# Workshop W-1

**(repeated as Workshop W-4 on Sunday)**

## GEOPHYSICAL METHODS OF PROSPECTING

**Frank Revetta**
SUNY Potsdam
Friday, September 17, 2004
Timerman Hall, Room 120
1:00 – 5:00 p.m.

**Field work will be conducted on Soccer Field**

1:00 – 2:30 p.m. Electrical Resistivity Surveying
- (A) Vertical Electrical Sounding (VES)
  1. Wenner Method
  2. Lee Modification of Wenner Method
  3. Schlumberger Method
  4. Dipole-Dipole Method
  5.

2:30 – 4:00 p.m. Seismic Surveying
- (A.) Seismic Refraction Survey
  1. Forward and Reverse Shooting (Sledgehammer)
  2. Shotgun shooting
- (B.) Reflection Survey
  1. Optimum Offset Method
  2.

4:00 – 5:00 p.m. Gravity and Magnetics

This workshop is repeated on Sunday, September 19 at 8:00 A.M.

### EQUIPMENT

**Seismic Refraction and Reflection**
- StrataView 24-Bit Exploration Seismograph
- Betsy Seisgun
- General Hole Digger
- Hammers and Plates

**Electrical Resistivity**
- Abem Terrameter SAS 300C
- Electrodes and Cables

**Magnetics**
- Proton Precession Magnetometer Memory G856 Mag
- K-2 Magnetic Susceptibility Meter

**Gravity**
- Worden Gravity Meter – Prospector Model
- GPS – GeoExplorer

**Radioactivity**
- Portable Gamma Ray Scintillometer

## WHAT GEOPHYSICISTS DO

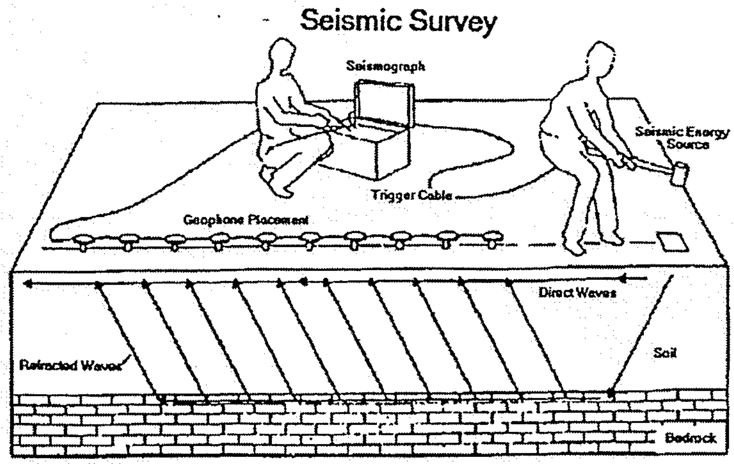
**Geophysicists and geophysical engineers are explorers!**

***Their target:*** the subsurface of the Earth (and other planets)
*Their range:* the entire globe—all continents, oceans, environments
*Target depths:* a few meters in environmental applications
hundreds of meters in mineral exploration
up to 8 km in oil exploration
down to the Earth's crust, mantle, outer core and inner core
in studies of Earth processes
*Their methods:* measurement of physical properties of the Earth
its gravity field
its magnetic field
its electromagnetic field
its electrochemical field
its seismic-wave field
*Geophysicists:* hunt for oil and minerals
delineate hydrocarbon and water reservoirs
search for groundwater and geothermal energy sources
seek out contaminant spills and other environmental hazards
search for faults beneath large-scale engineering projects
hunt down hidden land mines
study volcanoes, predict earthquakes
study the Earth and its processes down to its core
*Working with and as geophysicists are:*
geologists, civil engineers, mechanical engineers,
electrical engineers, computer scientists, physicists,
and mathematicians
*Geophysicists work for:*
oil and mining companies
exploration contracting companies
consulting companies
software and hardware companies
state and federal geologic surveys
universities
themselves

## SEISMIC REFRACTION METHOD

### Applications

The seismic refraction method has many applications in shallow subsurface geologic investigations. The classic application is the determination of depth to bedrock. The method also plays an important role in groundwater investigations since it is possible to determine depth to water table. It is also an excellent tool in engineering and environmental studies since it makes possible the evaluation of dam sites, highways, bridges and landfill sites. Finally it is an excellent method of teaching refraction seismology principles that are used to investigate the crustal structure of the earth. Our seismic refraction survey will be used to determine the depth to bedrock and water table on the Potsdam College Campus.



The basic setup for a seismic survey.

## Seismic Equipment

A StrataView, 24 channel Exploration Seismograph is used to conduct the seismic survey. It is ideal for refraction and reflection surveys. It operates from a 12 volt DC battery which is rechargeable. The data is stored in the SEG standard format for processing on personal computers or seismic workstations. The StrataView Exploration Seismograph simplifies seismic surveys. It is excellent for simple refraction surveys and for shallow and deep reflection surveys. Besides the seismograph you will need a power source, geophone cables, geophones and an energy source.

## Energy Source

The energy source is the source of seismic energy used to generate the elastic waves. Our survey will involve the use of a sledgehammer and Betsy Shotgun.

The sledgehammer is the most common energy source for shallow surveys. It is popular because it is lightweight (8 lbs.), portable, low cost, efficient, and safe. Its main limitation is its limited depth range. However, the energy from several blows may be stacked to increase depth range. A hammer switch is attached to the sledgehammer to trigger the seismograph.

The Betsy shotgun uses shotgun shells as an energy source. A hole is drilled from 1.5 to 3 feet in depth. The shotgun with shell is placed in the hole and soil is then compacted well to assure the energy penetrates into the earth. This method does produce better records to greater depths. However, conducting the survey requires more work such as drilling and a compaction of soil.

## Geophone Cable and Geophones

A standard geophone cable consisting of 12 geophone takeouts at 10 foot intervals is used to acquire the travel times. Two of these cables are used with our 24 channel StrataView. The seismograph is located in the center of the line and the geophone cable (1-12) is connected to one connector and geophone cable (13-24) is connected to the other connector.

A moving coil geophone is the basic vibration sensor (Fig. 1). The coil and its support spring make a pendulum with a natural frequency of 14 Hz. The geophones are less sensitive to vibrations with frequencies lower than their natural frequency. Much noise tends to be low frequency. For shallow surveys, seismic signals tend to have much higher frequency and a geophone with a natural frequency around 14 Hz is a good compromise for use in refraction surveys.

### Display

The liquid-crystal display is easy to see in daylight. A backlight is provided for viewing at night time. Some darkening of the screen may occur in hot weather and bright sunlight caused by thermal heating. An umbrella is useful for shading the display on hot sunny days.

### Menus

When the MENU key is pressed the display will show a list of menus shown below.

Geometry Acquisition File Display D_Survey Answers Other

One of the selections will be highlighted in reverse video. Below this line, overlaying the data display, will be a box containing secondary menu selections. The selections will correspond to the highlighted main menu item. There may be a single selection shown, or a long list. Some selections are execution statements, meaning that an action will be performed if ENTER is pressed while the selected item is highlighted.

Other selections will cause another menu to be displayed, or a request for a number to be entered, or suggestions for further action. In operation, the menu system is quite easy to use.

GEOMETRY menus are used to record the locations of the geophones and the energy source.

ACQUISITION menus control the data gathering parameters (such as sample interval, record length, filters).

FILE menus control the saving and reading of data files onto disk.

DISPLAY menus control the way the data is displayed on the screen and plotted.

DO-SURVEY contains the functions normally used to acquire, display, and analyze data in a production mode.

ANSWERS menus are used to run the field quality control software programs to analyze the data.

### Seismic Methods

The two types of seismic methods of prospecting are the refraction and reflection methods (Fig. 2). The travel times of critically refracted waves are measured in refraction surveying while the travel-times of reflected waves are measured in reflection surveying. Figure 2 shows the wave paths for each method.

The mechanism for transmission of refracted waves is shown in Figure 3. The wavefront is used to describe the disturbance and a line perpendicular to the wavefront known as ray path. The ray is refracted along the higher velocity layer at the critical angle. The critical angle is given as:

$$i_c = \sin^{-1} \frac{V_1}{V_2}$$

Where V1 and V2 are the upper ad lower velocities.

## Refraction Method

The travel-times of the first arrivals are measured in the refraction method. These represent the waves that take the minimum travel-time path to reach the geophones and are the waves refracted at the critical angle. Figure 4 shows the refracted wave paths and the travel-time graph drawn from the travel times. This graph shows a three-layer case. The inverse slope of the travel time curves gives the velocity and the crossover distances or intercept times enable depths to be calculated.

## Seismic Record

Figure 5 shows a typical seismic refraction record of a forward shot. The horizontal lines are 5 millisecs time lines and the vertical traces are output from the 24 channels. The numbers above each trace are geophone numbers and gain of each channel. The shotpoint is located at the left side at an offset of 10 feet. The record shows the first arrivals or first breaks that are used to construct the travel-time curve as well as airwaves and ground roll.

Figure 6 shows the seismic record of a reverse shot. Reverse shots should always be done during seismic refraction surveys since they provide additional data and enable dips of the layers to be determined. This record shows the picks of the first breaks which are made by the computer software but usually need to be adjusted. The forward and reverse times are shown in milliseconds beneath the traces.

Figure 7 shows a cross section drawn by the software indicating a 3-layer model of the subsurface geology at the site. The area consists of a low velocity layer about 10 feet thick overlying a higher velocity material extending to a depth of 62 feet. The third layer has the highest velocity around 16000ft/sec. Well logs in the area indicate the 3 layers are a near surface silty sand layer overlying a compact clay. The third layer is the Potsdam sandstone.

## Travel-Time Graph

A travel-time graph produced by the computer software is shown in Figure 8. This graph shows three shots were made. Two end shots were made with an offset of 5 feet and one shot located in the center of the spread. The travel time graph shows the times for the refracted waves to travel to the geophones. The graph indicates 3 layers as shown in the model.

## Seismic Velocities

Velocities of compressional (P) waves in feet/sec and meters/sec are shown in Table 1. The refraction method requires that the lower layers have a higher velocity than the upper layer, otherwise no critically refracted wave will occur. Fortunately in most areas this is the case. However there may be cases where the upper layer has a higher velocity.

## Reflection Method

Figure 9 shows the basic principle of the seismic reflection method. Acoustic energy is produced at the shotpoint which could be a sledgehammer hitting a steel plate or a shotgun shell set off below ground level. Elastic waves travel through the earth and are reflected from boundaries of rocks having a contrast in density and velocity.

## Seismic Reflection Method

The StrataView may be used to conduct seismic reflection surveys. The basic idea behind the seismic reflection method is shown in Figure 10. The travel times of the elastic waves to travel down and reflect from a reflector is measured. Several seismic reflection methods exist such as common midpoint, split spread and optimum offset method. We will use the optimum offset method, which measures the reflected time to each geophone while keeping the offset the same (Fig. 10). An offset is chosen that provides the record that shows reflections that arrive at times that are not the same as other waves such as ground roll, air waves or refracted waves. An optimum offset shallow reflection record is shown in Figure 11.

Figure 1 - Geophone coupled to ground to detect seismic waves.

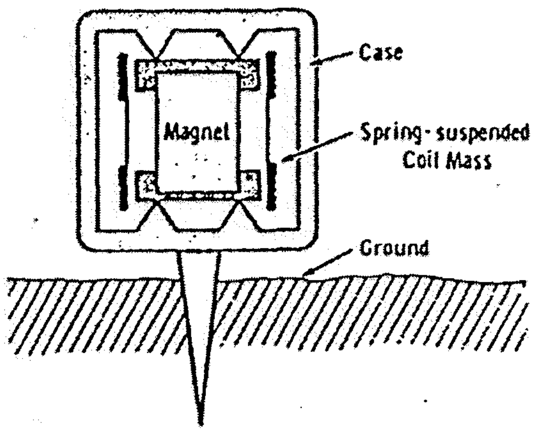



Figure 2 - Seismic wave paths of a reflection and refraction survey.

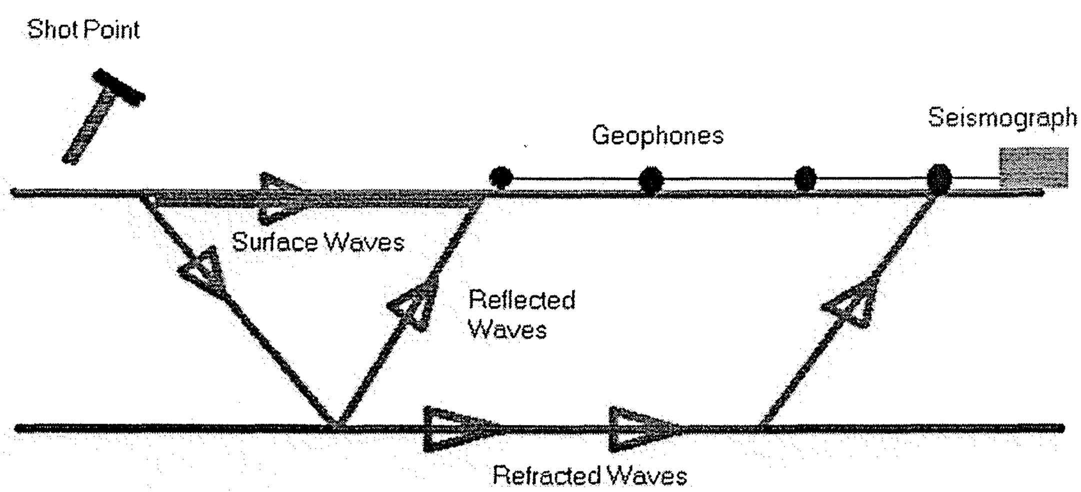
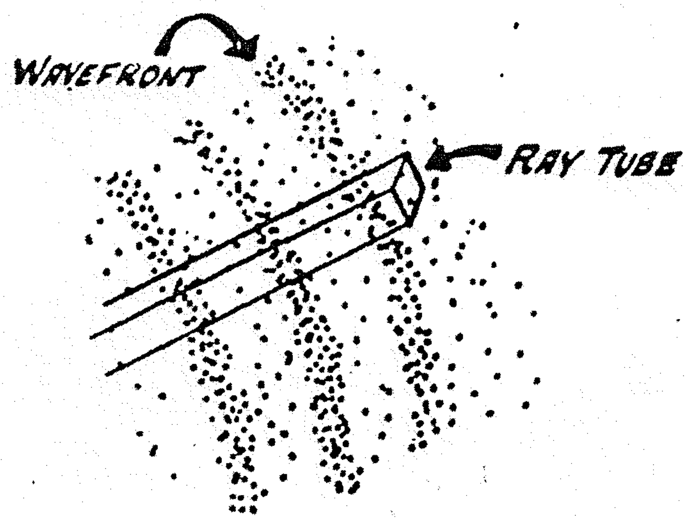


Figure 3 - Mechanism for transmission of seismic waves.

## WAVEFRONTS & RAYPATHS




WAVEFRONT – SURFACE OF THE MOST FORWARD POSITION OF A PROGRESSIVE DISTURBANCE AT A PARTICULAR TIME.

WAVEFRONT – SURFACE OVER WHICH THE PHASE OF A TRAVELING WAVE DISTURBANCE IS THE SAME.

