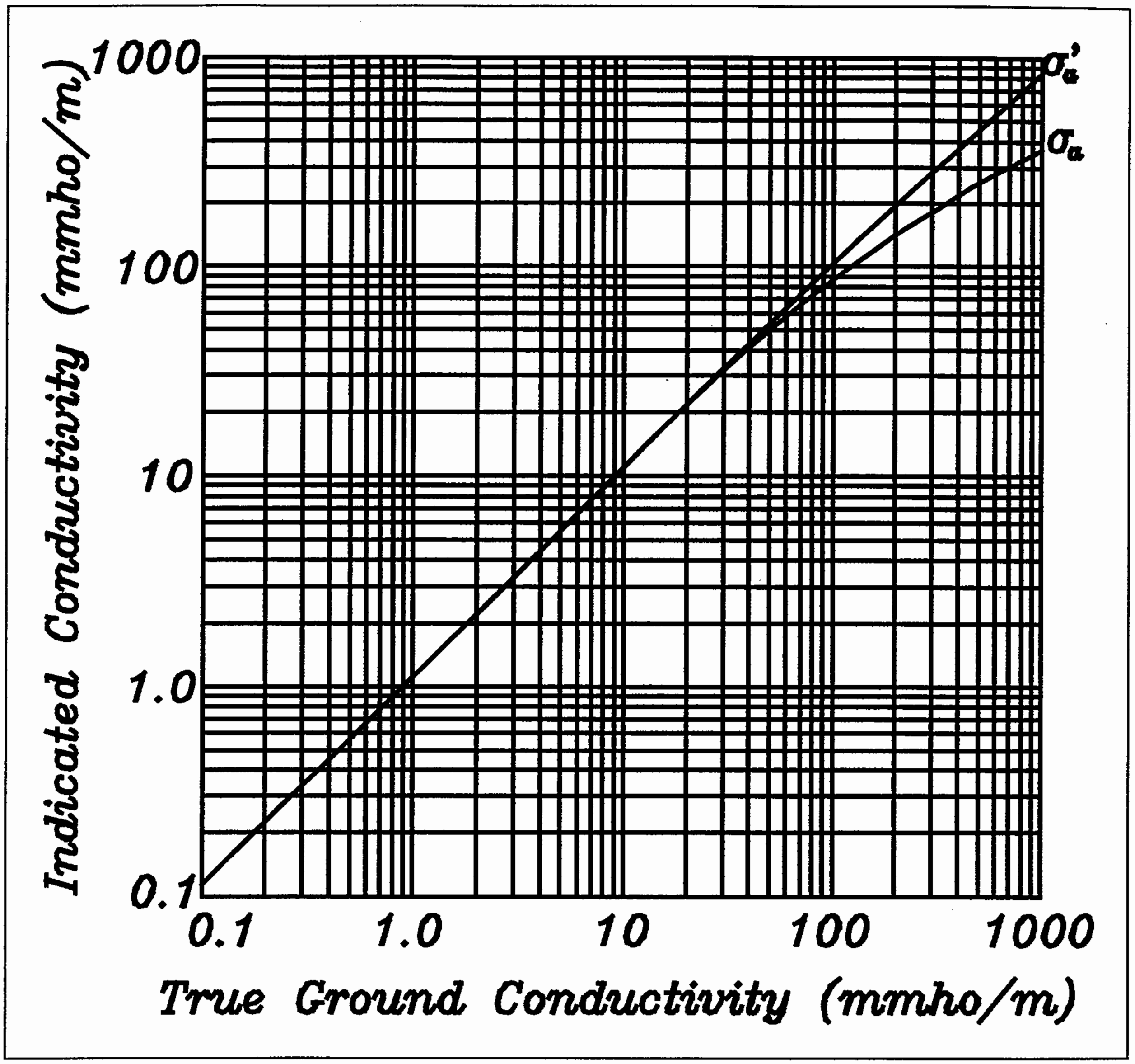


Figure 2: Conductivity Correction: Instrument on the ground surface

4.0 **SURVEY TECHNIQUE**

Surveying with the EM31 is straightforward. As pointed out in 2.1.3. (c) measurements may be made either continuously or on a station-by-station basis. In either case it is always recommended, as for any other geophysical survey, that survey lines and measurement stations be carefully laid out, and the survey performed in a systematic fashion with the resulting data accurately plotted for each measurement station. The most common survey error is to have the survey lines too short, in which case they do not extend sufficiently far off the expected anomalous region to permit the operator to establish the background values of terrain conductivity.

The decision as to the correct spacing will be based on a knowledge of the lateral dimension of the anticipated resistivity anomaly. To ensure the correct spacing, it is useful at the start of the survey to continuously observe the conductivity values that are encountered as the operator moves along the survey line.

The resolution in conductivity of the EM31 is also high, with changes of 5% being quickly perceived. This instrument is capable of giving an extremely precise survey with information on small variations in the terrain.

It was seen in Section 1 that current flow within the earth consists of a series of concentric circles, assuming that the conductivity is laterally uniform. Therefore, in the case of a uniform half-space, rotation of the instrument in a horizontal plane about the transmitter coil as a pivot will produce no change in the meter reading. Conversely, any change in the reading as this procedure is carried out is an indication of lateral inhomogeneities in conductivity. It is simpler and usually sufficiently accurate for the operator to rotate the instrument through 90° using himself as pivot

4.0 **SURVEY TECHNIQUE** (cont'd)

at each measurement station. Thus if the lines are in a north-south direction the operator would normally walk along the line with the instrument pointing in a north-south direction; at each measurement station he can also take a reading with the instrument pointing east-west to check that this is essentially the same as the north-south reading. In the event that this reading is significantly different it may be worthwhile for the operator to then rotate the instrument to the points where the conductivity reading is both a maximum and a minimum, and to record both values. The average value can then be used for the data reduction.

The EM31 is sensitive to underground conductors such as large pipes, drums, etc. These are usually easily recognized by the large meter fluctuations which occur within a short distance, as shown in Figure 3. The negative going peak indicates the location of the pipe. It is then possible to accurately determine the location and strike the direction (azimuth) of the conductor axis as follows: the approximate location is determined as above, and a traverse is then made over the conductor with the EM31 pointing in the approximate direction of the conductor axis. The meter reading will now be a positive maximum when the instrument is both directly over the conductor **and** pointing accurately along the conductor axis.

The instrument is relatively unaffected by fences, overhead power lines, and other nearby metallic objects. In order to determine whether the reading is influenced by such structures the operator should rotate the instrument to check for changes in reading, becoming suspicious if a maximum or minimum occurs when the instrument points either perpendicular or parallel to the structure. Before recording the measurement the operator should move away from the structure until no evidence of lateral inhomogeneity is seen when the instrument is rotated.

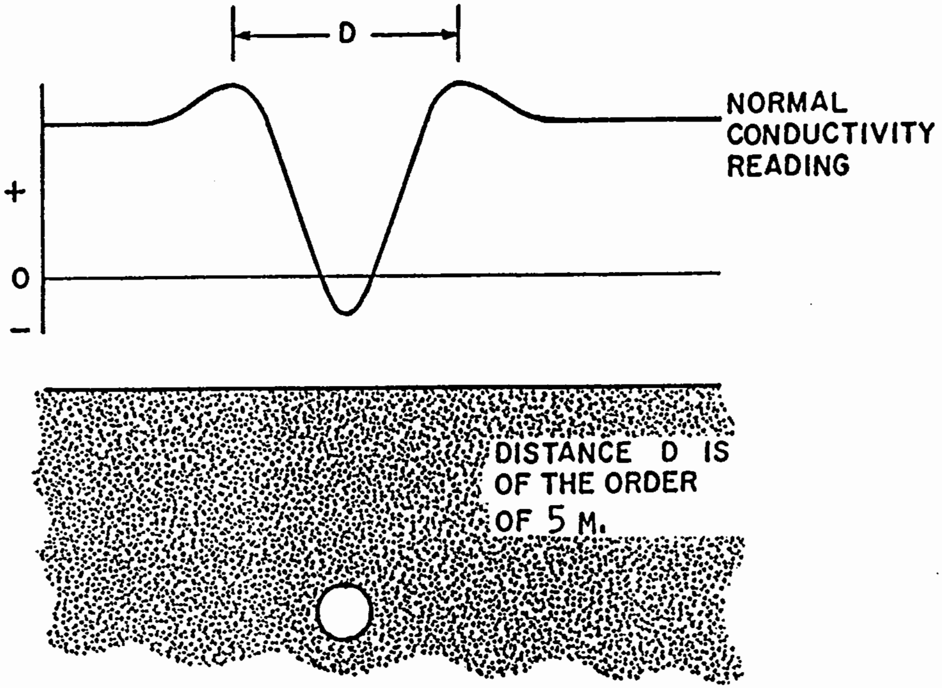


***Figure 3**: Typical Response over a Pipe*

4.0 **SURVEY TECHNIQUE** (cont'd)

It should be remembered that the EM31 is an electromagnetic tool and care should be taken near obvious conductors until the operator has satisfied himself as to their possible effect. In every case this is determined by rotating the instrument and determining whether there is a maximum and minimum which appears to be related to the structure. If a structure is giving such an effect it is not advisable to take the average value of the two readings as in an indicator of the terrain conductivity.

4.0 **SURVEY TECHNIQUE** (cont'd)

In general the conductivity readings obtained with the EM31 will vary smoothly from one region to another. In some cases, however, as for example where a well defined vertical contact separates a poor conductor from a very good conductor, edge effects may be seen in which the readings vary rapidly with position and are no longer a good indicator of the terrain conductivity. Edge effects may also occur where a very good conductor (a few ohm-meters or less) has dimensions of the order of the intercoil spacing, and again the indicated readings may not accurately reflect the true terrain conductivity. In any circumstance where the apparent conductivity varies significantly in a distance which is short compared with the intercoil spacing the possible presence of edge effects or local subsurface conductors must be considered.

Finally, particularly during mid-summer afternoon, electrical static (electromagnetic radiation from local or distant thunderstorms) may cause the meter readings to become noisy. This is usually evidenced by sudden flicks of the meter display, however, in very severe cases the meter display may simply wander about an average reading. Should this occur it is recommended that measurements cease until the "spherics" are over, usually later in the afternoon. Similarly, noisy readings may also be noted when making measurements near large power lines.

5.0 DATA INTERPRETATION

5.1 Uniform Halfspace

The EM31 has been designed to operate over a range of resistivities from a few ohm-meters to a thousand ohm-meters. For higher conductivities the instrumental response departs from linearity as shown in Figure 2, where it will be seen that up to one hundred mS/m the indicated conductivity (σ_a) closely approximates the true conductivity. A departure from linearity is evident for true conductivity greater than one hundred mS/m and beyond one thousand mS/m the instrument response decreases with increasing conductivity. As stated in the introduction, it is generally more informative to observe the spatial variations of terrain conductivity rather than the absolute value of conductivity itself. Figure 2 shows that even at the higher values of terrain conductivity the instrument will be adequately sensitive to small changes in conductivity although it does not read the actual value of conductivity accurately. If necessary, Figure 2 can be used to correct values of indicated conductivity to actual conductivity.

It should be noted that the graph refers to the worst case viz that of the uniform halfspace. If only a portion of the subsurface ground beneath the instrument is of high conductivity as in the case of horizontal layering, the influence of the high conductivity layers will be proportionately reduced and the indicated conductivity will accurately read the "apparent conductivity" as defined in the following section.

