DEVELOPMENT OF DETAILED GROUND MAGNETIC SURVEY INSTRUMENTATION AND ITS ROLE IN MINERAL EXPLORATION

by

JAMES RICHARD LOISELLE

A Thesis
presented to the University of Manitoba
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ABSTRACT

The magnetic method of geophysical exploration has been in use many years by the mining industry in its search for economic mineral deposits. Many of these deposits contain some magnetic minerals, notably magnetite, ilmenite, or pyrrhotite, which may be detected directly by the magnetic survey. During the early years of mineral exploration, balance and torsion magnetometers such as the Schmidt Z Field and Askania were in common use. These units were mounted on bulky tripods, requiring a 1-2 minute /reading set up time, depending on the skill of the operator. As a consequence of the long set up time, and the existance at that time of large, near surface ore bodies, a fifty or one hundred foot measurement interval was deemed adequate to detect these large bodies and maintain survey costs at tolerable levels. With the advent of the new electronic magnetometers such as the fluxgate and proton precession units, the largest consumer of time/measurement shifted from the magnetometer to the operator, who had to make the measurement and write its value in a log book. Even with the increased measurement speed of the new magnetometers mining companies maintained the use of the fifty and one hundred foot sample interval while conducting their magnetic surveys.

These conventional sampling intervals were maintained by the mining companies for primarily two reasons. First, it was a commonly held belief that the information content of the data collected using a continuous or near continuous sampling interval was not significantly greater than magnetic data collected using the conventional fifty or one hundred foot sample interval. Secondly, the survey cost and time required to conduct a ground survey, using a continuous or near continuous measurement interval, with conventional magnetic survey techniques and instrumentation was prohibitive.

Research by the author carried out in conjunction with his MSc thesis, has shown this reasoning to be erroneous in several aspects. First, inadequate sampling below the Nyquist frequency will lead toward a low frequency bias in the spacial frequency and amplitude information collected during the survey. Secondly, the distortion introduced by this low frequency bias will prevent the establishment of a distinct "signature" character which may be used to magnetically define geologic features beneath overburden. Finally, important geologic features of narrow width and long strike extent may be missed due to the lack of data redundancy in magnetic field data supplied by surveys using conventional sampling intervals.

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INTRODUCTION

1.1 DEVELOPEMENT OF THE DETAILED MAGNETIC SURVEY METHOD

The use of detailed sampling intervals while conducting ground magnetic surveys has been up until now primarily restricted to archeological surveys. The earlier use of balance and torsion magnetometers by the mining industry had precluded the use of detailed sampling intervals of five to ten feet, since the time and therefore cost limitations of such a survey were prohibitive. With the advent of the new electronic magnetometers such as the fluxgate and proton precession units, the ability to conduct detailed surveys became technically feasible. These new units were faster as they did not need the lengthy set up time required by the tripod mounted magnetometers, also the new magnetometers provided electrical analog outputs, allowing the interfacing of advanced data acquisition systems. The use of detailed surveys did not occur and the 50 and 100 foot sampling intervals continued to be used, partly as a carry- over from the tripod magnetometer days and partly due to the belief that the added information would not be significant enough to warrant the cost and time required to conduct such a survey.

Detailed ground magnetic surveys in archeology using various winching methods to provide a uniform, closely spaced survey have been in use for a number of years and described in papers published by Briener (1966), Ralph (1968), and Stanley (1975). This type of survey relies on the extreme sensitivity of the alkali vapor magnetometer (.001 nT), and a very detailed interval ranging from .1 to 1 meter to provide the spacial resolution to delineate any ancient buried structures such as walls, tiles, bricks, fire pits, etc., which commonly have dimensions less than 1 meter. This concept of using sampling intervals less than or equal to the dimension of the structure surveyed has its origins in digital data analysis, and has apparently been overlooked and certainly not implemented in the search for mineral deposits. C.D. Anderson, in two papers published in October and December of 1974, clearly demonstrated the value of nearly continuous ground magnetic surveys in mineral exploration. Nearly continuous surveys would reduce the probability of missing important, small scale (less than 15 feet wide) magnetic features of significant strike extent, and provide the data redundancy to better define the anomaly envelope of magnetically active zones. Some of the early ideas leading toward the concept of nearly continuous surveys applied to minerals exploration and geologic mapping were formulated by C.D. Anderson at the University of Manitoba in 1970. It was observed that magnetic field values collected during a ground survey over the Bird River Sill intrusive complex, exhibited higher frequency variations in amplitude as more detailed (10 - 15 foot) sampling intervals were used (Trueman, 1970). On further inspection it was determined that this high spacial frequency variation was caused by distinct zones or layers of mafic minerals (notably magnetite) within the sill. By using the smaller sampling interval, this fine structure within the sill was able to be observed.

The increased spacial resolution of surveys conducted at detailed sampling intervals of 5 - 10 feet was confirmed with observations made by Anderson and McGowan in 1973. A magnetic survey to determine whether the intrusive contact between the Falcon Lake stock and steeply dipping metavolcanics possessed a magnetic expression was initiated in 1973 as part of a BSc. field project. Initially, the survey used a 50 foot sampling interval, which yielded negligible results as neither lithology was found to produce any difinitive magnetic expression at this resolution level. Anderson, calling to mind successful results he had obtained using a smaller sampling interval, suggested that a 10 foot interval be tried. At this resolution level magnetic amplitude and frequency characteristics were seen to be quite different for each lithology. This difference was due mainly to the increased magnetite content and layered nature of the metavolcanics versus the low magnetite content, homogenous nature of the granite stock. Also a narrow, linear anomaly of large amplitude (8000 - 10000 nT) which was missed by the initial 50 foot survey, was resolved by the more detailed survey. This anomaly was caused by a narrow vein of pyrrhotite within the shear zone marking the contact between the two units, and extending for several hundred feet across the grid area. The observations made during this survey, and other detailed surveys carried out in Manitoba and Ontario, indicated that geologically valuable magnetic information regarding rock lithology, structure,and mineralization may be obtained from magnetic surveys conducted at detailed sampling intervals of 5 - 10 feet. An excellent summary of potential uses of detailed magnetic observations was made by D.G. Leckie (March, 1975) in his BSc thesis (University of Manitoba).

The 5 - 10 times greater spacial resolution achieved by detailed surveys yields a corresponding increase in the number of readings to be collected and plotted. This type of survey would be exceedingly costly to conduct, as well as very time consuming if conventional equipment and survey techniques are applied. It was realized that if detailed magnetic surveys were to become a viable exploration tool for industry, a much more efficient data collecton method would have to be developed and proven effective. This thesis is concerned with the development and testing of such a system, as well as demonstrating how the spacial resolution obtained from detailed magnetic surveys may aid in the location and interpretation of mineral deposits, as well as geologic mapping in overburden areas. The main design constraints affecting the development of such a system were cost, durability, data acquisition speed, and the presentation of survey results in a readily interpretable format.

1.2 DESIGN CONSTRAINTS OF INSTRUMENT DEVELOPMENT

The main design criteria controlling the planning and construction of instrumentation for this thesis were equipment cost, durability, weight, data acquisition speed, and output format.

The amount of funding available for the design and construction of the equipment was limited, so from the outset of the project it became obvious that shortcuts had to be taken in the design and construction phase of the system. These shortcuts consisted of modification, whenever possible, of existing commercial equipment rather than primary design. The main components involved in the modification scheme were a mini-chart recorder purchased from Linear Instruments of California, which was used for analog recording of the data, and a Canon P-10D calculator, which provided the digital output for the system.

The unit had to be rugged enough to withstand the extremes of temperature, humidity, and vibration which are often encountered while conducting magnetic surveys in the bush, while being light- weight enough to allow the operator to function in rugged mountainous terrain. The use of solid state components, the majority of which were built to military temperature specifications (-55 to +125 C.), generally alleviated instrument malfunction caused by extremes of temperature and vibration. This was demonstrated by the stable performance of the unit in such thermally diverse regions as southern British Columbia, where temperatures averaged 25 to 30 C. during the day, to mountainous areas in the Yukon where temperatures were commonly 0 to -20 C.. The components most affected were the batteries, as their performance degraded considerably at the lower temperature ranges. Humidity also played a major role in the design, as the unit had to be watertight to function in the rain and snow- storms regularly encountered in southern British Columbia and the Yukon Territory respectively. The weight and transport problems were solved by using a commercially available light-weight backpack frame, and medium gauge aluminum sheet for the instrument case. This combination limited the system weight to 20 pounds, which is evenly distributed to shoulders and hips, allowing 6 - 8 hours of continuous surveying with a minimum of aches and pains.

Since surveys of this type require magnetic field measurements at closely spaced stations (5 - 10 feet), a fast means of taking a reading had to be devised, as well as providing grid reference information. This was accomplished with a comparatively simple switching scheme, which is detailed in a later section. This switching method proved to be effective and fairly trouble free while collecting thousands of data points over the course of the 1979 field season.

For a detailed magnetic survey to be truly effective from an interpretation standpoint, the data must be presented in a form which allows monitoring of the magnetic data while the survey is being conducted, allowing immediate groundtruthing of any magnetically anomalous areas. Also a digital capability would be advantageous if the data is to be processed by computer at some later date. The characteristics of both analog and digital recording of near continuous magnetic field have been compiled in Table 1, which shows the comparative advantages and disadvantages of each format type. It is apparent when viewing the format characteristics chart that the main feature common to both format types is the 'real' time saving resulting from auto-recording of the magnetic field values. This auto-recording feature saves time in two ways: first, it releases the operator from the data acquisition task (he does not have to write the value in a book), and secondly, the data point is plotted automatically, saving camp time which is usually spent plotting the data, thus speeding presentation of the results to the head office. Two other characteristics which are of considerable importance are the "Quick Look" ability of the analog format, and the unlimited dynamic range and interfacing capabilities of the digital format.

Consideration was given to logarithmic plotting on the chart record in an attempt to reach a compromise between these two data formats. However, the logarithmic plot could prove difficult to use if any quantitative measurements were to be made on any large amplitude anomalies, and the scale distortion introduced would preclude easy interpretation by the untrained eye, since it is difficult to work in a non-linear format. Therefore so as to maintain the effectiveness of the two formats, the system was designed to employ both analog and digital formats either singly or in parallel, yielding a hybrid acquisition system incorporating the best characteristics of each format.

TABLE 1

FORMAT CHARACTERISTICS - ANALOG and DIGITAL

ADVANTAGES

Analog Format	Digital Format
1).“Quick Look Ability”- able to see data in profile form, allows operator to observe and analyze magnetically anomalous areas while conducting the survey.	1).No dynamic range problem, restricted only by magnetometer sensitivity.
2).“Real Time” saving, since the analog signal is plotted immediatly upon acquisition. Time savings of up to 30 seconds per reading.	2).Allows ease of computer interfacing.
3).Point of cultural noise or geology may be marked directly onto the chart record, or indicated by fiducial system.	3).Varied storage methods; A.Magnetic tape B.Hard copy printout

DISADVANTAGES

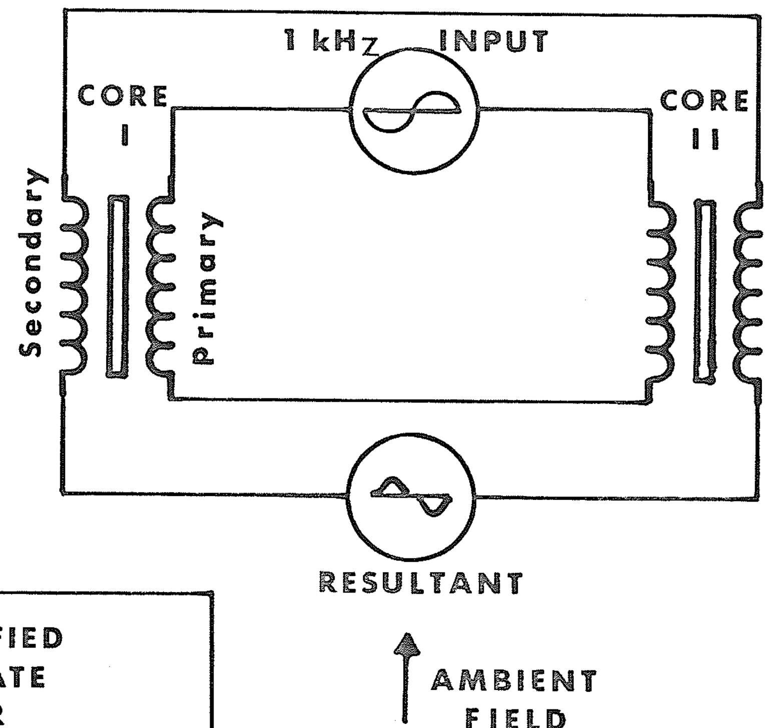
Analog Format	Digital Format
1).Dynamic range problem, since the dynamic range of an analog recorder is restricted by the physical dimensions of the chart record.	1).No “Quick Look” ability as a numerical format is visually difficult to interpret.
2).Digitation error involved in any computer interfacing and and conditioning routines.	2).Must have more complex electronics for signal conditioning.

1.3 COMPONENT DESCRIPTION AND DESIGN--(FLUXGATE MAGNETOMETER)

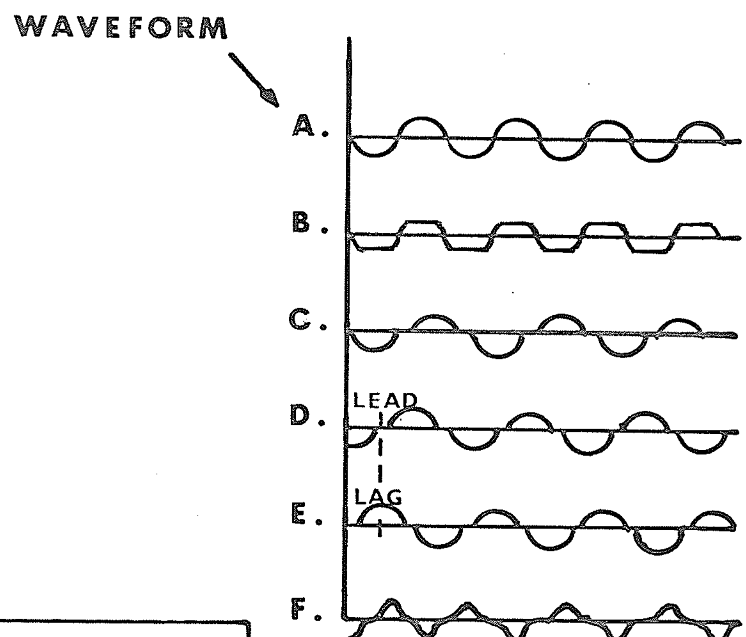
The magnetic field sensor used with the system is a Scintrex Model MF-2 Fluxgate magnetometer, which is a rather compact unit, measuring 6.5"x2.25"x10.0", and weighs approximately 5.75 pounds. The unit has five scales (1K, 3K, 10K, 30K, 100K nT.), and a maximum sensitivity of 20 nT./division, on the 1K nT. full scale setting.

The field sensing element of the fluxgate or "saturable core" magnetometer consists of two strips of highly permeable material such as Mu metal, which are laminated to reduce eddy current losses. The permeability of this core material is such, that the earth's magnetic field induces a magnetization which is a significant part of its saturation value. A 1 kHz sine wave current is passed through the primary coils, which are wound around the two laminated cores figure (1). These cores are magnetized with the same flux density but in opposing directions, since the primary windings are wound clockwise around core 1, and counter-clockwise around core 2. Now when the earth's steady state magnetic field is superimposed upon the cyclically varying field within each core, it will add to the magnetization in one core, and oppose the magnetization in the other. This will have the dual effect of causing one core to reach saturation early in the cycle, while the second core saturates later in the cycle, these phase relationships are illustrated in figure

(2). The respective advance and retardation of the saturation interval within each core will cause the sine waveforms which are induced within the secondary coils, to lead or lag the other an amount depending on how early or late in the cycle saturation occurs. When the secondaries from each core are connected in opposition, a waveform results (see curve F, figure 2) whose height is proportional to the ambient magnetic field strength. This signal, which varies between 0-100 mV. is accessed to both the analog and digital arms of the system simultaneously upon closing of the Data switch, which is located within the Control box on the magnetometer (figure 12).

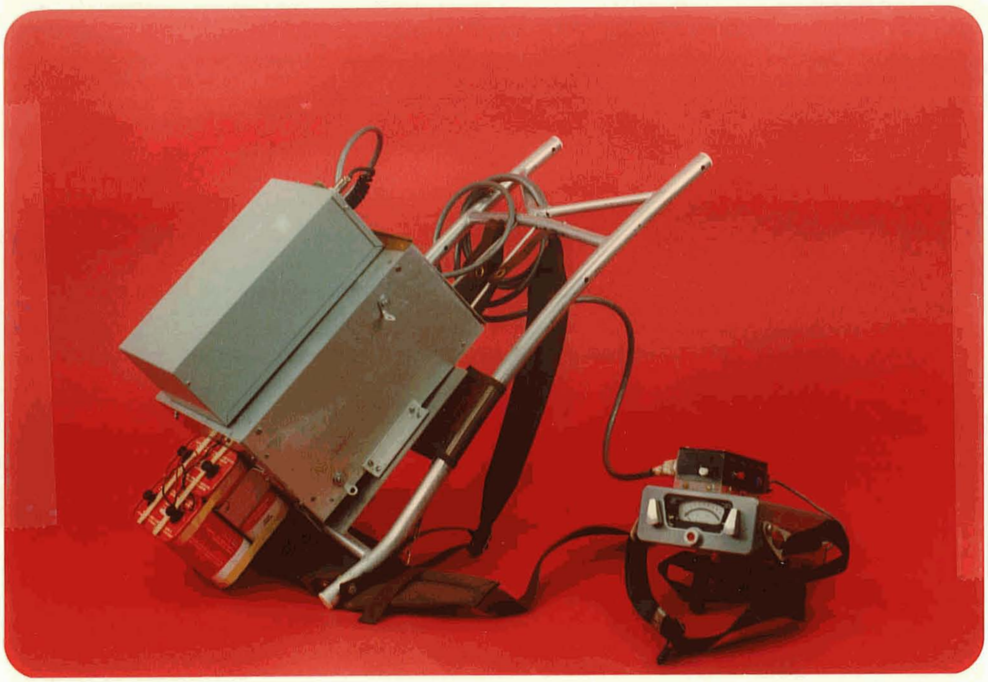


SIMPLIFIED FLUXGATE SENSOR
FIGURE 1.



INDUCED CURRENT PHASE RELATIONS
FIGURE 2.

Figure 3: Photograph of Detailed Magnetic Survey Equipment



1.4 COMPONENT DESCRIPTION AND DESIGN--(DIGITAL SECTION)

1.4.1 Description

The digital arm of the Detailed Magnetic Profiling System is housed in an aluminum case measuring 4"h x 7"w x 12"l, and mounts on top of the analog case with four screws (Figure 1.3). The unit is encased in 1" thick styrofoam panels, which are in turn wrapped with aluminum tape (not shown). The tape gives the styrofoam some resistance to breakage and thermal effects. Electrical connection between the magnetometer and analog-digital sections is provided by six conductor and four conductor Canon military connectors, while power to the unit is controlled by a single pole-single throw switch mounted on the front of the case. The weight of the unit is 7 pounds with battery, and 2 pounds without the battery, making the battery the largest contributor of weight to the system. The battery, which is a lead- acid Gel Cell type chosen for its recharging capabilities, is rated for a discharge of 250 mA. over 20 hours, allowing the unit to function several days on one charge.

1.4.2 Power Supply Circuit

Voltages for the operational amplifiers and logic components of the digital section of the system, are provided by the power supply circuit shown in figure (5). This power supply is designed around a ua791P5C power operational amplifier, which provides a maximum current of 700 mA. as determined by the value of output resistor RSc. The regulated 12 volts provided by the MC7812CP positive voltage regulator is split into + and - 6 volts, by the voltage divider network located in the feedback loop of the operational amplifier, with fine adjustment provided by a 10 K-ohm potentiometer. The gain of the circuit is determined by the value of Cc, which for a 100 pF capacitance equals one.

1.4.3 Amplifier Circuit

A 0 - 100 mV. DC current is produced by the fluxgate sensor as the direct electrical analog of the vertical magnetic intensity component. For this signal to be compatable with the ADC3711 (analog to digital converter) signal input requirements it had to be amplified. This single stage amplification is accomplished using a Fairchild ua741 operational amplifier in a non-inverting configuration (Figure 6). The output of the amplifier is attenuated by a 50 K-ohm potenticmeter in its feedback loop to match its output with that of the 2 volt precision reference of the A/D converter, where it is accessed directly to pin 9 (v filter) of the ADC3711CN.

1.4.4 Analog / Digital Converter Circuit

The conversion of the 0-2 volt analog output of the amplifier to a binary coded decimal format is accomplished by the circuitry shown in figure (7). The heart of the circuit is the ADC3711 analog to digital converter, which is a monolithic device using MOS (CMOS) technology. The conversion process is initiated within the converter when the Data switch mounted in the Control box on the magnetometer is closed, triggering a 555 TC timer circuit, set up in a monostable mode. This timer circuit is used to negate any effects of switch bounce, which may occur as the Data switch opens and closes, causing false triggering pulses to be input to the converter. This monostable circuit generates an output pulse of width T=1.1Rt Ct, which for this circuit is .011 seconds, producing a clean low to high trigger pulse at the start conversion terminal (pin 7, ADC3711). When this low to high transition occurs, the converter begins to transform the analog signal from the amplifier into a binary coded decimal. The rate of this conversion is set by an internal oscillator within the device. The frequency of this oscillator may be varied by changing component values in an external R-C network, as shown in figure (7, pins 17 and 18 - ADC3711). At the end of the conversion cycle a conversion complete pulse is output from pin 6 of the ADC3711. The BCD digits are selected on demand by two digit select inputs D0 and D1 (pins 20 and 21). These digit select inputs are latched by a low to high transition on the digit latch enable input (DLE), and remain latched as long as the DLE remains high. The pulse modulation circuitry shown in figure (9) produces a precise sequence of low to high pulses at the two digit select inputs. The state of each digit select input relative to the other then determines which of the four BCD digits will be output from the ADC3711 (pins 23, 24, 3, 4).

As each BCD digit is output by the ADC3711 it is decoded by a National DM7442N BCD/Decimal decoder. Each of the output pins of the decoder corresponding to the digits 0-9 (pins 1,2,3,4,5,6,7,9,10,11) are then connected to the relay contacts of the ten PRME Picoreed dip relays seen in figure (9). As each BCD digit is output by the ADC3711, a high to low transition occurs at the output of the corresponding decimal digit on the decoder, which provides a current sink of up to 16 mA, and actuates the relay for that digit.

The interfacing between the digital circuitry and the Canon P-10-D calculator occurs when the appropriate relays are actuated, connecting calculator line 11 to the appropriate scan lines of the calculator (Figures 9 and 10), representing the digit output by the ADC3711. This digit is then stored in the calculator memory, while each suceeding decimal digit of a four digit sequence, is output and stored in the same way. When all four digits representing the magnetic field value are stored in the calculator, timing circuitry turns the decoder off and actuates the print command within the calculator. After this field value is printed the print command is turned off and the decoder returns to the ready state, awaiting the next input from the converter.