RAY PATH – LINE EVERYWHERE PERPENDICULAR TO WAVEFRONT (IN ISOTROPIC MEDIA).

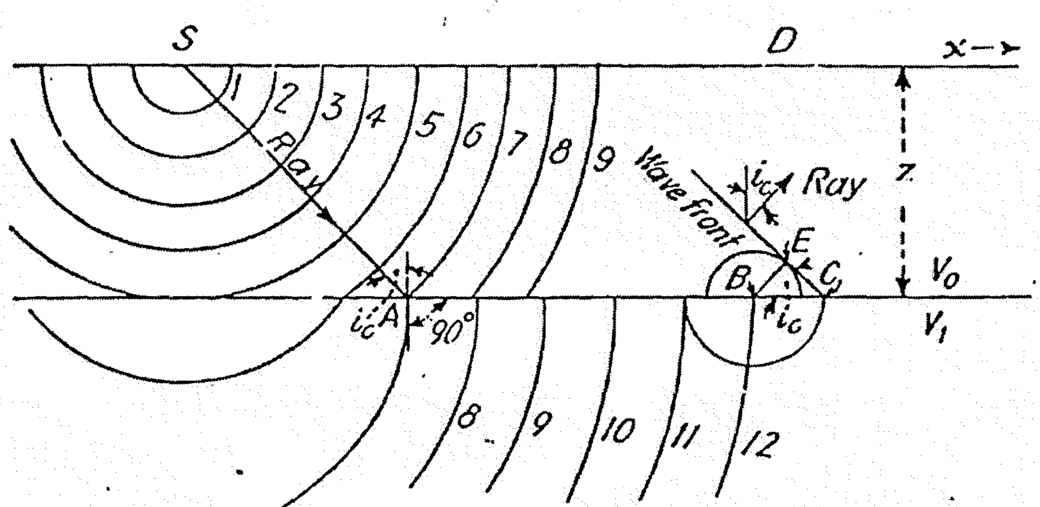


Figure 4 - Travel-time graph, seismic record and wave paths of a seismic refraction survey.

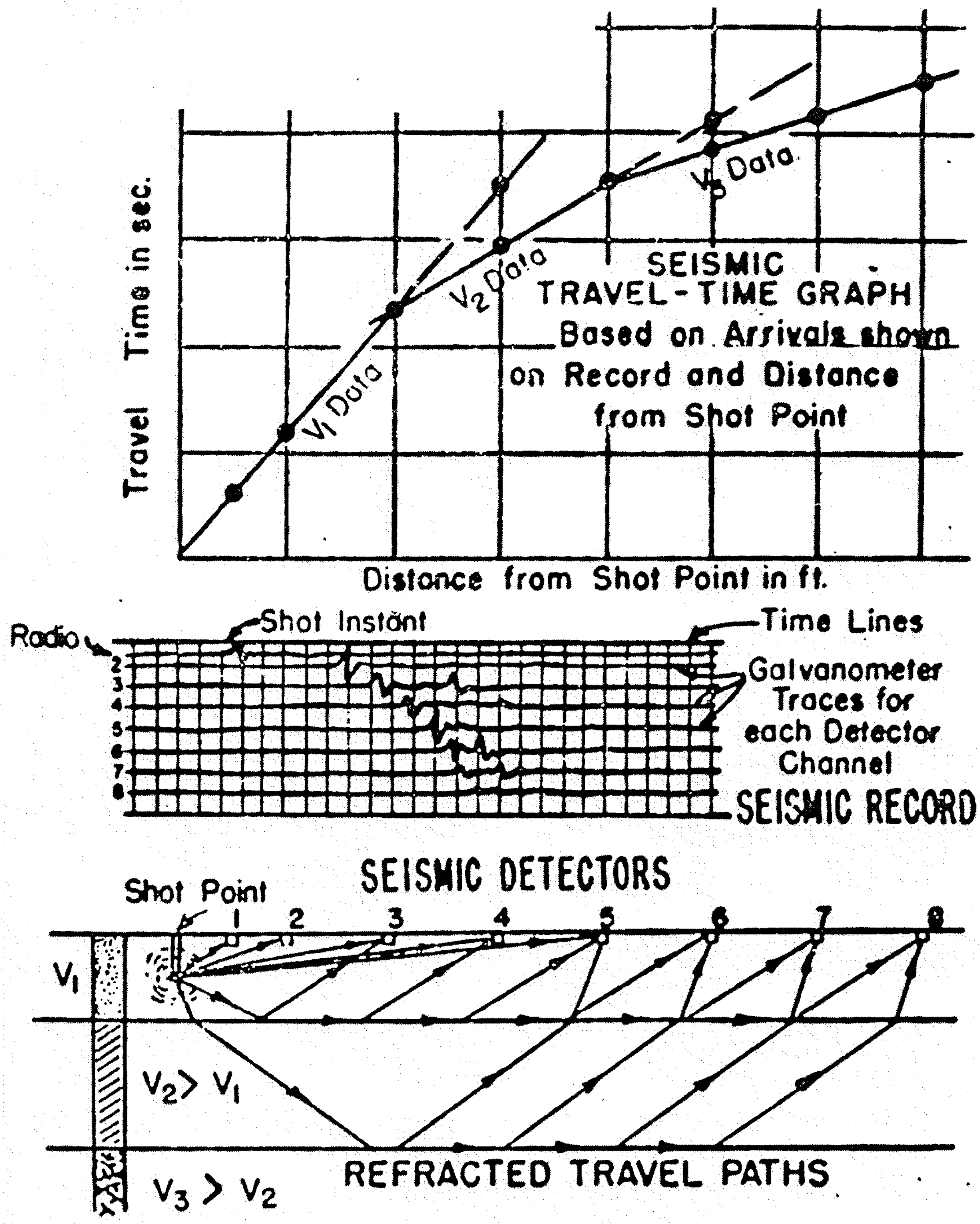
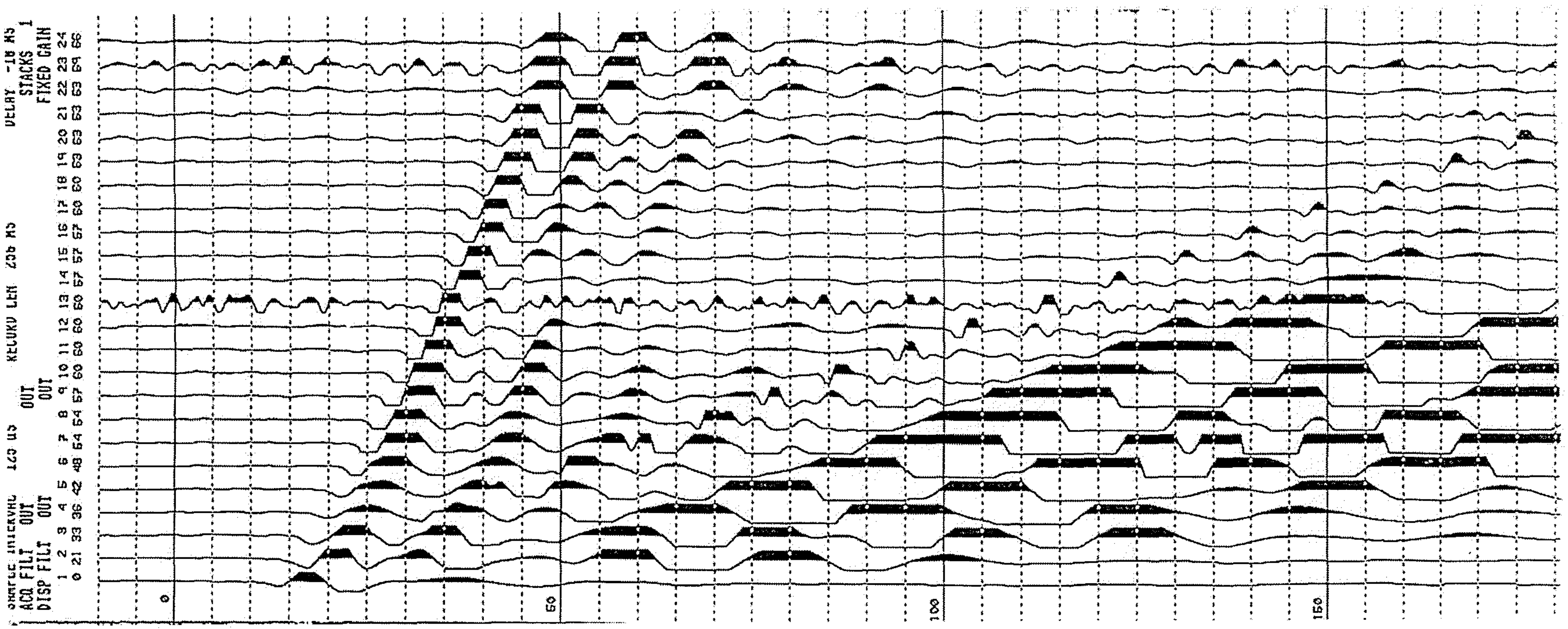
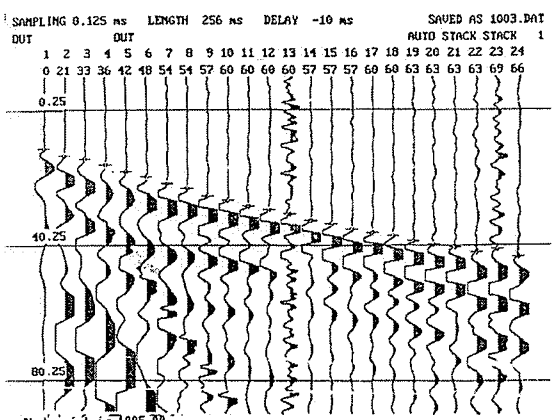


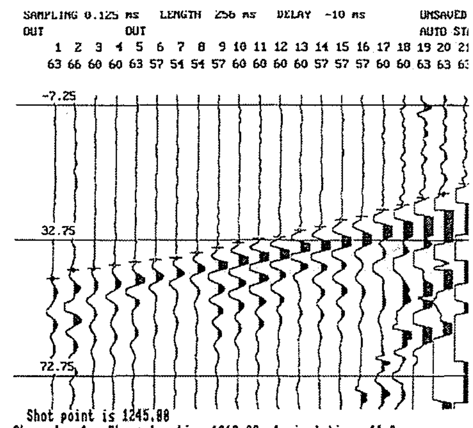
Figure 5 - Seismic record of a shot in one direction (Forward Shot).






Shot point is 1005.00

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Channel | 1 | Phone location | 1010.00 | Arrival time | 11.5 | msec |
| Channel | 2 | Phone location | 1020.00 | Arrival time | 13.8 | msec |
| Channel | 3 | Phone location | 1030.00 | Arrival time | 14.8 | msec |
| Channel | 4 | Phone location | 1040.00 | Arrival time | 16.5 | msec |
| Channel | 5 | Phone location | 1050.00 | Arrival time | 18.6 | msec |
| Channel | 6 | Phone location | 1060.00 | Arrival time | 20.1 | msec |
| Channel | 7 | Phone location | 1070.00 | Arrival time | 22.0 | msec |
| Channel | 8 | Phone location | 1080.00 | Arrival time | 23.5 | msec |
| Channel | 9 | Phone location | 1090.00 | Arrival time | 25.9 | msec |
| Channel | 10 | Phone location | 1100.00 | Arrival time | 27.0 | msec |
| Channel | 11 | Phone location | 1110.00 | Arrival time | 28.8 | msec |
| Channel | 12 | Phone location | 1120.00 | Arrival time | 29.9 | msec |
| Channel | 13 | Phone location | 1130.00 | Arrival time | 31.0 | msec |
| Channel | 14 | Phone location | 1140.00 | Arrival time | 33.0 | msec |
| Channel | 15 | Phone location | 1150.00 | Arrival time | 34.0 | msec |
| Channel | 16 | Phone location | 1160.00 | Arrival time | 35.5 | msec |
| Channel | 17 | Phone location | 1170.00 | Arrival time | 36.5 | msec |
| Channel | 18 | Phone location | 1180.00 | Arrival time | 37.5 | msec |
| Channel | 19 | Phone location | 1190.00 | Arrival time | 39.0 | msec |
| Channel | 20 | Phone location | 1200.00 | Arrival time | 40.0 | msec |
| Channel | 21 | Phone location | 1210.00 | Arrival time | 40.8 | msec |
| Channel | 22 | Phone location | 1220.00 | Arrival time | 42.3 | msec |
| Channel | 23 | Phone location | 1230.00 | Arrival time | 41.3 | msec |
| Channel | 24 | Phone location | 1240.00 | Arrival time | 43.5 | msec |




Shot point is 1245.00

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Channel | 1 | Phone location | 1010.00 | Arrival time | 44.0 | msec |
| Channel | 2 | Phone location | 1020.00 | Arrival time | 41.7 | msec |
| Channel | 3 | Phone location | 1030.00 | Arrival time | 41.0 | msec |
| Channel | 4 | Phone location | 1040.00 | Arrival time | 40.0 | msec |
| Channel | 5 | Phone location | 1050.00 | Arrival time | 39.4 | msec |
| Channel | 6 | Phone location | 1060.00 | Arrival time | 38.5 | msec |
| Channel | 7 | Phone location | 1070.00 | Arrival time | 38.0 | msec |
| Channel | 8 | Phone location | 1080.00 | Arrival time | 36.5 | msec |
| Channel | 9 | Phone location | 1090.00 | Arrival time | 35.0 | msec |
| Channel | 10 | Phone location | 1100.00 | Arrival time | 33.6 | msec |
| Channel | 11 | Phone location | 1110.00 | Arrival time | 32.3 | msec |
| Channel | 12 | Phone location | 1120.00 | Arrival time | 31.0 | msec |
| Channel | 13 | Phone location | 1130.00 | Arrival time | 29.0 | msec |
| Channel | 14 | Phone location | 1140.00 | Arrival time | 28.0 | msec |
| Channel | 15 | Phone location | 1150.00 | Arrival time | 26.0 | msec |
| Channel | 16 | Phone location | 1160.00 | Arrival time | 25.9 | msec |
| Channel | 17 | Phone location | 1170.00 | Arrival time | 23.0 | msec |
| Channel | 18 | Phone location | 1180.00 | Arrival time | 22.4 | msec |
| Channel | 19 | Phone location | 1190.00 | Arrival time | 20.2 | msec |
| Channel | 20 | Phone location | 1200.00 | Arrival time | 19.1 | msec |
| Channel | 21 | Phone location | 1210.00 | Arrival time | 16.1 | msec |
| Channel | 22 | Phone location | 1220.00 | Arrival time | 15.1 | msec |
| Channel | 23 | Phone location | 1230.00 | Arrival time | 12.4 | msec |
| Channel | 24 | Phone location | 1240.00 | Arrival time | 3.6 | msec |

Figure 6 - Seismic record of forward and reverse shot. Picks of first breaks and travel times are shown.