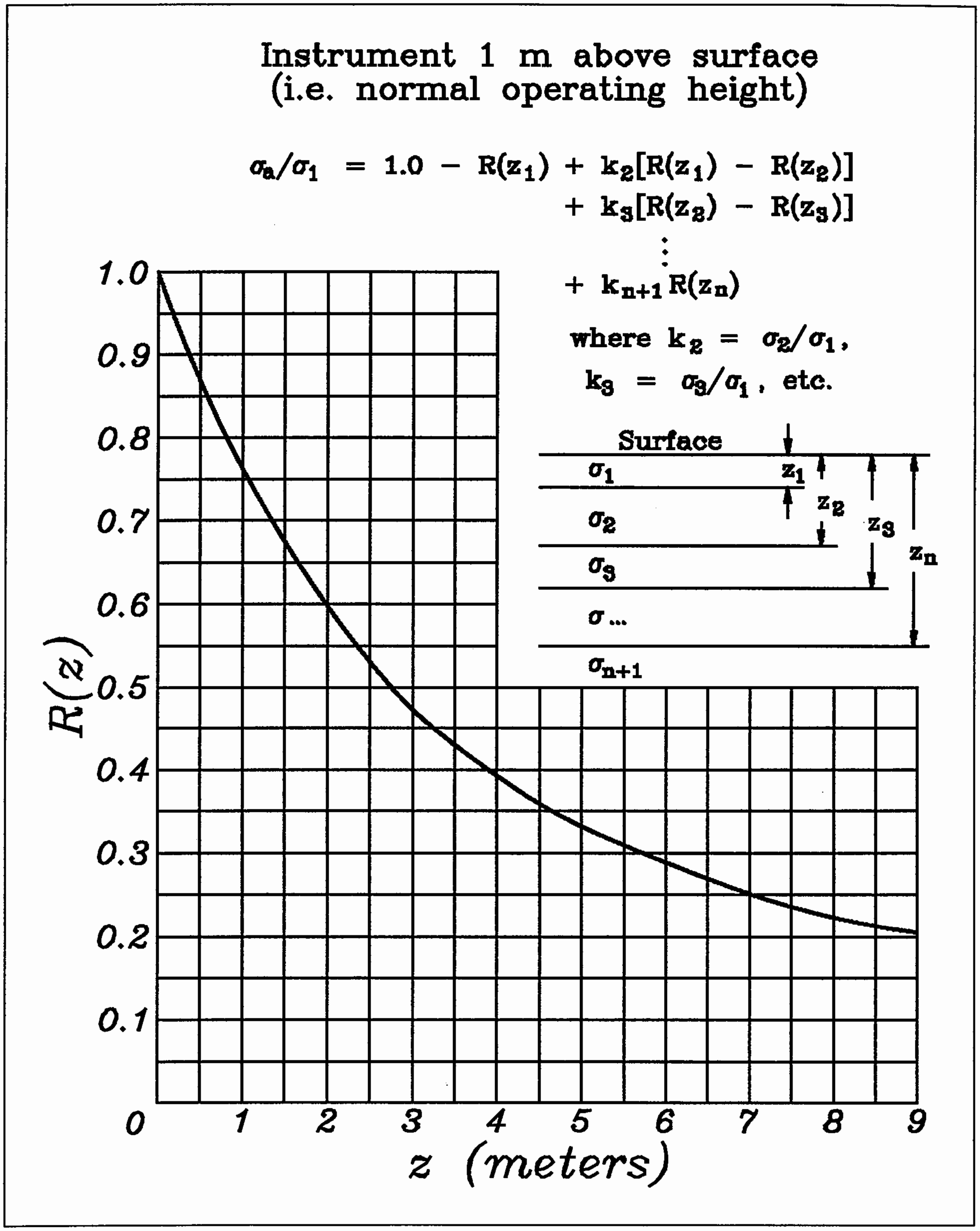
5.2 Multi-Layered Earth

A geophysical model that is of particular importance is the horizontally layered earth, and the EM31 allows a very simple interpretive technique for this model. In order to utilize the model the terrain layering must be well defined and constant over a lateral distance of at least five meters in any direction from the instrument. This condition is often satisfied and this fact is responsible for the usefulness of the technique described herein.

Figure 4 is a plot of R(Z), a function which describes the cumulative relative contribution of all of the material below a depth to the instrument reading. Thus, if we multiply this function by one hundred (to yield percent) all of the ground below a depth z of two meters yields 59% of the response, the ground below three meters yields 47%, the ground below six meters yields 29%, etc., assuming that the conductivity itself does not vary with depth.

The algebraic expression given on the figure illustrates the technique which is used to calculate the "apparent conductivity" that will be measured by the instrument for any number of layers, for any values of conductivity and for any thickness. Consider for example Figure 5, which illustrates in cross section a buried river valley cut into shale and subsequently infilled with glacial till. We wish to calculate the instrument response as such a structure is traversed. This is a two layer problem and the expression for the apparent conductivity reduced to:

$$\frac{\sigma_a}{\sigma_1} = 1.000 - R(Z_1) + k_2 R(Z_1) \qquad (1)$$

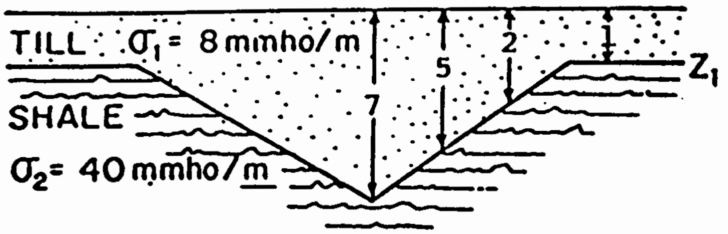


Instrument 1 m above surface
(i.e. normal operating height)

$$\begin{aligned}\sigma_a/\sigma_1 = 1.0 - R(z_1) &+ k_2[R(z_1) - R(z_2)]\\ &+ k_3[R(z_2) - R(z_3)]\\ &\quad\vdots\\ &+ k_{n+1}R(z_n)\end{aligned}$$

where $k_2 = \sigma_2/\sigma_1$, $k_3 = \sigma_3/\sigma_1$, etc.

Figure 4*: Multi-Layer Response Diagram*

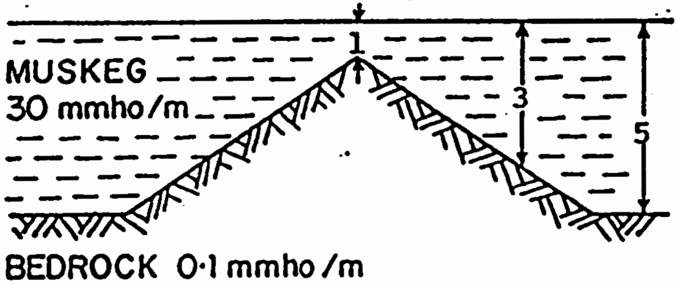


$$\frac{\sigma_a}{\sigma_1} = 1{\cdot}000 - R(Z_1) + k_2 R(Z_1) \qquad (1)$$

$$k_2 = \frac{\sigma_2}{\sigma_1} = \frac{40}{8} = 5$$

$Z_1 = 1\text{m},\ \sigma_a = 8(1.00 - 0.77 + (5 \times 0.77)) = 32.6$ mmho/m
$Z_1 = 2\text{m},\ \sigma_a = 8(1.00 - 0.59 + (5 \times 0.59)) = 26.9$ "
$Z_1 = 5\text{m},\ \sigma_a = 8(1.00 - 0.33 + (5 \times 0.33)) = 18.6$ "
$Z_1 = 7\text{m},\ \sigma_a = 8(1.00 - 0.25 + (5 \times 0.25)) = 16.0$ "

Fig. 5 CROSS SECTION BURIED RIVER VALLEY

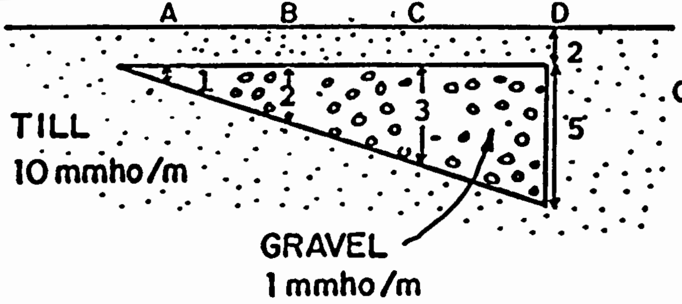


$$\frac{\sigma_a}{\sigma_1} = 1{\cdot}000 - R(Z_1) + k_2 R(Z_1)$$

$$k_2 = \frac{0{\cdot}1}{30} \approx 0{\cdot}0033$$

$Z_1 = 5\text{m},\ \sigma_a = 30(1.00 - 0.33) = 20.1$ mmho/m
$Z_1 = 3\text{m},\ \sigma_a = 30(1.00 - 0.47) = 15.9$ "
$Z_1 = 1\text{m},\ \sigma_a = 30(1.00 - 0.77) = 6.9$ "

Fig. 6 CROSS SECTION BEDROCK HIGH



$$\sigma_a = \sigma_1\,[1{\cdot}000 - R(Z_1) + k_2R(Z_1) - k_2R(Z_2) + k_3R(Z_2)]$$

$$k_2 = \frac{\sigma_2}{\sigma_1} = \frac{1}{10} = 0{\cdot}10$$

$$k_3 = \frac{\sigma_3}{\sigma_1} = 1{\cdot}00$$

(A) $\sigma_a = 10\ (1.00-0.59+(0.10\times0.59)-(0.10\times0.47)+(1.00\times0.47)) = 8.9$ mmho/m
(B) $\sigma_a = 10\ (1.00-0.59+(0.10\times0.59)-(0.10\times0.39)+(1.00\times0.39)) = 8.2$ "
(C) $\sigma_a = 10\ (1.00-0.59+(0.10\times0.59)-(0.10\times0.33)+(1.00\times0.33)) = 7.7$ "
(D) $\sigma_a = 10\ (1.00-0.59+(0.10\times0.59)-(0.10\times0.25)+(1.00\times0.25)) = 6.9$ "

Fig. 7 CROSS SECTION GRAVEL DEPOSIT

5.2 **Multi-Layered Earth** (cont'd)

The table accompanying the figure shows the calculations which yield the value of apparent conductivity at various thicknesses of the upper layer. Thus as we traverse such a structure we would find that the apparent conductivity fell from 32.6 millsiemens per meter at a large distance from the buried river valley to 16.0 millsiemens per meter at the centre of the valley.

Figure 6 illustrates a second situation where the objective is to locate bedrock highs within muskeg. This is again a two layer case and the table illustrates the calculations to determine the apparent conductivity. For this configuration, i.e. a conductor on top of an insulator and k_2 a small quantity, the measured apparent conductivity becomes relatively independent of the actual value of the conductivity of the lower layer. For $k_2 << 1$, the apparent conductivity simply becomes a function of the thickness of the upper conductive layer.

Finally, a third example is given in Figure 7. In this case we wish to traverse a thickening gravel deposit; the maximum thickness is such that the instrument still responds to material below the deposit. This is an example of the situation of an insulator sandwiched between two conductors and is inevitably the most difficult geometry for electromagnetic systems to detect, as evidenced by the tabulated values of apparent conductivity. Even at a thickness of five meters (station D) there is still significant response from the till beneath the deposit and this response tends to keep the apparent conductivity high.

The three examples show how to calculate the response of the EM31 over a variety of geological environments.

5.2 Multi-Layered Earth (cont'd)

Since the instrument operates at a fixed intercoil spacing it is not possible to completely "sound" or evaluate differing conductivity layers with depth. Section 5.3 will show how to further resolve the two-layer case, however, it is always useful to be able to calculate the apparent conductivity which would arise from a given multi-layer model to see whether that model fits the measured data.

Figure 8 shows the apparent conductivity over the two limiting cases of a two layer geometry where the conductivity contrast is very large. In Figure 8A the upper layer is assumed to be very resistive and the figure shows the apparent conductivity with respect to the lower layer conductivity (assumed known) as a function of the depth below the surface of the lower layer, for values of k of ten and infinity. Thus for large k the figure permits the operator to quickly convert the measured values of apparent conductivity to depth, and to estimate the error if the conductivity contrast is not infinite.

Figure 8B performs the same task for small values of conductivity contrast. It should be noted that Figure 8B plots the apparent conductivity with respect to the upper layer conductivity.

It is stated in the data sheet that the effective depth of penetration of the EM31 is approximately six meters. Justification for this claim is shown in Figure 8 where it is seen that for either a resistive ($k = \infty$) or conductive ($k = 0$) upper layer the apparent conductivity is still satisfactorily sensitive to changes in the upper layer thickness at six meters. The limitation in resolving further changes in thickness is imposed by probable variations in the conductivity of either layer.