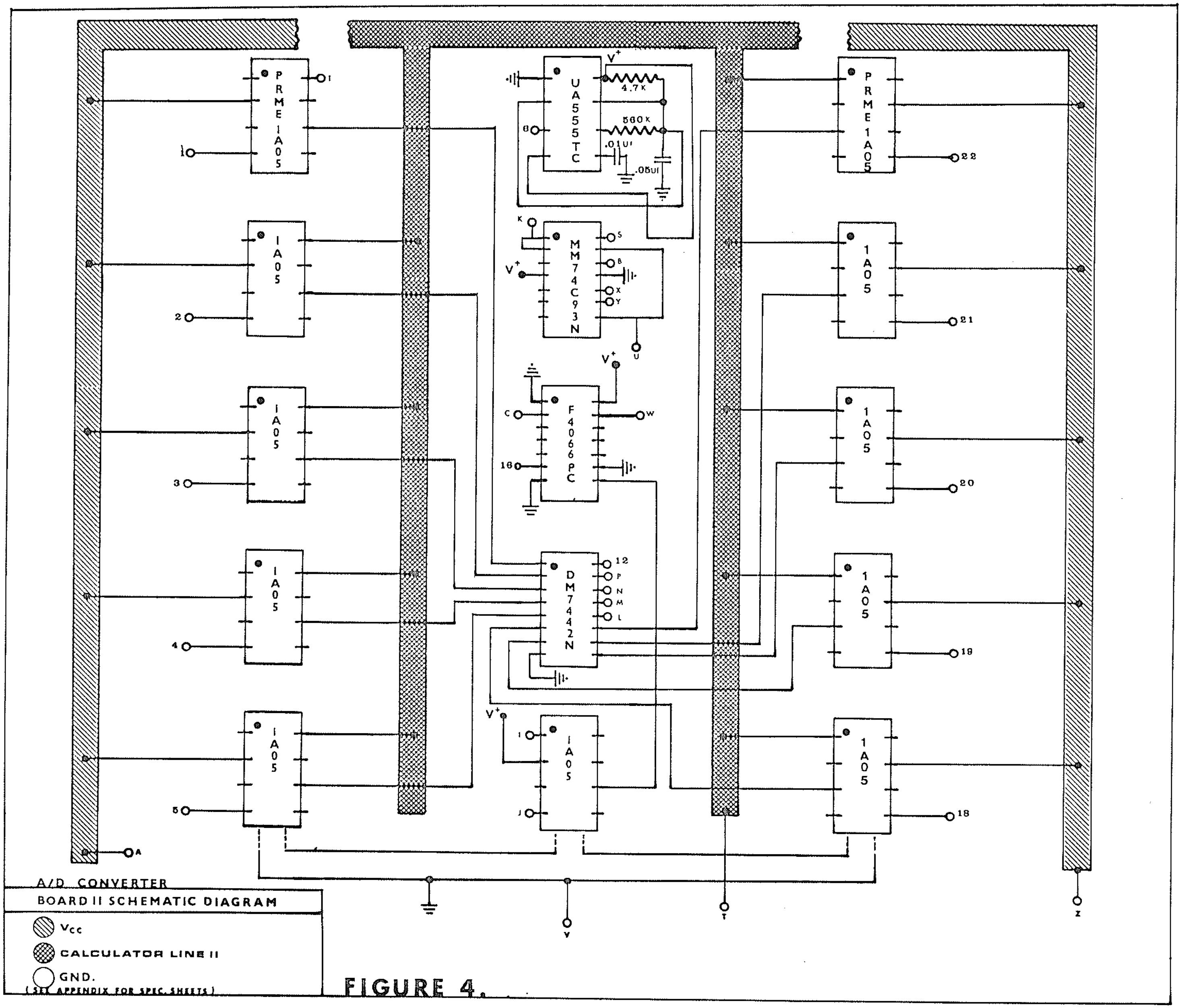
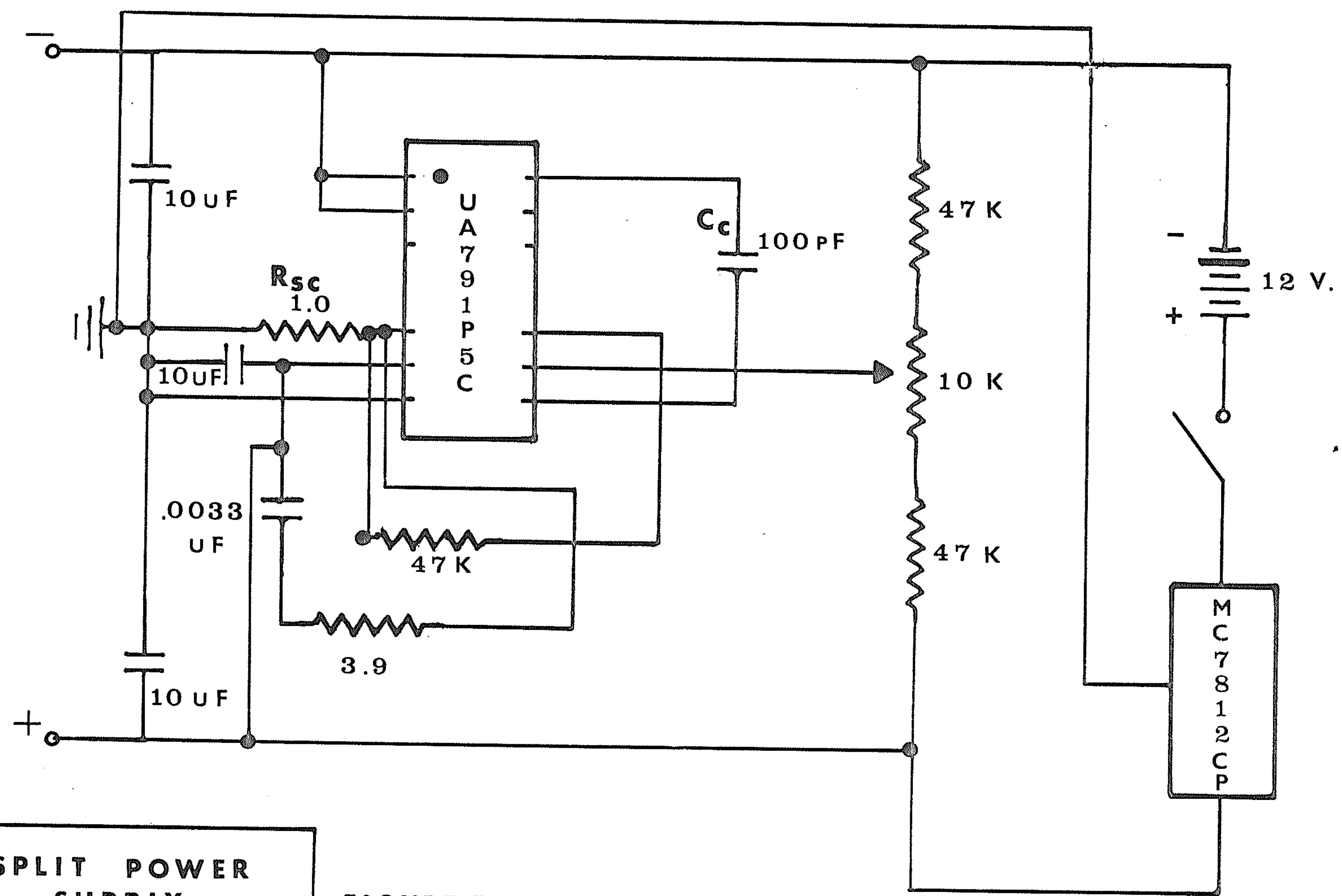

A/D CONVERTER
BOARD II SCHEMATIC DIAGRAM
Vcc
CALCULATOR LINE II
GND.
(SEE APPENDIX FOR SPEC. SHEETS)
PRME IA05
IA05
UA555TC
4.7K
560K
.01Uf
.05Uf
MM74C93N
F4066PC
DM7442N
V+

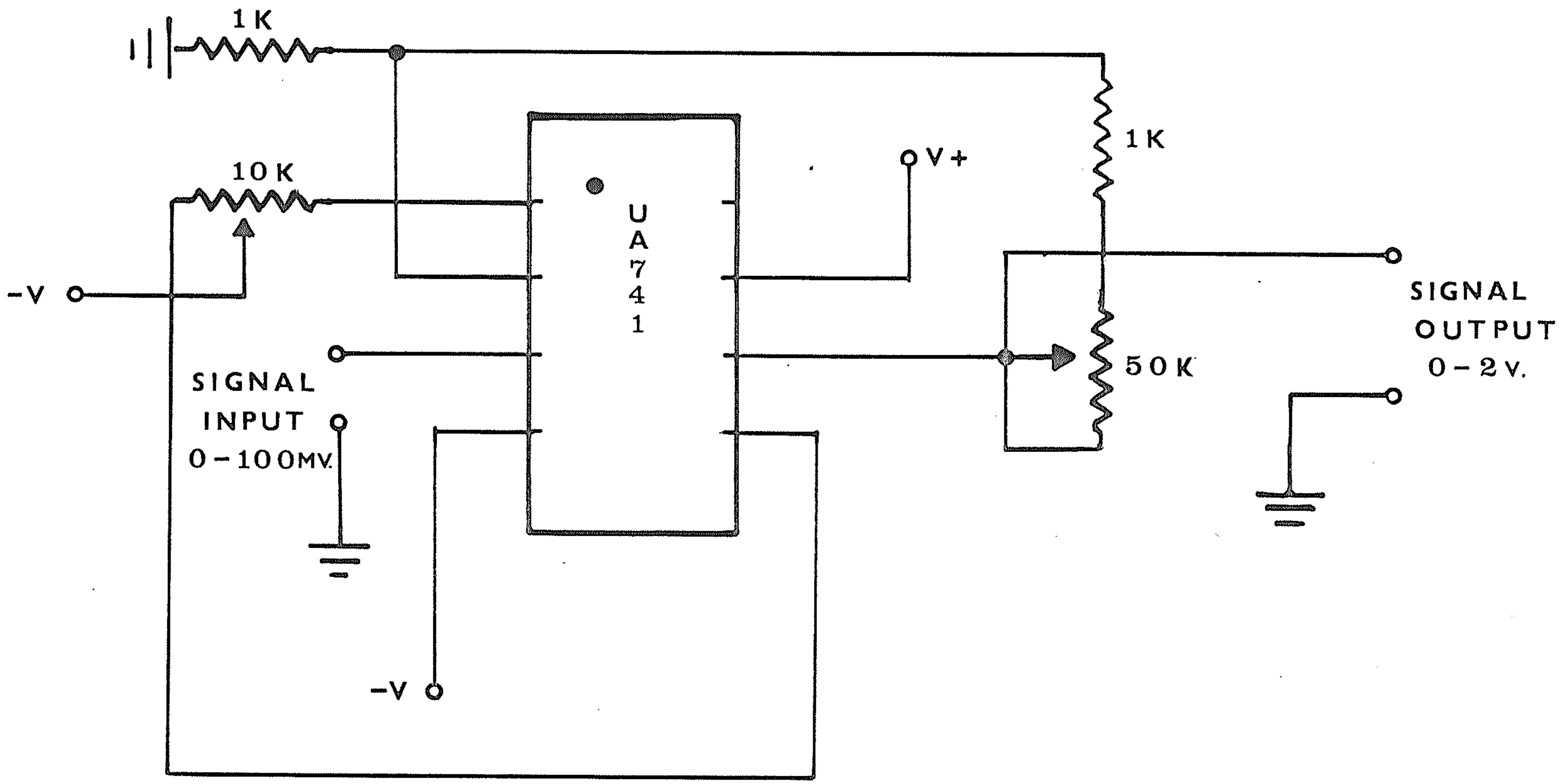
FIGURE 4.



SPLIT POWER SUPPLY

(Ref. Board 1)

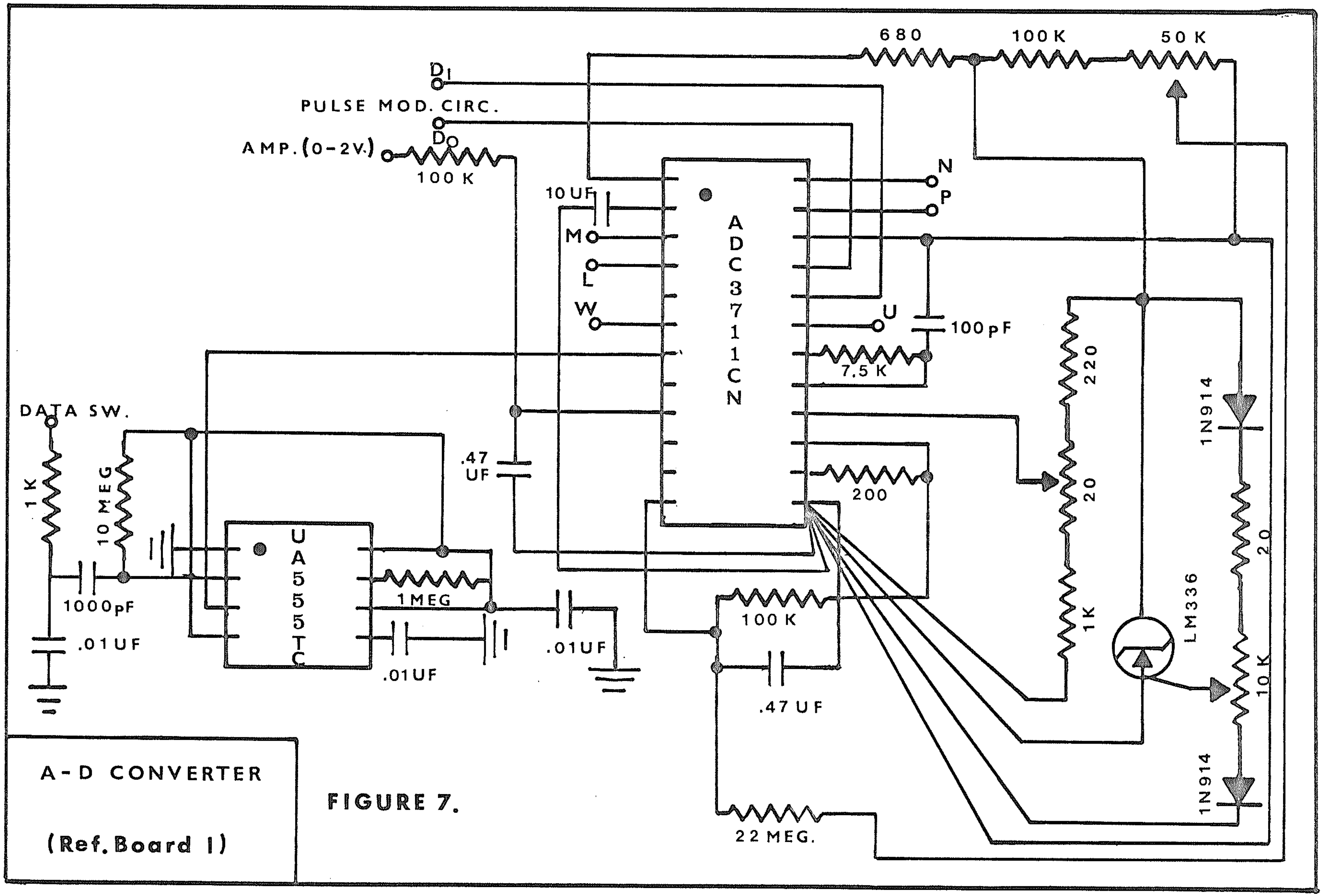
FIGURE 5.



AMPLIFIER SECTION

(Ref. Board I)

FIGURE 6.



A-D CONVERTER

(Ref. Board 1)

FIGURE 7.

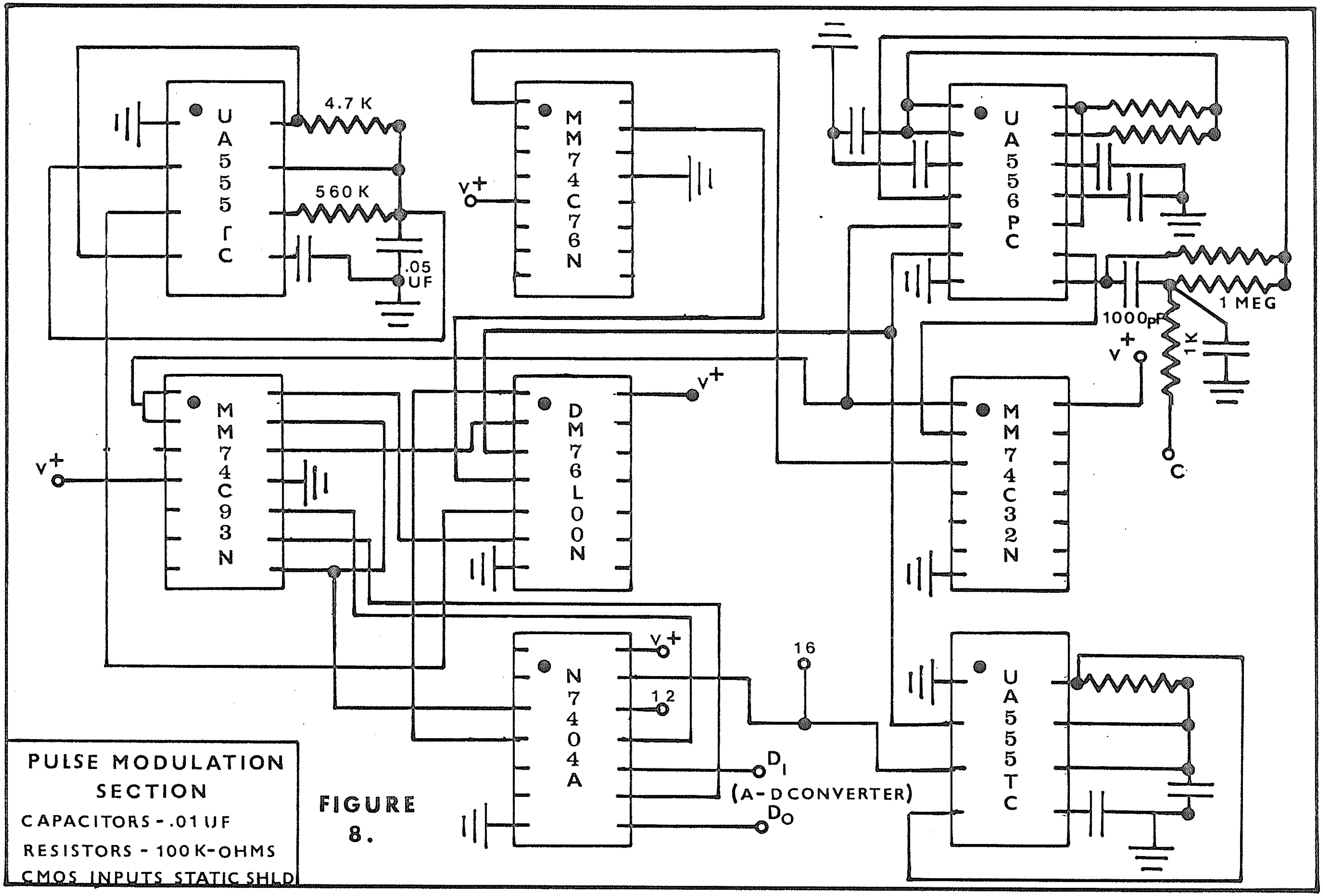
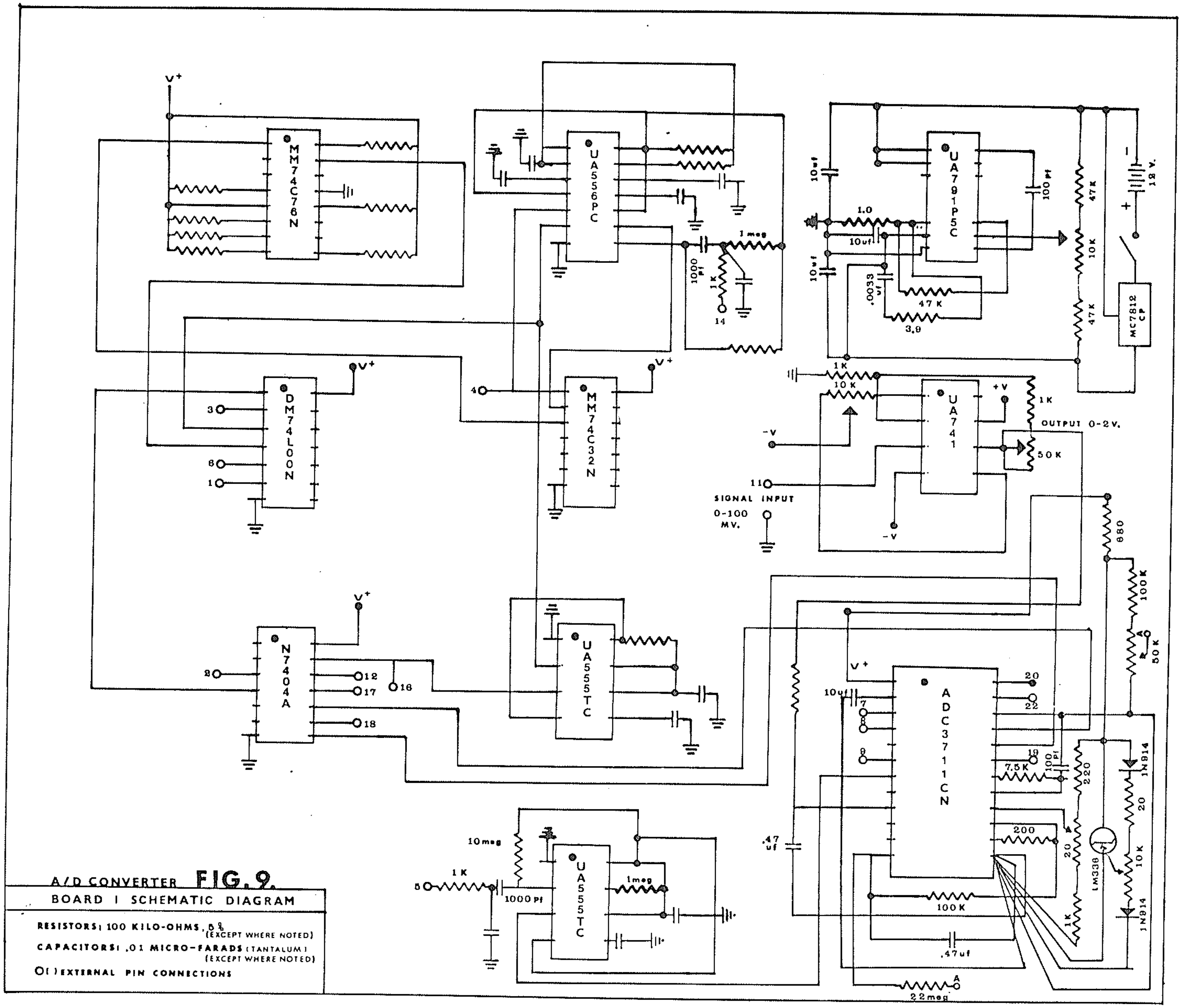

4.7 K
560 K
.05 UF
MM74C76N
V+
UA556PC
1000pF
1 MEG
1K
C
MM74C93N
DM76L00N
MM74C32N
N7404A
16
12
D_I
(A-D CONVERTER)
D_O
UA555TC
PULSE MODULATION SECTION
CAPACITORS - .01 UF
RESISTORS - 100 K-OHMS
CMOS INPUTS STATIC SHLD

FIGURE 8.