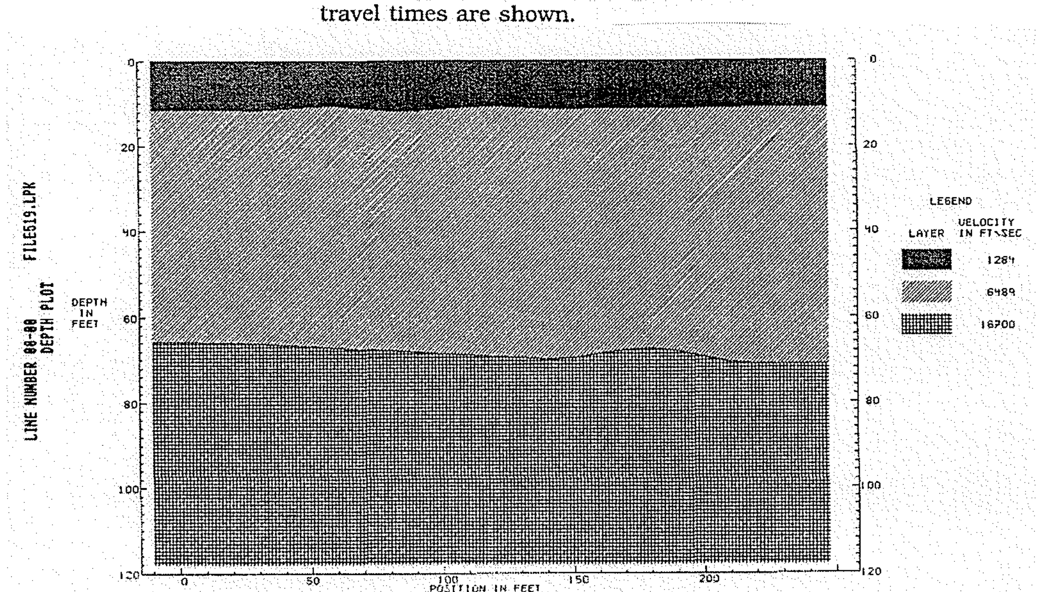



Figure 7 - Geologic cross section showing a 3 layer case based on seismic refraction survey.

Figure 8 - Travel-time curves based on two end shots and a center shot. Graph indicates 3 layers.

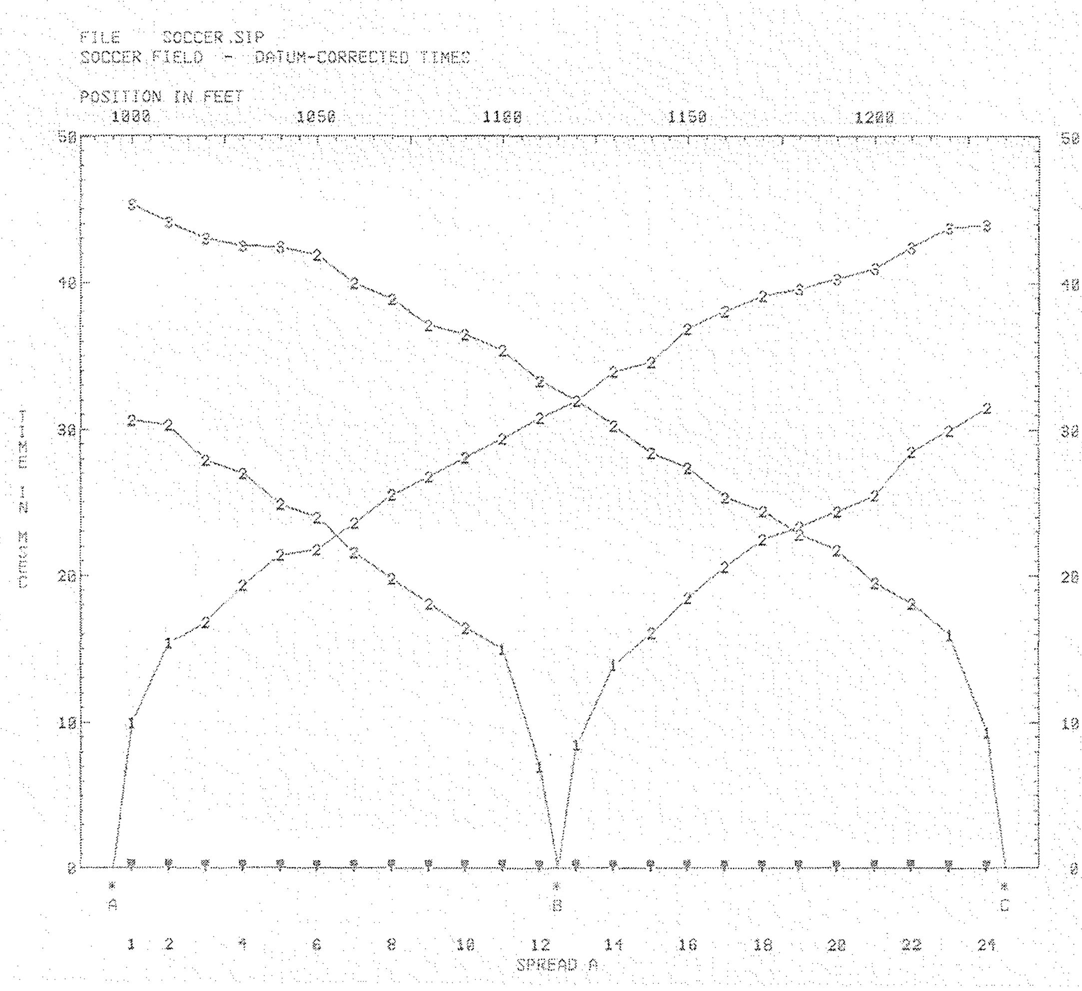


Table 1 - Typical compression wave velocities (Vp) for earth materials. These are useful for determining type of rock in a refraction survey.

## TYPICAL COMPRESSION WAVE VELOCITIES ($V_p$) FOR EARTH MATERIALS

| Material | mps | fps |
|---|---|---|
| Air | 330 | 1,100 |
| Loam, dry | 180 - 300 | 600 - 900 |
| Loam, wet | 300 - 750 | 1,000 - 2,500 |
| Sand, dry | 450 - 900 | 1,500 - 3,000 |
| Gravel | 600 - 800 | 2,000 - 2,600 |
| Sand, cemented | 850 - 1,500 | 2,800 - 5,000 |
| Sand, loose saturated | 1,500 | 5,000 |
| Water (shallow) | 1,450 - 1,600 | 4,800 - 5,100 |
| Clayey soil, wet | 900 - 1,800 | 3,000 - 6,000 |
| Till, basal/lodgment | 1,700 - 2,300 | 5,600 - 7,500 |
| Rock, weathered Sedimentary | 600 - 3,000 | 2,000 - 10,000 |
| Rock, weathered Igneous and Metamorphic | 450 - 3,700 | 1,500 - 12,000 |
| Shale | 800 - 3,700 | 2,600 - 12,000 |
| Sandstone | 2,200 - 4,000 | 7,200 - 13,000 |
| Basalt, fresh | 2,600 - 4,300 | 8,500 - 14,000 |
| Metamorphic Rock | 2,400 - 6,000 | 8,000 - 20,000 |
| Steel | 6,000 | 20,000 |
| Dolostone and Limestone, fresh | 4,300 - 6,700 | 14,000 - 22,000 |
| Granite, fresh | 4,800 - 6,700 | 16,000 - 22,000 |

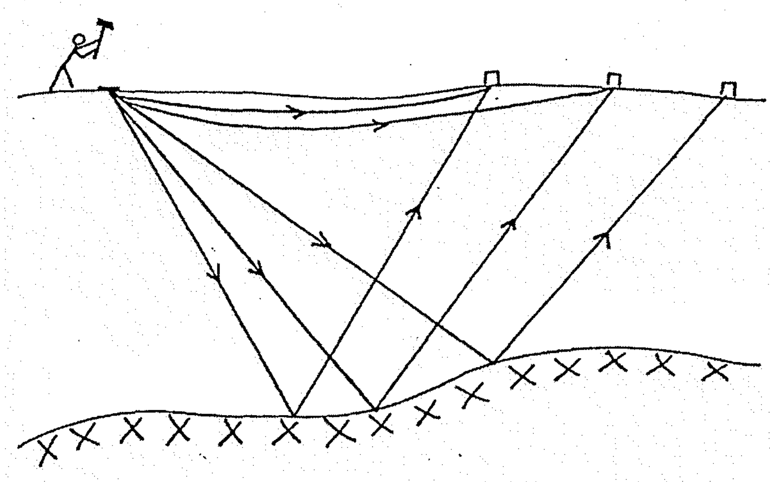


Figure 9 - Basic principle of the seismic reflection method.

## Seismic Reflection Survey:
## Optimum Offset Method

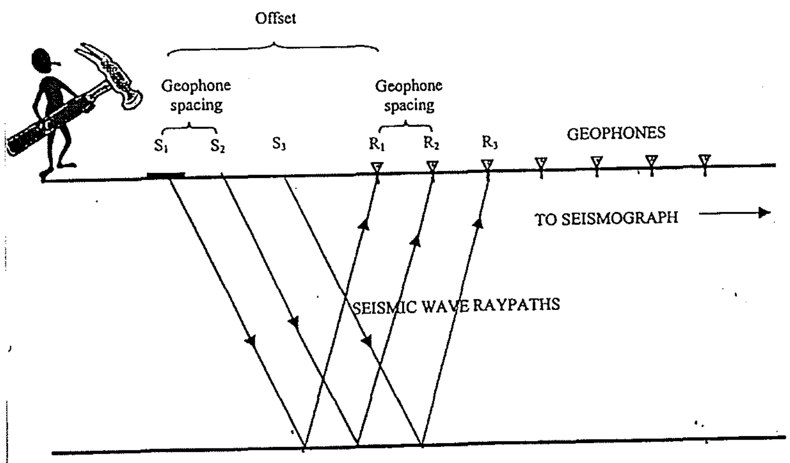



Figure 10 - Optimum offset method. The offset is kept constant for each geophone.

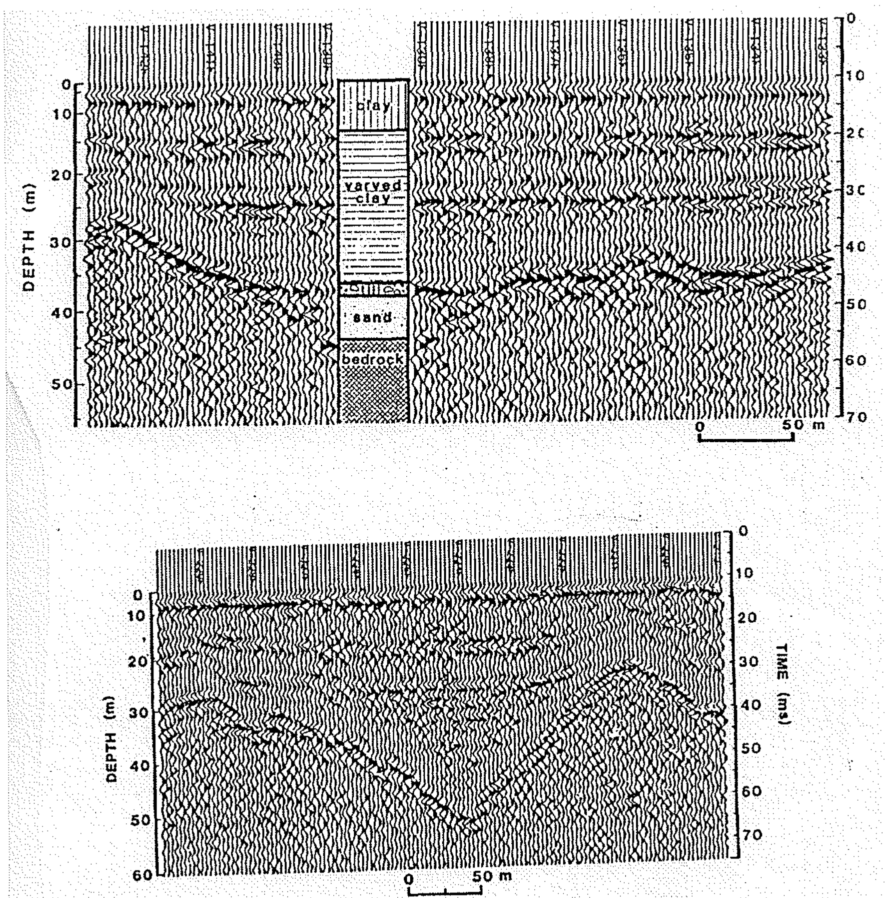



Figure 11 - "Optimum offset" shallow reflection section from ValGagne, Ontario.

## EARTH RESISTIVITY SURVEY

**Applications**

The electrical resistivity method has many applications in shallow subsurface geologic studies. The method may be used to determine depth to bedrock and water table. It can be used to locate sand and gravel deposits, buried stream channels and mineral deposits. It is also an effective tool for mapping salt water-fresh water interface and contaminant areas associated with landfill sites. Some other uses are in geothermal exploration and mapping archaelogical sites.

### Earth Resistivity Methods

Electrical resistivity surveying measures the apparent earth resistivity from the surface. Various types of earth materials have resistivities that can be distinguished from one another. The basic types of field procedures used are vertical electrical sounding and resistivity profiling. In vertical electrical sounding (VES) we determine how resistivity varies with depth by increasing electrode spacing. In resistivity profiling, a fixed electrode separation is maintained, however, the location of the spread is changed to determine horizontal variations in resistivity.

**Vertical Electrical Sounding (VES)**

Figure 1E shows the main elements of electrical resistivity surveying and illustrates the procedure used in vertical electrical sounding. Four electrodes are laid out along a line. The outer electrodes (C1 and C2) are current electrodes and the inner electrodes (P1 and P2) are potential electrodes. A current is supplied through the current electrodes and the voltage drop is measured between the potential electrodes. Measurements of the current flow, potential drop and electrode spacing are used to calculate the apparent resistivity of the material to a depth assumed equal to the electrode spacing. Measurements at greater depth are made by increasing the spacing between electrodes. The method for most vertical electrical sounding surveys is the Wenner configuration where the spacing between electrodes is kept equal. When the Wenner method is used the apparent resistivity (p) is computed by the formula:

$$\rho = 2\pi A \frac{V}{I}$$

Where P = apparent resistivity
A = electrode spacing
V = voltage drop
I = current flow

The term V/I is resistance with units of ohms. The electrode spacing will be measured in meters so our resistivity values will have units of ohm-meters. As a rough guide, materials with resistivities less than 100 ohm-meters are considered low and materials greater than 1000 ohm meters are considered high. Resistivities of various earth materials are listed in Table 1E.

### Field Procedure

Figure 2E is a data sheet used to record the resistivity values for vertical electrical sounding by the Wenner method. Readings are made at intervals shown in the left column. Note these spacings begin with 1 meter then proceed through values equally spaced on a logarithmic scale. This is done because a larger electrode spacing yields information over a much larger volume of earth, thus a given volume becomes proportionately less important. A second reason is that normally data is plotted on log-log graph paper. We record resistance values for current flow from C1 to C2 under R1 or R2 on the data sheet.

## Resistivity Equipment

Our resistivity survey will be conducted with a Terrameter SAS 300c instrument manufactured by ABEM. The instrument can be used for both self potential surveys and resistivity surveys. In the resistivity surveying mode it comprises a battery powered deep-penetration resistivity meter with output sufficient for a current electrode separation of 2000 meters. The instrument contains three main units all housed in a single casing: the transmitter, receiver and microprocessor. The instrument measures and displays the resistance in ohms or milliohms.