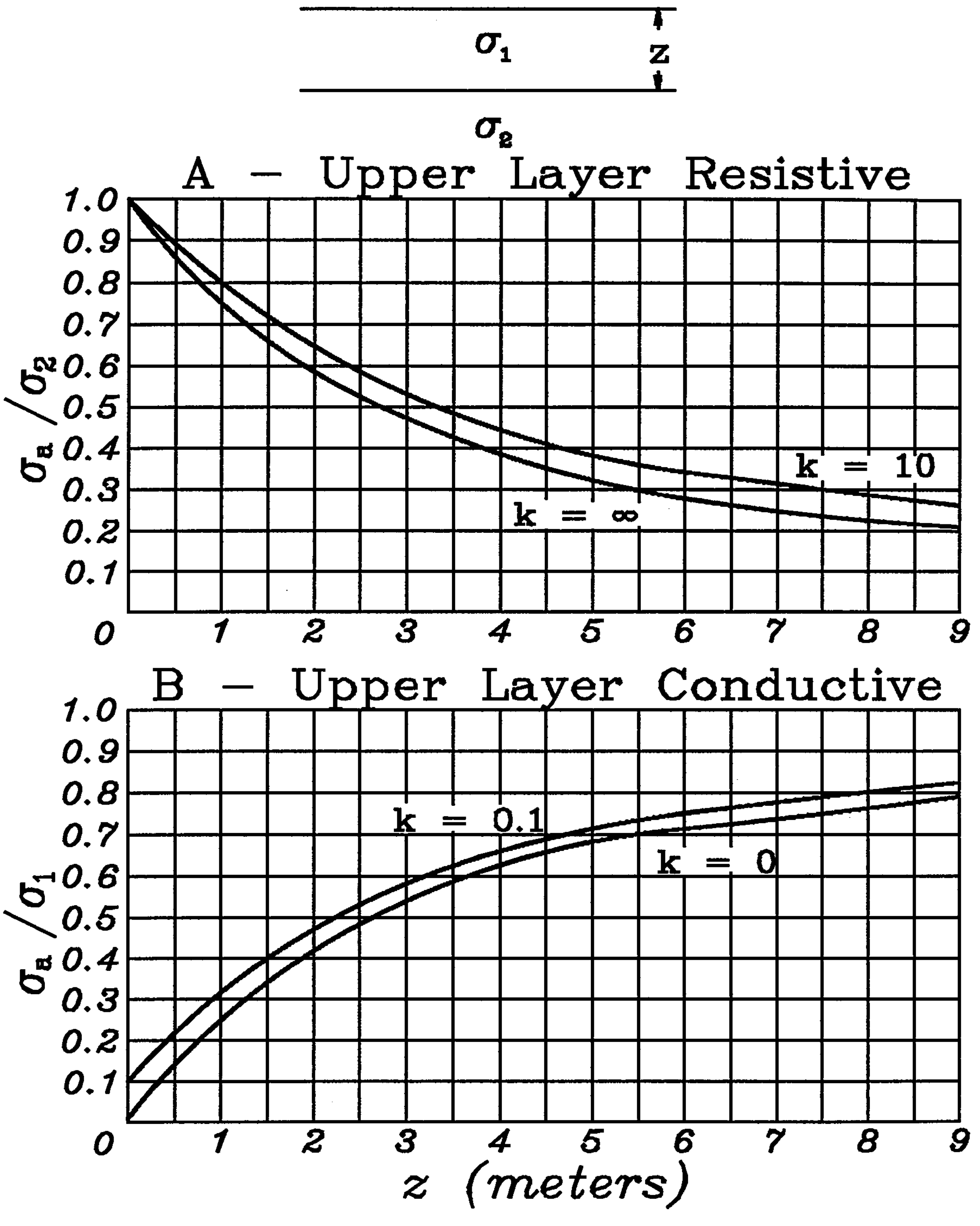


Figure 8:*Response vs. Upper Layer Thickness; Instrument at 1m above ground*

5.3 Geometrical Sounding of Two Layered Earth

It is possible with the EM31 to determine whether the conductivity increases or decreases with depth by laying the instrument on the ground, noting the reading, and then placing the instrument on its side so that the meter face is vertical and again noting the instrument reading. The reason for this is that when the instrument is on its side the new transmitter and receiver coil orientation with respect to the earth causes the effective depth of penetration of the instrument to be essentially halved. It should be noted that in this configuration the current flow does not exhibit the circular symmetry shown in Figure 1. Thus let σ_a be the apparent conductivity indicated by the instrument on the ground in its normal operating position and let σ_a' be the apparent conductivity indicated when the instrument is lying on its side. If σ_a is greater than σ_a' we know that the conductivity is increasing with depth and vice versa. The ability of the EM31 to indicate whether the conductivity is increasing or decreasing with depth is often of considerable diagnostic value.

It will be observed from the above that it is now possible to obtain two measured quantities at each measurement station. In the event that the earth consists only of two layers, there are three unknown quantities i.e. the conductivity of the upper and lower layer and the thickness of the upper layer. If one of these is known it is possible, using the technique described above, to determine the other two. More importantly, when there is a large conductivity contrast so that the conductivity of either the upper or lower layer can be ignored with respect to the other layer then it is possible to completely resolve the two layered earth. An example of the importance of this can be seen in Figure 8

5.3 Geometrical Sounding of Two Layered Earth (cont'd)

which gives the instrumental response as a function of upper layer thickness for either a resistive or conductive upper layer. In order to use these graphs it is necessary to know the conductivity of the lower or upper layer respectively, since both graphs are normalized with respect to these quantities. An inaccurate knowledge of σ_2 in the case of a resistive upper layer or σ_1 in the case of a conductive upper layer can result in a substantial error in the calculated thickness of the upper layer. Any technique which allows us to determine the conductivity of the more conductive layer is of considerable importance since by definition the EM31 is most useful when one layer presents a significant conductivity contrast with respect to the other.

Figure 9 shows a multi-layer response diagram R(Z), completely analogous to Figure 4 but with the instrument now laying on the ground. Figure 10, which presents the function $R'(Z)$ as a function of depth is the same function as Figure 9 but now with the instrument rotated on its side so that the meter face is vertical. It will be noted from Figure 9 that with the instrument on the ground in its normal operating configuration the total contribution from all ground in excess of a depth of five meters is 34% whereas Figure 10 shows that with the instrument lying on its side the ground in excess of five meters causes a total contribution of only 17.5% of the total response. This is the justification for stating earlier that the instrument has effectively one half the depth penetration when lying on its side. Figure 9 also contains a plot of the ratio R'/R and Figure 10 a plot of the ratio $(1-R')/(1-R)$, both as a function of depth.

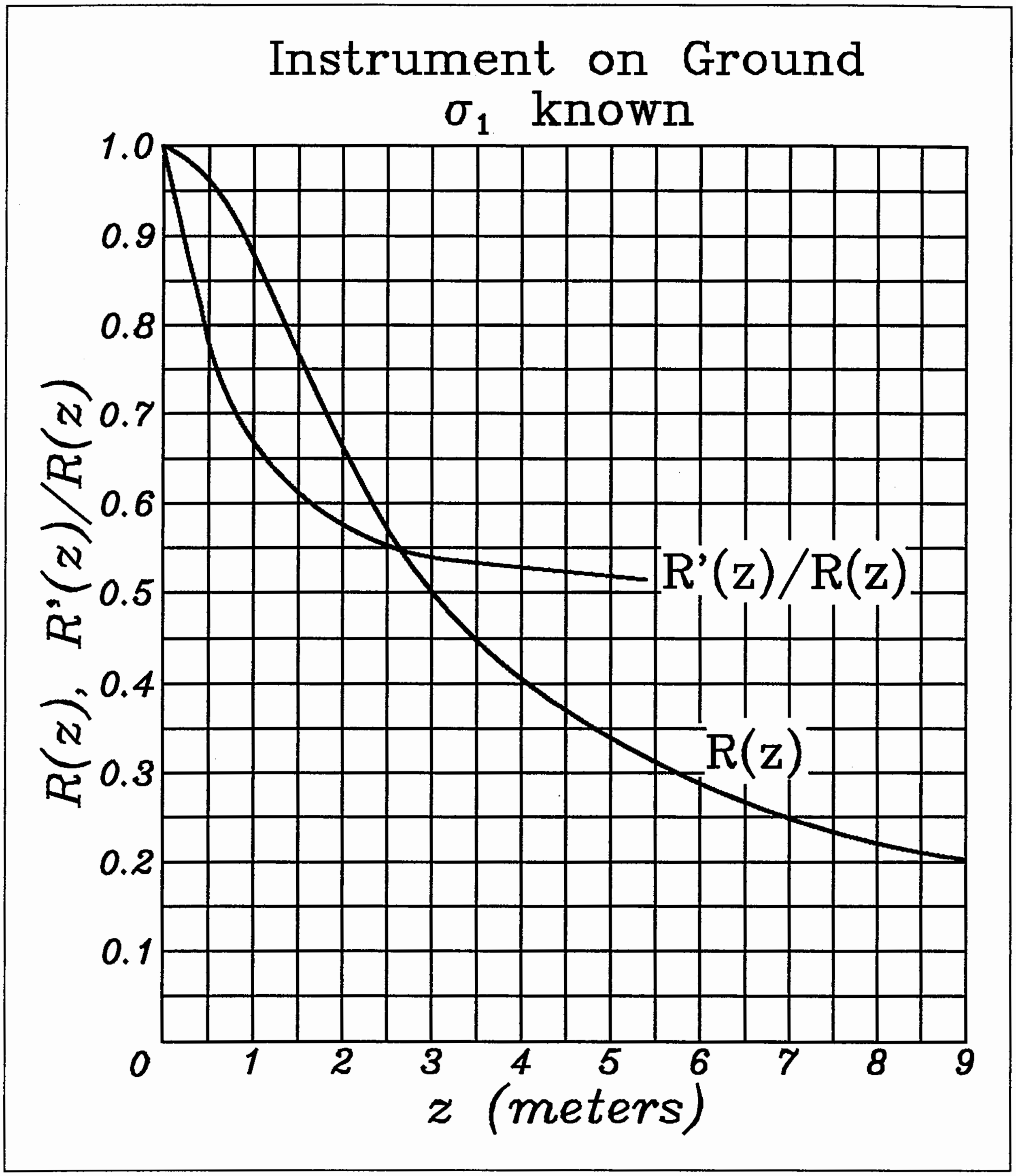


Figure 9: Two Layer Response, Part 1

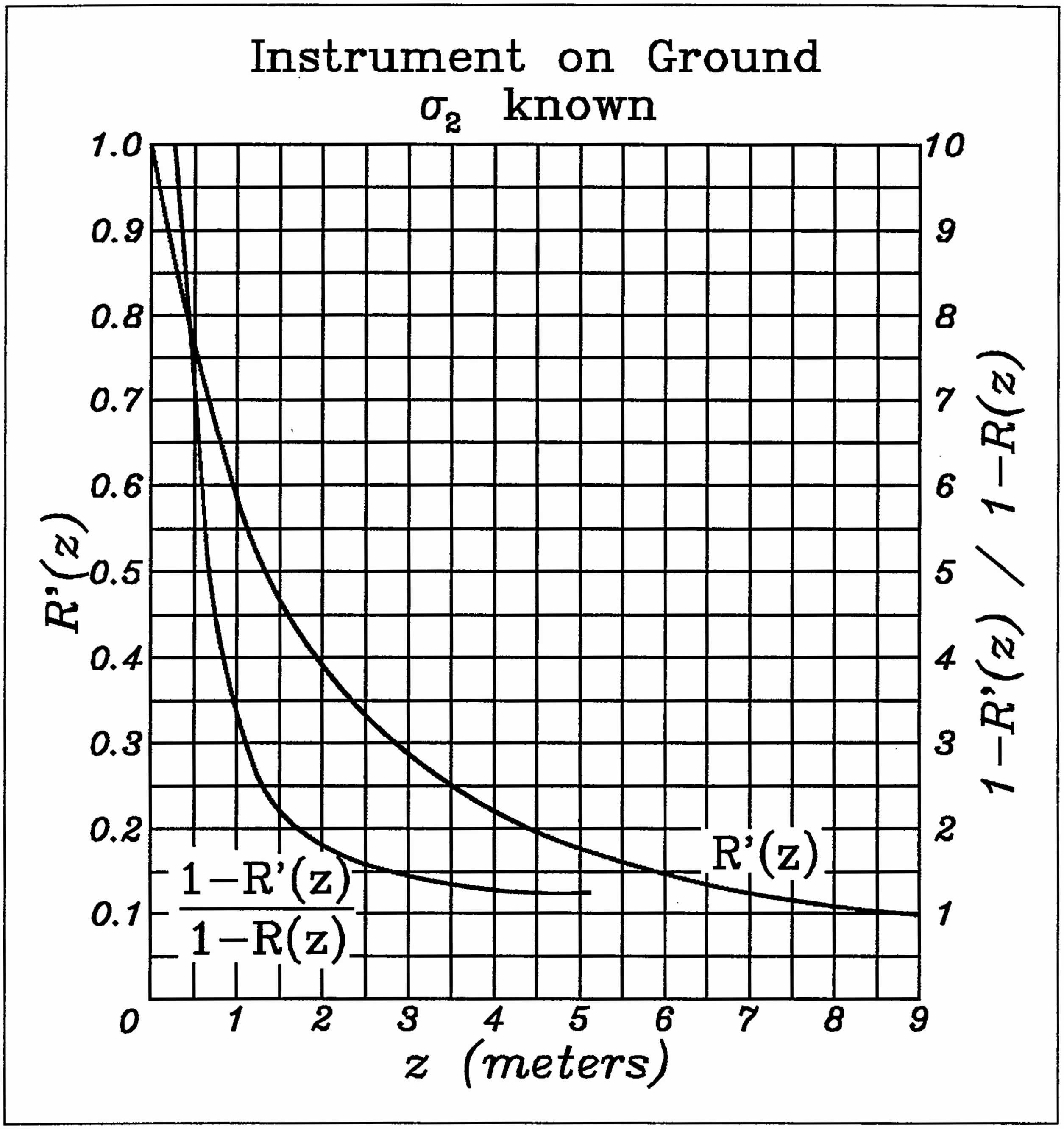


Figure 10: *Two Layer Response, Part 2*

5.3 Geometrical Sounding of Two Layered Earth (cont'd)

Case 1. σ_1 and σ_2 comparable and σ_1 known. It is shown in Appendix 1 that for this case

$$\frac{R'(Z)}{R(Z)} = \frac{\dfrac{\sigma'_a}{\sigma_1} - 1}{\dfrac{\sigma_a}{\sigma_1} - 1} \quad , \quad \sigma_2 = \frac{\sigma_a - \sigma_1 + R\sigma_1}{R} = \frac{\sigma'_a - \sigma_1 + R'\sigma_1}{R'}$$

thus given σ_a', σ_a , and σ_1 , R'/R is calculated; Figure 9 then gives the thickness of the upper layer as a function of R'/R; with this thickness Figure 9 or 10 is used to determine R or R' and the second equation given above is used to determine σ_2 thus fully resolving the two layer case.