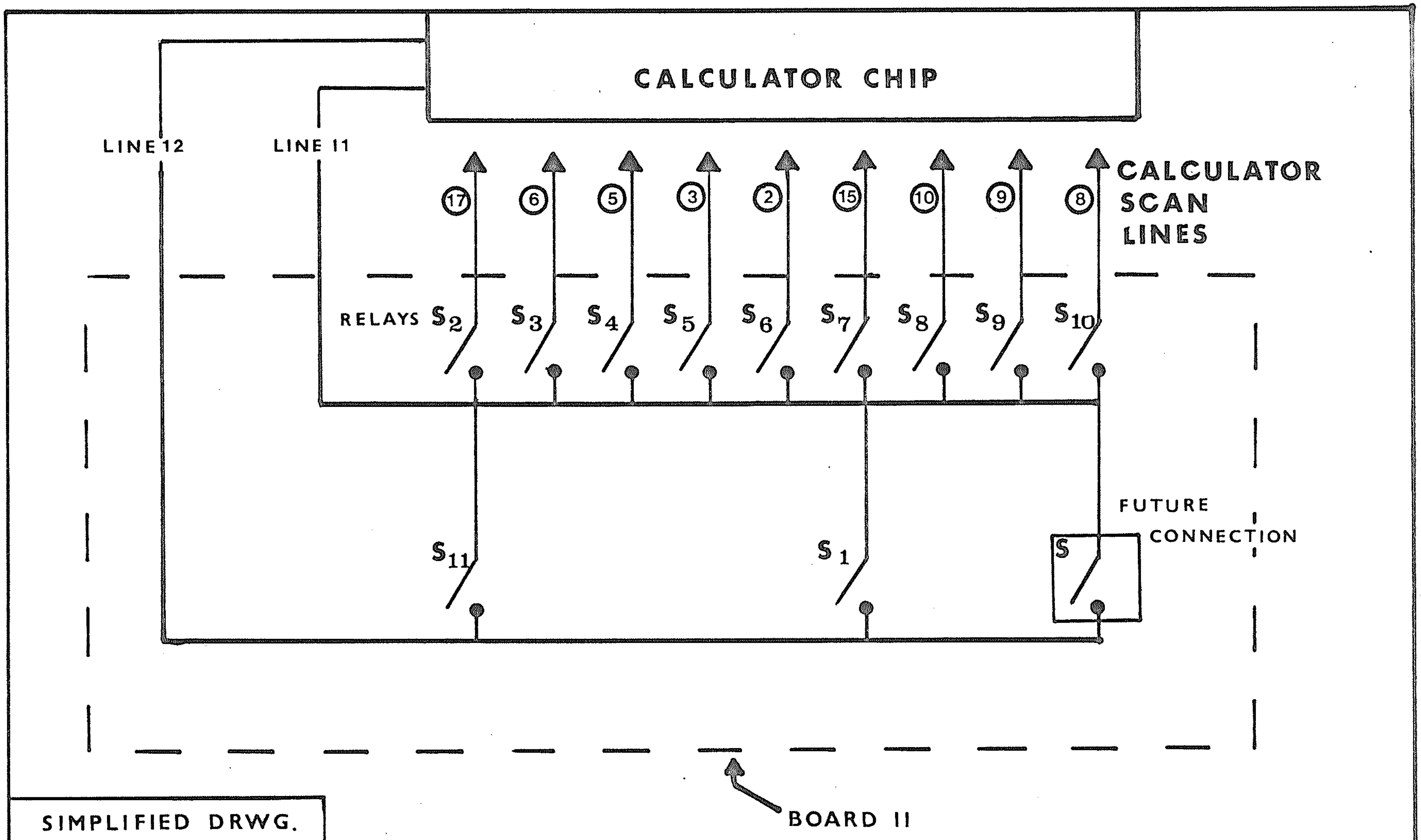
A/D CONVERTER **FIG. 9.**

BOARD I SCHEMATIC DIAGRAM

RESISTORS: 100 KILO-OHMS, 5% (EXCEPT WHERE NOTED)

CAPACITORS: .01 MICRO-FARADS (TANTALUM) (EXCEPT WHERE NOTED)

O( ) EXTERNAL PIN CONNECTIONS



SIMPLIFIED DRWG.
BOARD 2 - CALC.
INTERFACE

FIGURE 10

1.5 COMPONENT DESCRIPTION AND DESIGN--(ANALOG SECTION)

1.5.1 Description

The analog section of the Detailed Magnetic Profiling unit is housed in a rugged aluminum case measuring 6.5"h x 10.5"w x 13"l, with a (.125") wall thickness. The case is lined with a .5" thickness of styrofoam, to moderate both thermal and vibrational shock to the recording unit. All the metal-metal joins are sealed with G.E. silicone cement, to both wind and waterproof the unit. A sealed plexiglass plate is mounted in the front of the case to allow visual access to the chart record without opening the unit. The casefront is also hinged to allow easy access to the recorder mechanism and graph. All electrical connections interfacing the magnetometer to the analog and digital units are made by Canon military jacks, enabling electrical connection to be made without breaking the integrity of the weather seal. The unit is mounted on a light-weight aluminum backpack frame for ease of movement and weight distribution. The total weight of the analog system including batteries is approximately 20 pounds. The power source for the unit is a 12 volt lantern battery which can be quickly mounted or dismounted from the rear of the unit by undoing two screws.

The chart recorder unit itself measures 6.0"h x 9.0"w x 10.7"l, and weighs approximately 11 pounds. It has multiple span input ranges from 1 mV. to 10 V., with variable attenuation to 100 volts DC. The chart drive has ten speeds ranging from .5 cm./hour to 10 cm./minute, and uses 30 m.x .1 m. rolls of chart paper, as well as disposable fiber pens. The majority of the electronics are CMOS, placing very little current strain on the battery. The largest power consumer within the unit is the stepper motor used to advance the chart record. This power consumption is minimized by electronically turning off power to the motor between step pulses. The battery life has been found to be excellent, as shown by use in such thermally diverse and rugged areas as southern British Columbia (ave. temp.80-90 F.)and the Yukon (ave. temp.less than 30 F.), lasting an average of two days with 7 - 8 hours of use each day. The unit has been modified internally to make it suitable for detailed magnetic surveys, while keeping the external control functions intact.

1.5.2 Circuit Design

Circuit design for the analog section of the system centered about two main criteria. First, readings are to be made at discrete points during the course of the survey. Secondly, an efficient method of interfacing the magnetometer to the chart recorder unit had to be found.

The first criterion was satisfied using a timer-gating circuit in conjunction with the stepper motor circuitry present in the unit. This circuit (Figure 11) is designed around an SE555 timer and a CD4011 Quad Nand gate (And gates were not available during circuit construction so series Nand gates were substituted). Circuit operation begins when either Chart Advance switch 1 or 2 , mounted respectively in the Control box on the magnetometer and on the recorder unit, are closed. When this occurs a negative trigger pulse starts a two second timing interval within the SE555 circuit, resulting in a two second "high" output pulse. As a consequence, pin 2 of Nand gate 1 goes high for two seconds, while pin 1 which is connected to the stepper- driver oscillator of the recorder, goes alternately "high" and "low" at a frequency dependent on the chart speed selected. The current to the stepper motor is logically Anded for as long as pin 2 remains in a "high" state, supplying current to the motor for the timing cycle. In this way the spacing between the discrete readings may be changed by merely switching to a lower or higher chart speed.

The second criterion providing for a means of efficiently interfacing the magnetometer to the recording unit is satisfied by the circuit shown in figure (12). In this circuit, a series of switches called the Chart Advance switch 1, Fiducial switch, and the Data switch are mounted in the Control box unit on the magnetometer. This control unit is connected to the recorder by means of a six conductor shielded cable, and allows the operator to switch the electrical analog signal produced by the magnetometer into the chart recorder and or digital unit, if a digital output is required, by closing the Data switch. The chart record is then incremented forward one unit by closing the Chart Advance switch 1. If the particular sample location occurs at a grid picket or feature of geologic interest, its location may be noted on the chart record by closing the Fiducial switch, thereby placing a fiducial marker along the side of the chart record. This particular feature is useful for the subsequent alignment of the profiles by station number during the data interpretation stage.

As previously mentioned the chart may also be incremented forward by Chart Advance switch 2, which is mounted on the recorder unit. Alsc located on the recorder unit is the Polarity Inverter switch which reverses the polarity of the magnetometer signal at the inputs to the chart recorder unit. This feature allows the pen plot direction to be reversed, allowing profiles to be plotted in inverted form. This feature is again useful during grid surveys when alternate grid lines are magnetically surveyed in an alternately forward and reverse manner to save survey time. For example, if line 1 is surveyed from station 0 to station 9, the surveyor upon completing station 9 will cross over to line 2 and magnetically survey line 2 from station 9 to station 0. If the profile from line 2 was not inverted relative to line 1, the station order would be reversed, making subsequent stacking of the data impossible. The length of the increment is controlled by the chart recorder speed setting, allowing a maximum spacing of 3 mm. and a minimum spacing of less than .1 mm.

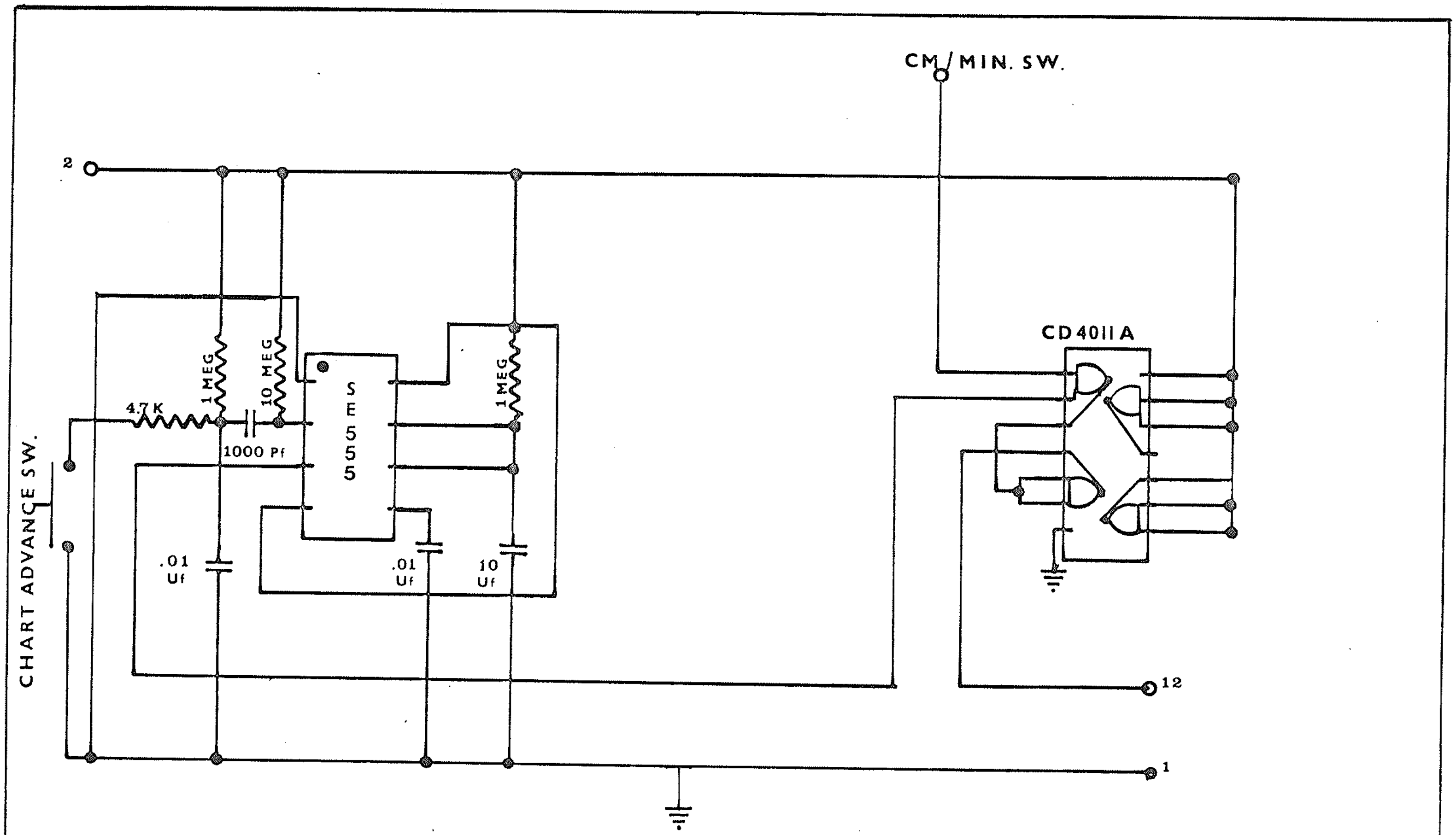
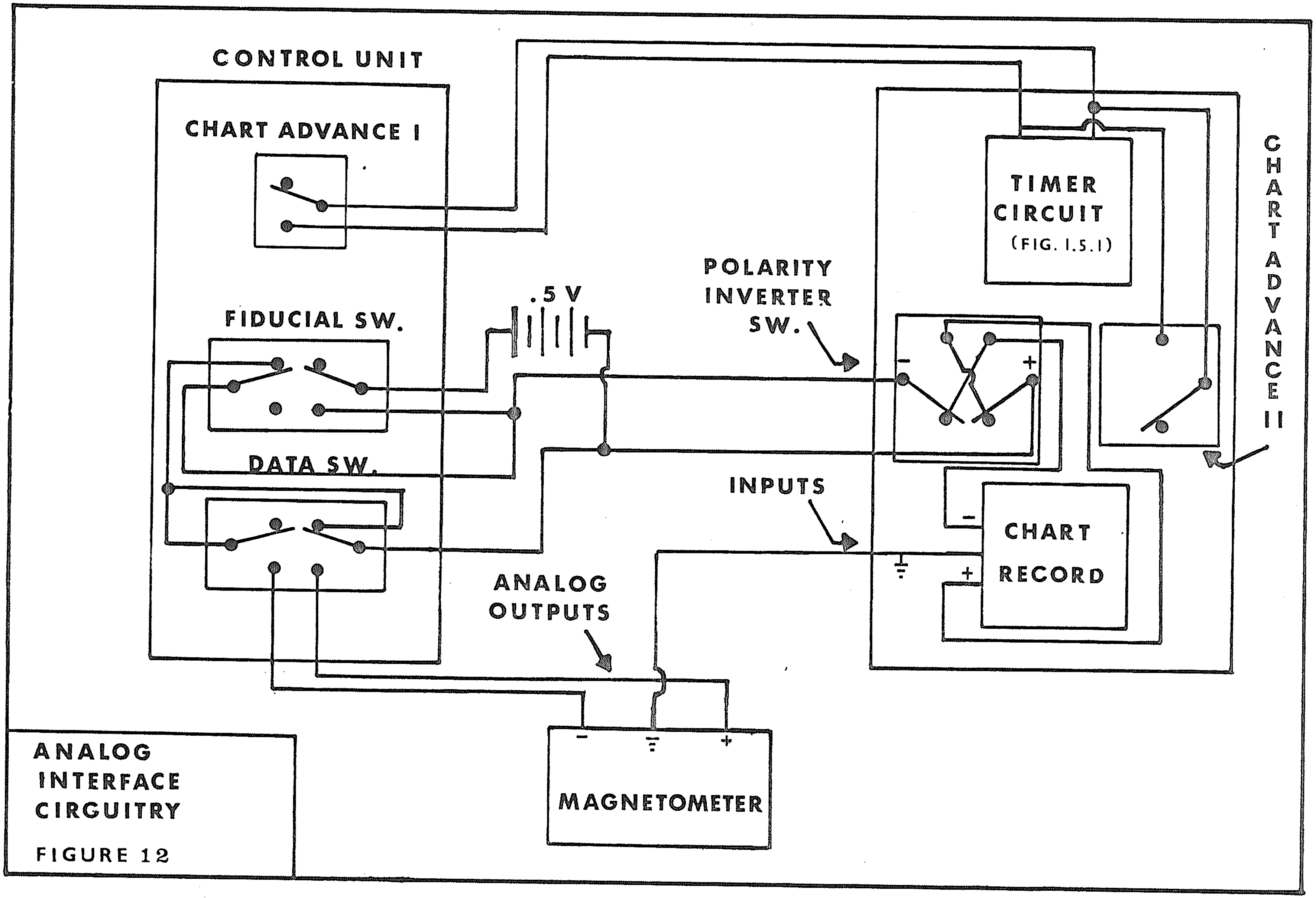


CHART ADVANCE CIRCUIT

O ( ) STEPPER BOARD PIN NUMBER

FIGURE 11



ANALOG INTERFACE CIRCUITRY

FIGURE 12

Chapter II

ALIASING EFFECT

2.1 INTRODUCTION

One of the major problems involved in the collection of magnetic information at "conventional" sampling intervals of 50 or 100 feet, is aliasing of the data. Aliasing occurs when the sampling frequency is less than one half of the signal frequency, effectively cutting off frequencies greater than one half of the signal frequency. This cutoff point is termed the Nyquist frequency, and is sometimes termed the fold frequency.

Figure (13) demonstrates that if a periodic function possessing given frequency and amplitude characteristics is sampled at discrete points with a frequency less than the Nyquist frequency, a waveform devoid of the original frequency and amplitude characteristics will result (aliased waveform). This effect then manifests itself in actual survey data by decreasing the frequency and amplitude content of the profiles as progressively larger sampling intervals are used. An area of significant magnetic activity which has been sampled using 10, 50, and 100 foot sample intervals is shown in figure (14).

ALIASING EFFECT

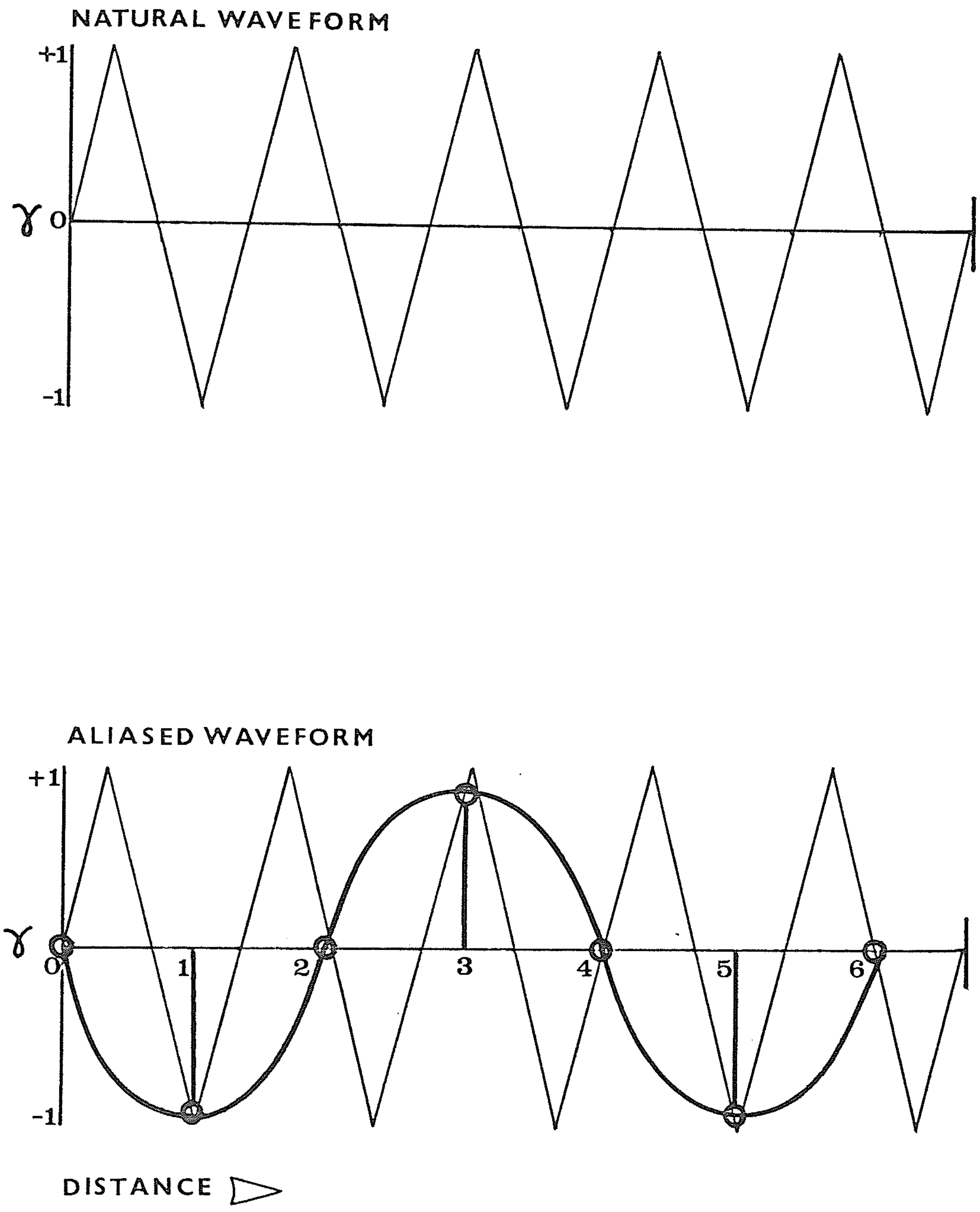
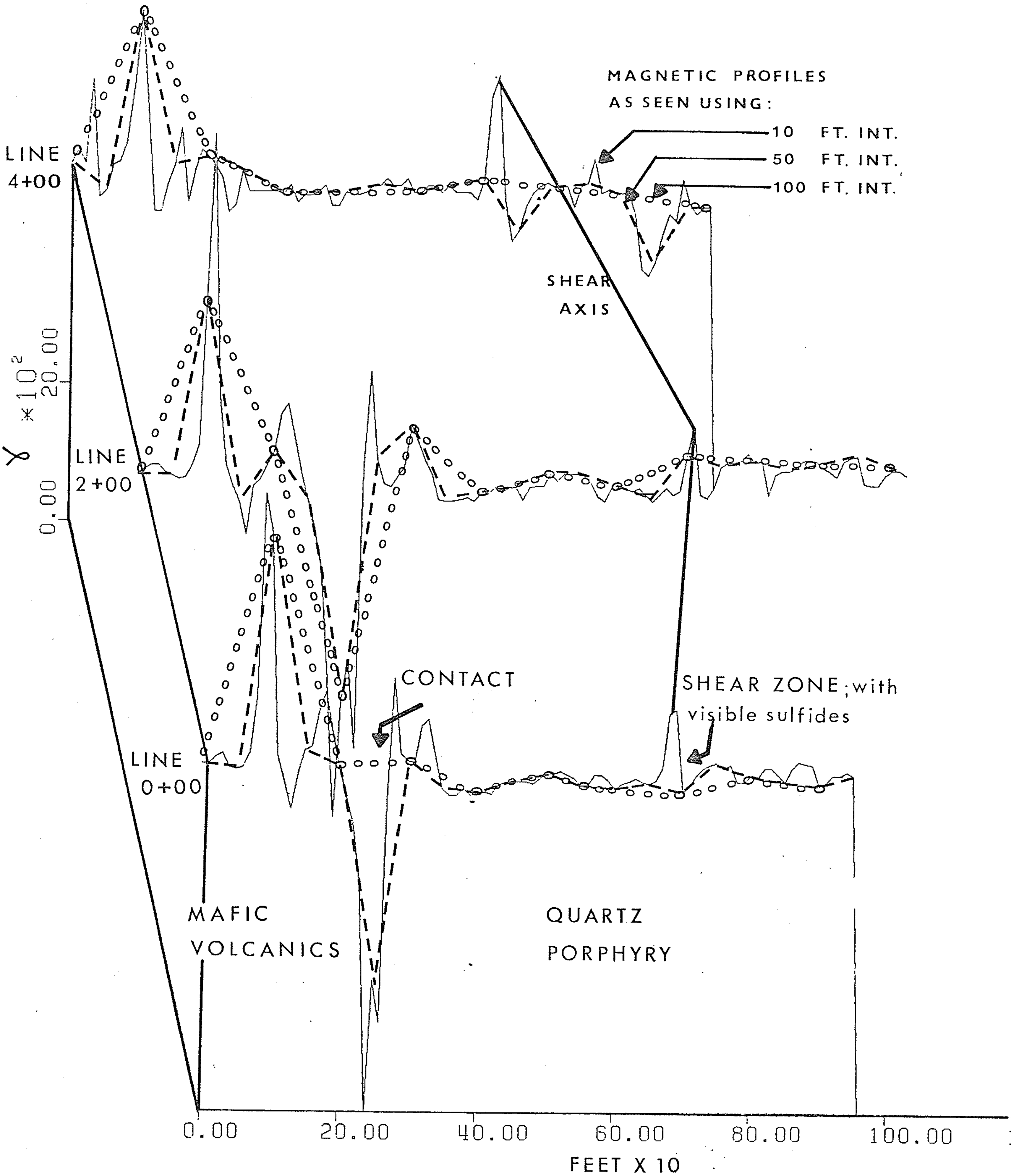