The Terrameter SAS300c is shown in Figure 3 E. The instrument is turned on with off-on toggle switch. Battery should be checked to see if it is properly charged at 12.5-15 Volts. If reading is less than 11.5V, then battery will soon need recharging.

## Resistivity Surveying Mode

The procedures for conducting a survey are as follows:

Position the SAS300c midway between the potential electrodes. Connect electrodes P1 and P2 into P1 and P2 terminals, connect C1 and C2 electrodes to C1 and C2 terminals.

Turn the MODE selection to the Ohms (r) position and the CYCLES selector to position 4.

Turn the current selector to 20ma. Switch the power on and press the MEASURE button. If an error mode Code 1 appears and a beeper sounds, reduce the current step by step until the beeper stops. A reading will appear on the display. Observe the four readings that appear successively on the display. If they are nearly equal, the noise level is low. If the readings differ significantly turn the CYCLES to position 16 or even 64.

The proper functioning of the meter should be checked periodically by using a known resistor, usually 15000 ohms. The instrument should be tested at least weekly.

## Lee Modification of the Wenner arrangement

In the Lee Modification of the Wenner Method, an electrode is placed midway between P1 and P2. Three potential measurements are made ocross three pairs P1P2, P1P0, P2P0. The resistivity is calculated by using the expression:

$$\rho = 4\pi A \frac{V}{I}$$

This method has the advantage of detecting horizontal variations in resistivity whenever one is conducting vertical electrical sounding.

## Schlumberger Method

For vertical electrical sounding the Schlumberger Method is recommended, although the Wenner is acceptable. The Schlumberger arrangement has a smaller spacing than Wenner for the potential electrodes. Figure 5E shows the Schlumberger arrangement. A widely used condition in this method is that MN is kept less than 40% of L. This method has the advantage of being less sensitive to lateral variations in resistivity. It is also faster in field operation since only the current electrodes must be moved between readings.

### Dipole-Dipole Method

The dipole-dipole arrangement is shown in Figure 6E. It can be used for sounding by increasing the distance between C1C2 and P1P2 or profiling. It is useful in deep geothermal studies and in mining. Keller (1974) recommends it as a preferred electrode arrangement for resistivity mapping. A formula for calculating resistivity for this method is:

$$\rho = \pi \left( \frac{r^2}{a} - r \right) R$$

Where a is electrode spacing, R is resistance measurement in ohms and r is the distance between electrode pairs.

### Interpretation of Data

While the acquisition of resistivity data is relatively simple, the results are difficult to interpret. A procedure normally followed for the interpretation of the resistivity data is as follows. First the resistivity data is plotted on log-log paper with one axis being electrode spacing and the other being apparent resistivity. This preferred method of plotting on log-log paper makes the shape and size of the curve independent of units and electrode separation used. The standard procedure used to interpret resistivity sounding data consists of the following steps.

1. Assume a resistivity model based on the resistivity profile and any other information you may have such as well logs and seismic surveys. A model consists of the number of layers, resistivity of each layer and thickness of each layer.

2. Compute the apparent resistivities expected from your assumed model. This is usually done with a computer program.

3. Compare the observed resistivity field curve with the computed values based on your assumed model.

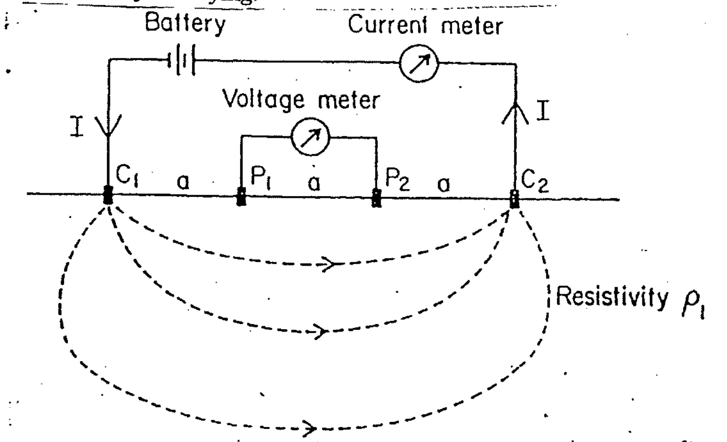
4. Modify the model until a best possible agreement is obtained between computed and field values. Keep in mind that a good fit means only the fit is good and that the model isn't necessarily the correct one. It is always possible that many different models may produce equally good fits. Additional information such as well logs are always needed to choose the most likely correct model. Also computer software is available (Burger 1992) that will modify your model until an excellent fit occurs between the field curve and computed resistivity values. Some typical resistivity curves are shown in Figure 7E with their interpretation or model shown below the curve.

It is difficult to correlate resistivities with specific rock types without geologic information because of the great range of resistivity values of rocks. No other physical property of naturally occurring rocks or soils displays such a wide range of values. Bedrock has higher resistivities than saturated sediments. Unsaturated sediments above water table have higher resistivities than saturated sediments. Table 2E from Burger (1992) shows various materials and their resistivities in ohm-meters.

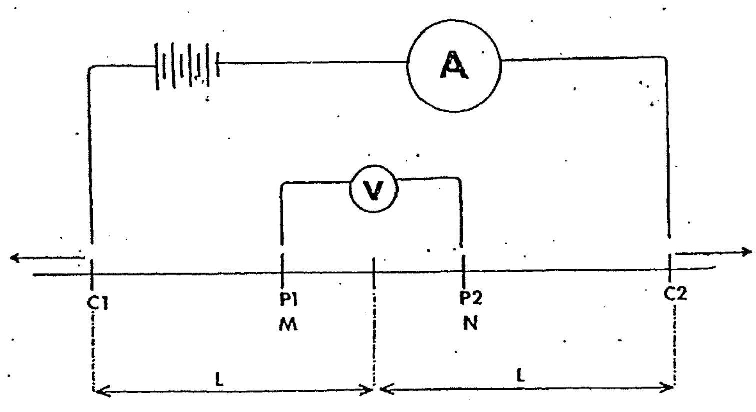
## Resistivity Profiling

In resistivity profiling the location of the spread is changed while maintaining a fixed electrode spacing. Profiling is done when we wish to learn how resistivity varies in a horizontal direction. Some applications are locating boundaries between different lithologies, location of faults, locating contaminated or salt water or permafrost zones. The Wenner electrode arrangement is used in profiling and an electrode spacing of twice the depth of interest is chosen. Measurements may be made at distances equal to electrode spacing, however, if more detailed coverage is needed then the measurement could be made at intervals less than electrode spacing. Resistivity profiling data may also be presented as a contour map by conducting a series of profiles parallel to each other over an area. Profiles may also be conducted to present a resistivity cross section by doing a series of profiles over an area with increasing electrode spacings (Fig. 8E).

Figure 1E - Setup and principle of Wenner Method of resistivity surveying.




The Wenner array. This is the setup and principle behind the Wenner method. The battery symbol represents the battery source. The current meter and voltage meter are both inside the Terrameter SAS 300C and are what our readings are based on, (Voltage/Current = Resisitance). C1 and C2 represent the two current electrodes and P1 and P2 are the two potential electrodes.




The basic setup and principle behind the Schlumberger method. Again the current and voltmeter are inside thee Terrameter SAS 300 C. There is the battery source. The different distances for the formula to solve the Schlumberger way are also given in this picture.

Table 1E - Resistivities of various materials.

3. Representative resistivity values

As a rough guide, we may divide earth materials into

| | |
|---|---|
| — low resisitivity | less than 100 ohm meters |
| — medium resistivity | 100 to 1000 ohm meters |
| — high resisitivity | greater than 1000 ohm meters |

Some representative resisitivity values are:

*Regional soil resistivities*

| | |
|---|---|
| — wet regions | 50-200 ohm meters |
| — dry regions | 100-500 |
| — arid regions | 200-1000 (sometimes as low as 50 if the soil is saline) |

*Waters*

| | |
|---|---|
| — soil water | 1 to 100 |
| — rain water | 30 to 1000 |
| — sea water | order of 0.2 |
| — ice | $10^5$ to $10^8$ |

*Rock types below the water table*

| | |
|---|---|
| — igneous and metamorphic | 100 to 10,000 |
| — consolidated sediments | 10 to 1000 |
| — unconsolidated sediments | 1 to 100 |

*Ores*

| | |
|---|---|
| — massive sulfides | $10^{-4}$ to 1 |
| — non-metallics (gypsum, quartz, dry rock salt) | order of $10^{10}$ |

*Effect of water salinity*

| | |
|---|---|
| .005 g/liter | 1050 |
| .10 | 110 |
| .5 | 12 |

| Material | Resistivity (Ω·m) |
|---|---|
| Wet to moist clayey soil and wet clay | 1s to 10s |
| Wet to moist silty soil and silty clay | Low 10s |
| Wet to moist silty and sandy soils | 10s to 100s |
| Sand and gravel with layers of silt | Low 1000s |
| Coarse dry sand and gravel deposits | High 1000s |
| Well-fractured to slightly fractured rock with moist-soil-filled cracks | 100s |
| Slightly fractured rock with dry, soil-filled cracks | Low 1000s |
| Massively bedded rock | High 1000s |

Table 2E - Resistivities of various earth materials.

Figure 2E - Data sheet for recording resistivity data by using the Wenner survey.

WENNER SURVEY

Sounding Location/Number____________________

Operator/Date____________________

Equipment____________________

Computation Formula: $\rho_a = K\ (V/I)$. $K = 2\pi a$

| a(m) | TAPE P | TAPE C | K | $R_1$ | $R_2$ | R (AV) | | $\rho_a$ |
|---|---|---|---|---|---|---|---|---|
| 0.47 | | | 2.95 | | | | | |
| 0.68 | | | 4.27 | | | | | |
| 1.00 | 0.50 | 1.50 | 6.28 | | | | | |
| 1.47 | 0.75 | 2.25 | 9.24 | | | | | |
| 2.15 | 1.07 | 3.22 | 13.5 | | | | | |
| 3.16 | 1.60 | 4.74 | 19.9 | | | | | |
| 4.64 | 2.32 | 6.96 | 29.2 | | | | | |
| 6.81 | 3.40 | 10.22 | 42.8 | | | | | |
| 10.0 | 5.00 | 15.00 | 62.8 | | | | | |
| 14.7 | 7.35 | 22.00 | 92.4 | | | | | |
| 21.5 | 10.75 | 32.25 | 135 | | | | | |
| 31.8 | 15.80 | 47.40 | 199 | | | | | |
| 46.4 | 23.20 | 69.60 | 292 | | | | | |
| 68.1 | 34.05 | 102.15 | 428 | | | | | |
| 100 | 50.0 | 150.0 | 628 | | | | | |
| 147 | 73.5 | 220.50 | 924 | | | | | |
| 215 | 107.5 | 322.5 | 1351 | | | | | |
| 316 | 158.0 | 474 | 1985 | | | | | |
| 464 | 232 | 696 | 2915 | | | | | |
| 681 | 340 | 1021 | 4279 | | | | | |
| 1000 | 500 | 1500 | 6283 | | | | | |

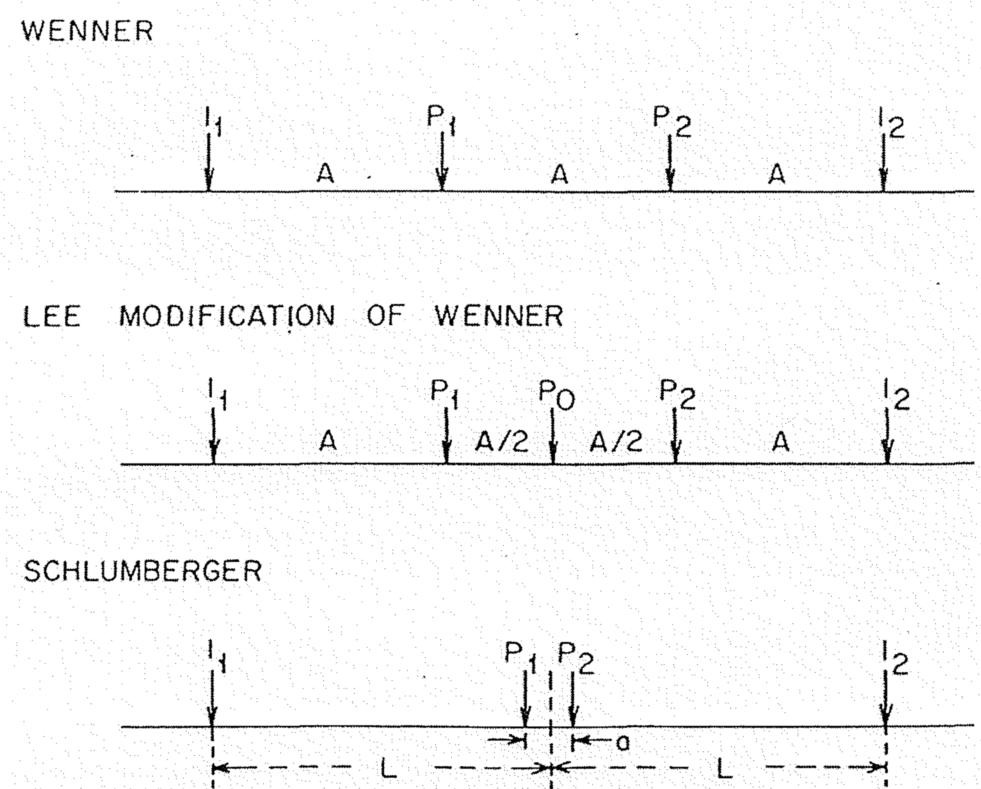
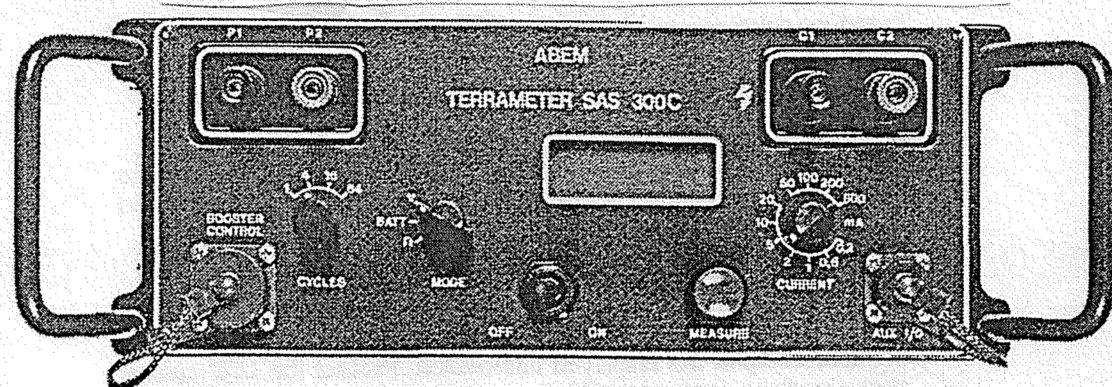



FIGURE 4-1. Common electrode arrangements

8

Figure 4E - Wenner, Lee Modification of Wenner and Schlumberger Methods of resistivity surveying.