Case 2. σ_a and σ_2 comparable and σ_2 known. In this case Appendix 1 shows that

$$\frac{1 - R'(Z)}{1 - R(Z)} = \frac{\dfrac{\sigma_a/}{\sigma_2} - 1}{\dfrac{\sigma_a}{\sigma_2} - 1} \quad , \quad \sigma_1 = \frac{\sigma_a - \sigma_2 R}{1 - R} = \frac{\sigma_a/ \quad - \sigma_2 R'}{1 - R'}$$

Knowing σ_a', σ_a, and σ_2, (1-R')/(1-R) is calculated; Figure 10 gives the thickness and given the thickness Figure 9 or 10 gives R or R' so that the second equation given above is used to calculate σ_1.

5.3 **Geometrical Sounding of Two Layered Earth** (cont'd)

Case 3. Upper layer resistive. σ_1 much less then σ_2. In this case Appendix 1 shows that

$$\frac{R'(Z)}{R(Z)} = \frac{\sigma_a'}{\sigma_a}, \qquad \sigma_2 = \frac{\sigma_a}{R} = \frac{\sigma_a'}{R'}$$

and the same procedure as for Case 1 above is used to determine the thickness of the upper layer and the conductivity of the lower layer.

Case 4. Upper layer conductive. σ_1 much greater than σ_2. Again Appendix 1 shows that

$$\frac{1 - R'(Z)}{1 - R(Z)} = \frac{\sigma_a'}{\sigma_a}, \qquad \sigma_1 = \frac{\sigma_a}{1 - R} = \frac{\sigma_a'}{1-R'}$$

and the calculations for Case 2 yield the thickness and the conductivity of the upper layer.

To illustrate the above let it be assumed that the upper layer is known to be 10 millisiemens per meter and the EM31 indicates 3.8 millisiemens per meter when laying on the ground in its normal configuration and 6.5 millisiemens per meter when lying on its side. Figure 2, which also gives the correction factor to use when the instrument is lying on its side, shows that no correction is necessary.

5.3 Geometrical Sounding of Two Layered Earth (cont'd)

Since the instrument has been calibrated to be operated at one meter above the ground both of these numbers must be multiplied by .88 since the instrument is being used on the ground. This results in σ_a = 3.3 millisiemens per meter and σ_a' = 5.7 millimhos per meter. Then

$$\frac{R'(Z)}{R(Z)} = \frac{\dfrac{\sigma_a'}{\sigma_1} - 1}{\dfrac{\sigma_a}{\sigma_1} - 1} = \frac{\dfrac{5.7}{10} - 1}{\dfrac{3.3}{10} - 1} = 0.64$$

whereupon Figure 9 shows that the thickness of the upper layer is 1.25 meters and R(Z) = 0.825 whereupon

$$\sigma_2 = \frac{\sigma_a - \sigma_1 + R\sigma_1}{R} = \frac{3.3 - 10 + 0.825 \ x \ 10}{0.825} = 1.9 \ mS/m$$

The technique for the other cases described above is exactly the same.

The calculations described above assume that the earth is known to be two-layered. It is possible to determine whether this is true by measuring the apparent conductivity with the EM31 elevated to various heights above the ground and comparing the results with a family of curves given in Appendix II. If the measured variation of apparent conductivity with height matches one of the curves, one can immediately calculate the conductivity of both layers and the thickness of the upper layer, as described therein.

6.0 CASE HISTORIES: ELECTROMAGNETIC NON-CONTACTING GROUND CONDUCTIVITY MAPPING

6.1 Introduction

This short note gives some illustrative examples of surveys that have been carried out using electromagnetic techniques to measure terrain conductivity. The instruments employed were the Geonics Limited EM31 and a prototype version of the Geonics Limited EM34. Both instruments were calibrated to read terrain conductivity in millimhos per meter directly; however, in some of the case histories illustrated in this note the measurements have been converted to resistivity in ohm-meters.

Two features which often limit the usefulness of conventional ground resistivity surveys are their high cost and in some regions (granular material, frozen ground) difficulties associated with generating sufficient current in the ground. The use of inductive electromagnetic techniques avoids both problems since ground probes are not required. This allows measurement over any type of terrain and greatly reduces the time to perform a survey.

Basically the technique consists of energizing a small coil at an audio frequency and measuring the resultant total magnetic field from this coil and the ground with another coil a fixed distance away. Theoretical studies show that, if the intercoil spacing is maintained at a small fraction of the electrical skin depth in the ground, all of the information about the ground conductivity is in the quadrature-phase response. Furthermore, the quadrature-phase response is essentially linearly related to ground conductivity, thus permitting an instrument design in which the output is calibrated to read conductivity (or resistivity) directly. Also under these conditions, the

6.1 **Introduction** (cont'd)

the effective depth penetration of the system is determined by the intercoil spacing and is independent of skin depth and thus of ground conductivity. This feature greatly simplifies interpretation of survey results. In order to vary the depth to which the resistivity is sensed one simply varies the intercoil spacing in analogy with conventional resistivity surveys. Conversely each survey carried out at a fixed intercoil spacing is essentially analogous to a survey carried out with conventional resistivity equipment at a fixed interprobe spacing.

The Geonics EM31 is a one-man portable instrument designed for engineering geophysical applications down to depths of the order of six meters. The intercoil spacing is fixed at twelve feet (3.66 meters). The effective penetration referred to above is an average value; in those regions where a conductive medium is to be located beneath a resistive layer the penetration depth is substantially larger.

The EM34 is operated at 3 intercoil spacings viz 10, 20 and 40m, resulting in effective depth penetrations of the order of 7.5 to 60m (25 to 50 meters) depending on the intercoil spacing employed for the particular survey. Operation of the EM34 requires two men; however, measurements are still taken virtually as fast as the team walks.

Most of the case histories in the technical note have been taken with the EM31; however, in some cases data from EM34 surveys are presented in order to further elucidate the features of inductive electromagnetic terrain resistivity mapping.

6.2 **Example A**: **Heart Lake, Ontario (EM31)**

Measurement Interval: 100 feet over till,
10 feet over sand/gravel

This survey line compares the results obtained with conventional resistivity equipment (Wenner array with "a" spacings of 1 foot and 20 feet) and the Geonics EM31. It is seen that over the till, where the resistivity is slowly varying, the agreement between the two techniques is excellent. In the region shown as "sand and interbedded gravel" there was a good deal of concretion which caused the resistivity to vary greatly over short distances and which accounts for the discrepancy between the two techniques. Over the till the EM31 was read continuously although the data was only recorded, with one exception, at every 100 feet. The exception occurred at station 7+50 where it was noted that a local resistivity high occurred; this was of course not observed on the Wenner array since measurements were taken only at every 100 feet.

6.3 **Example B**: **Sunnybrook Park (EM31, EM34)**

Measurement Interval: 100 feet

This case history shows measurements made with both the EM31 and the EM34 and illustrates the effective depth penetration of the two systems. The second sheet shows the results of expanding Wenner spreads at station 4+00 and 12+00. At station 4+00 we would expect the EM31 to read approximately 9.8 ohm-meters and the EM34 50 to 60 ohm-meters, which is the case. At station 12+00 the resistivity increases with depth and thus the EM31 should read a relatively low value and the EM34 a higher value which increases with intercoil spacing. This is indeed the case.

6.4 **Example C**: **Cavendish Test Site (EM31)**

Measurement Interval: 50 feet

This survey, which was carried out over line C to establish the overburden resistivity shows that with the exception of the swamp area the overburden is extremely resistive. The value of resistivity obtained over the swamp is in good agreement with that from other measurements. The example also illustrates the performance of the instrument over Zones A & B, both of which are small highly conductive mineralized zones and cause the instrument to read off scale.

6.5 **Example D**: **Lake Scugog (EM31)**

Measurement Interval: 50 feet

This survey illustrates the extremely high resolution achievable with the EM31 or the EM34 systems since neither technique requires electrical contact with the ground. Resolution in conductivity of the order of 3% or 4% is easily achieved and completely repeatable as long as the terrain remains unchanged. The example also illustrates the speed with which a survey can be carried out. In this particular case 1.9 line miles of survey was performed in seventy minutes with a station interval of 50 feet. Furthermore since the measurements were actually taken continuously any unusual activity in the resistivity between stations would have been recorded.

6.6 **Example E**: **Cooksville/Mississauga, Ontario (EM31)**

Measurement Interval: 25 feet

This example illustrates a survey carried out with the EM31 to search for a buried river channel. The channel, which is filled with glacial till, has been cut into the Dundas shale which, as seen from the example, has a resistivity of the order of 25 to 30 ohm-meters. The total time to plot out the profiles shown in the figure was approximately 1½ hours, with a measurement interval of 25 feet. A shortcoming of the technique is seen on line 5, where a region was encountered which was so conductive that it was not possible to take readings.

The second sheet illustrates the application of the two layer curves to interpret the survey results in terms of depth.

6.7 **Example F**: **Discontinuous Permafrost (EM31)**

Measurement Interval: Variable

These two examples were taken in Northern Canada and compared the results obtained with the EM31 with a medium frequency version of the Radiohm (Geonics EM16R) technique operating at 250 kHz. The data interval is fairly coarse, nevertheless there is good agreement between the two techniques, which is particularly interesting in view of the fact that the current distribution in the ground is totally different for the two systems. Furthermore the EM31 operates at a frequency of approximately 9.8 kHz whereas the MF radiohm operates at 250 kHz.

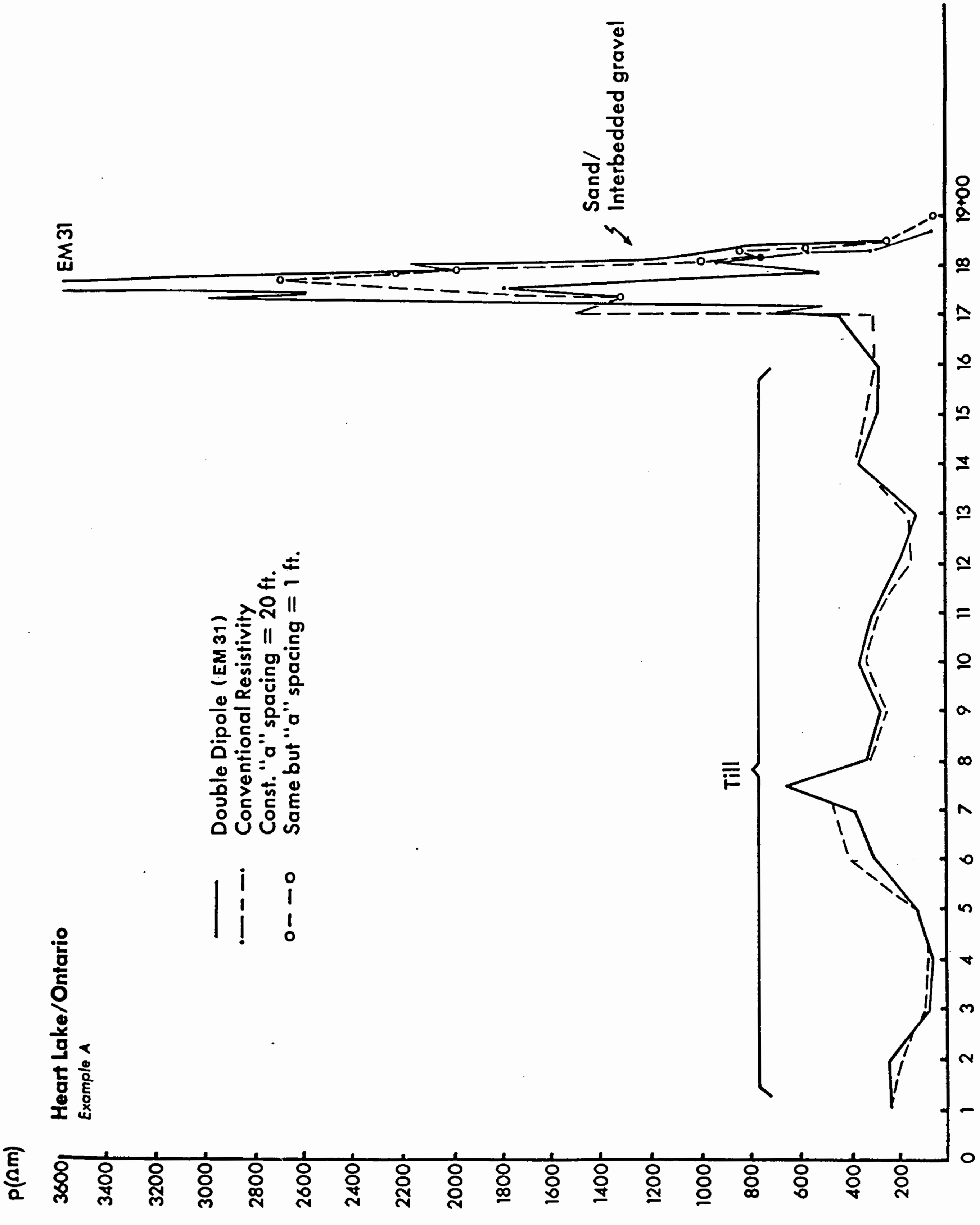
6.8 **Example G**: **Pre-glacial River Valley (EM31, EM34)**