FIGURE 13

2.2 FIELD EXAMPLE

Figure 14 represents a geophysical grid located near Falcon Lake in northwestern Ontario. The grid lines strike magnetic E-W and are spaced 200 feet apart. The grid is situated on the contact between a plutonic intrusive consisting of quartz porphyry, and a mafic volcanic suite composed of andesite flows. The magnetic disparity between the andesite and quartz porphyry is quite evident in the survey results shown in figure (14). At the 10 foot interval (solid line) the quartz porphyry is characterized by fairly low amplitude (+/- 90nT.), short period variations of 10 to 20 feet, while the andesites are typified by high amplitude (+/- 475 nT) variations, with periods ranging between 20 and 40 feet. The survey results obtained by using a 50 foot sampling interval, show a distinct low frequency bias due to aliasing. This bias toward the lower frequencies causes the short period variations seen at a 10 foot sample interval to increase in dimension, reaching lengths of 100-150 feet within the quartz porphyry, and 75-100 feet within the andesites. This aliasing phenomena also affects the amplitude in a negative way by decreasing the amplitude range of the porphyry from +/- 200 nT. at the 10 foot sample interval, to +/- 100 nT. at the 50 foot sample interval. Within the andesites amplitude values decrease from the +/- 475 nT. range seen at the 10 foot sample interval, to values of +/- 230 nT. at the 50 foot sampling interval. This aliasing trend continues in the survey data obtained using a 100 foot sampling interval, with a further decrease in the amplitude range and a lengthening of the period of the magnetic variations within each rock unit.

The general lack of resolution inherent in most magnetic ground surveys carried out today may result in missing important small scale geologic features, or economic concentrations of minerals in veins of long strike length and narrow width. This problem is evident in figure (14), where the shear zone, having a narrow width of 10-15 feet, is missed on line 2+00 W. at both the 50 and 100 foot intervals. This sort of feature, lacking apparent continuity would be considered a discontinuous, single station anomaly, and be discarded as a magnetic boulder or some other form of geologic or cultural noise. In actuality however, the feature when observed with the higher resolution survey, is seen to be quite continuous and relevent to the structural regime of the area, as it can be seen paralleling the intrusive contact.



FALCON LAKE GRID - LINES 0+00 TO 4+00 WEST

FIGURE 14

Chapter III

MAGNETIC SIGNATURE CHARACTERIZATION APPLIED TO MINERAL EXPLORATION

3.1 INTRODUCTION

The importance of magnetic signature characterization in geology and geophysics cannot be overemphasized, particularly in the shield areas of Canada and the United States. These areas are characteristically covered by a veneer of glacial debris which ranges in thickness from 0 feet to greater than 50 feet, with average depths of 5-10 feet. As a result very little outcrop is exposed, making geologic mapping and interpretation extremely difficult. A well defined magnetic signature, which is determined by its spacial frequency and amplitude characteristics, can only be observed if the sampling interval is less than or equal to one half period of magnetic variations within the rock type under examination. If observations are not made using this criterion, a bias toward lower frequency, low amplitude magnetic variations will be introduced, seriously distorting the observed signature (see aliasing section).

Susceptibility contrasts between rocks of differing lithologies, and remanence effects, such as normal and reversed magnetic polarities, are two of the most important factors involved in determining the spacial frequency and amplitude characteristics of the earth's magnetic field as seen during a ground based magnetic survey. Quite a large body of literature resulting from numerous paleomagnetic studies exists, and may be used to derive several broad generalizations concerning the magnetic behavior of rocks.

Work done by Mooney and Bleifuss (1953) in Minnesota on a Precambrian rock suite yielded susceptibility values for basic extrusives ranging from .001 to .004 cgs/cc, while values for rocks of granitic composition were less than .0001 cgs/cc. This same trend was noted in work done by Currie, Gromme, and Verhoogen (1963), on granitic plutons in the Sierra Nevada mountains. Typical rock susceptibilities ranging from 0.0002 to .0045 cgs/cc. were found, while remanence measurements ranged from .0001 to .0008 cgs/cc. yielding Q ratios (ratio of the remanent magnetization to the product of susceptibility and the earth's field strength) which were considerably less than 1. In contrast, research by Bull, Irving, and Willis (1962) on diabase samples from Antarctica, indicated Q ratios of 1.0 and 2.0 existed, demonstrating the importance of remanence in certain rock types and areas. Also work by Hood (1961) on rocks from the Sudbury Basin of Ontario, which were dated 1.7 billion years yielded Q ratios ranging from 0.1 to 20.0. Generally therefore, it can be said that dark, mafic volcanic rocks are more magnetic than rocks of granitic composition, although the opposite relation has also been observed. Also, the amplitude and spacial frequency characteristics of the magnetic envelope produced by a particular litholcgy or structure, are determined largely by the complex interaction of susceptibility and remanence effects within the lithology or structure. Observations by the author during the course of detailed magnetic surveys over a number of regions in Canada and the United States indicated that magnetically active areas, due to magnetic reversals or large order susceptibility variations, may be quite narrow (5-10 feet). In order to produce a well defined profile of such a narrow zone of activity for use in mapping etc., the sampling frequency must be greater than or equal to the Nyquist frequency, if a bias toward lower frequencies is to be avoided, thereby necessitating the use of a very detailed sampling interval while conducting the survey. The detection and use of these magnetically active zones for mineral exploration and geologic mapping will be demonstrated by the following case histories.

3.1.1 Steeply Dipping Metavolcanic Sequence-TransCanada Hwy.

Figure (15) represents a detailed magnetic survey carried out along the TransCanada highway from the Manitoba-Ontario border, eastward for approximately one mile. The rock units in the area consist of near vertical assemblages of metavolcanics, metasediments, and intrusive basalt phases. Many of these units contained pervasive interlayering, giving their magnetic signature a distinct high frequency component.

This figure demonstrates the very complex magnetic behavior layered mafic sequences posses, and the very distinct aliasing phenomenon taking place at the 50 foot sample interval (dashed line). Zones of extreme magnetic activity (+16000 nT. to -1400 nT.) are due to sheared metavolcanic sequences which have been subsequently mineralized with sulfides, most notably pyrrhotite. Using this rapid and intense magnetic variation as signature criteria, these zones may be easily traced beneath overburden using a detailed sampling interval (10 feet), allowing accurate geologic mapping of these magnetically distinct horizons, without near continuous outcrop exposure.

Figure 15: Metavolcanic Sequence-TransCanada Highway

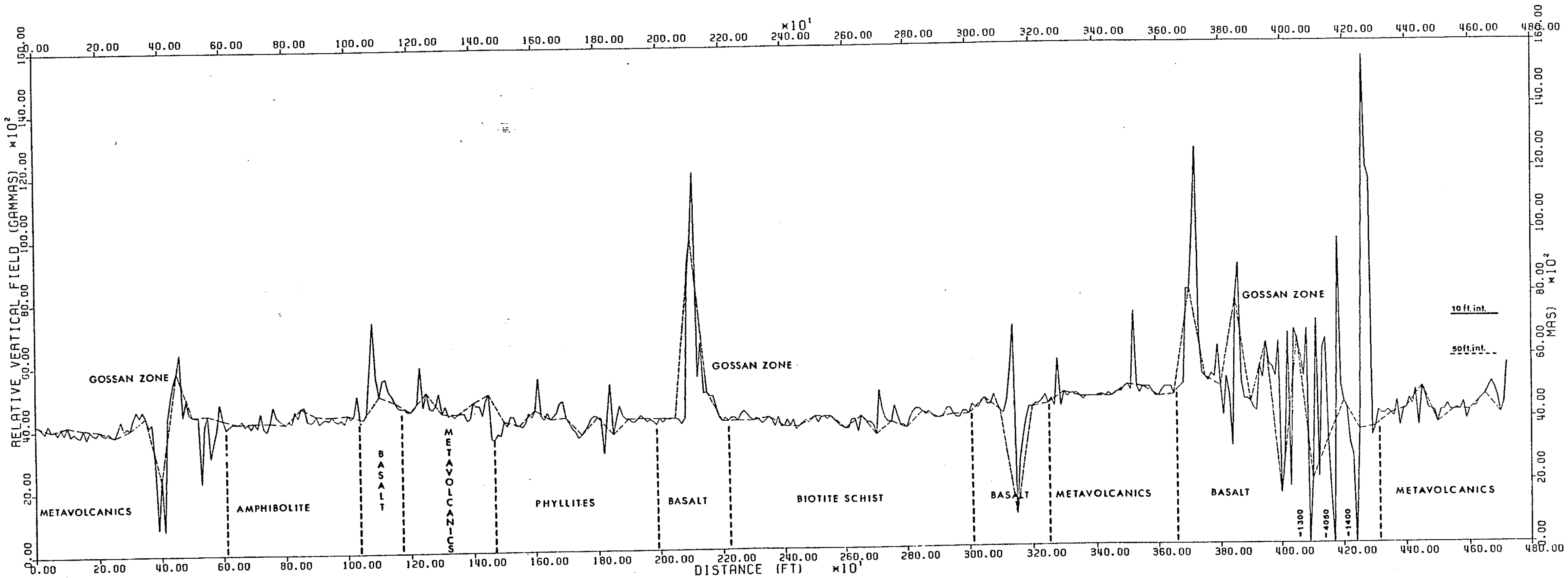


FIGURE 15
STEEPLY DIPPING VOLCANICS AND METASEDIMENTS - TRANSCAN HWY.

3.1.2 Fuki-Donen Deposit-Beaverdell, southern British Columbia

Figure (16) represents a detailed magnetic traverse using a 5 foot sampling interval carried out over the Fuki-Donen uranium deposit, located north of Beaverdell, in southern British Columbia.

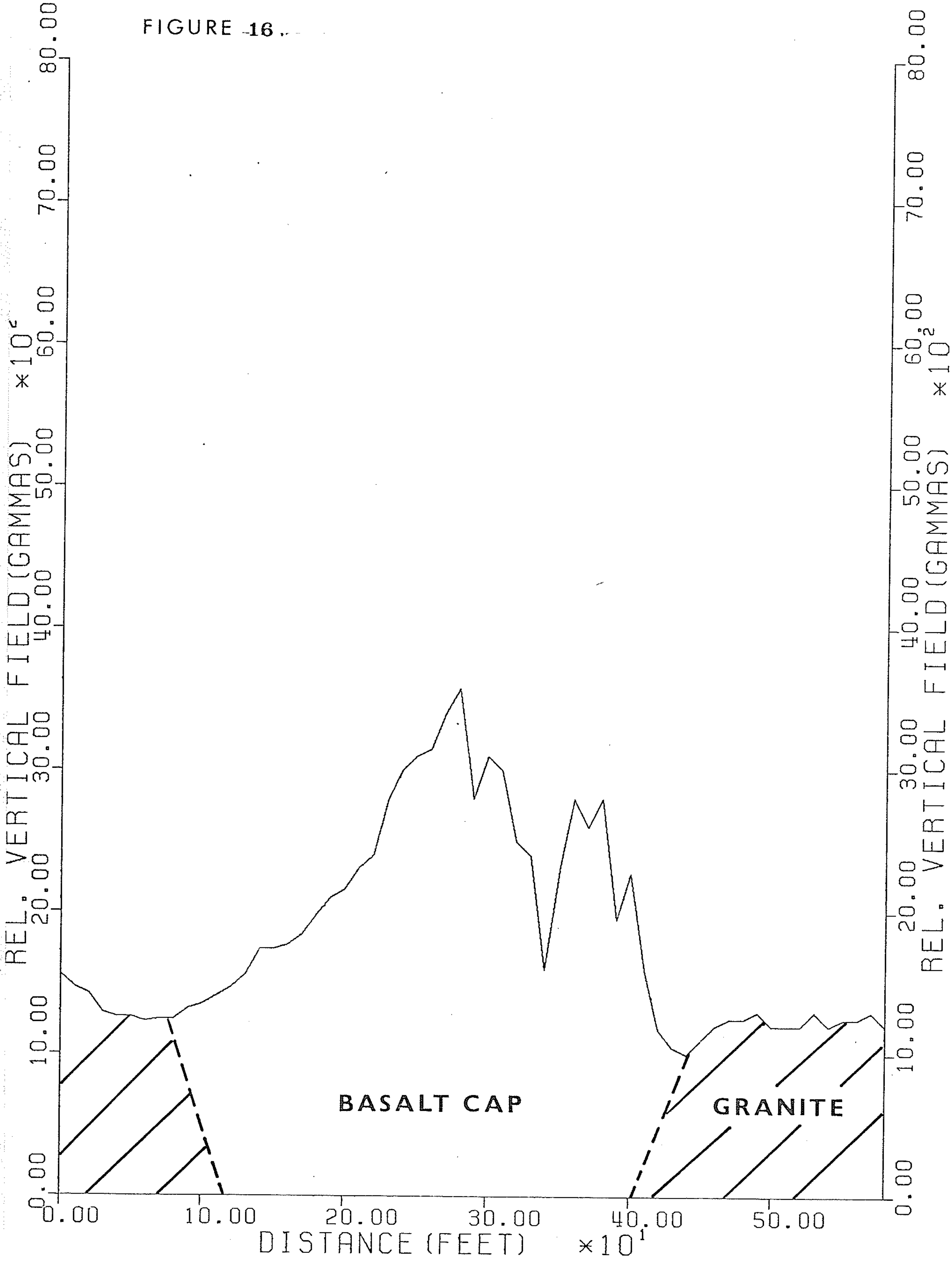
This deposit is known as a basal type or epigenetic deposit, as the mineralization consisting mainly of urano-phosphates, generally occurs within organic rich, unconsolidated, fluvial sediments overlain by Tertiary lava flows (figure 17). Deposits of this type began forming during the mid-Miocene to early Pliocene, when rivers flowing over the Precambrian granitic basement rocks, began to cut meandering river channels into this old surface. Organic debris, collected in sections of the channel along with boulders and gravel. During the Tertiary geolcgic period extensive volcanism occurred, covering the surface with extensive sequences of basalt lava flows. This basalt cap played a dual role in the formation of this type of deposit, as it restricted groundwater travel to these old paleostream channels, and also protected the non-resistant, unconsolidated sediments from erosion during Quaternary glaciation. As the groundwater percolated through, and over the anomalous granitic rocks, the uranium minerals present dissolved and were transported to the organic rich areas in the channels. Here a reducing environment formed by the decaying organic material, caused the uranium to precipitate as uranophosphate coatings on the cobbles and gravels present. During the subsequent Quaternary glacial event the area was scoured by glaciers, leaving remanenet cappings of basalt on the Precambriam basement rocks, as well as a 12 to 50 foot covering of glacial overburden.

Japanese explorationists discovered the Fuki-Donen properties in 1969 during a road radiometrics survey in the Beaverdell area. The local forestry department used gravel from the deposit to pave a road, making it extremely anomalous in radioactivity, as the ore contains approximately 2 pounds/ton uranium oxide. The area is currently under an exploration moratorium, resulting in a shut-down of any development work.

Except for this one instance when ore grade material occurred close enough to the surface to allow for detection using common radiometric methods, deposits of this type are generally extremely well shielded from the surface by both basalt and thicknesses of glacial overburden. In these instances detailed magnetic surveys would be valuable for delineating flow-granite contacts, as can be seen in figures (16) and (18), which exhibit sharp contrasts in magnetic relief between the two rock types. Figure (18) is another detailed profile from the same locality, where again the flow-granite contact is seen in sharp relief. The overburden thickness in the area varied between 0 and 12 feet, affecting the magnetic signature cf each rock type very little, as the magnetic response of each would be attenuated to the same degree with increasing overburden thicknesses.

BEAVERDELL, B.C., FUKI-DONEN BASAL TYPE URANIUM DEPOSIT

FIGURE 16.



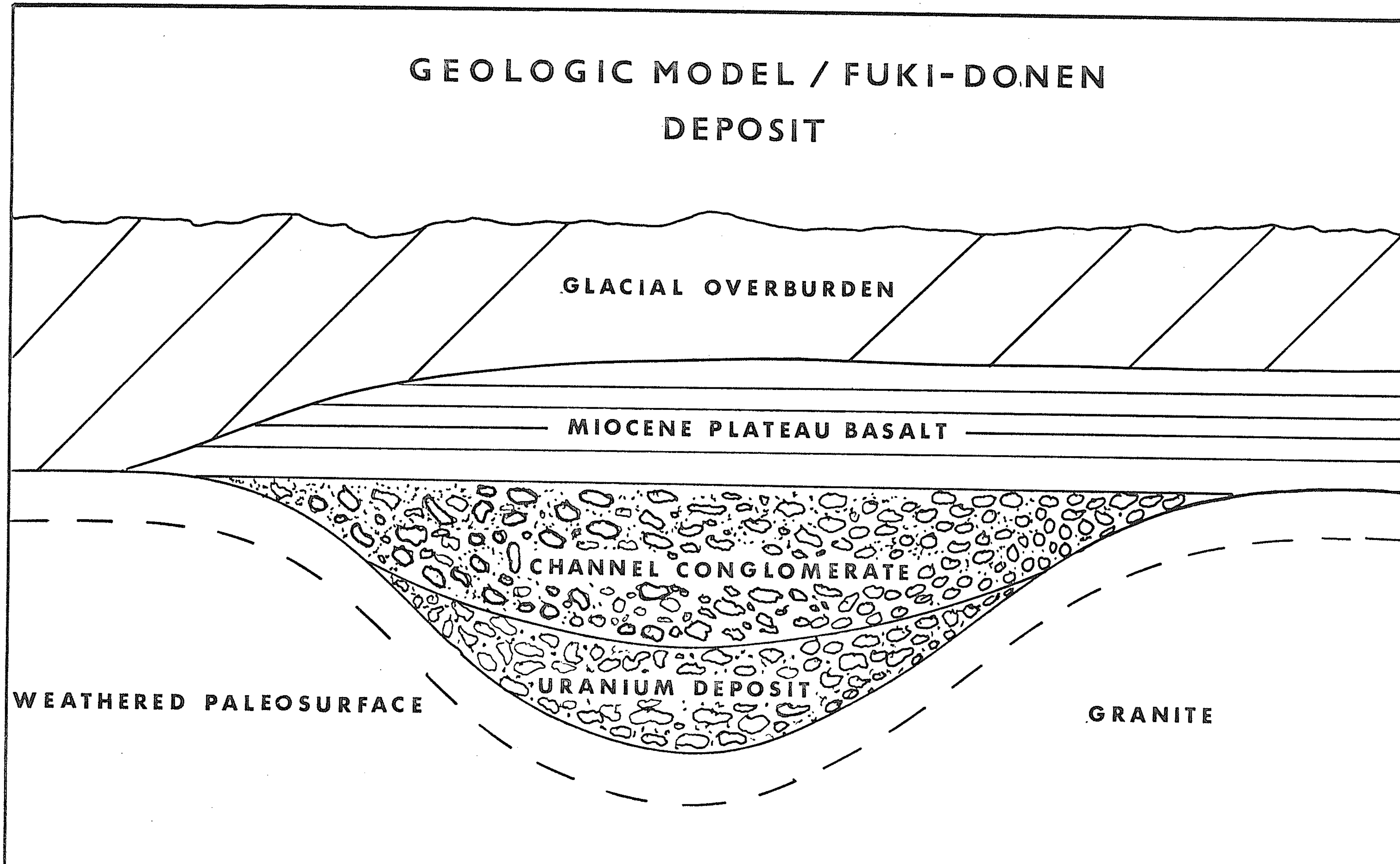
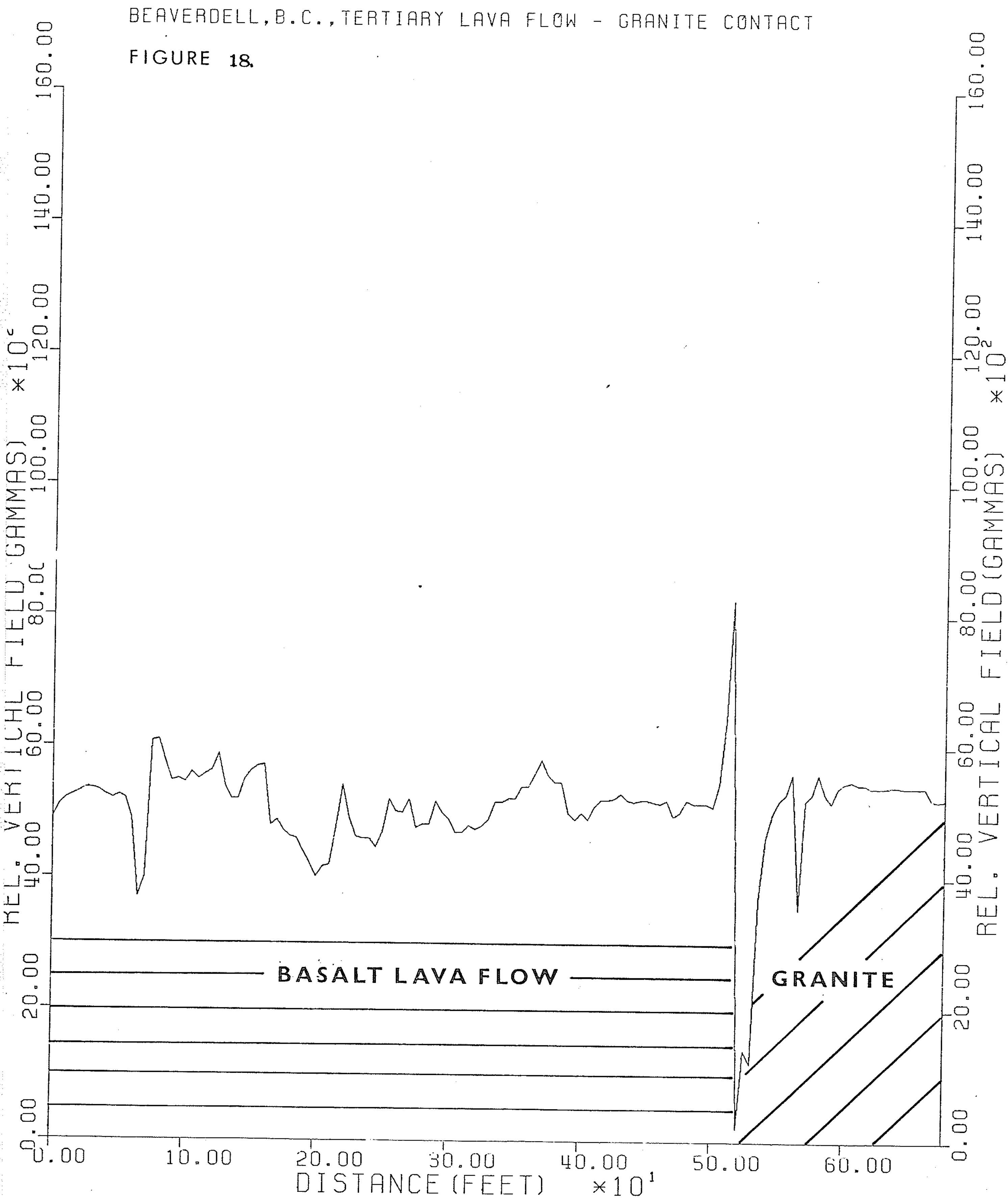

GEOLOGIC MODEL / FUKI-DONEN
DEPOSIT
GLACIAL OVERBURDEN
MIOCENE PLATEAU BASALT
CHANNEL CONGLOMERATE
URANIUM DEPOSIT
WEATHERED PALEOSURFACE
GRANITE

FIGURE 17.