Figure 3E - Resistivity equipment used for resistivity surveys (ABEM Terrameter SAS 300C).



SCHLUMBERGER METHOD

schematic diagram

C1, C2, — CURRENT EIECTRODES

P1, P2 — POTENTIAL EI ECTRODES

A — AMMETER

V — VOLTMETER

MN — DISTANCE BETWEEN P1 AND P2

2L — DISTANCE BETWEEN C1 AND C2

$$\rho = \pi MN\left[\left(\frac{L}{MN}\right)^2 - \frac{1}{4}\right]\frac{V}{I}$$

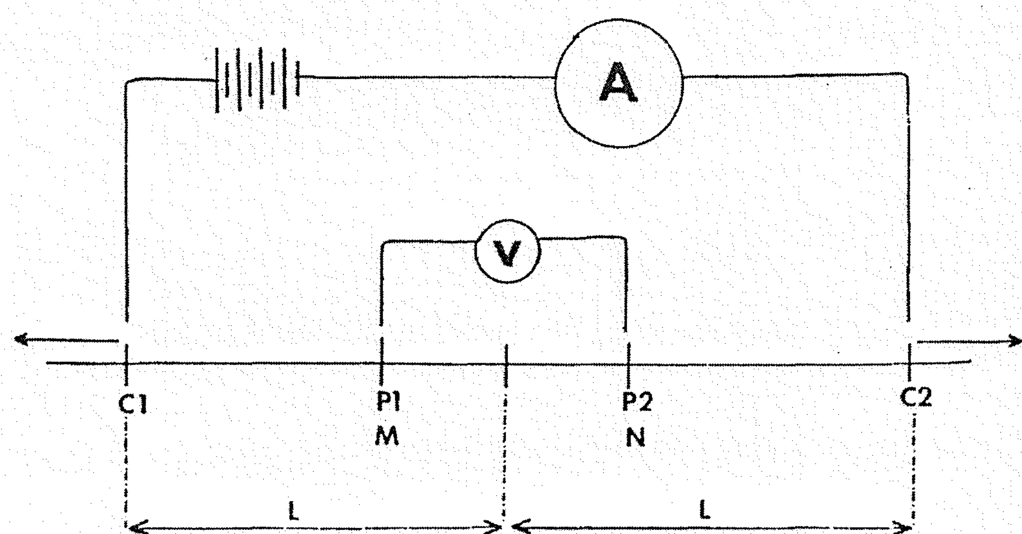
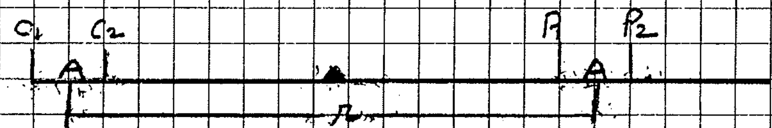



Figure 5E - The Schlumberger Method of conducting resistivity surveys.

# Resistivity Survey

## DIPOLE-DIPOLE



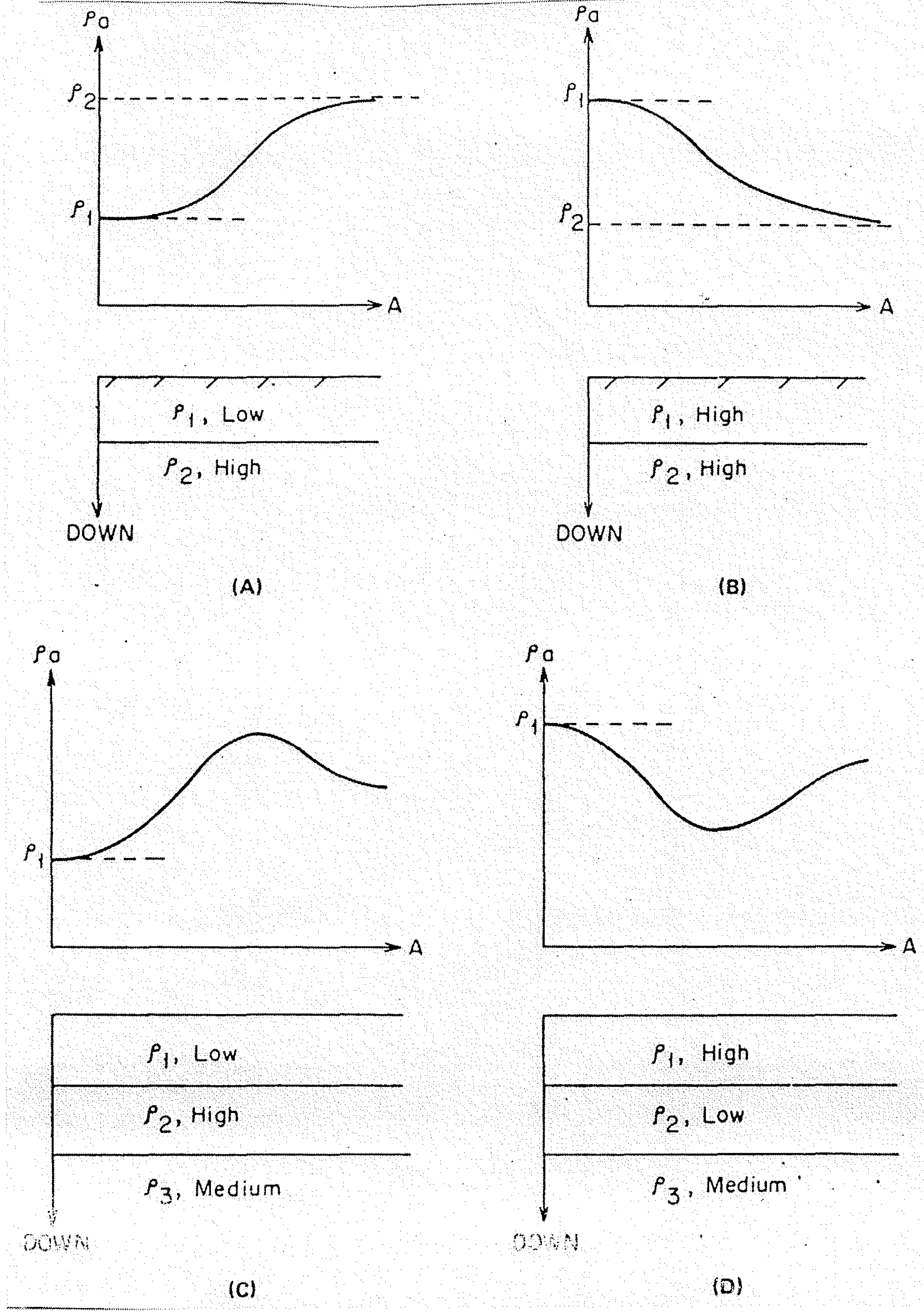

Current electrodes well separated from the potential electrodes

$$\rho_a = \pi \left( \frac{r^2}{a} - r \right) R$$

| a (Meter) | r (Meters) | R ohms | ρ ohm-meter | a | r meter | R ohms | ρ ohm-meter |
|---|---|---|---|---|---|---|---|

Figure 6E - Dipole-Dipole Method of resistivity surveying.

Figure 7E - Resistivity sounding curves over two and three layer models.



## Profiling of Soccer Field

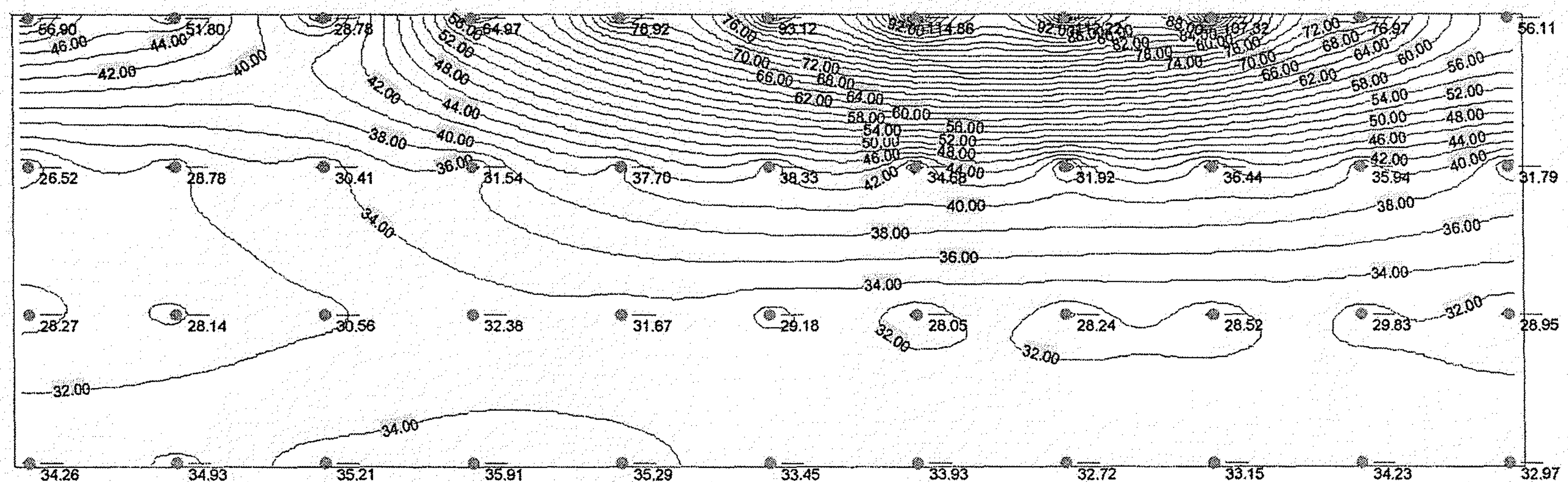



Figure 8E - Resistivity cross-section showing variations in resistivity with depth.

## GRAVITY AND MAGNETICS

Gravity and magnetic maps show how the subsurface rocks produce changes in the gravity and magnetic fields. A gravity map shows the gravitational field produced by subsurface rocks of varying density. A gravity high of 10 mGals shown on the gravity map (Figure 1G) just north of Plattsburgh indicates a high density body beneath the surface in that area. Other gravity highs are located northwest of Plattsburgh. South of Dannemora is a gravity low of -16 mGals indicating a low density body in that area. Again, these gravity anomalies or irregularities in the gravitational field reflect the variation in the densities of the rocks in the area.

The magnetic map shows a magnetic high over a 55 gallon buried drum on Potsdam Campus. The anomaly caused by the drum indicates it is a magnetized body at shallow depth causing a distortion in the earth's magnetic field. This distortion (anomaly) in the Earth's magnetic field is detectable from magnetic measurements made with a magnetometer. The measurements are contoured to produce a magnetic anomaly map showing the location of the buried drum.

### What Gravity and Magnetic Data Can Do For You

"Ten Commandments"
by Robin Riddihough
Chief Scientist
Geological Survey of Canada

1. Gravity and magnetic surveys are both methods of REMOTE SENSING. They can detect the properties of rocks at distance - from the air, on the ground or at the sea surface.
2. Anomalies and changes in the value of gravity (after allowance of varying elevation and topography) reflect changes in DENSITY.
3. Anomalies and changes in the value of the Earth's magnetic field (after allowing for changes with time) reflect changes in MAGNETIZATION.
4. These two properties of rocks are often diagnostic. Taken together they can eliminate many possible geological alternatives and provide fundamental constraints on a geological model.
5. Both gravity and magnetic anomalies are a function of the distance between the detector and the source (rocks). Amplitudes decrease faster with distance for magnetic anomalies therefore they tend to "see" shallower structures. Both methods, however, provide an INTEGRATED depth spectrum of the sources they are seeing - they see much more than just the surface rocks.
7. The PATTERN of a gravity or a magnetic anomaly map is a powerful indicator of how subsurface rocks and formations are distributed. It can provide rapid indications of TRENDS, GRAIN and DISCONTINUITIES. The style of the pattern may be diagnostic of a particular rock sequence or assemblage (for example: sea-floor magnetic anomalies).
8. The SHAPE of individual anomalies can be used to determine the shape and position of density or magnetic contrasts (rock units). In theory, there are a number of geometries that will "fit" a particular anomaly. IN PRACTICE, by using realistic geological or other geophysical controls, anomaly "fits" will provide REAL NUMERICAL CONSTRAINTS on the anomaly sources.
9. However, always understand and appreciate the weaknesses and inaccuracies of the data. Never waste time trying to "fit" anomalies with greater precision than they were measured at.

10. Any final interpretation must satisfy ALL the available geophysical and geological data. Gravity and magnetic anomaly information cannot be ignored. It will not go away. It is real and it is telling us something even if we do not always understand it and even if it appears to be contradicting the surface geology.

## Gravity Meter

In principle, the gravity meter is simply an extremely sensitive weighing device. It consists of a mass suspended on a spring (Figure 3G). The gravitational attraction on the mass changes with variations in the gravitational field. The change in the elongation of the spring is proportional to the change in gravity so the gravity meter measures changes in gravity. The readings made with the gravity meter are in scale divisions. The differences measured in scale divisions are changed to units of acceleration by using the calibration factor (.1015mGals/SD) of the meter. The Worden Meter is very light and portable and housed in a thermos to keep the temperature nearly constant. Changes in temperature will cause changes in the elongation of the spring.

These changes are corrected for drift by returning to a base station several times a day for readings. The unit commonly used in gravity surveying is the milliGal, which is an acceleration of .001 cms/sec$^2$.

## Determination of Observed Gravity with the Gravity Meter

Measurements of differences in gravity with the meter enables one to calculate the observed gravity at a point. This is done by taking readings at a base (a station where the absolute value of gravity is known) and a station where you desire to know the observed gravity. An example of how to determine the observed gravity at a station is given below. The calibration factor of the meter is .1015 mGals/SD.

| | |
|---|---|
| Base Gravity | 980558.04 |
| Base Reading | 1100.8 S.D. |
| Station Reading | 1300.8 S.D. |
| Difference in Scale Divisions | 200.0 |
| Difference in Gravity | 20.30 mGals |
| Observed Gravity at Station | 980578.34 mGals |

## Calculating the Simple Bouguer Anomaly

The simple Bouguer anomaly (SBA) is the difference between the observed gravity (go) and the expected or theoretical gravity. It is the value that is plotted and contoured to produce the gravity map or profile. The Bouguer anomaly is corrected for latitude and elevation. The simple Bouguer anomaly is calculated as shown below:

$$SBA = g_o - (\gamma - .06h)$$

where

SBA = simple Bouguer anomaly (mGals)
go = observed gravity (mGals)
$\gamma$ = theoretical gravity at latitude of measurements at sea level
.06h = correction for elevation and attraction of material between sea level and station
"h" = elevation in feet

A sample of a calculation of the simple Bouguer Anomaly is in Figures 4G and 5G.

## Modeling of Gravity Anomalies

Normally, gravity profiles are drawn across selected gravity anomalies and geologic models are constructed that produce computed gravity values that satisfy the observed gravity profile. A program GM-SYS computes gravity and magnetic values of two-dimensional geologic models. Figure 6G shows models of Precambrian basement in western New York. The solid line is the observed gravity and the dots are computed gravity values based on the model.