Measurement Interval: 100 Feet

This survey was performed to outline a pre-glacial river valley whose existence had been suggested from water-well data. The survey was performed with the EM34 at a station interval of 100 feet and with intercoil spacings of both 50 and 100 feet. (An earlier model of the EM34 made use of 50 and 100 feet intercoil spacings. These spacings are not available with the current EM34 model). At either spacing the time required to complete the 8400 foot survey line was 1.5 hours. The same line was subsequently surveyed with the EM31.

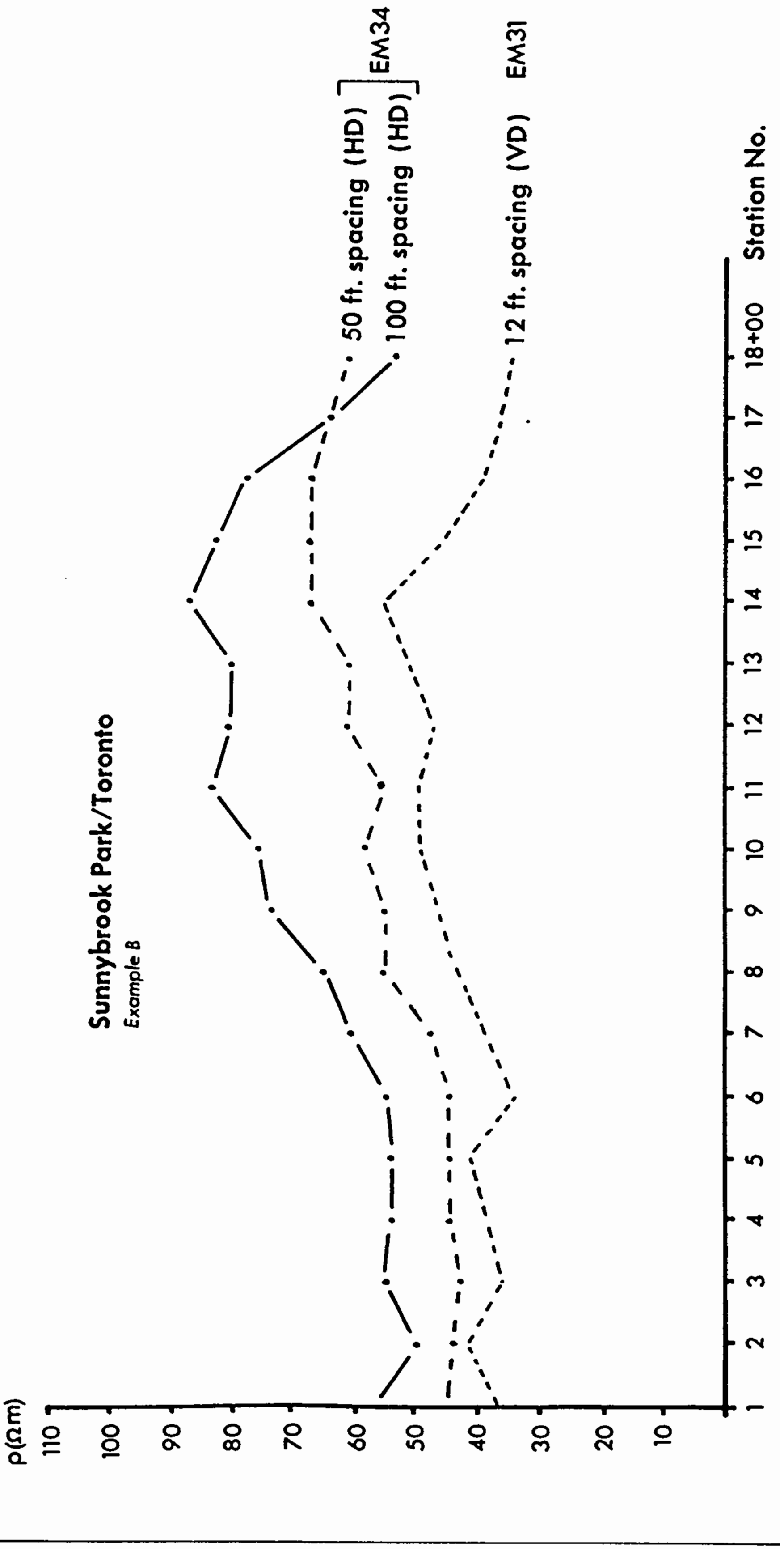
Typical bedrock conductivity in the area is approximately 32 millimhos per meter, whereas an average value for the conductivity of the infilling glacial till is of the order of 8 to 12 millimhos per meter. Thus the EM34 at either intercoil spacing yields approximately 30 to 34 millimhos per meter at the valley edges where the overburden is thin and 12 to 24 millimhos per meter at the valley centre. The EM31 yields values of 14 to 18 millimhos per meter at the valley edges (slightly affected by the presence of bedrock) and approximately 10 millimhos per meter at the valley centre. The interpreted depth of the valley, based on the model shown in the figure, is approximately 120 feet which is in reasonable agreement with the water-well data value of 150 feet, bearing in mind that the three sets of data show that a two layer model is an over simplification.

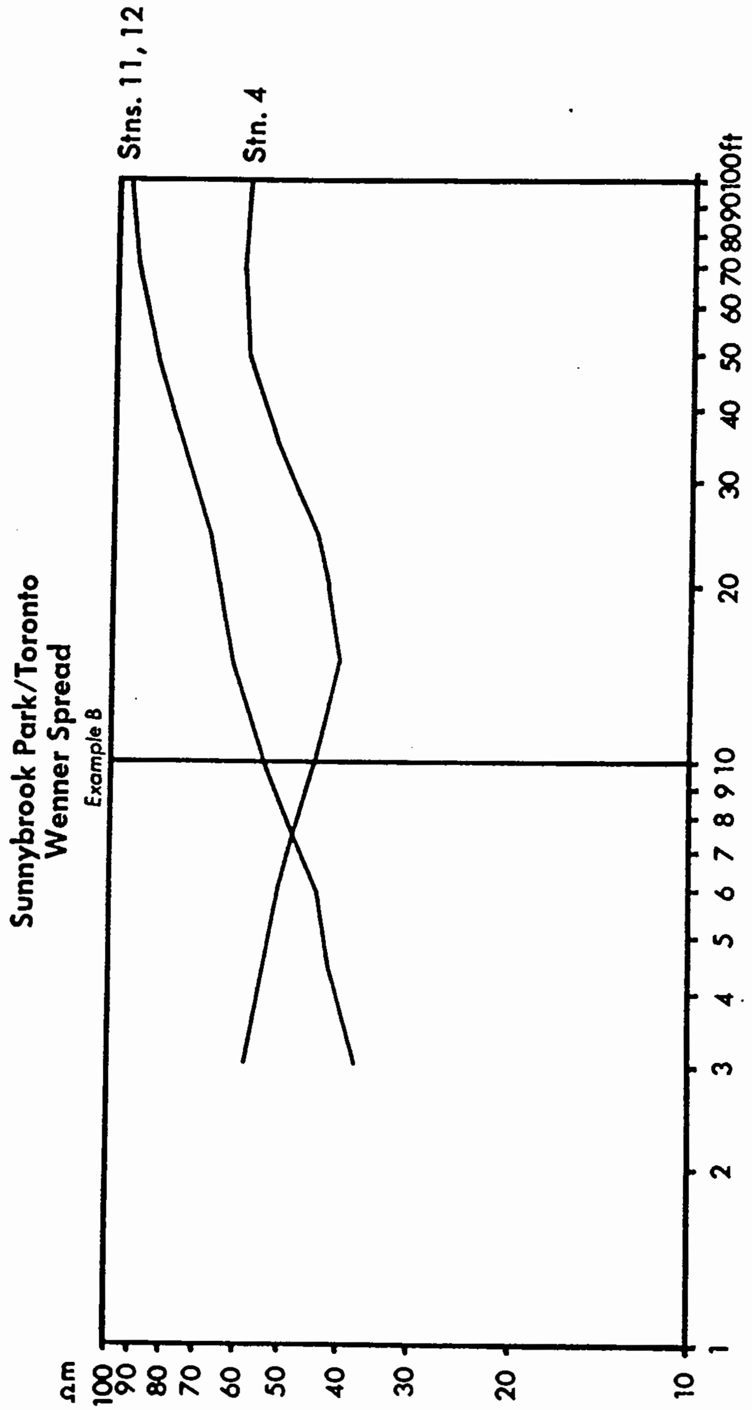
The conductivity high which occurs between station 32 and 38 results from a very large pile of waste furnace ash lying on the surface.



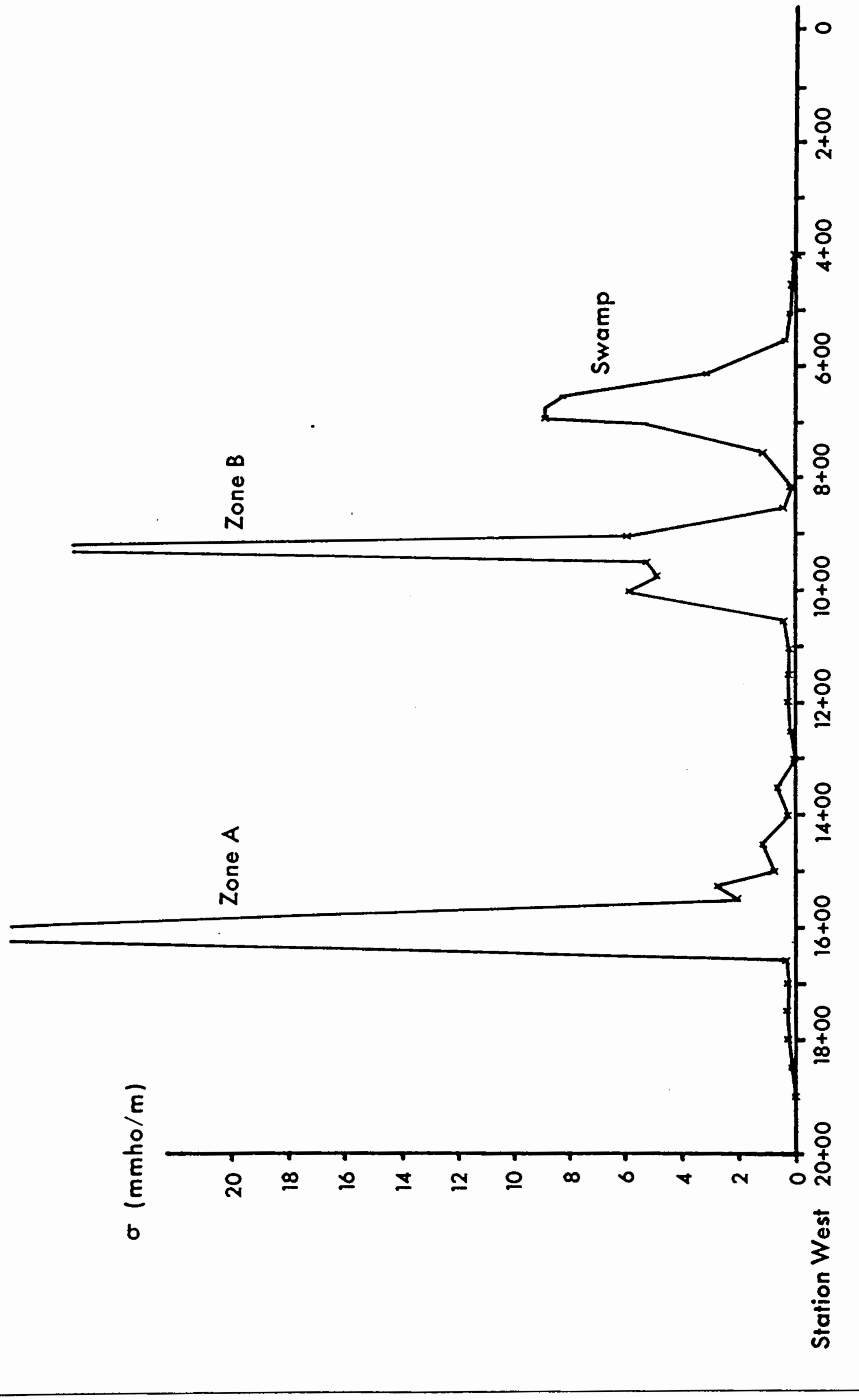
Heart Lake/Ontario

Example A


Sunnybrook Park/Toronto
Example B
50 ft. spacing (HD)
100 ft. spacing (HD)
EM34
12 ft. spacing (VD)
EM31
Station No.
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18+00
ρ(Ωm)
110
100
90
80
70
60
50
40
30
20
10