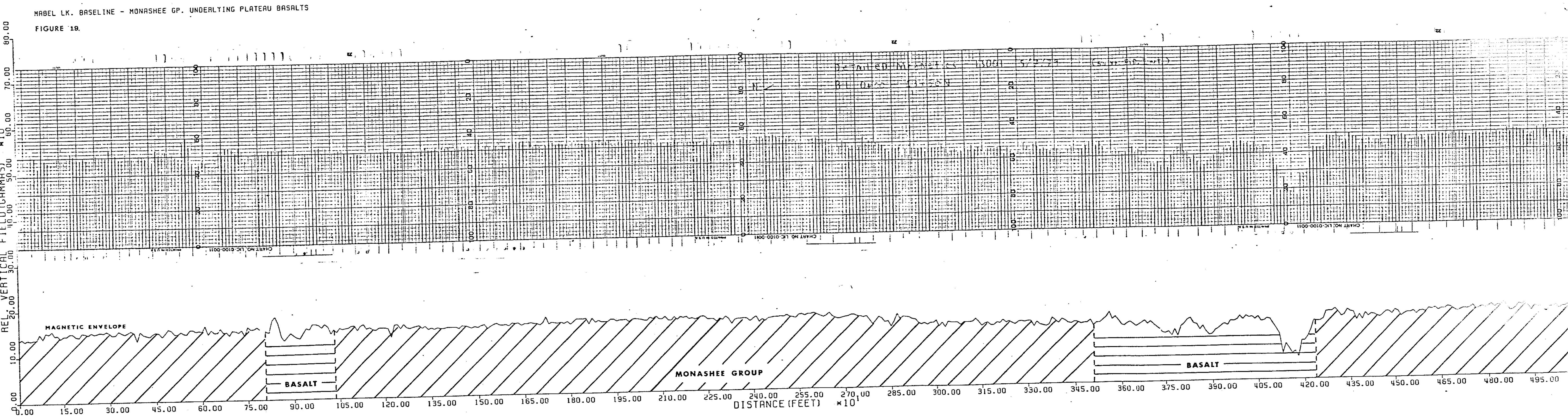

BEAVERDELL,B.C.,TERTIARY LAVA FLOW - GRANITE CONTACT
FIGURE 18.
REL. VERTICAL FIELD (GAMMAS) ×10²
DISTANCE (FEET) ×10¹
BASALT LAVA FLOW
GRANITE
0.00
10.00
20.00
30.00
40.00
50.00
60.00
80.00
100.00
120.00
140.00
160.00

3.1.3 Mabel Lake Area-southern British Columbia

Detailed magnetic survey work done during the summer of 1979 for Noranda Mines Ltd., Mattagami Lake Exploration division, is shown in figure (19). In this area of southern British Columbia geochemical surveys conducted the previous summer detected ancmalous contents of uranium in several streams draining a plateau area. It was originally thought that the ancmalous streams may have been draining one of the paleo- channel regimes discussed in the previous section. Acting in my position as party chief, and in agreement with the exploration head for the Western field office, it was decided to conduct a detailed magnetic traverse to determine the location of the buried basement- basalt contact. This location would then control the placement of the geochemical grid, which had to be located as close to the contact as possible, to allow a precise determination of the source location. As can be seen by the graphical output of the Detailed Magnetics Unit in figure (19), a large part of the baseline was located over the Monashee basement complex, which is magnetically unresponsive. The magnetic relief associated with the basalts was considerable however, allowing us to pinpoint the contact location quite easily.

Figure (19) shows the graphical output produced by the Detailed Magnetics equipment as previously discribed in the instrumentation

Figure 19: Detailed Magnetic Survey Results-Mabel Lake Area, S.B.C.



section. The time required to conduct the survey (510 measurements) was approximately 4.5 hours, each measurement averaging 30 seconds (10 seconds for data input and 20 seconds to walk to the next station). If this survey was conducted using conventional equipment, 1-2 minutes would have been required for each reading, making the actual survey time 8-16 hours, with another 3-4 hours spent in camp plotting the results. Therefore, in terms of dollars and cents the savings to the company were considerable.

3.1.4 Weir Mountain Property--Yukon Territory

Subsequent to the work in southern British Columbia, Noranda Mines Ltd., Mattagami Lake Division, had several properties which needed to be evaluated in an area north of Atlin, British Columbia.

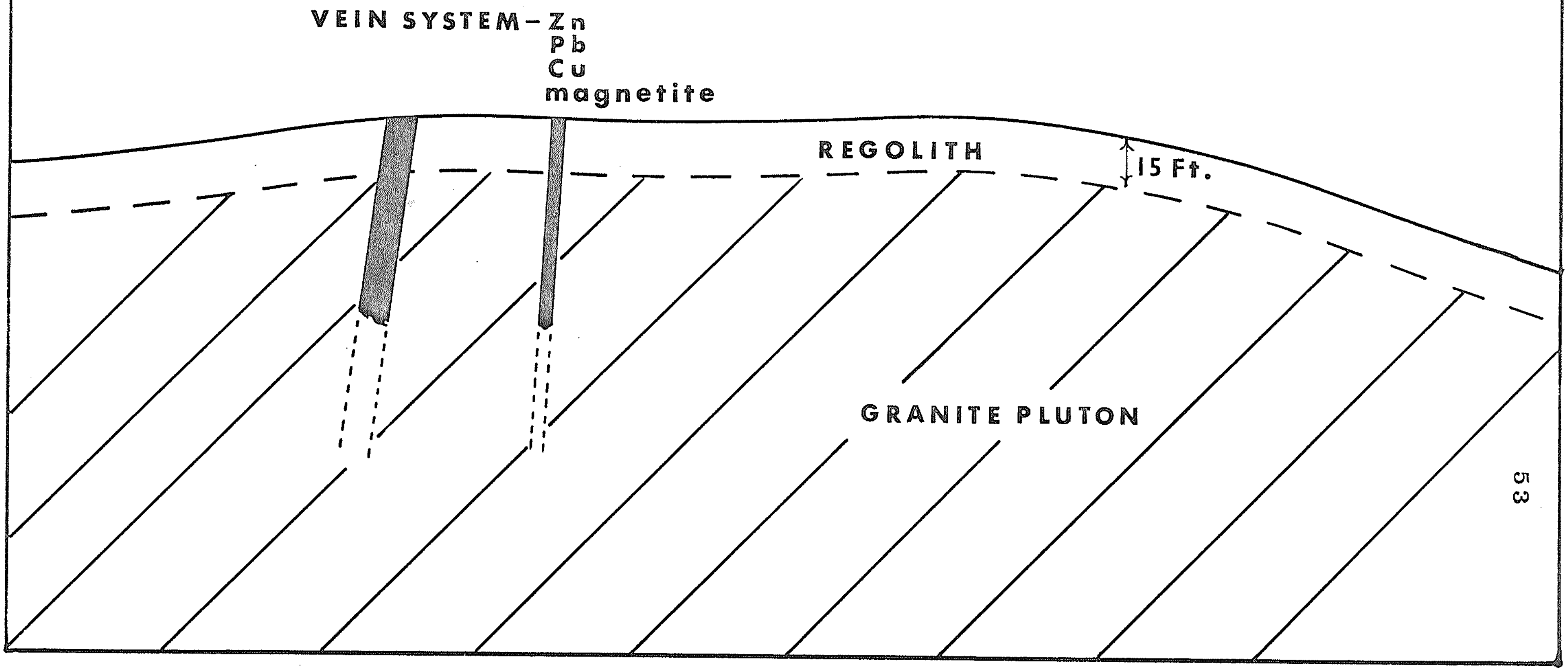
Geologically the Weir Mountain area (figure 20) consists of a deeply weathered, differentiated granite pluton which has undergone several stages of deformation, resulting in well defined zones of shearing. These zones were subsequently mineralized at several different periods, by metal rich hydrothermal solutions depositing sphalerite, galena, and cassiterite. Associated with these ore minerals, which makes the area interesting magnetically, is magnetite. The depositional sequence and occurrance of these metals are as yet poorly understood. Due to the overall poor response of the sphalerite and cassiterite to most geophysical techniques, coupled with the very high cost of closely spaced induced polarization surveys to detect the galena, the magnetic method proved to be the most definitive technique available.

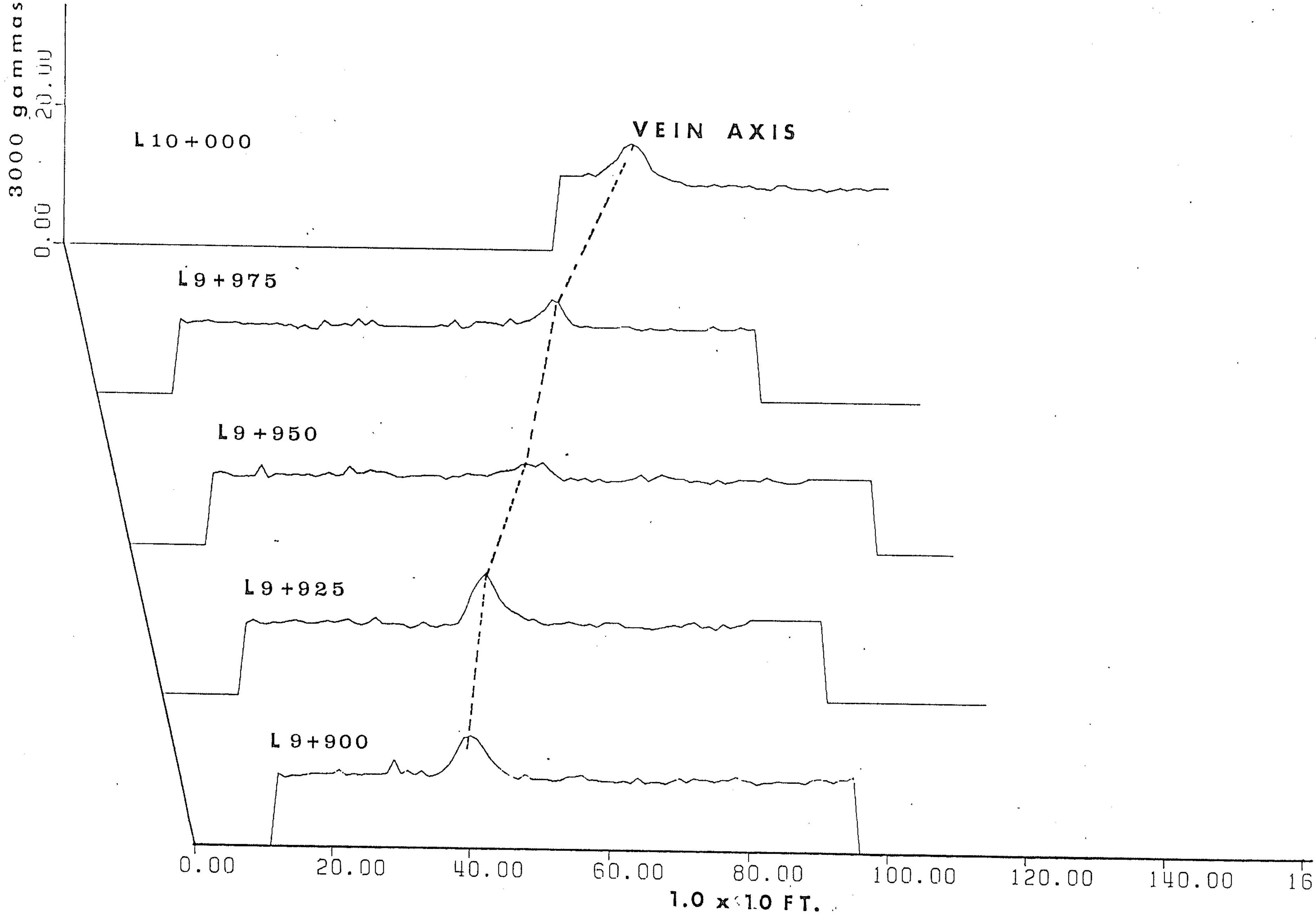
Consequently, detailed magnetic surveys using the author's equipment, were undertaken at several areas in the Weir Mountain locality. Figure (21) shows one such area of moderate activity, and demonstrates the very distinct, narrow, linear nature of the mineralization along the shear areas. Obviously the degree of definition required to locate these areas, due to their narrow width (2-10 feet), precludes any but a detailed survey. In this case particularly, narrow veins would be considered economic due to their appreciable tin content, if they possessed the requisite strike length. The sample interval used in figure (21) was two feet, with the lines spaced 75 feet apart. With the analog output, geologic observations were able to be made and registered on the graph using the fiducial marking system. With this method time savings are considerable, as groundtruthing of the data was done at the time of its collection, a distinct advantage in mountainous terrain.

Figure (22) is another area within the Weir Mountain claim block, showing more intense magnetic activity, with anomalous zones approaching 1680 nT. above background. The mineralogy and linear trends are

GEOLOGIC MODEL / WEIR MTN.

FIGURE 20.





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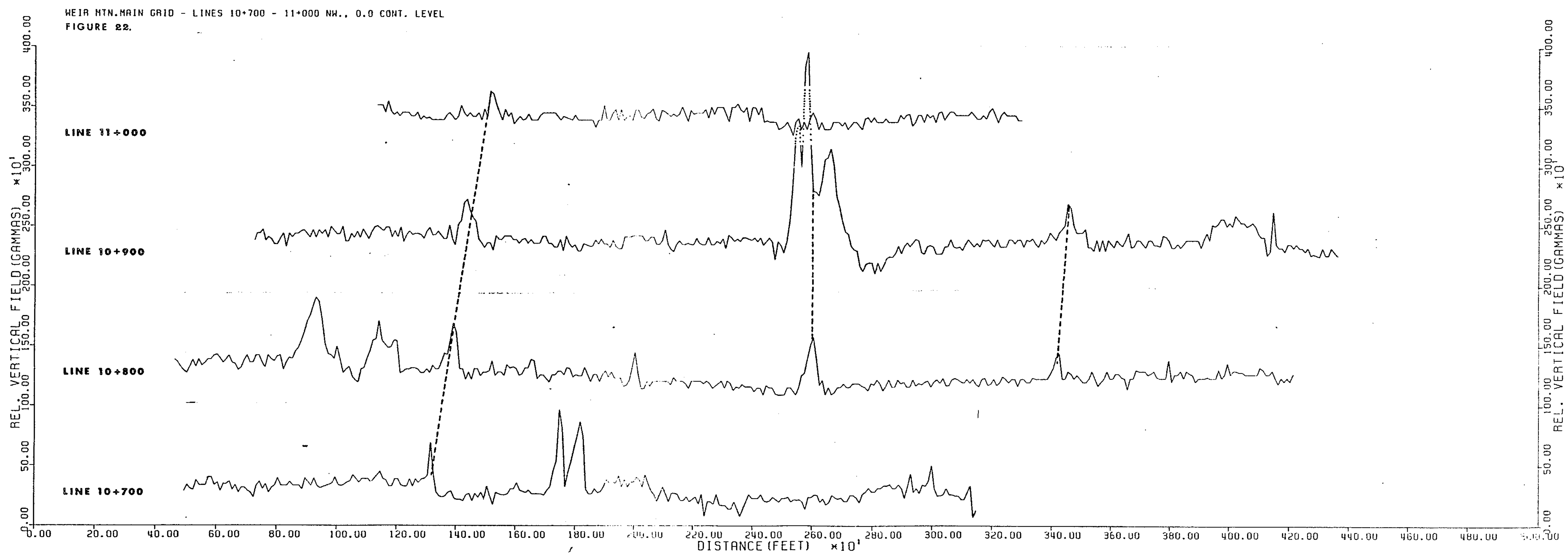
WEIR MTN. MINI-GRID, LINES 10+000-9+900, 3K SCALE, 2 FT. INT., 0.0 CONT. LEVEL

FIGURE 21.

Figure 22: Detailed Magnetic Survey Results-Weir Mountain Main Grid



consistant with those in figure (21). The anomaly envelopes are quite symmetric, indicating a vertical to near vertical orientation of the vein systems. The large order anomaly located on line 10+900 is fairly complex, consisting of three distinct peaks. This complexity of the anomaly envelope may be caused by three closely spaced veins, or three areas of magnetite concentration within one large vein, only drilling will tell. The vein widths in this area are again quite narrow, ranging in width from 2-18 feet.

These distinct linear trends were readily apparent when the profiles were stacked side by side, and aligned using the fiducial station markers. Using this method the turnover time from survey to presentation is cut considerably, as a minimal amount of drafting and interpretation effort is necessary.

3.1.5 Sulfur and Cofer Properties-Central Virginia, U.S.A.

During May 1980, I was given the opportunity to test the Detailed Magnetics unit on two properties owned by Callahan Mining Corporation, in the Piedmont area of central Virginia. Bedrock in the area is characteristically overlain by a 50-100 foot thickness of saprolite, which formed as an in situ decomposition of bedrock in response to heavy rainfall over extended periods of time. Because of this thickness of overburden, outcrop exposure is restricted to river and creek valleys, making any degree of lithologic correlation difficult, if not impossible. Drilling through overburden to establish lithologic control is very costly, particularly if the correlation is to be extended over large areas.

Susceptibility measurements made on drill core taken from the Sulfur and Cofer properties, indicated that distinct horizons containing fairly large quantities of pyrrhotite and magnetite existed, and could be used as marker beds within the section, if a magnetic survey with a high spacial resolution could be utilized. To verify this supposition, the Detailed Magnetics Unit was used to carry out high spacial resolution surveys over previously drilled and logged properties, providing good geologic control over the survey results.

3.1.5.1 Geology-Cofer and Sulfur Properties

The lithologies present in the area consist of metavolcaniclastics and clastic sediments, which have undergone lower amphibolite to greenschist metamorphism. The bedding of the units generally strikes N 30 E, and dips steeply toward the southeast at 60 to 80 degrees. The thickness of each individual bed varies considerably along strike due to the metamorphism, but generally falls within the 20-200 foot thickness range.

3.1.5.2 Ore Mineralogy

The Sulfur and Cofer properties are generally considered to be proximal syngenetic, massive sulfide deposits. In this type of deposit mineral rich solutions containing pyrite, sphalerite, galena, chalcopyrite, pyrrhotite, and minor amounts of silver (1 ounce/ton), were vented by a local volcanic center, filling bottom depressions on the seafloor, and forming today's mineral rich localities. The two magnetic minerals present are magnetite and pyrrhotite, the concentration of each varying considerably between individual beds, and along strike. The magnetite occurs as disseminations or distinct bands within the ore, examples of which are seen in figures (23 and 24). The sulfides are thought to pinch and swell along strike due to the metamorphism, and in certain areas may be found as lensoid concentrations of massive ore.

3.1.5.3 Magnetic Survey-Sulfur Property

The magnetic survey on the Sulfur property used a 10 foot station interval, on three lines spaced 200 feet apart. The lines extended for 1500 feet northwest, and were oriented roughly perpendicular to strike. The magnetometer used with the system was a Scintrex model MF-2 Fluxgate magnetometer, which measured the vertical field component, and was set for a sensitivity of 3000 nT. full scale.

Figure 23: SULFIDE MINERALIZATION FROM SULFUR PROPERTY
The lower section is composed dominantly of magnetite and amphibolite.

Figure 24: SULFIDE MINERALIZATION FROM THE COFER PROPERTY
In this sample the dark bands consist mainly of amphibolite, with minor amounts of magnetite.

The stacked magnetic profiles output by the unit are seen in appendix (A). Essentially three areas of differing magnetic activity can be seen in the results. Area 1, which is comparatively inactive, consists dominantly of schistose units containing biotite, sericite, cherty quartzites, and minor amounts of pyrite, which occurs as individual cubes, stringers and disseminations. The corresponding susceptibilities of the rocks from this part of the section range between .0002 to .0005 cgs units, explaining the distinct lack of magnetic expression.