## Recording Gravity Data in the Field

Figure 7G is a data sheet showing how gravity measurements are recorded in the field. The following is a discussion of this data sheet.

1. First measurement is made at a base. Time is recorded to construct drift curve.
2. First column is station number. This number is also written on a map showing location of station.
3. Column 2 is station reading and column 3 is time of measurement needed for drift correction.
4. Column 4 is elevation in feet obtained from topographic map.
5. Column 5 is the latitude in degrees and minutes measured with a GPS or from maps in the lab.
6. Column 6 is the longitude in degrees and minutes.
7. The second line from top is the second base reading used to construct a drift curve.

The top of the data sheet shows the Potsdam base was used and the measurements were made in the Potsdam Quadrangle.

**Computing the Simple Bouguer Anomaly**

Figure 4G shows an example of a calculation of the simple Bouguer anomaly. These calculations can be done by using a calculator or EXCEL spread sheet. The calculations are discussed below.

1. Base RD column is base reading corrected for drift.
2. $\Delta S$ column is the difference between Station RD and Base RD in scale divisions. Station 1 is 28.2 scale divisions higher than the base reading.
3. $\Delta g$ is obtained by multiplying $\Delta S$ by the calibration factor which in this example was .1032 mGals/SD.
4. Base gravity is already known and in this example is 980558.04 mGals.
5. Observed gravity column is the Base Gravity plus the 2.91 mGals which is 980560.95.
6. Theoretical gravity column is value of gravity at the stated latitude at sea level. This is obtained from tables of calculations using the 1930 formula.
7. Elevation correction is .06h where h is elevation in feet.
8. The last column is the simple Bouguer anomaly calculated by using the formula:

$$SBA = g_0 - (\gamma - .06h)$$

The SBA is -11.35 mGals which means the observed gravity is 11.35 mGals less than expected.

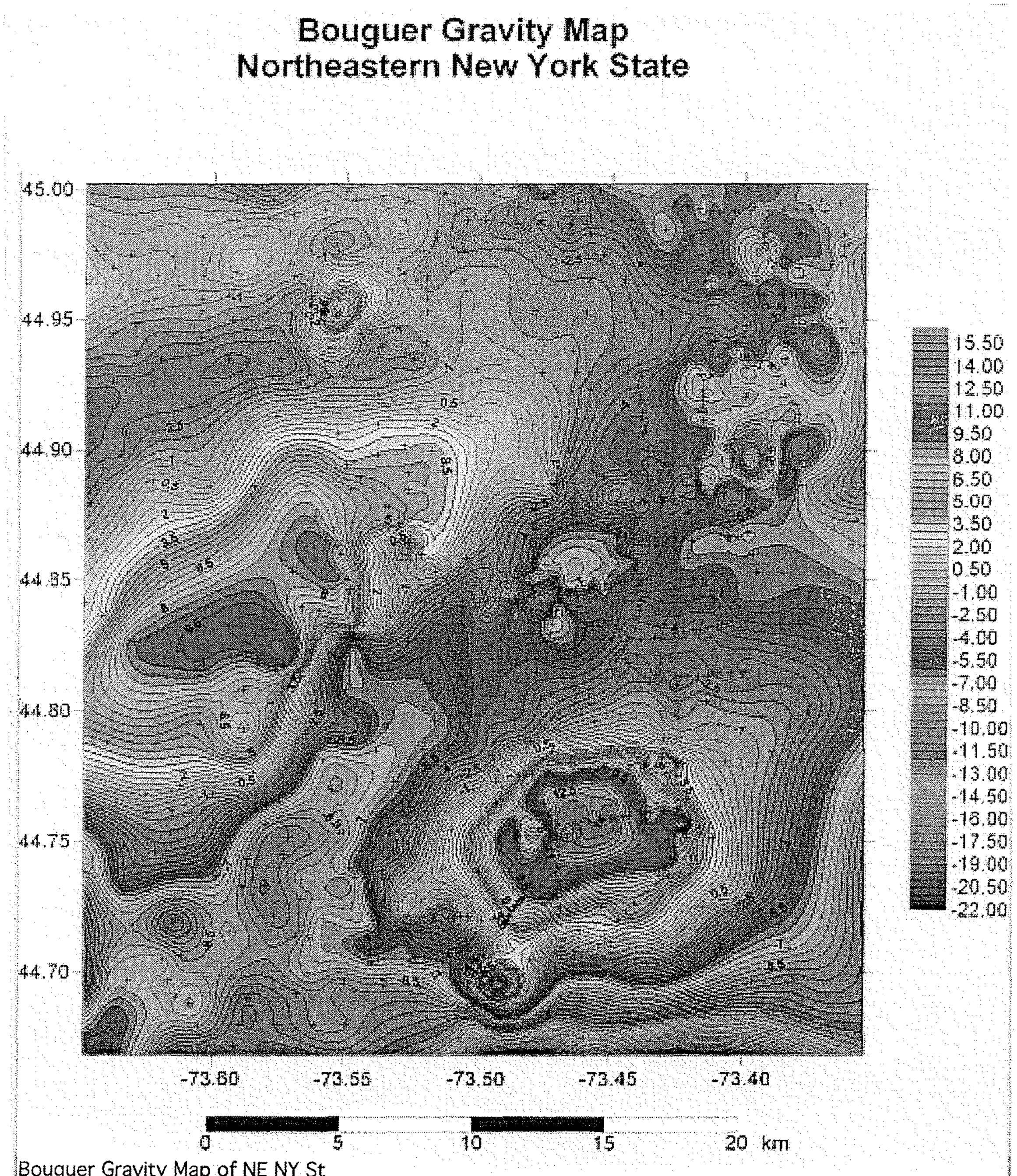



Figure 1G - Gravity map of Lake Champlain Valley showing the gravity high north of Plattsburgh.

# Map of Lehman Park and Location of 55 Gallon Drum

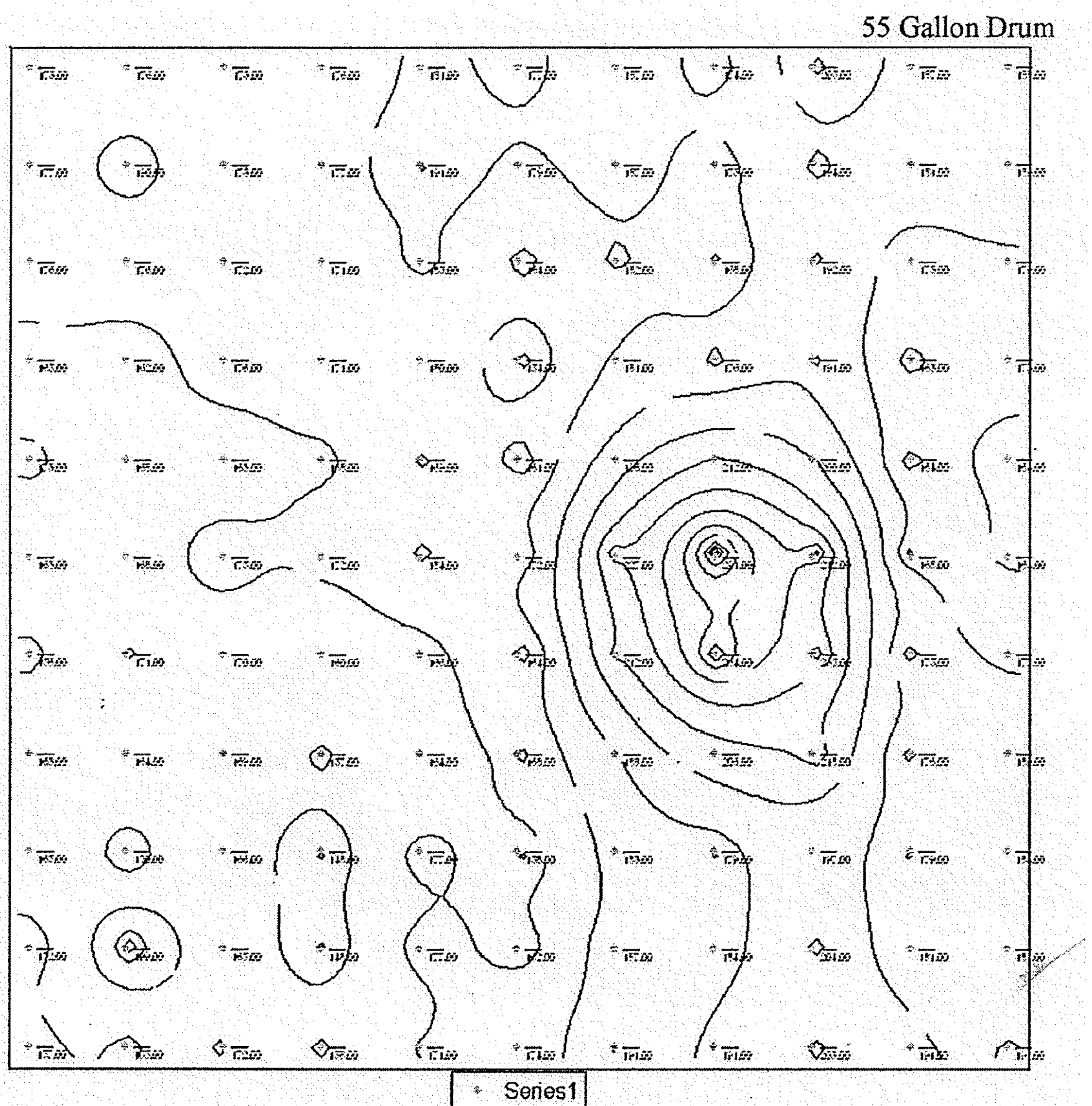
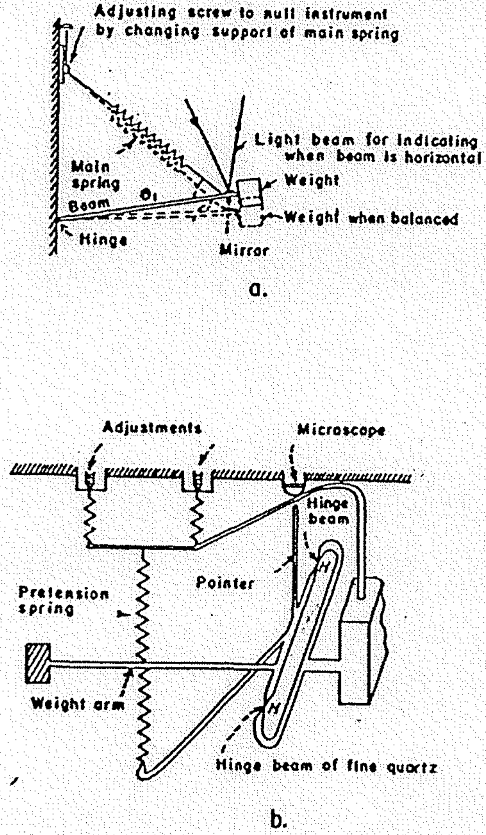
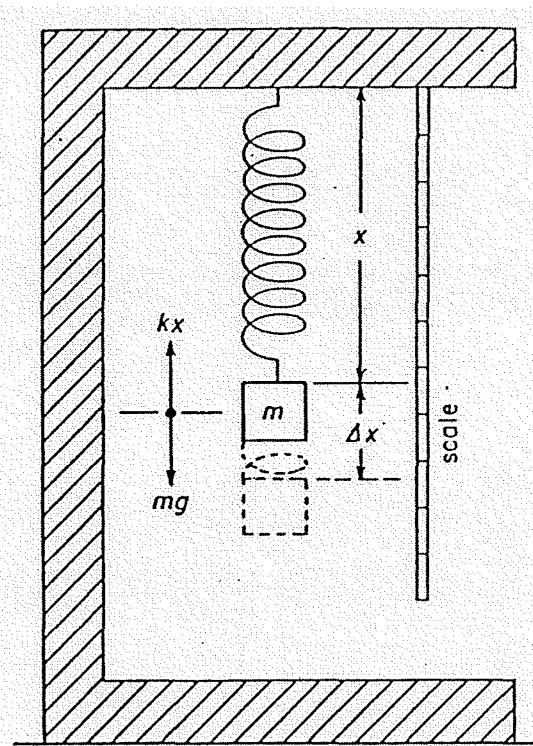



Figure 2G - Magnetic high over a 55 gallon drum buried in Lehman Park.




**Gravimeters.** (a) La Coste-Romberg schematic. (b) Worden schematic.




Mass supported by a vertical spring. A change in gravity will produce a change in the distension of the spring.

Figure 3G - Worden and LaCoste Romberg gravity meters consist essentially of a mass supported by a spring.

SAMPLE PROBLEMS

COMPUTING THE BOUGUER ANOMALY

ΔS .1032 mgals/SD

| ST # | LAT | LONG | ELEV (FT) | STATION RD scale div | BASE RD corrected for drift | ΔS SCALE DIV | Δg Caliber × ΔS mgals | BASE GRAVITY (milligals) | OBSERVED GRAVITY go (milligals) | Theoretical GRAVITY γ (milligals) | ELEV CORR (.06h) milligals | SBA Bouguer Anomaly (milligals) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 44° 40.0 | 75° 1.3 | 450 | 1252.8 | 1224.2 | +28.2 | +2.91 | 980558.04 | 980560.95 | 980599.3 | 27.00 | -11.35 |
| 2 | 44° 40.2 | 75° 3.1 | 418 | 1295.6 | 1224.7 | +70.9 | +7.32 | " | 980565.36 | 980599.6 | 25.08 | -9.16 |
| 3 | 44° 40.3 | 75° 4.1 | 384 | 1329.4 | 1224.9 | | | " | | | | |
| 4 | 44 40.2 | 75 5.4 | 366 | 1362.0 | 1225.0 | | | " | | | | |

Figure 4G - A sample calculation of the simple Bouguer anomaly. The SBA is corrected for latitude, free air effect and Bouguer Effect.

## How to calculate the Bouguer Gravity Anomaly

Gravity Anomaly = observed gravity - expected gravity

$$\Delta g = g_o - (\gamma - .06h)$$

$\Delta g$ = gravity anomaly (m Gals)

go = observed gravity (measured with gravimeter)

$\gamma$ = theoretical gravity at latitude of measurement at sea level. (Obtained from formula)

.06h = Correction for elevation (free air) and attraction of material between sea level and station.
h = elevation of station in feet

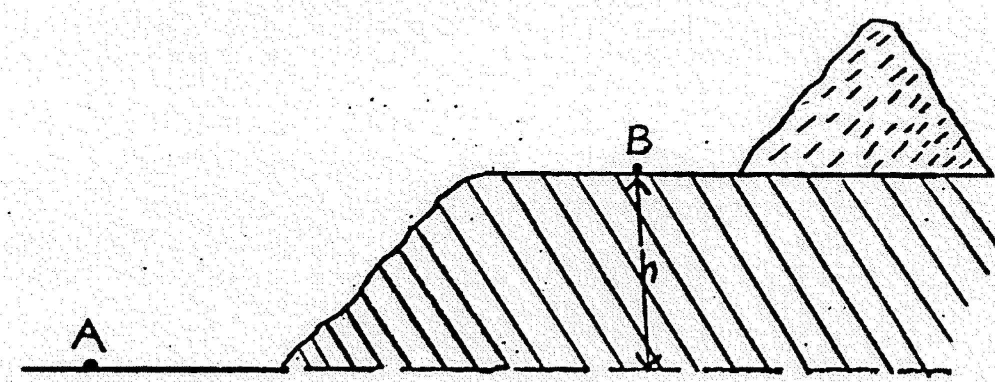



Figure 5G - Calculation of the Simple Bouguer Anomaly.