Sunnybrook Park/Toronto
Wenner Spread
Example 8

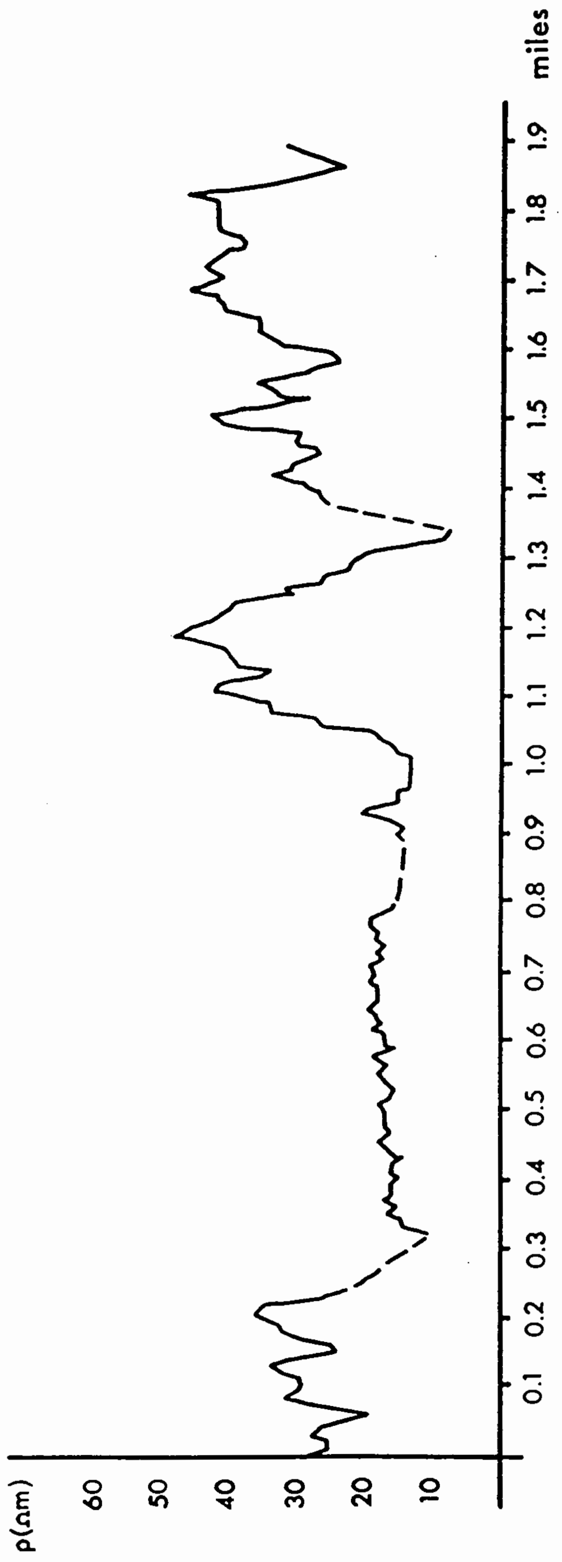


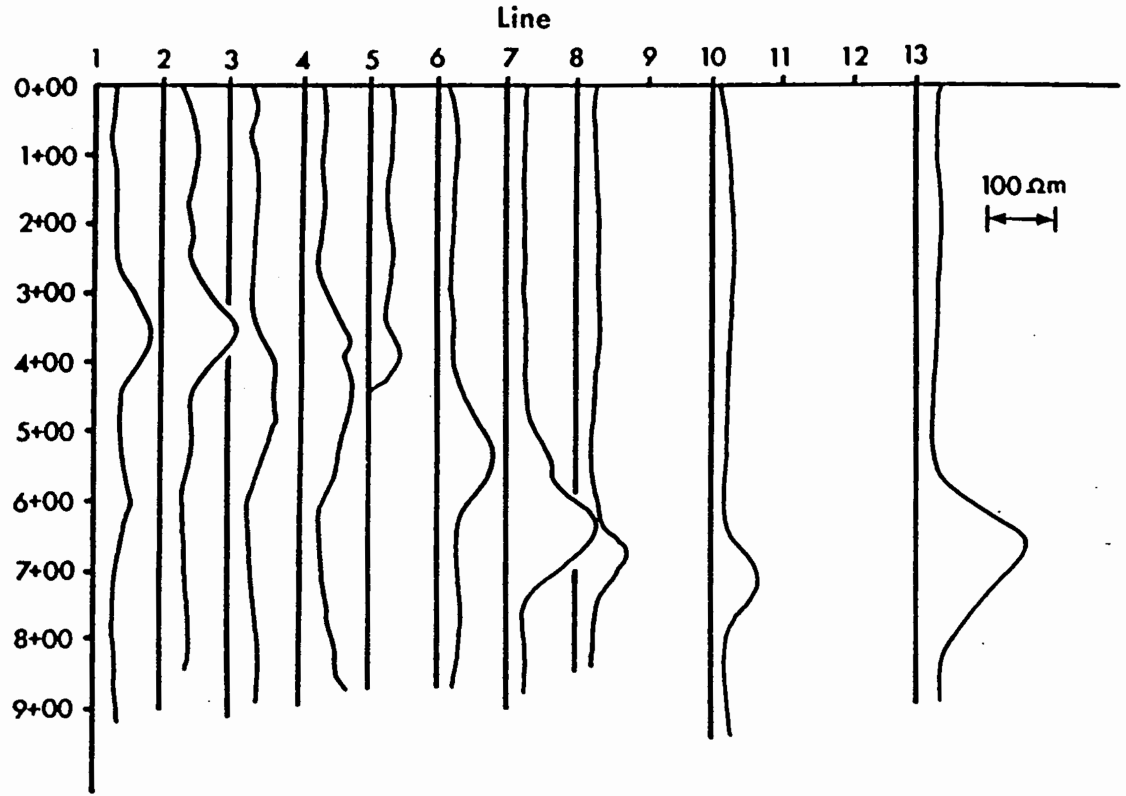
Cavendish Test Range — Line C

Example C

Lake Scugog/East Causeway *Example D*

Note (1) Station interval = 0.01 mile
(2) Survey duration =70 minutes
(3) Total no. of stations = 190
(4) 2.7 stations per minute