Area 2, defined by a magnetically high trend approximately 350-500 feet wide, is seen in drill core to be caused by mafic lithologies consisting of biotitic sericite cherty fragmentals, and transiticnal amphibolites, which have a large mafic mineral component (dominantly amphibole and chlorite), as well as large amounts of magnetite, and increasing amounts of pyrite, sphalerite, galena, and chalcopyrite. This increase in magnetic mineral content is mirrored by the susceptibility log, with average values ranging between .001 and 0.004 cgs units.

Area 3, is characterized by high spacial frequency variations in the magnetics, which is seen in drill core to be caused by a biotite sericite schist unit, composed primarily of sericite and biotite, along with significant amounts of quartz, chlorite, amphibole, garnet, and magnetite. Within this unit, the sulfides consisting of pyrite, sphalerite, chalcopyrite, pyrrhotite,and galena occur in stringy to submassive zones, producing the observed high spacial frequency variation in the magnetic profile. This effect is particularly apparent in this part of the section since the overburden is quite thin, ranging between 5-50 feet. Susceptibilities for this part of the section are consistant with the observed magnetics, with values of .00145 cgs units.

3.1.5.4 Magnetic Survey-Cofer Property

The magnetic survey in the Cofer area used a 10 foot station interval,on three grid lines spaced 150 and 100 feet apart. Each grid line extended for 2500 feet in a northwesterly direction. The overburden on this property was quite thick (120 feet), compared to the Sulfur property which averaged 20-50 feet. As a result, any high frequency variations within individual units would be attenuated. Lithologies in the area were not very magnetically expressive, as can be seen by the survey results in appendix (B). The lithologies comprising the magnetically flat area stretching from 0 west to approximately 1700 west consist of quartz sericite biotite schist, and biotite sericite schist, neither of which contain a significant magnetic component, as shown by the correspondingly low susceptibility values (.0005 cgs units). The magnetically active unit beginning roughly at 1700 west consists of a quartz sericite biotite schist, which contains a significantly increased magnetite content. The magnetite is fine grained and appears to be concentrated in thin layers throughout the unit. This layered characteristic of the magnetite is responsible for the spot highs seen in the susceptibility log, where where the measurement was made directly on a magnetite concentration. Abruptly, at the lower contact the magnetite content drops rapidly and abundant sulfide mineralization consisting of pyrite, sphalerite, galena, and chalcopyrite begins.

On each of the two massive sulfide properties examined, the detailed magnetic method was able to pinpoint zones of sulfide mineralization by either indirect or direct means. The sulfides at Cofer were able to be detected indirectly by their association with magnetically active rocks along their contact, as established by drilling. If this trend is found to be consistant, then even though there is no intimate association of magnetic minerals with the ore, its trend may be followed using the magnetically active bed as a marker. At the Sulfur property where there is an intimate association of magnetite and pyrrhotite with the ore, the sulfides may be detected directly. Due to the considerable depth of the overburden, the more subtle lithologic-magnetic effects were obscure, making magnetic evaluation of lithologies in this particular area tentative, although broad relations were observed.

Chapter IV

AEROMAGNETIC SURVEYING

4.1 INTRODUCTION

Low level (less than 100 meters) helicopter-borne magnetic surveys are being used more frequently by mining companies in place of the conventional ground based magnetic survey. The supposition has been that the greatly increased survey speed will allow much larger tracts of land to be surveyed magnetically, while the information content of the data would decrease only slightly. The first part of the supposition is true, as larger tracts of land would be able to be surveyed and processed using the new generation of digital airborne magnetometers, and data processing units now on the market. The second part of the supposition, that the information content will be decreased only slightly is not true. Error may be introduced into the aeromagnetic data at many points during its collection and subsequent processing. This chapter will deal primarily with the error introduced during the collection phase, more specifically it will deal with the aliasing error and resolution loss introduced by incorrectly chosen flight speed, flight level, or magnetometer cycling rate.

4.2 AIRBORNE MAGNETOMETERS

Many of the gains generated by the increased resolution and data processing capability of the new airborne magnetometers may be nullified if the survey is not carried out within the geologic constraints of the survey locality. Aliasing of the data due to improperly chosen flight line separations or sampling intervals (improper choice of magnetometer cycling rate), may result in misinterpretation, leading toward false assumptions regarding mineralization trends within an area. In addition, an improperly chosen flight level may cancel out much of the higher frequency magnetic variation, which has been shown to be a useful characteristic for delineating lithologic or structural trends within an area.

Three of the most common airborne magnetometers in use today are the Second Harmonic Fluxgate, Proton Precession, and Optically Pumped Alkali Vapor magnetometers. SQUID magnetometers (Superconducting Quantum Interference Device), based on the Josephson junction effect, are still in the developmental stage, but should be coming on-line in the near future, yielding an increased sensor resolution of .0007 nT..

4.3 FLUXGATE MAGNETOMETER (SECOND HARMONIC TYPE)

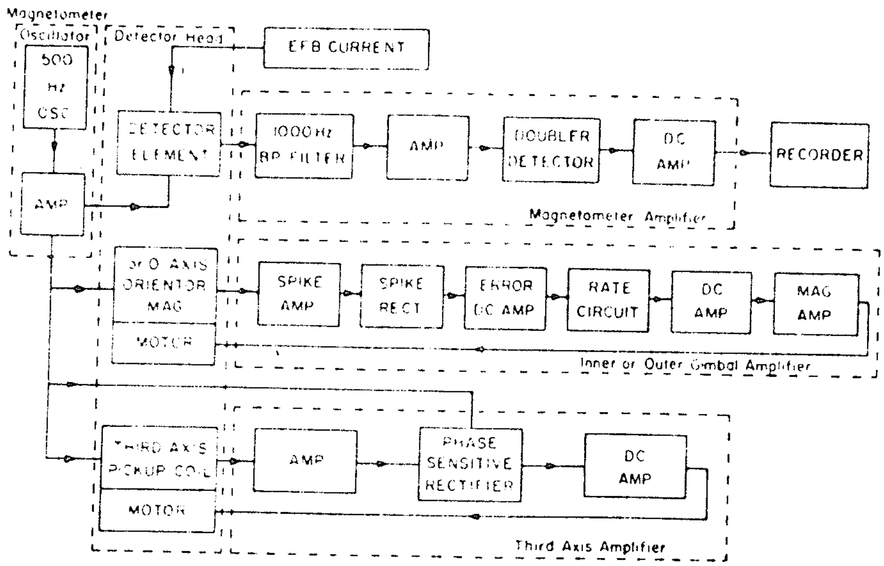
In the Second Harmonic Fluxgate (figure 25), a laminated core composed of mu metal or permalloy is wound with one or more coils and is magnetized by a sine wave current large enough to drive the core material into the saturation region of its hysteresis curve. If an ambient field induced by the earth's magnetic field, exists within the core, it adds to the magnetization during each alternating half cycle, and opposes the magnetization during the other half cycle. This results in a time difference between saturation intervals within the core, as each half cycle leads or lags the opposing cycle. This difference between saturation intervals creates secondary voltages which are even harmonics of the driving current. This second harmonic voltage is then selected by means of a filtering system, amplified, rectified, and fed into a recording system. The magnetude of the second harmonic voltage is proportional to the ambient field, provided the amplitude of the driving field is much larger than the field to be measured.

The maximum sensitivity of the unit is determined largely by the amount of noise generated within the core material and associated electronics. With the appropriate filtering devices noise can be reduced to less than .02 nT.. This unit is essentially a vertical (Z) field magnetometer, measuring only the field vector paralleling the core, which is held in a vertical plane by servo-orienting mechanisms.

The frequency response has an upper limit of several cycles/second, depending on the driving frequency, filters, demodulation circuitry, and recording equipment. The main advantage of this type of unit over the proton precession and optically pumped magnetometers is its lack of a cycling interval during which the unit does not respond to magnetic variation, allowing continuous monitoring of the magnetic field.

4.4 PROTON PRECESSION MAGNETOMETER

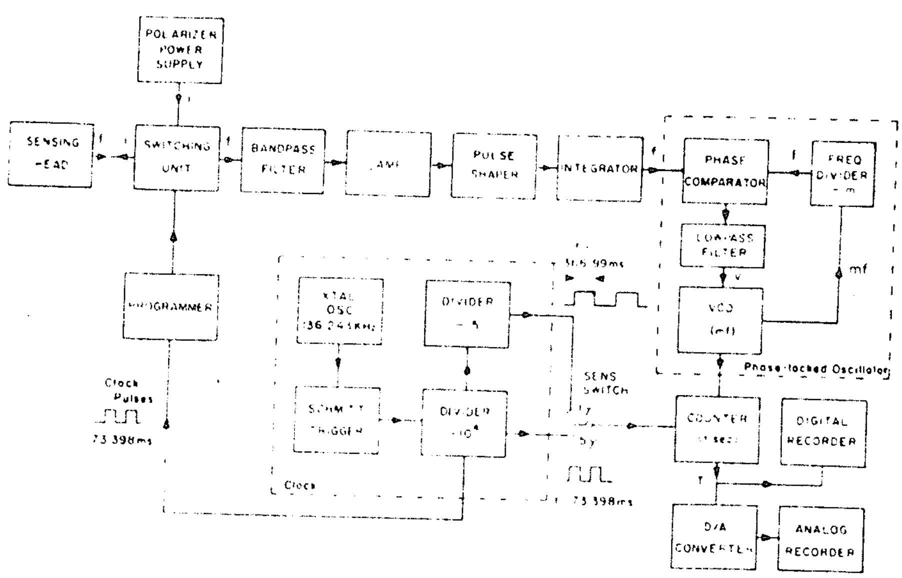
The underlying operation of a proton precession magnetometer is based on the magnetic moment of protons caused by their spin. If the protons are exposed to a strong magnetic field they will tend to align themselves so that their magnetic moment vectors are parallel to the flux lines of the applied field. When this polarizing field is removed, the protons come under the influence of the earth's magnetic field. This ambient field will generally have an orientation differing from that of the polarizing field. As a result the protons will precess about the ambient field vector at a frequency termed the Larmor frequency, which is dependent on the strength of the ambient field. This precession generally lasts for several seconds, decaying at an exponential rate with time. As the protons precess, their magnetic moment induces a small emf in the pickup coil, which is mounted at right angles to the



BLOCK DIAGRAM

SECOND HARMONIC FLUXGATE

Fig. 25
(HOOD, 1967)



BLOCK DIAGRAM

PROTON PRECESSION UNIT

Fig. 26
HOOD, 1967

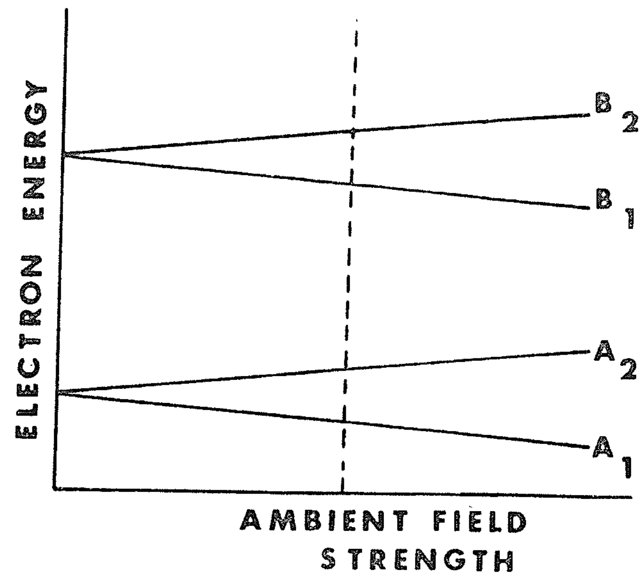
polarizing coil. The frequency of this emf will be measured by gating circuits for a timed interval, the length of which determines the accuracy of the frequency measurement. The total field value is determined using the relation T=kf, where T is the total field strength measured in nT., k is a constant representing 2xPi/gyromagnetic ratio of the proton, and f is the precessional frequency.

The performance of a proton precession magnetometer degrades considerably in the presence of a strong magnetic gradient, as protons in different sections of the sensor will precess at different frequencies, causing phase distortion in the output signal. The measurement intervals currently in use range from .5 to 2 seconds, allowing sensitivities from 10 nT. to .1 nT. to be achieved. The main advantage of this type of magnetometer are its greater sensitivity and total field measurement, allowing operation without need for the servo-orienting mechanisms of the fluxgate, thereby decreasing its operation cost. The main disadvantage of the system is its reliance on longer cycling rates to maximize resolution.

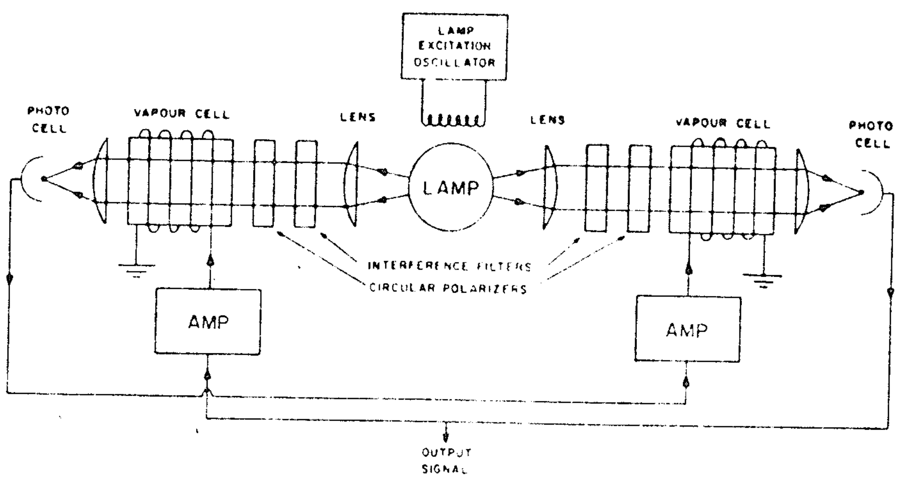
4.5 OPTICALLY PUMPED MAGNETOMETER

The optically pumped magnetometer, figure (27), relies on energy differences between three orbital levels within an atom. The transition of an electron from one energy level to another may take place in large or small steps depending on the energy available. Electron transition from a low to a high state may occur if bombarded with photons possessing sufficient energy, while on transition from a high to a low state a photon of energy is emitted by the electron.

In the presence of an ambient magnetic field, an orbit may contain slightly different energy levels depending on the orientation of the electrons spin axis with respect to the ambient field (figure 28). The stronger the ambient field, the greater will be the splitting of these energy levels (Zeeman effect). If a tube of gas is exposed to a monochromatic beam which has a frequency corresponding exactly to the energy difference between one of the lower energy states, and one of the higher energy states, light will be absorbed as electrons are raised from state A1 to B1. This absorption of energy subsequently reduces the amount of light which passes through the absorption cell by as much as 20%. Electrons in the high energy state drop back to the lower energy state emitting light in the process. But the electrons may drop back to state A1 or A2. If the electrons drop to state A1, they will be raised back to B1 by energy absorption from the light source. If the electrons drop to A2, they will tend to remain there, since the light source contains the wrong energy to raise them back to a higher state. Therefore, a high percentage of electrons will be at level A2, and a correspondingly lower percentage will be at level A1. So that the light source has effectively pumped the electrons from level A1 to A2.



OPTICAL PUMPING
EFFECT
FIG. 27



OPTIC. PUMPED MAG.
COMPONENTS
FIG. 28
(HOOD, 1967)

Leaf blank to correct

numbering

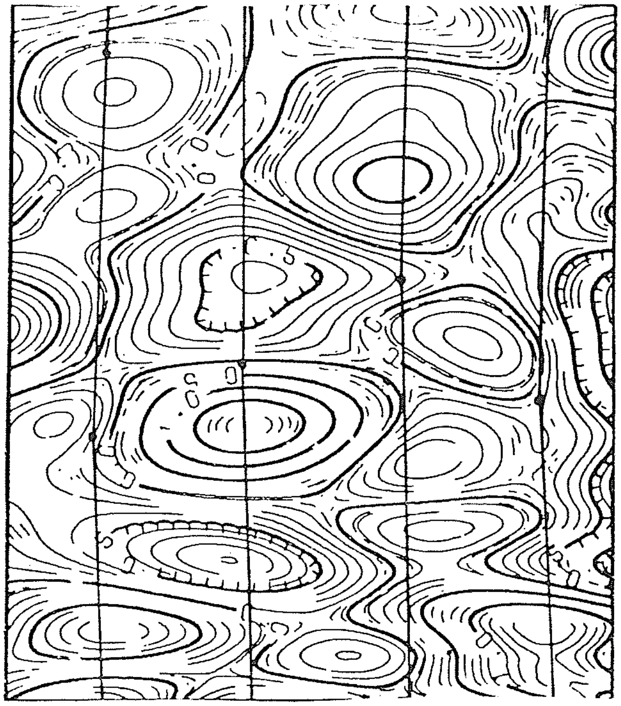
The main elements of an optically pumped magnetometer consist of a monochromatic light source, an absorption cell, and an Rf meter. Most of the commercial units use either helium or rubidium gas in the absorption cell. The light source consists of a heated tube of the same gas, ensuring the proper wavelength is present. This wavelength is selected by means of a high resolution filter, which effectively filters all unwanted frequencies, allowing only the frequency causing the A1-B1 state change to pass through. A photocell-feedback system varies the Rf to maintain maximum absorption within the cell, which is then measured to .1 Hz. accuracy. This allows a total field resolution of approximately .01 nT..

The main advantages of this type of system are absolute field measurement, no calibration or gradient problems, and high resolution. The main disadvantage which tends to weigh heavily against the system, especially in terms of aeromagnetic surveying, is its continued reliance on a frequency measurement interval to achieve its sensitivity.

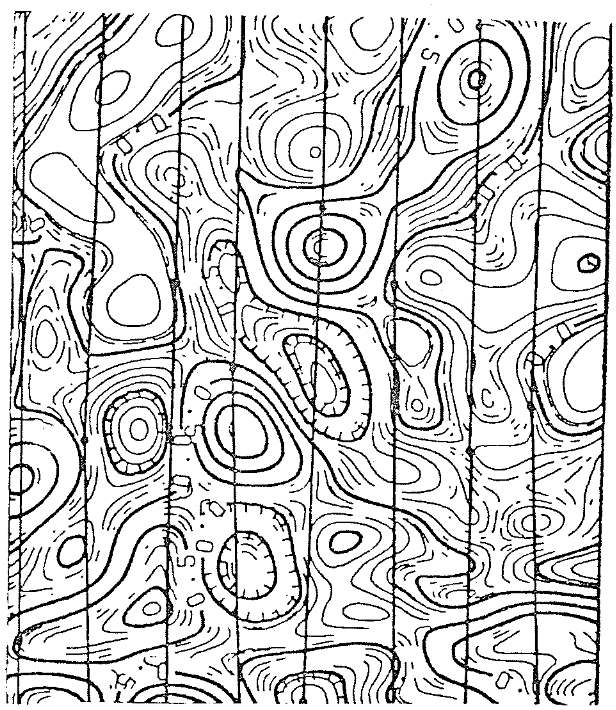
4.6 ALIASING IN AEROMAGNETIC DATA

The aliasing effect may also be observed in aeromagnetic data which has been poorly sampled. Figures 29 A,B,and C, are computer contoured segments of an aeromagnetic gradiometer survey flown at 500 feet altitude, with a 500 foot line spacing. Each segment covers the same area of the survey, but figure (C) was contoured using all the available data, figure (B) was contoured from every second flight line only, and figure (A) was contoured from every fourth flight line. As a result, figures (A,B) represent the end product as it would appear if the survey had been flown at 1000, and 2000 foot line spacings respectively.

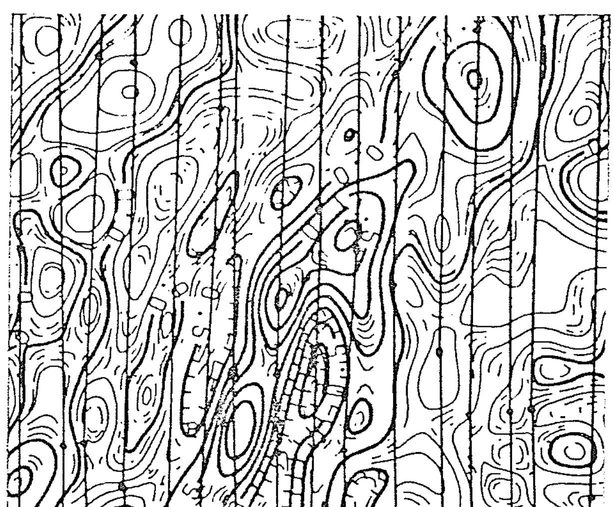
Figure (A) clearly demonstrates the characteristics associated with undersampled data, in the form of "potato" anomalies or "magnetic boudinage". This type of pattern, consisting of a patchwork of slightly elongate contours at right angles to the flight lines, makes the poor quality of the data quite obvious. Figures (B,C) are not as obvious in their presentation, with regard to data quality. The contours of figure (B) cross the flight lines at sharp angles, and have definite elongate trends, features characteristic of well sampled data. There is also a well developed trough, crosscutting the magnetic fabric of the area, making it appear as a real feature. However, if you assume that figure (C), having the highest sample density, is showing the true magnetic picture, then the magnetic trough of figure (B) does not exist. In reality there are four fairly prominant ridges separated by troughs running approximately 15 degrees NE, nearly at right angles to figure (B).



A.



B.



C.

ALIASING EFFECT IN
AEROMAG DATA
FIG.29 A,B,C
HOOD,1979

4.7 UPWARD CONTINUATION OF GROUNDLEVEL MAGNETIC DATA

The loss of spacial resolution, which is inherent in aeromagnetic surveying, and which makes them unacceptable as replacements for ground based magnetic surveys, is of considerable importance when searching for structures of small dimension (less than 10 feet). To determine the loss in spacial resolution due to an increased observation level, a computer program based on a mathematical filter function designed by Tsay (appendix C) was used. The accuracy of this continuation process was verified using model data generated by an Australian program based on Talwani's Method (appendix D). The ground level magnetic data used for this continuation was taken from two magnetically active areas surveyed in conjunction with this thesis.

Area 1, is located near Falcon Lake in northwestern Ontario. Geologically, (see chapt.2,fig. 14) the area is characterized by granitic quartz porphyries which are intruding mafic volcanics of andesitic composition. Magnetic relief along this mineralized contact is considerable, ranging from lows of -6000 nT. to high zones of +5000 nT. above background figure (30).