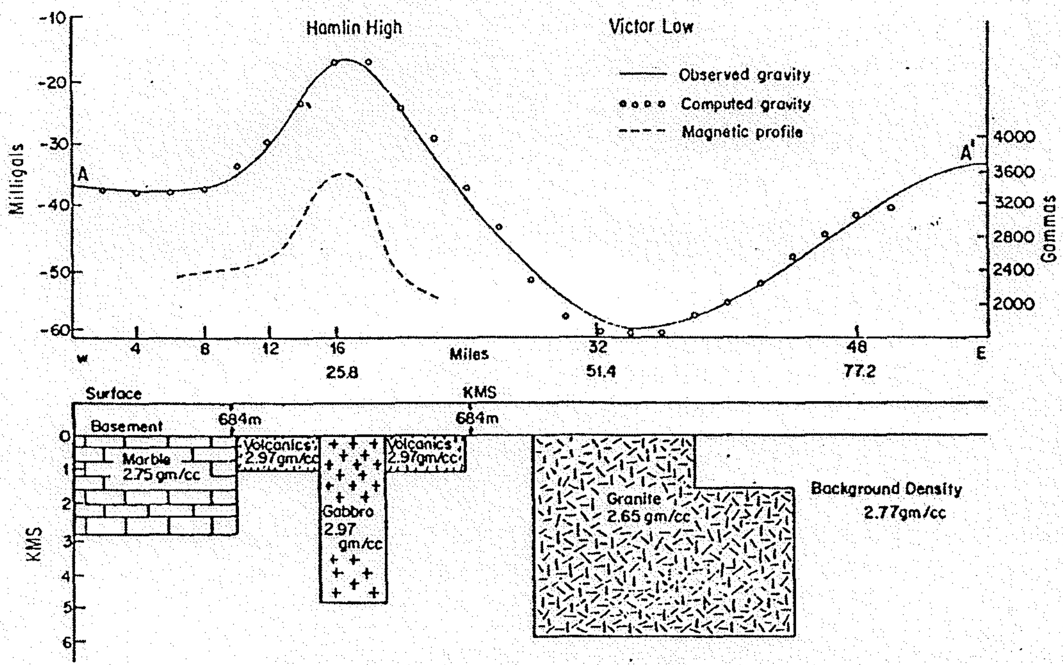



Figure 2. The Hamlin two-dimensional gravity profile AA'.

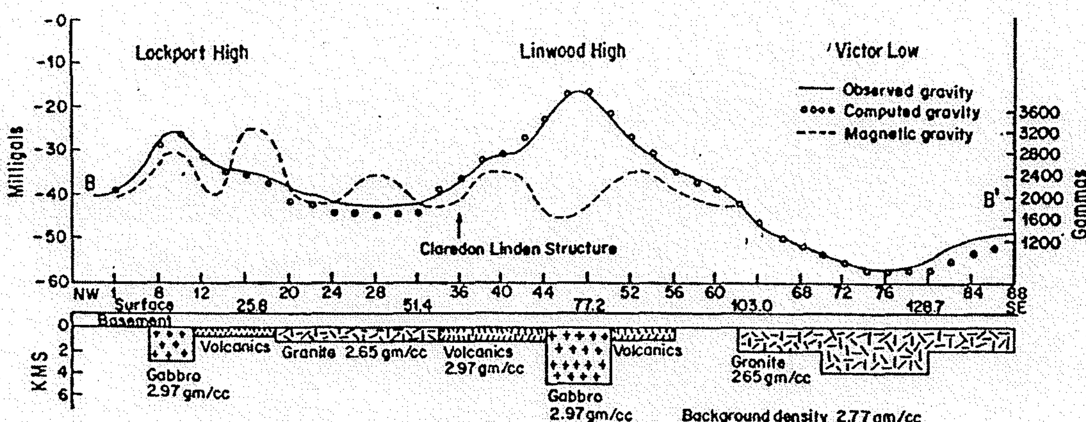



Figure 6G - Computed and observed gravity profiles and models of the Precambrian basement in western New York.

GRAVITY SURVEY

Operator: REVETTA  Sheet #: 1

Date: 1/14/95  Gravity Meter: Worden

Units (gal, mgal, g.u.): Mgal  Calibration Factor: .1013

Quadrangle Surveyed: Potsdam  Base: Potsdam

Base Gravity: 980558.04  Theoretical Formula (1930, 1967): 1930

| Station # | Reading | Time | Elevation | Latitude | Longitude |
|---|---|---|---|---|---|
| BASE (1) | 1414.8 | 11:25 | | | |
| BASE (2) | 1421.8 | 13:50 | | | |
| | | | | | |
| 1 | 1406.5 | 11:40 | 433 | 44° 39.0' | 74 58.1 |
| 2 | 1396.3 | 11:50 | 460 | 44 39.2 | 74 57.6 |
| 3 | 1361.7 | 12:05 | 490 | 44 38.6 | 74 57.1 |
| 4 | 1361.2 | 12:15 | 479 | 44 38.2 | 74 57.5 |
| 5 | 1331.5 | 12:30 | 520 | 44 37.8 | 74 57.3 |
| 6 | 1322.8 | 12:39 | 542 | 44 37.7 | 74 56.1 |
| 7 | 1225.8 | 12:47 | 654 | 44 37.7 | 74 53.5 |
| 8 | 1254.4 | 12:54 | 624 | 44 38.6 | 74 53.6 |
| 9 | 1338.4 | 13:05 | 521 | 44 39.0 | 74 55.6 |
| 10 | 1300.4 | 13:19 | 454 | 44 39.6 | 74 55.8 |

Figure 7G - Field gravity data sheet showing method of recording gravity measurements in the field.

# MAGNETIC METHOD

## Applications

A magnetometer measures changes in the earth's magnetic field strength. Any magnetic object that alters the earth's magnetic field can potentially be detected by magnetic surveying. Traditionally, magnetic surveys have resulted in the construction of magnetic maps (Figure 1M) that show patterns diagnostic of a particular rock assemblage; thus the method is useful in geologic mapping. The method has also been used to estimate depth to Precambrian basement by oil companies. Other applications are the use of magnetics to detect buried steel tanks and drums containing hazardous waste materials. Archeologists have also found the method useful for locating cultural features with anomalies being due to ferrous metals, hearths, and kilns.

Magnetometers also have the option of measuring the vertical magnetic gradient, which has several advantages over the use of total field measurements. Near surface sources of magnetic anomalies are accentuated over deeper regional bodies by the gradient measurements. The magnetic gradient also exhibits superior resolving power. This combined effect is important in locating lithologic contacts and shallow buried steel drums. Magnetic gradient data also aids in the interpretation of the physical characteristics of the source.

## Equipment

The G856 Memory-Mag magnetometer will be used to locate a buried 55 gallon metallic drum. This instrument is a proton-precession magnetometer that measures the total intensity of the earth's magnetic field in gammas. The readings are stored along with time, data and station number. The data is then fed into a computer and a printout may be obtained. A computer program MAGLOC and a contouring program can be used to plot magnetic contour maps based on the data. The magnetometer can also be used as a gradiometer. This is done by placing two sensors, one above the other, separated by 1 meter distance.

Physically, the G856 is compact and lightweight. It is weatherproof and operates over a wide temperature range. It is powered by eight D-cell batteries sufficient for about 3000 readings. It is a very high precision instrument.

The instrument comes with a sensor which is mounted on a staff. The sensor is mounted vertically for surveys in high latitudes and horizontally for lower latitudes having a dip of less than $40^{o}$. The sensor is marked with an arrow to align in a north direction for an optimum signal.

The instrument must also be tuned for the strength of the field in the survey area to achieve the best signal. For the Potsdam area the magnetometer would be tuned at 55000 gammas.

## Magnetic Surveying

The magnetometer measures the total intensity of the earth's magnetic field. Most rocks contain some magnetite, a common magnetic mineral that produces distortion in the earth's field. The volume of magnetite in the rock determines its magnetic susceptibility and intensity of magnetization. Magnetic surveys can be useful in finding iron or steel objects such as buried drums and storage tanks, archaeological features such as tombs, pottery and brick, pipelines, weapons, and many other metallic objects. In determining whether the magnetic survey is useful, it must first be determined whether the object is truly magnetic. The most important single factor determining the detectability is distance between the magnetometer and object. Most anomalies vary inversely as the cube of the distance. A second consideration is the degree of magnetism of the material. Figure 2M shows how a buried drum produces a magnetic anomaly that can be detected by magnetic surveys, and Figure 3M shows magnetic profiles over a buried drum in Lehman Park.

### What causes magnetic anomalies?

Differences in the intensities of magnetization of rocks cause variations in the strength of the earth's magnetic field. The total intensity of magnetization of a rock is due to the induced magnetization and remanent magnetization of the rock. The induced magnetization is given by the expression:

$$I = kH$$

where I is the intensity of the induced magnetization, k is the magnetic susceptibility and H is the strength of the earth's magnetic field. The magnetic susceptibility (k) is determined with a magnetic susceptibility bridge and the value of H is obtained from the magnetometer measurements. The induced magnetization is induced by the present earth magnetic field. The remanent magnetization of the rock is that magnetization instilled in the rock by the earth's magnetic field at the time the rock was formed. It is usually determined from cores placed in a spinner magnetometer. The remanent magnetization will not necessarily have the same direction or intensity as the induced magnetization.

### Field Procedure

In magnetic surveying it is important that the magnetic field measurements be as true as possible and not affected by articles of clothing or personal accessories such as keys, watches, knives, jewelry or zippers. Measurements should not be made near cars, fences, powerlines, buildings or railroad tracks. The operator need only to depress the READ key to observe the reading then the STORE key.

The sensor is normally mounted on the staff. However, it may be mounted on a backpack for rapid operation. Cardboard or plastic jacketed batteries should be used when mounted on your backpack.

### Depths from Magnetic Anomalies

The deeper the source of the magnetic anomaly, the broader the anomaly and the shallower the source, the steeper the gradient of the anomaly. This enables the determination of the approximate depth to the source. Several depth rules are shown in Figure 4M for calculation of depth to a source. One of the most important factors in the interpretation of magnetic anomalies is the relation between anomaly wavelength (width) to depth.

### Gradiometer Surveys

A gradiometer survey is conducted by mounting one sensor about 1 meter above a lower sensor. The G856 will then take two readings, the first from the bottom and the second from the top sensor. The gradient measurements accentuate near surface bodies over deeper bodies and exhibit superior resolving power. The combined effect is useful in locating shallow buried steel drums or lithologic contacts. Figure 5M shows a magnetic and gradiometer survey over a magnetic source.

**Some Important Considerations in Interpretation of Magnetic Anomalies**

1. A magnetic survey is only able to detect sources or map contacts of rock types or locate faults when there is a magnetization contrast.

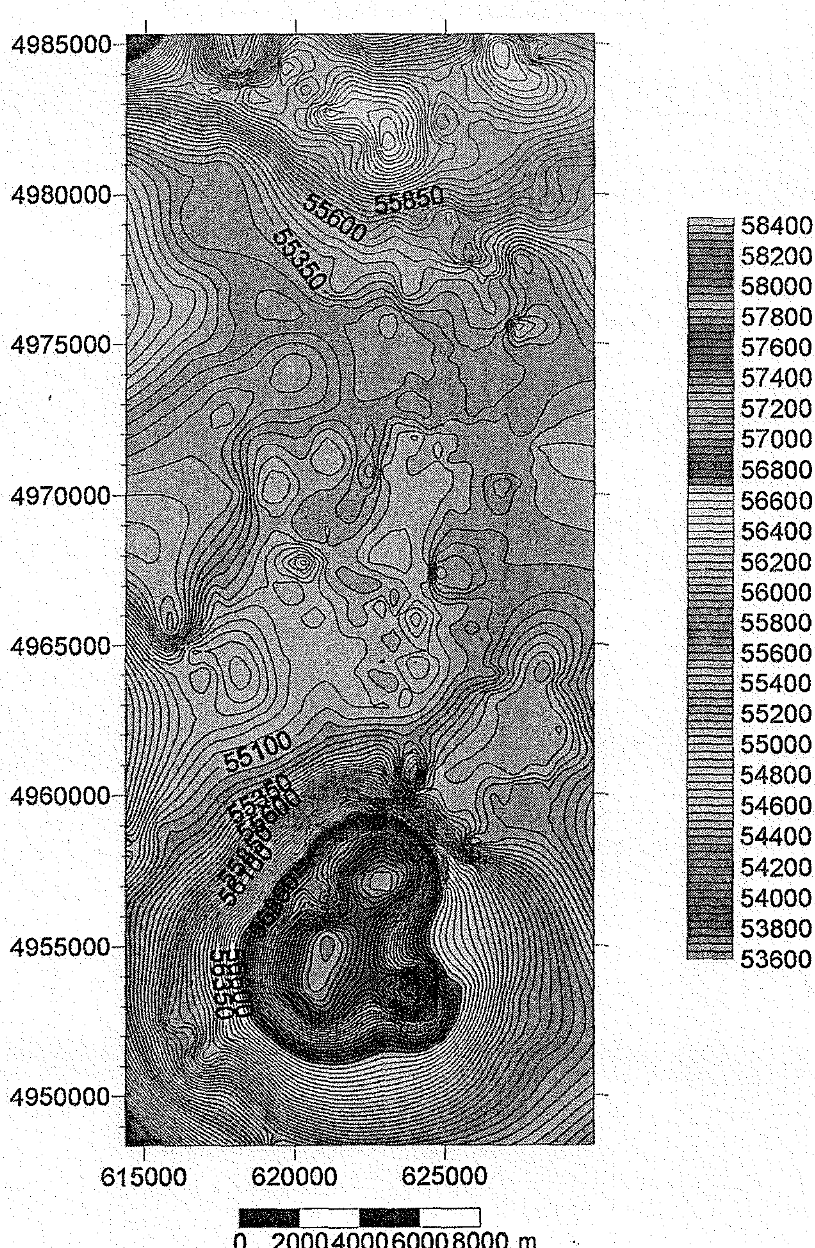
2. The most geologically significant anomalies on a map may be the subtle ones and not necessarily the largest most prominent anomalies.

3. Study the width and shape to determine a realistic geologic source and depth.

4. Know the geology of the area to arrive at a sound interpretation of the magnetic data.

Figure 1M - Magnetic map of Lake Champlain Valley. Note magnetic high north of Plattsburgh.