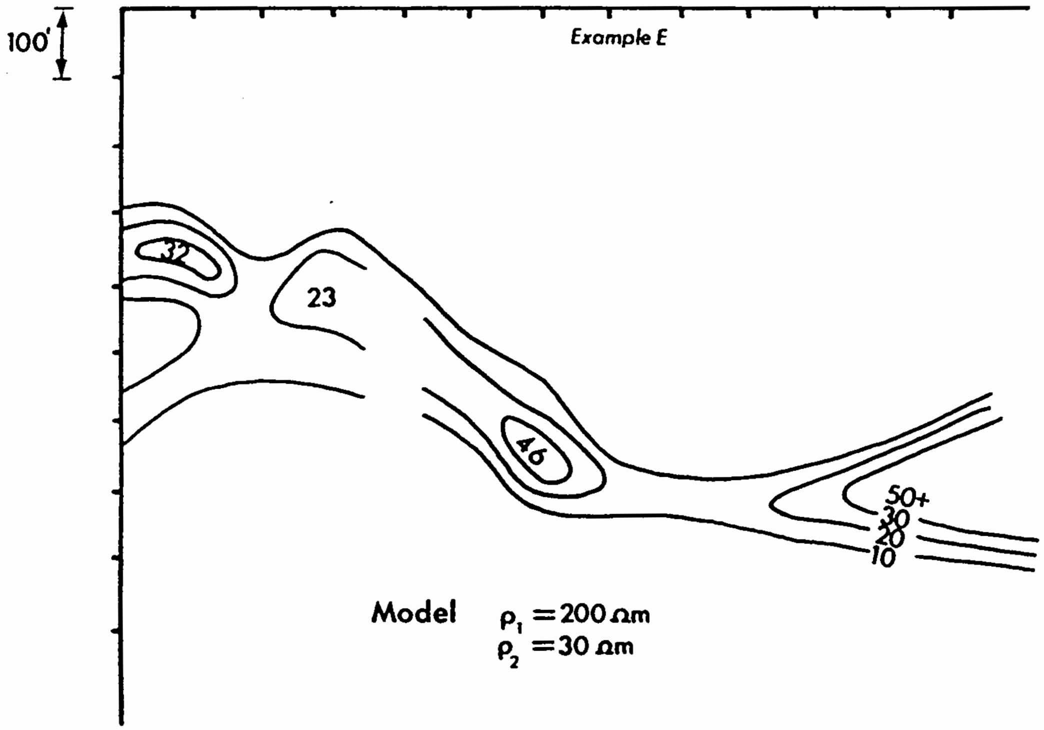


Cooksville/Ontario

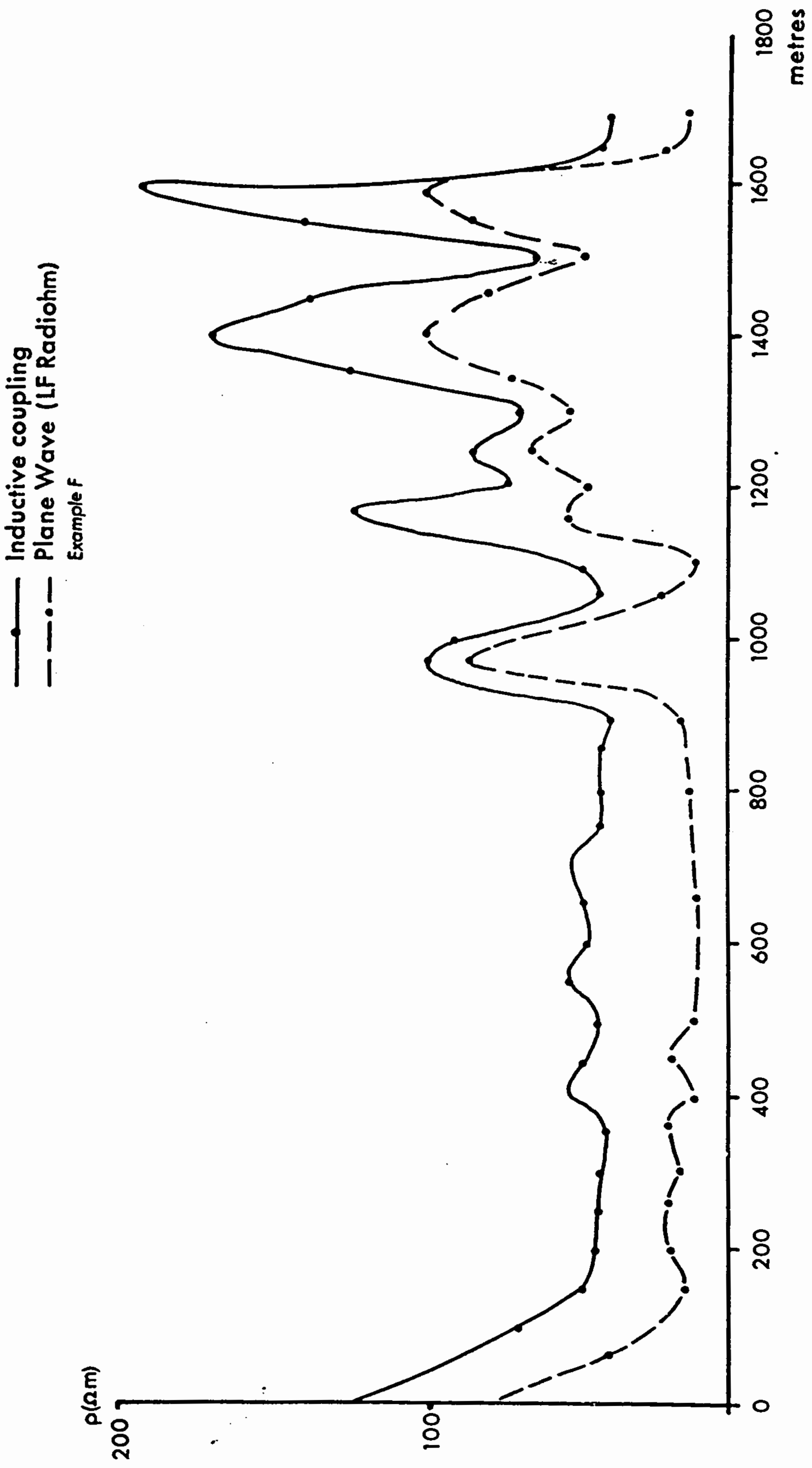
Example E

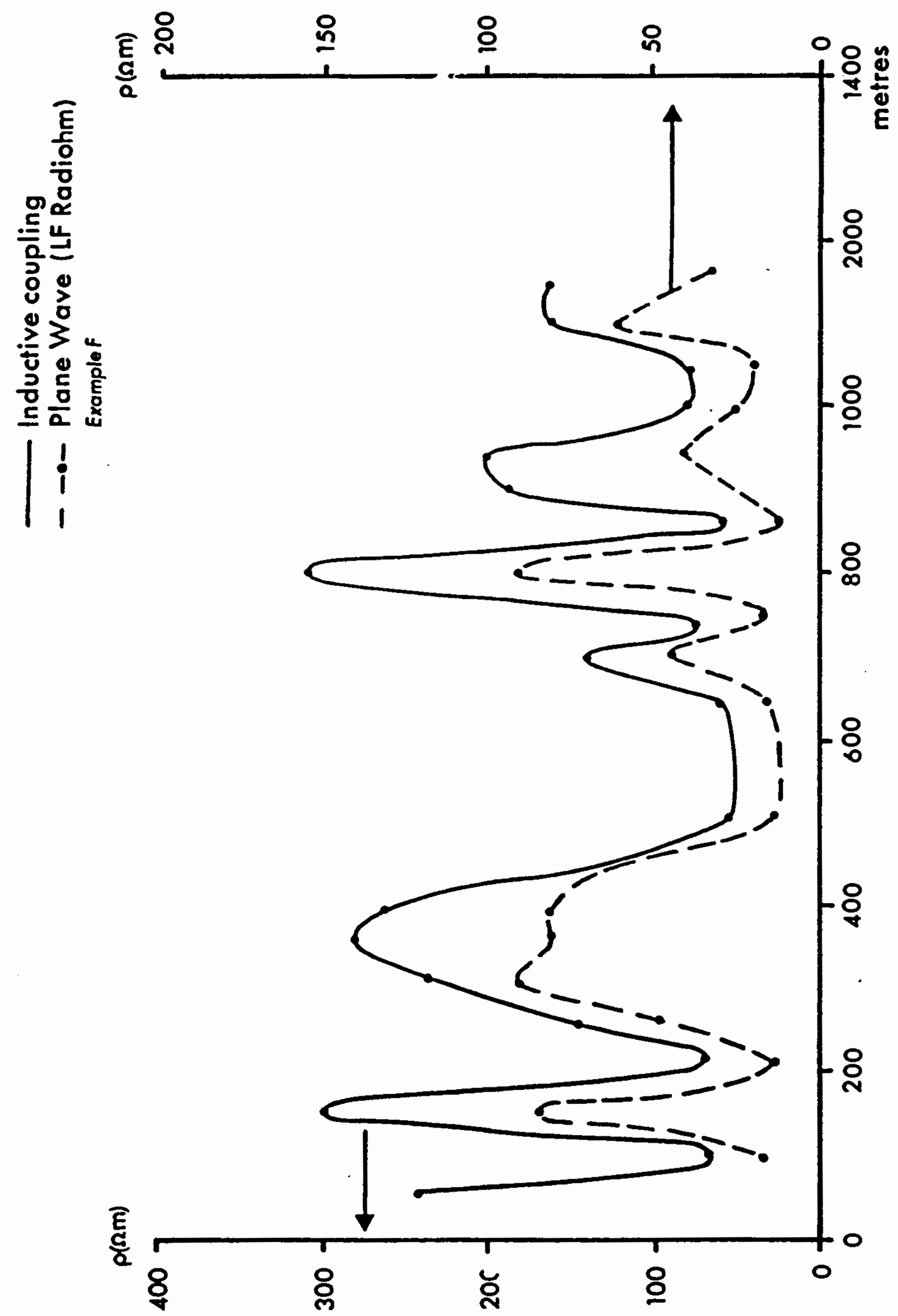
and

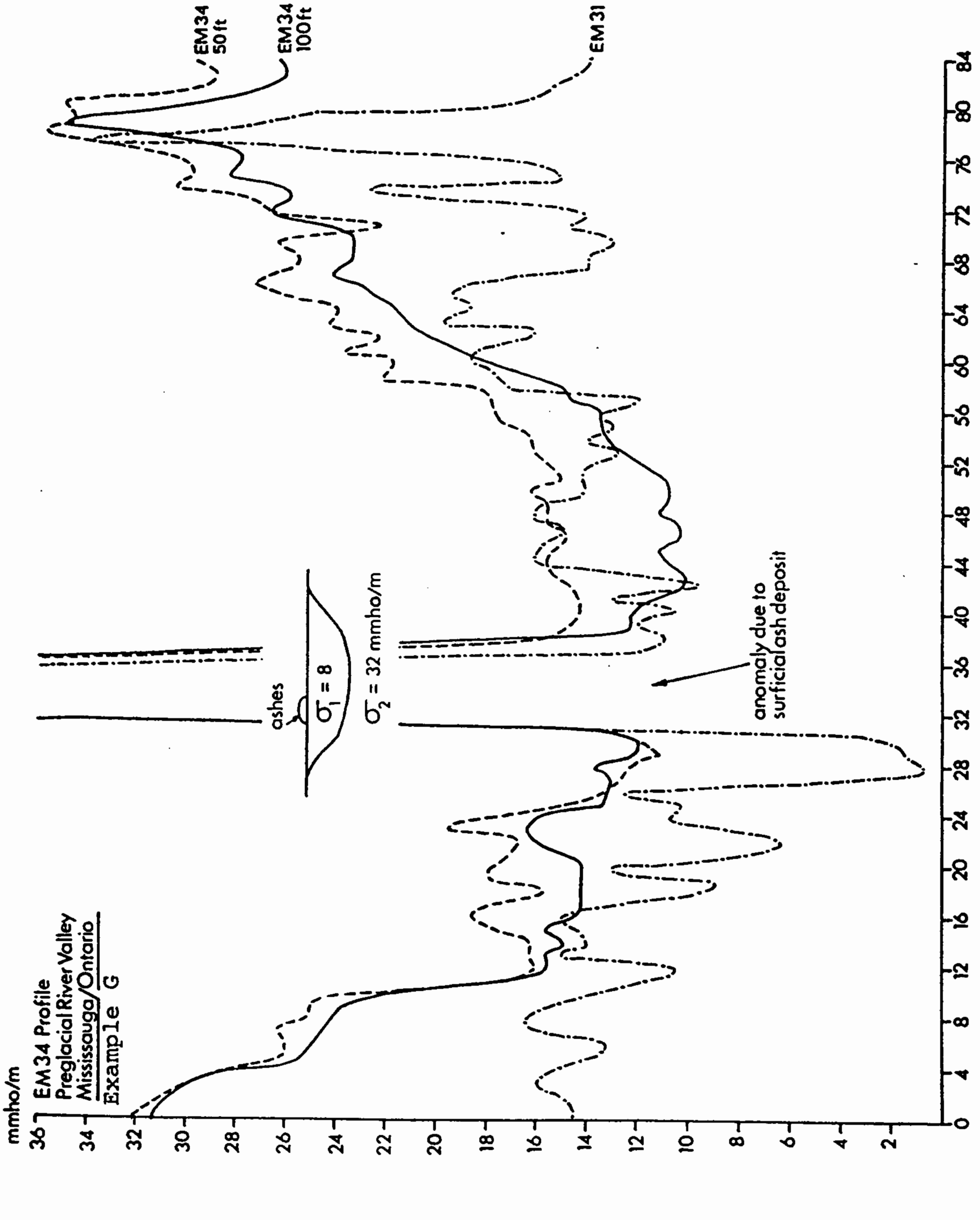
Contoured Depth



Model $\rho_1 = 200\ \Omega m$
$\rho_2 = 30\ \Omega m$


Inductive coupling
Plane Wave (LF Radiohm)
Example F
ρ(Ω.m)
200
100
0
200
400
600
800
1000
1200
1400
1600
1800
metres


Inductive coupling
Plane Wave (LF Radiohm)
Example F
ρ(Ωm)
400
300
200
100
0
ρ(Ωm)
200
150
100
50
0
0
200
400
600
800
1000
1200
1400
metres


mmho/m
36
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
64
68
72
76
80
84
EM34 Profile
Preglacial River Valley
Mississauga/Ontario
Example G
EM34 50ft
EM34 100ft
EM31
ashes
$\sigma_1 = 8$
$\sigma_2 = 32$ mmho/m
anomaly due to surficial ash deposit

APPENDIX I - Formulae for Geometrical Sounding of Two-Layered Earth

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In the case of a two-layered earth the apparent conductivity is given by:

$$\frac{\sigma_a}{\sigma_1} = 1 - R + kR = R(k - 1) + 1 \qquad (1)$$

with the instrument on the ground in its normal operating position, and

$$\frac{\sigma_a'}{\sigma_1} = 1 - R' + kR' = R'(k - 1) + 1 \qquad (2)$$

with the instrument on the ground on its side.
Case 1. Therefore

$$\frac{R'}{R} \quad \frac{\dfrac{\sigma_a'}{\sigma_1} - 1}{\dfrac{\sigma_a}{\sigma_1} - 1} \qquad (3)$$

and from the first and/or second equations,
with k = σ_2 / σ_1

APPENDIX I - (cont'd)

$$\sigma_2 = \frac{\sigma_a - \sigma_1 + R\sigma_1}{R} = \frac{\sigma_a/ - \sigma_1 + R'\sigma_1}{R'} \tag{4}$$

Case 2. When the conductivity of the lower layer is known, from equations (1) and (2)

$$\sigma_a/ = \sigma_1 - R'\sigma_1 + R'\sigma_2 \tag{5}$$

$$\sigma_a = \sigma_1 - R\sigma_1 + R\sigma_2 \tag{6}$$

$$\sigma_a/ - \sigma_2 = \sigma_1 - R'\sigma_1 + R'\sigma_2 - \sigma_2 \tag{7}$$

$$= (1 - R')(\sigma_1 - \sigma_2) \tag{8}$$

$$\sigma_a - \sigma_2 = (1 - R)(\sigma_1 - \sigma_2) \tag{9}$$

$$\frac{1 - R'}{1 - R} = \frac{\dfrac{\sigma_a/}{\sigma_2} - 1}{\dfrac{\sigma_a}{\sigma_2} - 1} \tag{10}$$

APPENDIX I - (cont'd)

$$\sigma_1 = \frac{\sigma_a - \sigma_2 R}{1 - R} = \frac{\sigma_a' - \sigma_2 R'}{1 - R'} \qquad (11)$$

Case 3. When the upper layer is resistive and σ_2 is much greater than σ_1, from equations (5) and (6)

$$\sigma_a \simeq \sigma_2 R \qquad (12)$$

$$\sigma_a' \simeq \sigma_2 R' \qquad (13)$$

$$\frac{\sigma_a'}{\sigma_2} = \frac{R'}{R} \qquad (14)$$

and

$$\sigma_2 = \frac{\sigma_a}{R} = \frac{\sigma_a'}{R'} \qquad (15)$$

Case 4. When the upper layer is conductive and σ_2 is much less than σ_1, from equations (5) and (6)

$$\sigma_a \simeq \sigma_1 (1 - R) \qquad (16)$$

APPENDIX I (cont'd)

$$\sigma_a' \simeq \sigma_1(1 - R') \tag{17}$$

$$\frac{1-R'}{1-R} = \frac{\sigma_a'}{\sigma_a} \tag{18}$$

$$\sigma_1 = \frac{\sigma_a}{1 - R} = \frac{\sigma_a'}{1 - R'} \tag{19}$$

APPENDIX II - Determination of Two-Layered Earth Geometry by Varying Instrument Height

The electrical conductivity of the earth often exhibits horizontal layering and it is possible with the EM31 to determine how closely this layering can be approximated by a two-layered earth geometry.