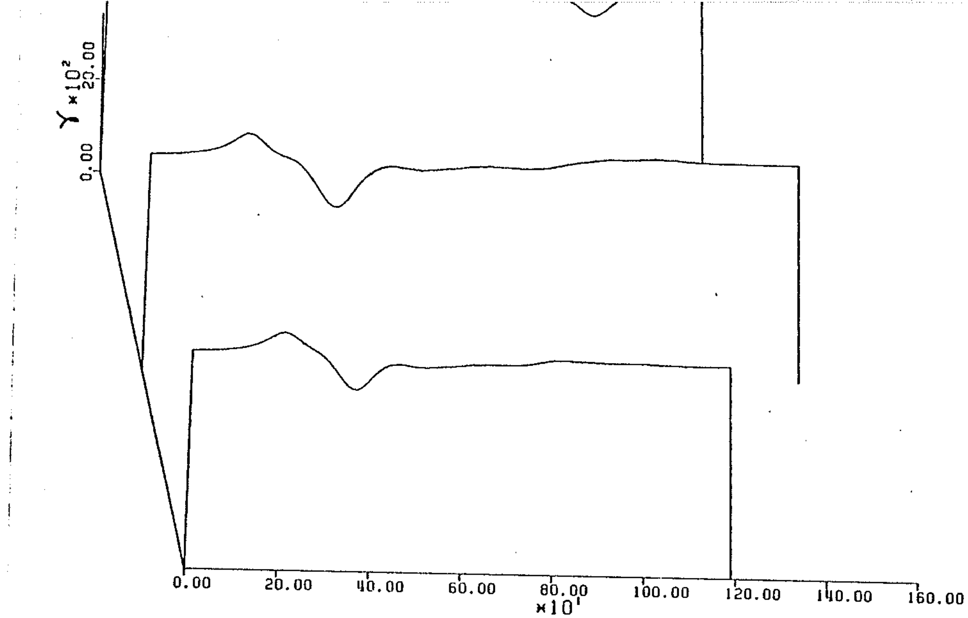
Figure (31) shows the considerable attenuation of the magnetics at a 50 foot observational level, where low values now range between -800 to -1000 nT., while the positive areas vary between +500-+600 nT.. In addition, the 1000 nT.

spike near the eastern edge of the grid, falls within background levels, making the shear zone unobservable at this altitude. At the 100 foot continuation level (figure 32), very little magnetic relief is observed due to the extreme attenuation and broadening of the anomalous areas. At this altitude the location of the contact is so ill defined, it would probably be missed during the course of the survey.

Area 2 lies on the Mattagami Lake Mines, Weir Mountain property in the Yukon. Geologically this area consists of weathered plutonic terrain, which had been faulted and mineralized by cassiterite, sphalerite, galena, and magnetite. Figure (33) shows the line with greatest magnetic relief in the area, having surface values ranging from +400 to +1600 nT. above background. Attenuation at the 50 foot observation level (figure 34), is considerable for the shallow +200 to +500 nT. regions, dropping them below background levels. The central ancmaly is still quite visible, dropping to +500 nT. at the 50 foot observation level, and to 250 nT. at the 100 foot level (figure 35), possibly indicating a greater depth extent. This attenuation is not enough to drop the region below background levels, making it quite visible during the course of the helicopter survey.

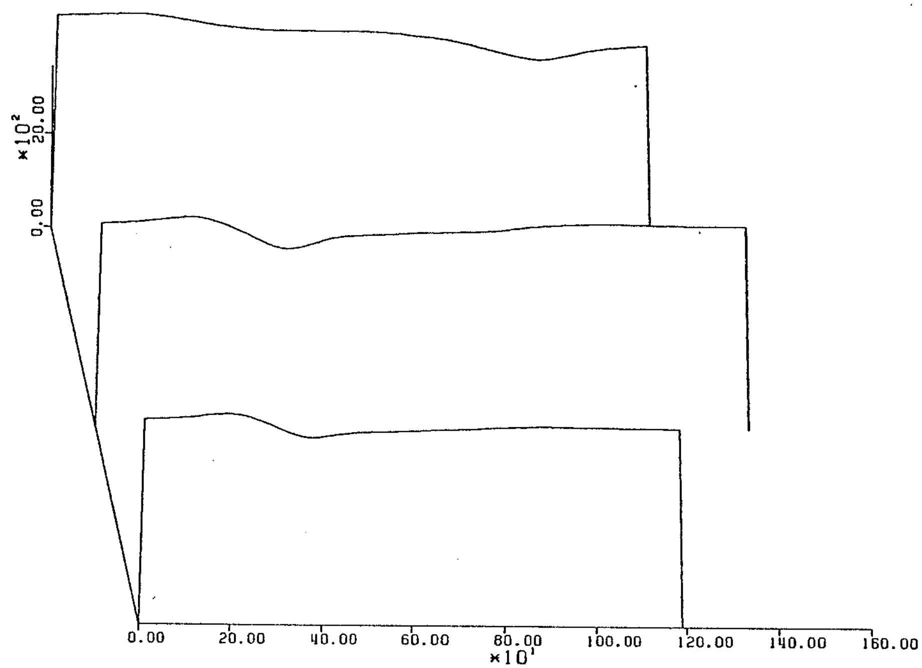
The narrowness of the features in this area (less than 30 feet), greatly increases their chances of being missed, if the helicopter speed versus sampling rate of the magnetometer is too large. A very important consideration in this regard, is the length of the cycling rates for the various magnetometer types (see sections 4.2-4.5). Both the proton precession and the optically pumped models rely on frequency measurement intervals of at least 1 second to give the requisite accuracy. For a helicopter traveling at a nominal rate of 60 mph, a distance of 88 feet would be traversed during the 1 second cycling interval, a distance exceeding the observed widths of the anomaly areas at Weir Mountain by greater than two. Therefore, a continuous or quasi-continuous (with sampling intervals much less than one second) digital fluxgate magnetometer would be the best instrument for mineralization of this type.

FALCON LAKE GRID LINES 0+00 W.- 4+00 W.,10 K SCALE.
FIGURE 30



FALCON LAKE GRID LINES 0+00 W.- 4+00 W.,10 K SCALE,10 FT. INT.,50 CONT.LEVEL

FIGURE 31

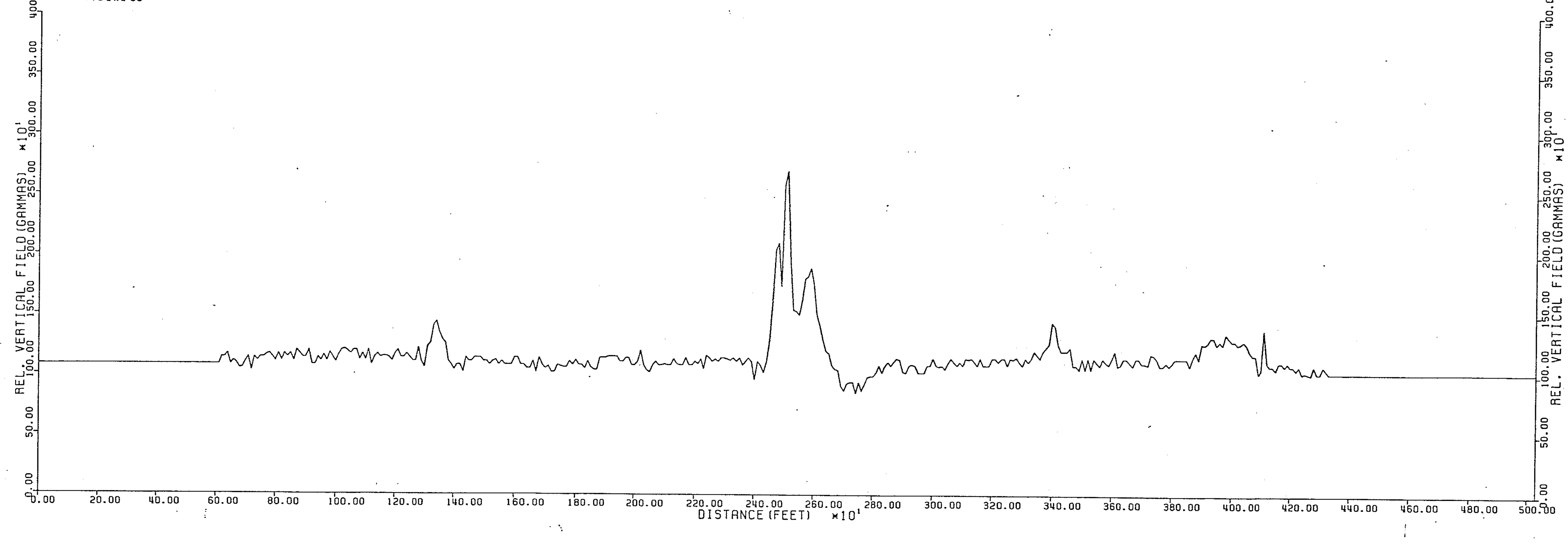


FALCON LAKE GRID LINES 0+00 W.- 4+00 W.,10 K SCALE,10 FT. INT.,100 CONT.LEVEL

FIGURE 32

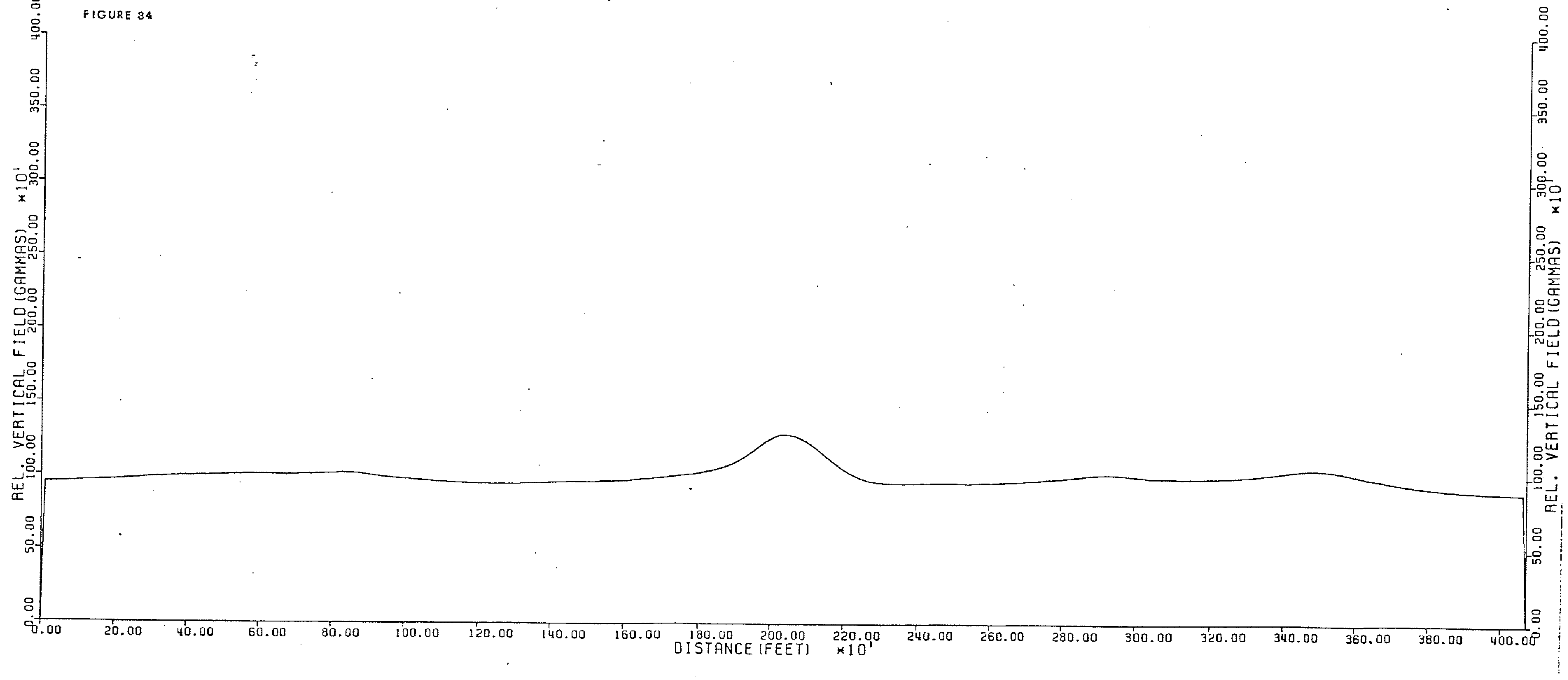
WEIR MTN. GRID-LINE 10+900 NW.3K SCALE. 10 FT. SAMP.INT. 0.0 CONT. LEVEL

FIGURE 33

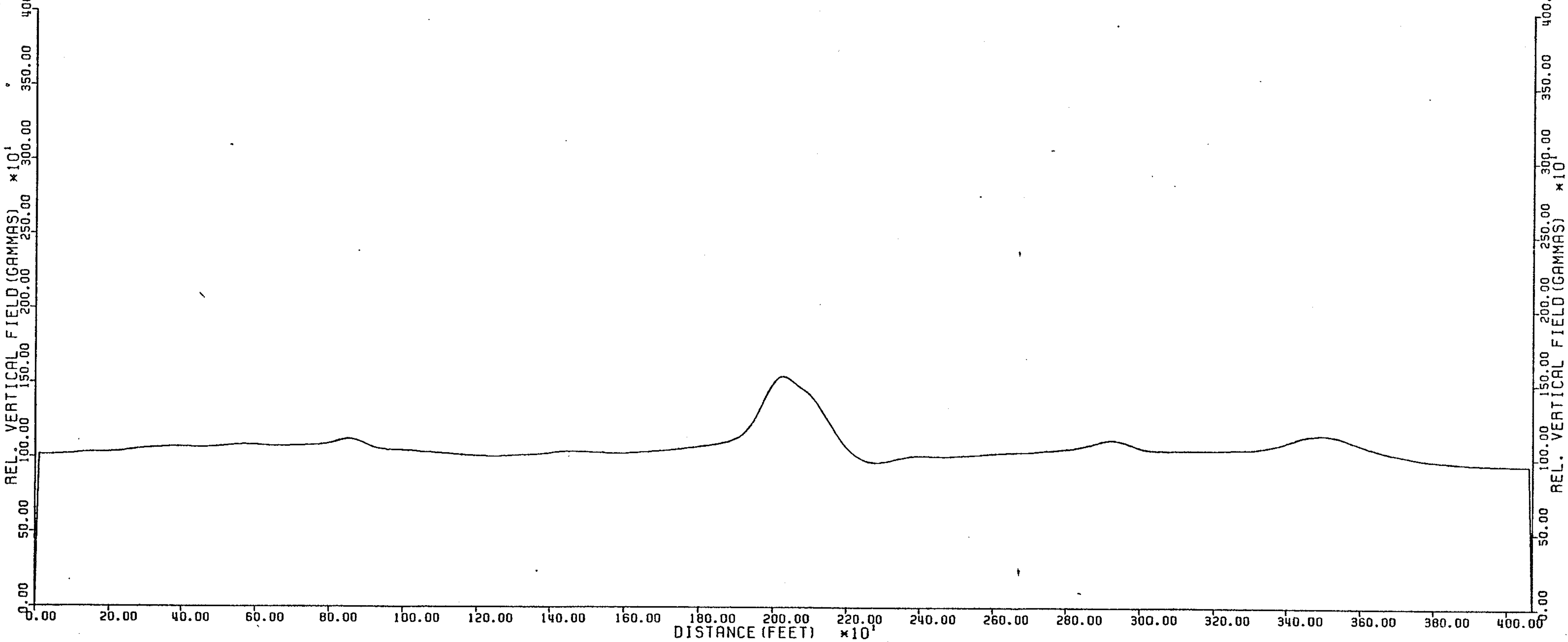


WEIR MTN. GRID-LINE 10+900 NW.3K SCALE. 10 FT. SAMP.INT. 100 CONT. LEVEL

FIGURE 34



WEIR MTN. GRID-LINE 10+900 NW,3K SCALE, 10 FT. SAMP.INT. 50 CONT. LEVEL
FIGURE 35



Chapter V

CONCLUDING REMARKS

The goals of this research project were essentially two fold. First, to develop equipment capable of conducting detailed magnetic surveys using measurement intervals of 10 feet or less, while keeping the time requirements needed to conduct such a survey within those imposed by conventional survey techniques. Secondly, to use the equipment in surveys over geologically diverse areas, to establish whether detailed magnetic surveys provide significant geologic information, not obtainable by surveys using conventional intervals of 50-100 feet.

The first goal was realized after approximately one and a half years of research and development by the author, at the University of Manitoba. A prototype Detailed Magnetics unit was produced which fulfilled the necessary speed and output criteria, and was sufficiently bush hardened to survive the rigors of tundra and rain forest conditions. Admittedly this is prototype equipment, and as such is in need of refinements both mechanical and electronic, but considering the time and cost limitations controlling its development it performed admirably. The two mining companies, Noranda Mines Ltd.-Mattagami Lake Expl. Div. and Callahan Mining Corporation, who were kind enough to allow the use of the information gathered on their respective properties in this thesis, both believed the unit filled a basic gap in magnetic surveying instrumentation, and inquired about future purchase of such equipment.

The second goal was also realized, as spacial frequency and amplitude characteristics defining the "magnetic signature" of the rock type or structure, were able to be observed by detailed surveys only, as conventional surveys produce aliased results, in accordance with sampling theory. The fact that such information is "valuable" both from a scientific and exploration viewpoint, was confirmed by the observations made in geologically diverse areas, and by the very favorable response of exploration people in the mining industry.

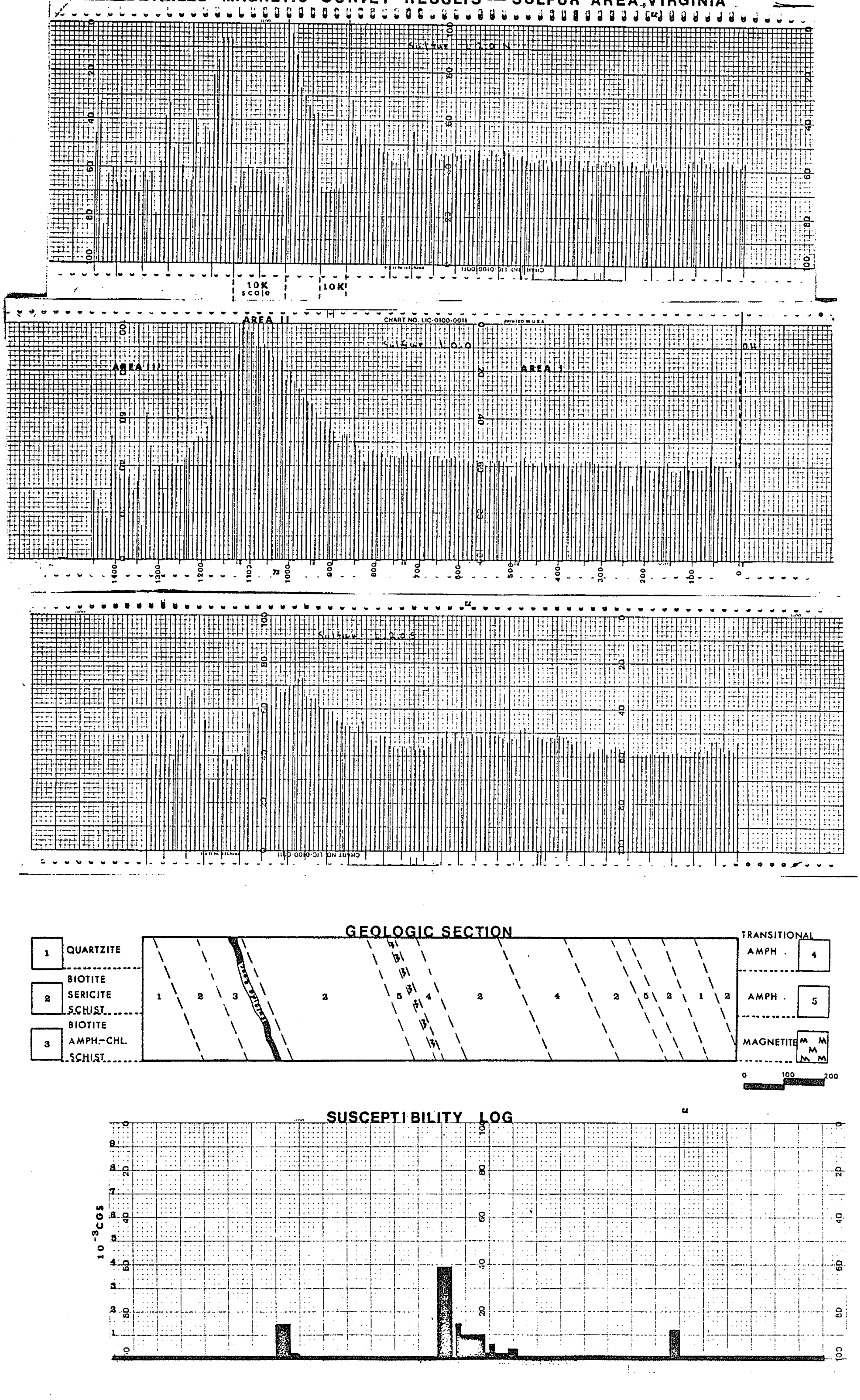
Further development in detailed magnetic survey technology, leading ultimately to continuous ground magnetic surveys should be pursued. This enhancement of survey technology could proceed along several avenues. First, a total field 3-component fluxgate sensor could be developed, removing any orientation problems. Secondly, digital recording of the data could be made more effective by using a cassette system, and thirdly, the capabilities of the analog system could be expanded, while decreasing weight. This system would enable the total magnetic picture to be seen, reducing interpretative error and cutting survey costs.