***Diurnally Corrected Total-Field Magnetic Map of the Champlain, Beekmantown and Northern Plattsburgh Quadrangles***



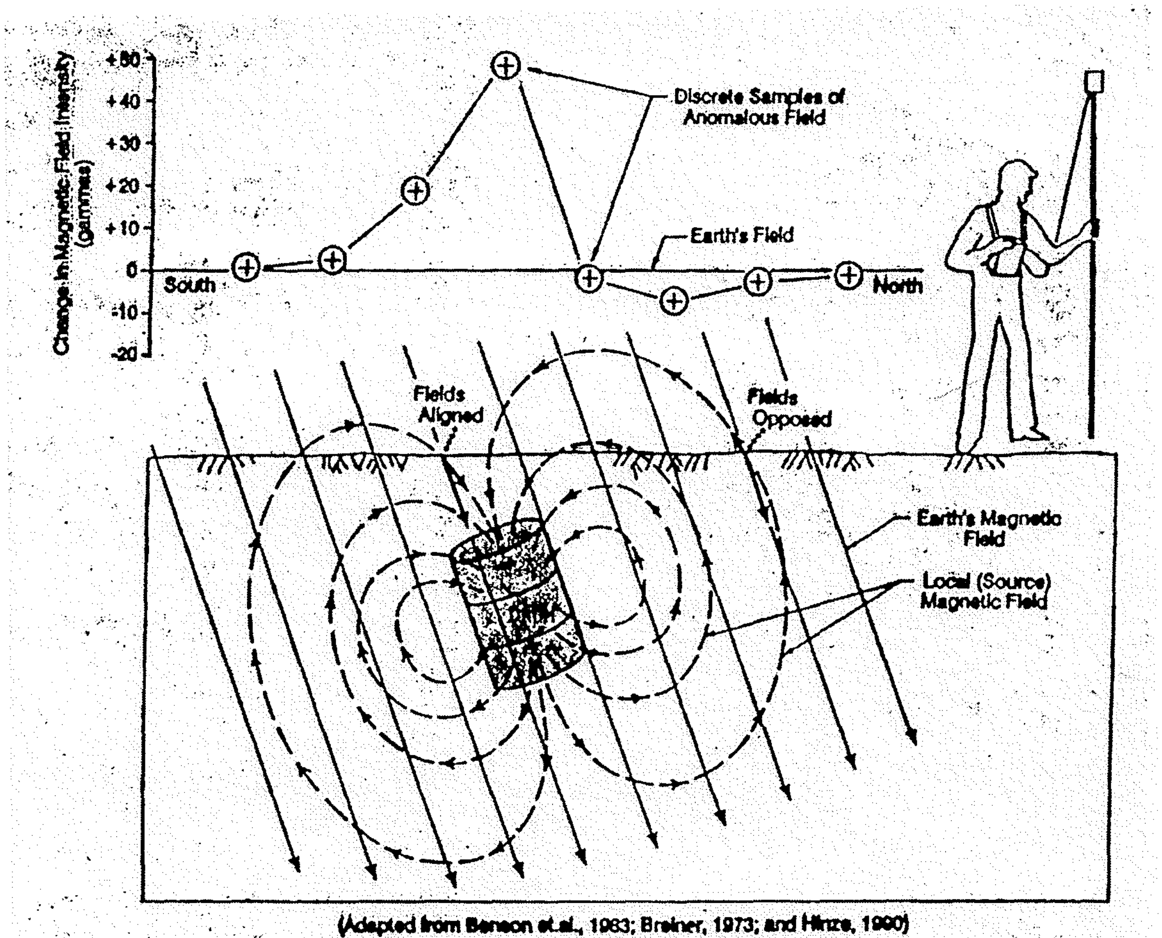



Figure 2M - Magnetic effect of a buried metallic drum.

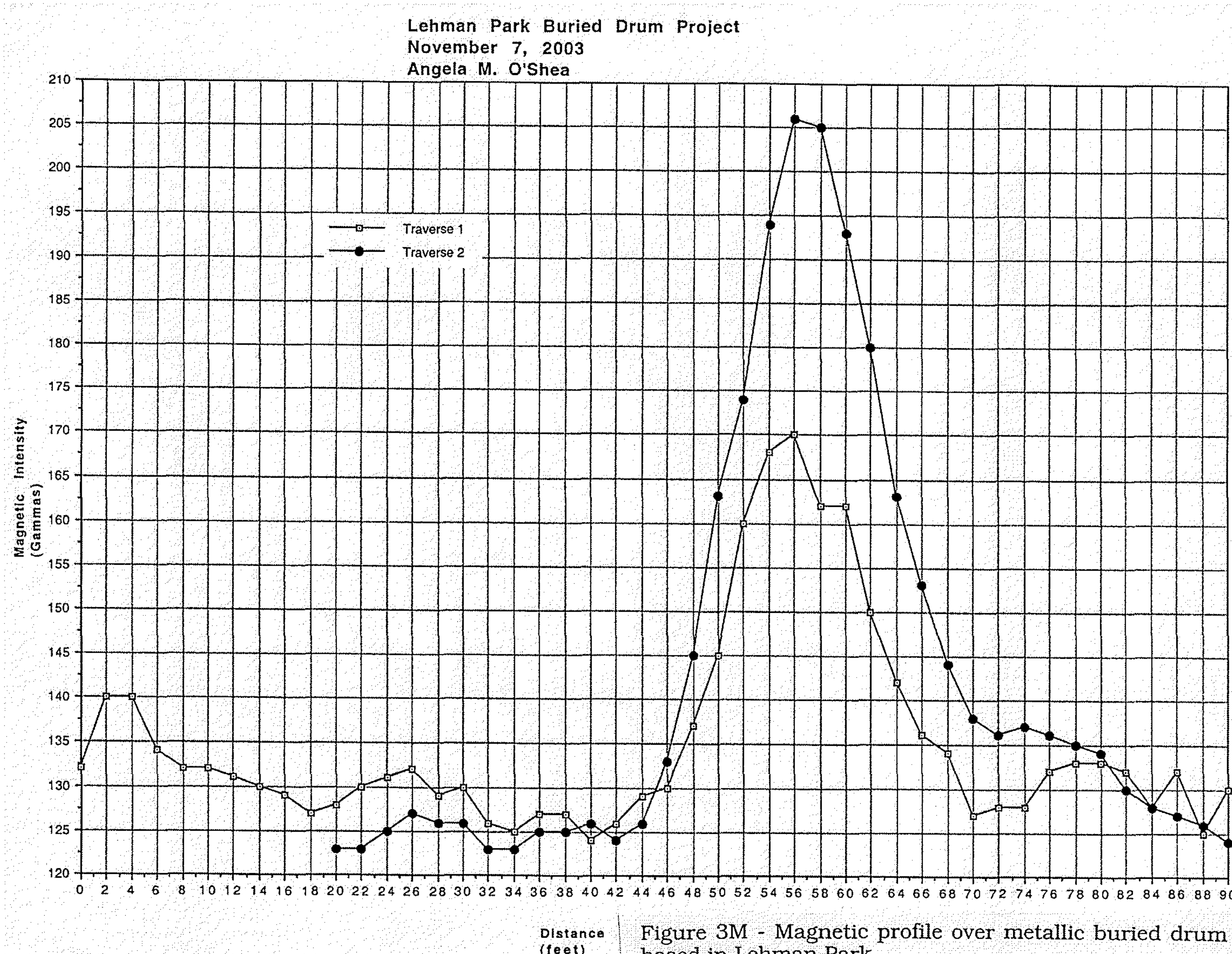



Figure 3M - Magnetic profile over metallic buried drum based in Lehman Park.

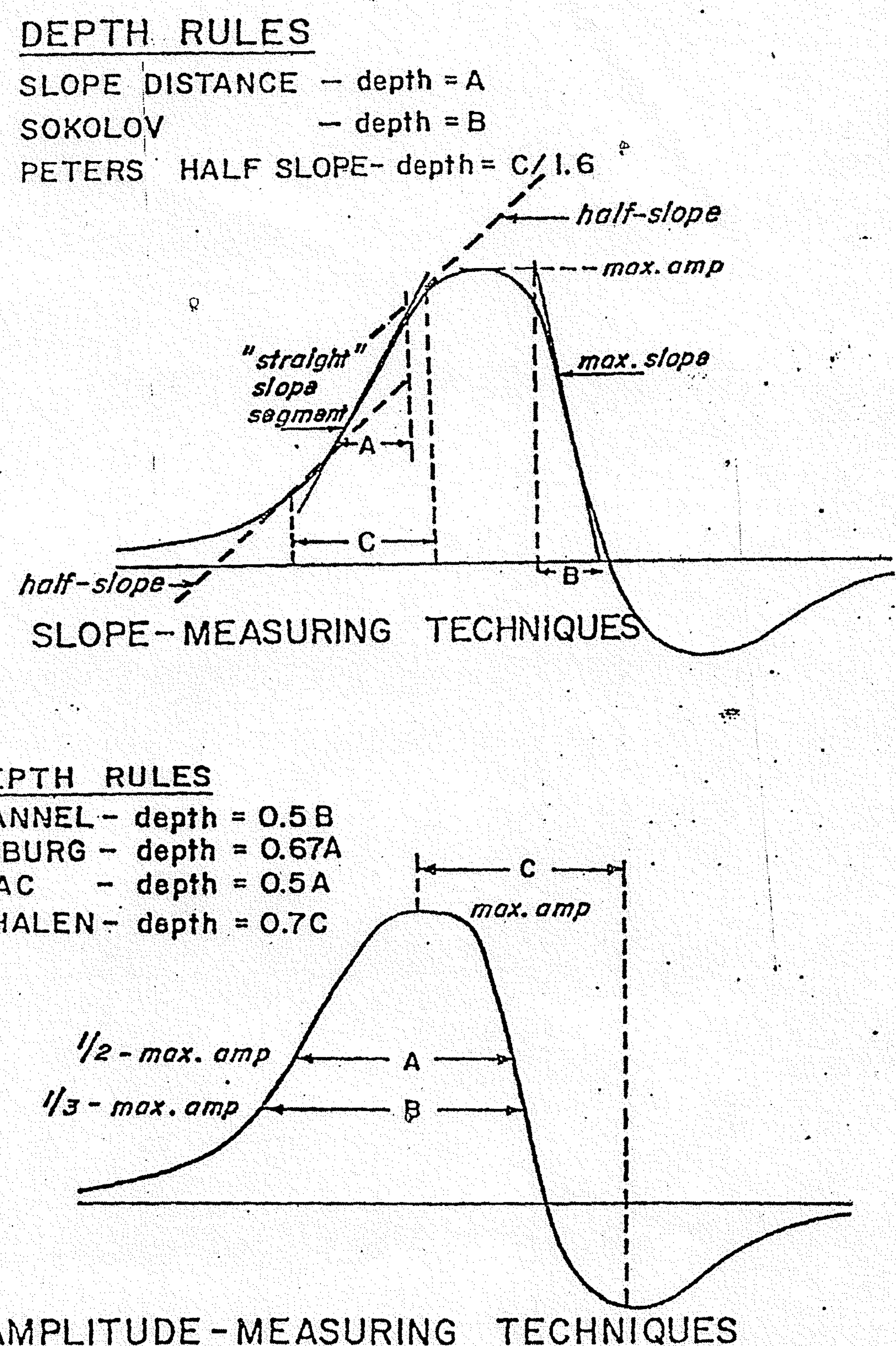



Figure 4M - Depth rules used to calculate approximate depth to magnetic source.

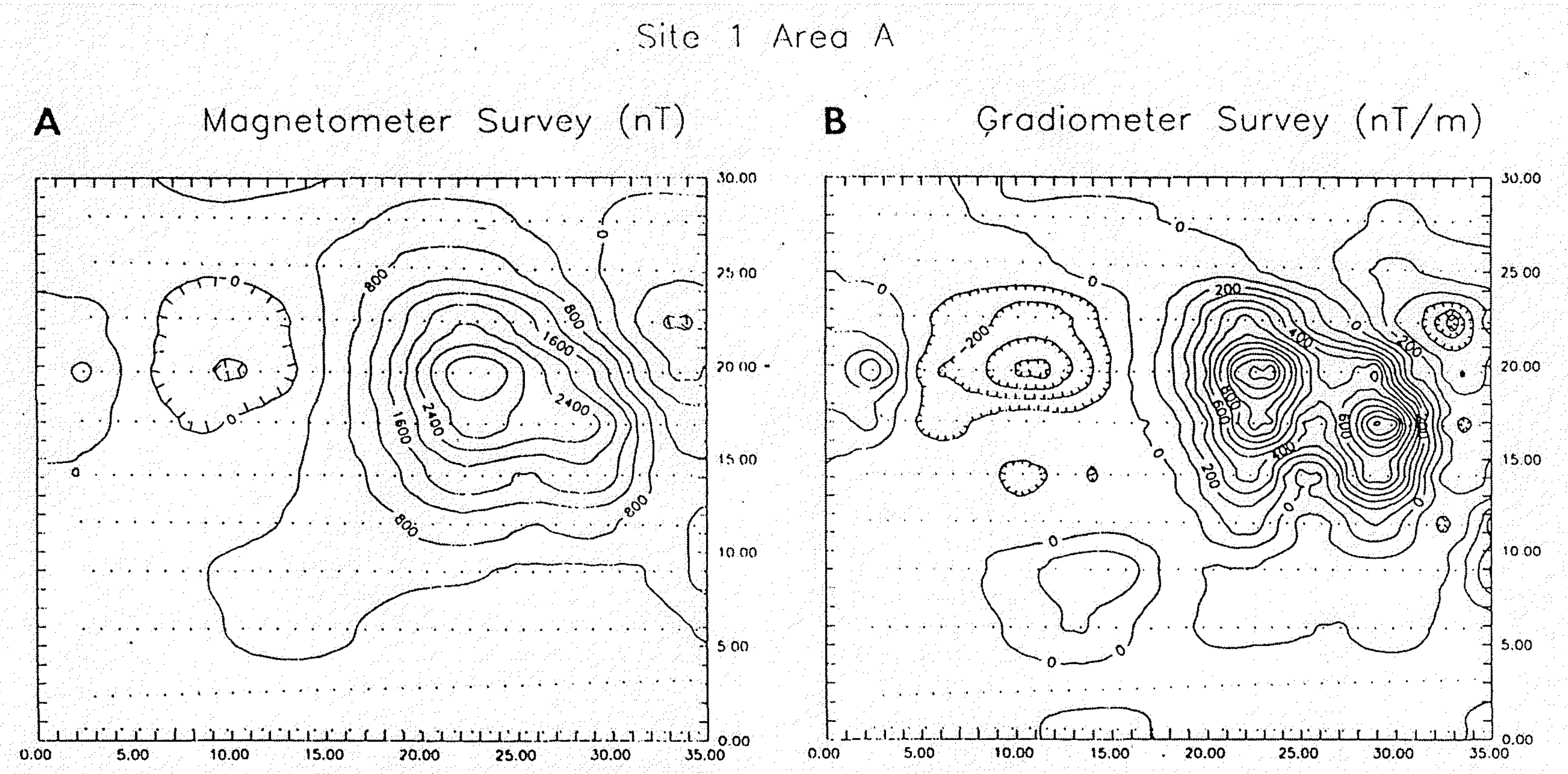



**Figure 4.** A) Contour map of anomalies in the earth's magnetic field strength for Area A of Site 1. Contour interval: 400 nT. B) Contour map of the vertical gradient of the earth's magnetic field strength for this site. Contour interval: 100 nT/m. The solid dots mark the locations of the observations. Horizontal distances are given in meters.

Figure 5M - Magnetic maps showing how a gradiometer survey increases resolving power on map.

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