Suppose measurements made with the instrument on the ground have yielded different values of apparent conductivity when the instrument meter is (a) face-up (i.e. the instrument is in normal position), and (b) the instrument is lying on its side. As discussed in Section 5.3 had the value of apparent conductivity been the same in both positions we would know that the earth was homogeneous, but the fact that the values are different for the two positions shows that the electrical conductivity varies with depth. We would now like to know whether the earth is two-layered.

To determine this we make measurements of the apparent conductivity with the instrument at various heights above the ground, as measured by the distance between the ground and the nearest point of the white tube. It is suggested that measurements be made at increments at least as small as one-half meter, for example at 0, 0.5, 1, and 1.5 meters. Measurements made at smaller increments will yield greater accuracy, as will measurements made up to 2 meters height if possible. Measurements should be made both with the instrument in its normal position (meter face upright, i.e. vertical dipoles,) and with the instrument on its side (meter face vertical, horizontal dipoles) since it will be seen from the curves that the fall-off with height for these two

APPENDIX II - (cont'd)

configurations is quite different and that this difference is therefore of considerable diagnostic value in determining the two-layered earth characteristic. It is important to make the measurements of height and apparent conductivity as accurately as possible.

The curves in the two figures show the variation of apparent conductivity (divided by upper layer conductivity) for instrument height varying from 0 to 2 meters and for five values of upper layer thickness vis 0.5, 1.0, 1.5, 2.0, and 3.0 meters. The relationship is shown for both vertical dipoles (meter face up, instrument in normal position) and horizontal dipoles (meter face vertical, instrument on its side) for various values of upper layer to lower layer conductivity contrast.

To use the curves one proceeds as follows:

(1) Place a piece of semi-transparent paper over either one of the graphs and on it plot the measured values of apparent conductivity versus instrument height to the scale used on the figures. Also sketch in on the transparent paper at any point a horizontal or vertical line to insure that when the transparent paper is translated over the figures in step 2 it does not rotate.

(2) Translate the transparent paper vertically and horizontally (i.e. without rotation) across the various plots shown on the figures to see whether the data points can be matched to one of the curves. In the event that no satisfactory match is achieved the earth cannot be represented by a two-layered case.

APPENDIX II - (cont'd)

(3) If a satisfactory match can be achieved, the parameters of the two-layered earth are immediately calculated as follows: suppose that the measured values of apparent conductivity with height are

Height	0.0	0.5	1.0	1.5	2.0 meters
σ_a (EM31 upright)	20.7	20.7	19.3	17.1	14.1 mS/m
σ'_a (EM31 on side)	26.0	19.0	14.3	11.2	9.0 mS/m

Upon plotting these data values to the scale of the figures and translating them we see that best agreement is achieved for an upper layer thickness of 1.5 meters and a conductivity contrast k = 0.5. We further observe that the value of 20.7 millimhos per meter for σ_a (instrument up-right) corresponds to a value of σ_a/σ_1 of 0.62.

$$\textit{Since} \quad \frac{\sigma a}{\sigma 1} = 0.62 \quad \textit{when} \quad \sigma_a = 20.7 \quad mS/m$$

$$\therefore \quad \sigma_1 \quad \frac{20.7}{0.62} = 33.4 \quad mS/m$$

$$\textit{Since} \quad k = \frac{\sigma_2}{\sigma_1} = 0.5$$

$$\therefore \quad \sigma_2 = 0.5 \times 33.4 = 16.7 \ mS/m$$

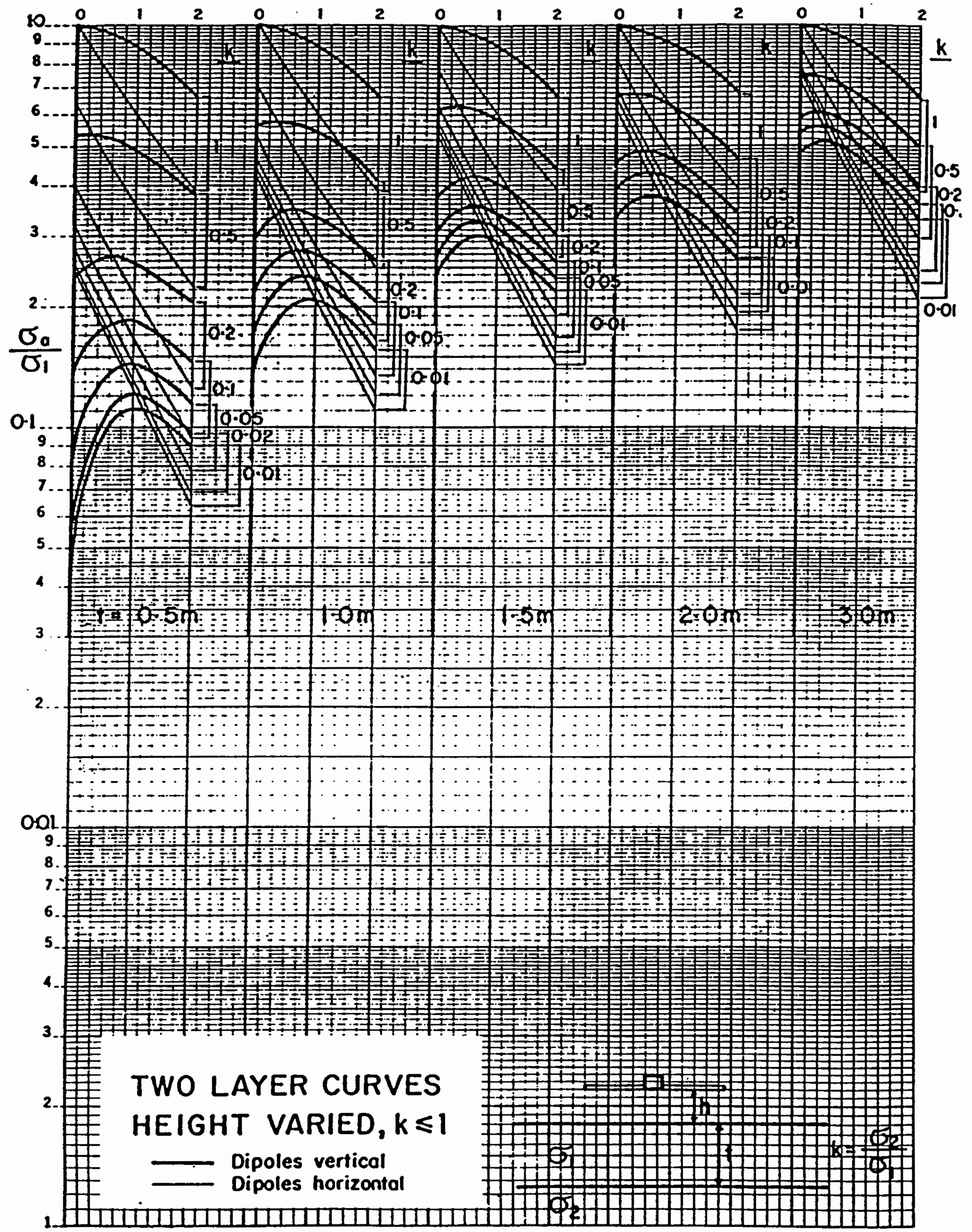
and t = 1.5 m from the figure

APPENDIX II - (cont'd)

The two-layered earth is fully resolved.

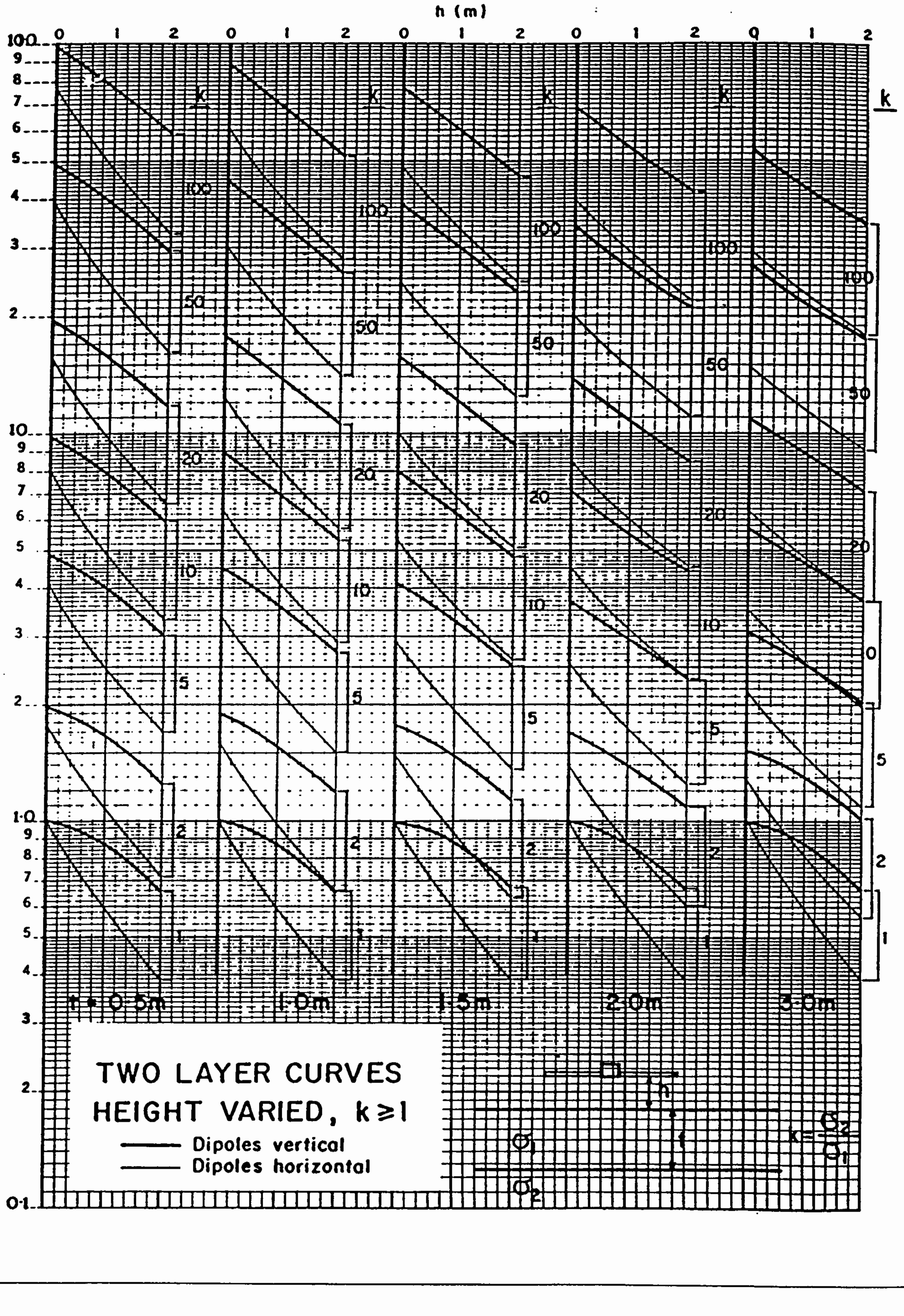
It will be observed that in some regions on these two figures the resolution or differentiation between the various curves is not very great. For example if one examines the curves for t = 1.0 meters, and k = 100, 50, or 20, one sees that these curve pairs are almost identical. If the process described in step 3 is carried out for each of these conductivity contrasts the result of the calculations will show that the lower layer conductivity and the upper layer thickness are the same regardless of which of the three curve pairs are used, and that the only calculated parameter that will vary will be the upper layer conductivity which is very small. This is an example of the well-known property of electromagnetic systems to accurately give both the distance to a good conductor and the actual conductivity of the conductor but to poorly define the intervening resistive material. A problem in unambiguously matching the curves may also occur for larger values of upper layer thickness, where the thickness is sufficiently great to prevent accurate resolution of its value.

These features notwithstanding it will be found that these curves are useful in (a) deciding whether the ground resembles a two-layer case and if so (b) giving a reasonably accurate estimate of the electrical parameters.



TWO LAYER CURVES

HEIGHT VARIED, k ≤ 1



TWO LAYER CURVES
HEIGHT VARIED, k ≥ 1

Dipoles vertical
Dipoles horizontal