Appendix A

SULFUR PROPERTY-SURVEY RESULTS

Magnetic Survey Results, Susceptibility Log, and Geologic Section

DETAILED MAGNETIC SURVEY RESULTS — SULFUR AREA, VIRGINIA

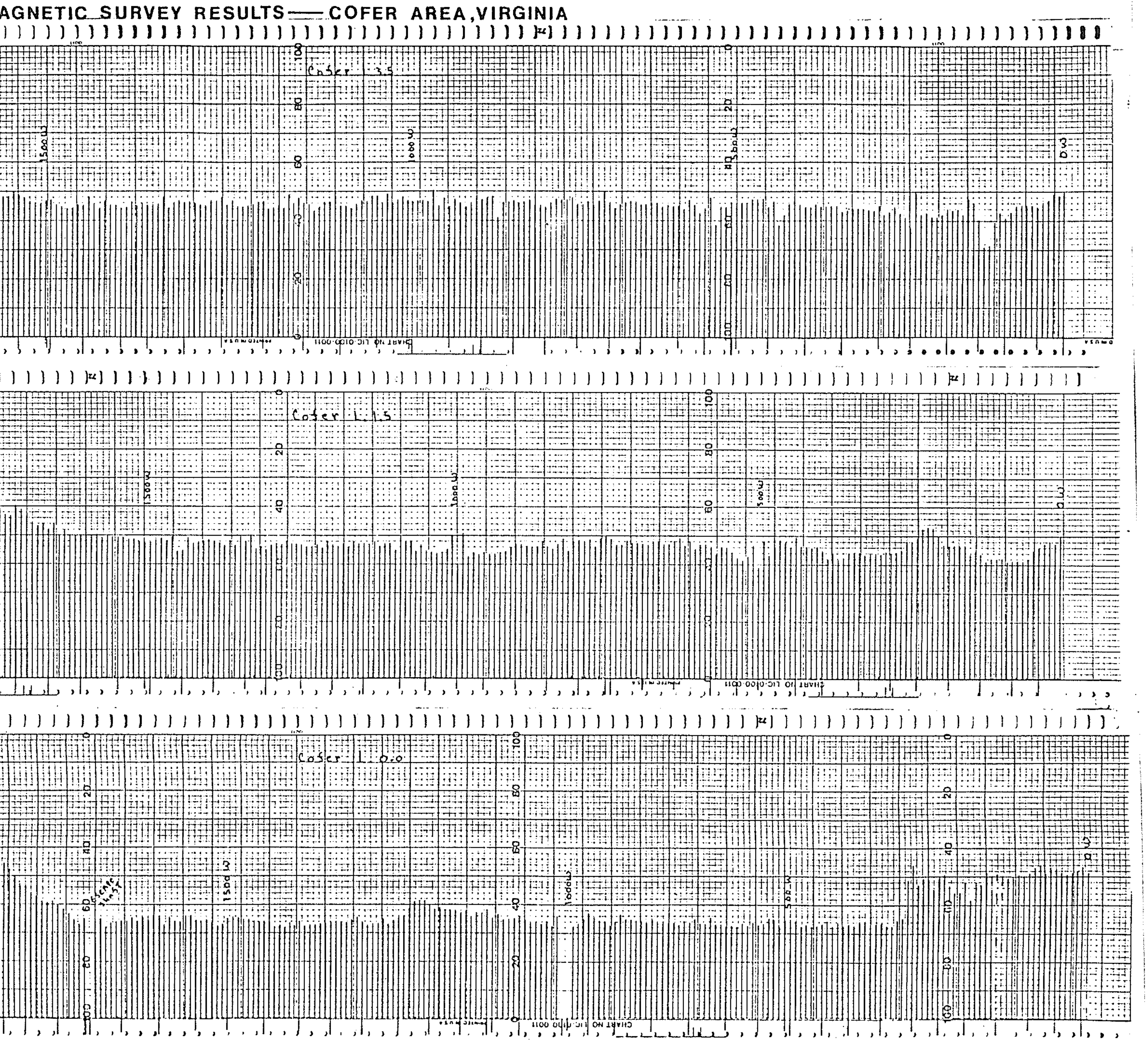


Appendix B

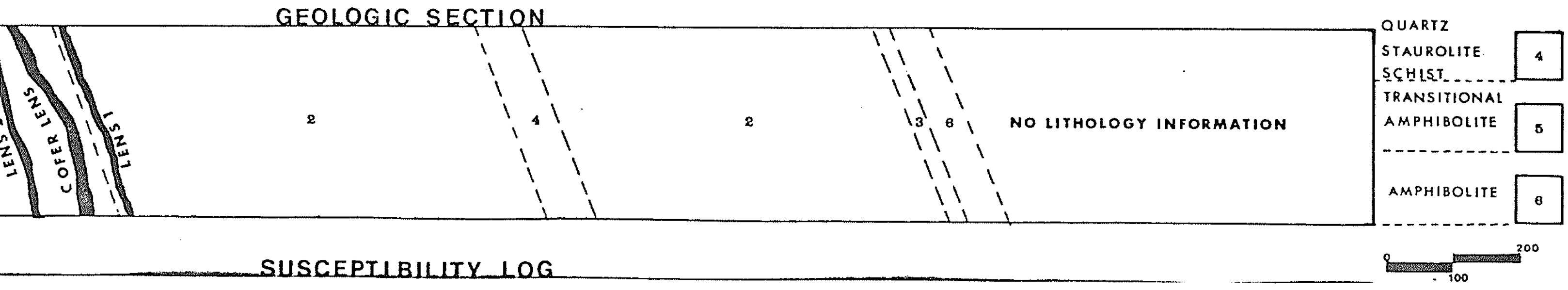
COFER PROPERTY-SURVEY RESULTS

Magnetic Survey Results, Susceptibility Log, and Geologic Section

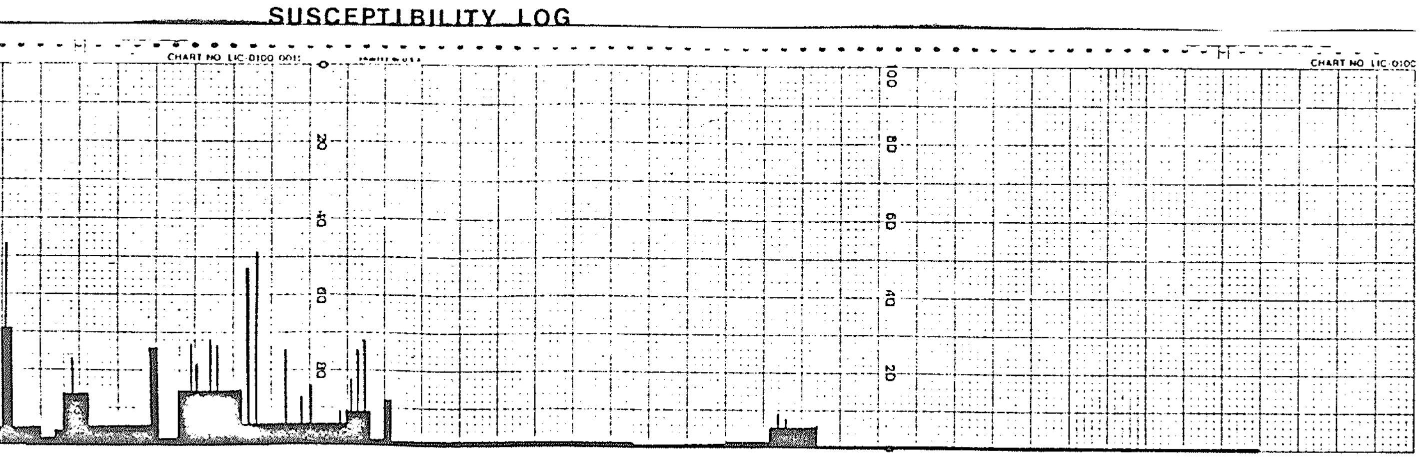
AGNETIC SURVEY RESULTS — COFER AREA, VIRGINIA



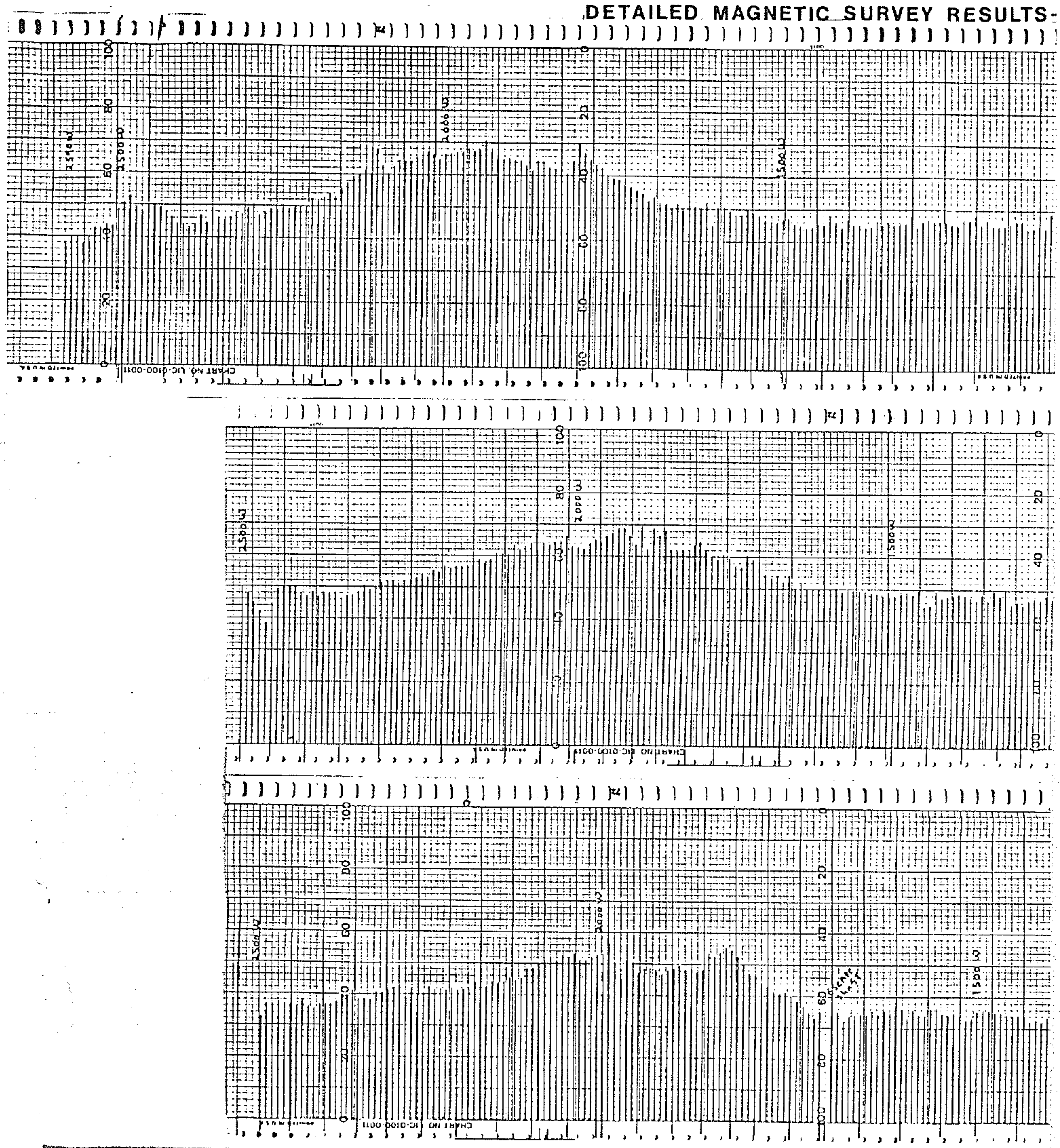
GEOLOGIC SECTION



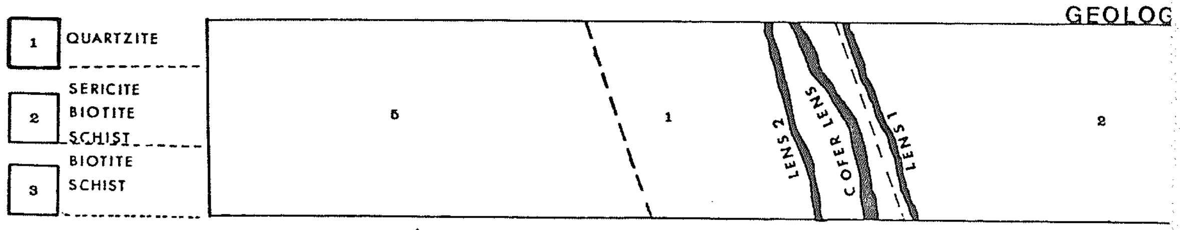
SUSCEPTIBILITY LOG



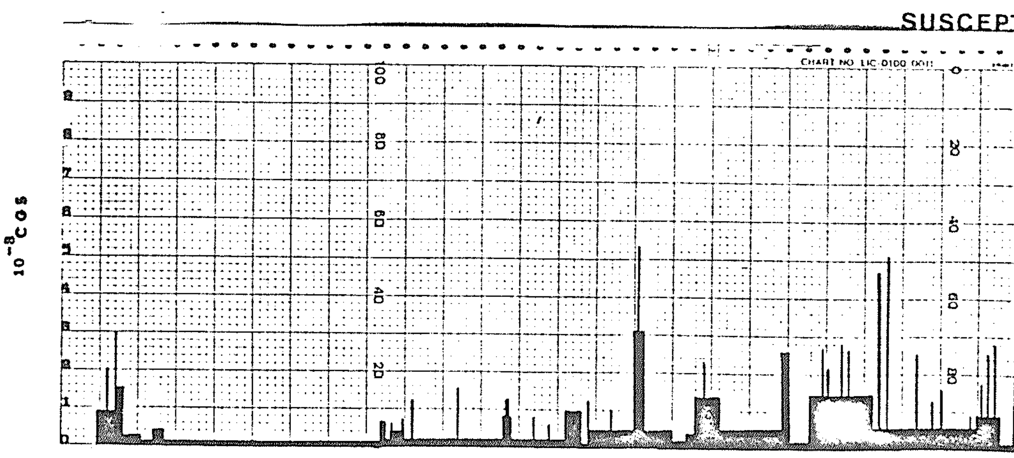
DETAILED MAGNETIC SURVEY RESULTS-



GEOLOG



SUSCEPT



Appendix C

UPWARD CONTINUATION PROGRAM USING TSAY FILTER

C THE PROGRAM DESIGNS AN IDEAL SYMMETRIC BANDPASS FILTER FOR ONE-DIMEN- C SIONAL DATA (TIME OR SPACE SER- IES). THE IMPULSE RESPONSE FUNCTION AND THE C FREQUENCY RESPONSE OF THE WEIGHTING COEFFICIENTS ARE CALCULATED AND C PLOTTED. C C C INPUT DATA IS AS FOLLOWS (ONE CARD ONLY - SEE FORMAT 20) C C N = THE NO. OF POINTS IN THE FILTER (N = THE NO. OF POINTS OF ONE SIDE C OF THE SYMETRIC OPERATOR PLUS THE CENTER POINT IE: THE TOTAL NO. OF C POINTS = 2N-1 C FL = THE LOW CUT FREQUENCY C FH = THE HIGH CUT FREQUENCY C DT = THE SAMPLING INTERVAL C C C FOR THE THEORY FOR SUBROUTINE 'BNDPSS' SEE E. A. ROBINSON--GEOPHYSICAL C PROSPECTING, VOL.14, NO.5, P.1. C C C

```
      DIMENSION FILT(1000),X(1000),RDATA(1000),RDOUT(1000)
      COMMON FILT,N,DT,Z,PI
      DIMENSION L(20)
      PI=3.141593
      READ(5,9) L
    9 FORMAT(20A4)
      WRITE(6,8) L
    8 FORMAT('1',///,' ',40X,'TITLE:- ',20A4)
      READ(5,10)LRDATA,DT,S,FSTART,FINC
   10 FORMAT(I4,4F8.2) C       IF(LRDATA.LE.0)GOTO 1
      READ(5,11) (RDATA(J),J=1,LRDATA)
   11 FORMAT(12F6.0)
      WRITE(6,12) (RDATA(J),J=1,LRDATA)
   12 FORMAT(11H1INPUT DATA/(1H ,12F6.0))
```

```
      DO 2 I=1,LRDATA
    2 X(I)=FLOAT(I-1) C      CALL GRAPH(X,CC,RDATA,DD,LRDATA)
      WRITE(6,26)
   26 FORMAT(16HOUNFILTERED  DATA)  C   1  READ(5,10)NSETS C
DO 81 J=1,NSETS
      READ(5,20) N,Z
      N2=N*2-1
   20 FORMAT(I4,1F8.0)
      CALL BNDPSS
      DO  70   I=1,N2  70      X(I)=FLOAT(I-1)     C       CALL
GRAPH(X,AA,FILT,BB,N2)
      WRITE(6,80)   80       FORMAT('0',T20,'FILTER  OPERATOR
(IMPULSE REPONSE FUNCTION)')
  100 WRITE(6,50)N2,FL,FH,DT 50      FORMAT('0',T 5,'RESPONSE
OF A',I5,'  POINT FILTER, LOW CUTOFF =',
     *F8.4,' , HIGH CUTOFF = ',F8.4,' ,    ( SAMPLING INTER-
VAL =',F12.6,'
     *)',/'1')
      CALL CONV(N,FILT,LRDATA,RDATA,RDOUT)
      CALL PROFIL(L,LRDATA,DT,S,FSTART,FINC,RDOUT)
   81 CONTINUE
      STOP
      END
      SUBROUTINE CONV(NJ,FILT,LRDATA,RDATA,RDOUT,X)
      REAL RDATA(1000),RDOUT(1000),FILT(1000),X(1000)
      NJ=2*NJ-1
      ILAST=LRDATA-NJ+1
```

```
      RDOUT(I)=RDATA(I)*FILT(NJ)
      DO 200 I=NJ,ILAST
      RDOUT(I)=RDATA(I)*FILT(NJ)
      DO 100 J=2,NJ
      JL=NJ-J+1
      JH=NJ+J-1
  100
RDOUT(I)=RDOUT(I)+FILT(JL)*RDATA(I-J+1)+FILT(JH)*RDATA(I+J-1)
  200 CONTINUE
      WRITE(6,25) LFILT,FL,FH,(RDOUT(I),I=1,LRDATA)
   25 FORMAT('-','FILTERED DATA CONVOLVED WITH',I4,
     *   ' POINT  OPERATOR;  BANDPASS  ',F8.4,' TO  ',F8.4,'
CYCLES/KM'/
     X  ' '/(1H ,10F10.1))
      WRITE(6,27)
   27 FORMAT(14HOFILTERED DATA)
      LFILT=LFILT/2+1
      RETURN
      END
      SUBROUTINE BNDPSS
      DIMENSION FILT(1000)
      COMMON FILT,N,DT,Z,PI
      FILT(N)=(ZR/PI)/ZR**2
      ZR=Z/DT
      DO 300 I=1,N
      FI=I-1
      J=N-I+1
```

```
      JJ=N+I-1
      FILT(J)=(ZR/PI)/(ZR**2+FI**2)  300    FILT(JJ)=FILT(J)
      N2=N*2-1
      WRITE(6,204) (FILT(L),L=1,N2)   204    FORMAT('1','FILTER
 COEFFICIENTS :'/' ',20(/' ',10F13.7))  C C C
      SUM =0.0
      DO 33 J=1,N
      SUM=SUM+ FILT(J)
   33 CONTINUE
      WRITE(6,205) SUM
  205 FORMAT(/24H SUM OF FILTER ELEMENTS=,F15.7) C C C C C C
      RETURN
      END
      SUBROUTINE   PROFIL(L,N,DI,S,FSTART,FINC,DATA)    C    C
 PROGRAM PROFILE PLOTS A PROFILE  FROM FIELD DATA POINTS.   C
 POINTS ARE READ IN FROM SOUTH TO NORTH, OR IN THE EVENT OF A
 C      E-W PROFILE, FROM WEST TO EAST.  C C      INPUT PARAME-
 TERS:     C C           THE FIRST  CARD  - FORMAT  (20A4)  C  C
 L          = LABEL  (ARBITRARY)  FOR  PLOT  IDENTIFICATION C  C
 SECOND CARD - FORMAT (I4,4F8.2)  C C            N       = NUM-
 BER OF POINTS  TO PLOT C            DI       = SAMPLE INTERVAL
 (FEET)    C            S        =  HORIZONTAL  DISTANCE  SCALE
 (FEET/INCH)   C          FSTART = THE Y-AXIS VALUE  (NANOTES-
 LAS)  AT  THE ORIGIN C             FINC    = THE   Y-AXIS SCALE
 (NANOTESLAS/INCH)  C   C        THIRD CARD -  FORMAT  (12F5.1)
 (AND FOLLOWING CARDS)  C C           DATA    = DATA VALUES C
      REAL DATA(1000),DATA1(1000),IBUF(8000)
```

```
INTEGER L(20) 10    FORMAT(20A4)
12 FORMAT('1',///,' ',40X,'TITLE:- ',20A4)
CALL PLOTS(IBUF,1000)
CALL PLOT (2.,11.,-3)
CALL PLOT  (0.,-9.5,-3)  15     FORMAT (I4,4F8.2)   20
FORMAT   (12F6.0)
21 FORMAT(//' ',2X,'NO OF  POINTS ',I4,'  SAMPLE INTERVAL
',F10.2,
1'  HOR.  SCALE ',F10.2,'   VER.  ORIGIN ',F10.2,'  VER
SCALE ',F10.2)
WRITE(6,22)
22 FORMAT(//' ',50X,'FIELD DATA'//)
23 FORMAT(' ',10X,10F10.2)
DO 30 J=1,N
DATA(J)          =          (DATA(J)-FSTART)/FINC         30
DATA1(J)=(J-1)*DI/S
CALL SYMBOL (0.,-1.,.1,L,0.,80)
CALL             AXIS(0.,0.,27HREL.               VERTICAL
FIELD(GAMMAS),27,8.,90.,FSTART,
*FINC)
X=(N-1)*DI/S
CALL          AXIS(X          ,0.,27HREL.            VERTICAL
FIELD(GAMMAS),-27,8.,90.,FSTART,
*FINC)
CALL AXIS  (0.,0.,14HDISTANCE(FEET),-14,X   ,0.,0.,S)
DATA1(N+1)=0.
DATA1(N+2)=1.0
```

```
DATA(N+1)=0.
DATA(N+2)=1.
CALL LINE (DATA1,DATA,N  ,1,C,1)
X=X+10.
CALL PLOT (  X,0.,999)
RETURN
END
```

Appendix D

TALWANI MODELING PROGRAM

```
      DIMENSION
 ALPHM(20),ZR(20),HR(20),KK(21),XC(4),DC(4),DP(100),
     *
 CC(100),CS(100),Y(500),XP(100),Z1(500),X1(500),FIELD(500)
     *,XF(500)
      DIMENSION FORM(2,3),PI(130)
      DATA THEND,FORM(1,1),FORM(2,1)/4HSTOP,4H  VE,4HRT. /
      DATA FORM(1,2),FORM(2,2)/4H HOR,4HIZ. /
      DATA FORM(1,3),FORM(2,3)/4H  TO,4HTAL /
      DATA WA,WB,WC,WD/1H ,1H.,1H*,1HO/
      IRD=5
      IPR=6
      IPN=7
      XOFF=0.0
   10 READ(IRD,501)  (ALPHM(J),J=1,20)
      IF(ALPHM(1).EQ.THEND)  GO TO 999
   11 WRITE(IPR,502)  (ALPHM(J),J=1,20)
      READ  (IRD,503)  NB,T,FINC,STRK,NLIM,DX,NEL,IOP
   14 WRITE(IPR,505)  T,FINC,STRK
      RAD=0.017453293
      STRK=-STRK*RAD
      FINC=FINC*RAD
      H=T*COS(FINC)
      Z=T*SIN(FINC)
      HSN=H*SIN(STRK)
      HCS=H*COS(STRK)
      I=1
```

```
      DO 202  N=1,NB
      READ(IRD,510) NP,FMAG,RINC,STRR,INF,PHI
   33 WRITE(IPR,512) N,NP,FMAG,RINC,STRR
      IF(INF-1) 35,34,35
   34 WRITE(IPR,513)  PHI
   35 WRITE(IPR,514)
      FMAG=FMAG*100000.0
      RINC=RINC*RAD
      STRR=STRR*RAD
      PHI=PHI*RAD
      ZR(N)=FMAG*SIN(RINC)
      HR(N)=FMAG*COS(RINC)*COS(STRR)
      KK(N)=I
      KF=I+NP-1
      KI=I
  100 READ(IRD,515)   (XC(J),DC(J),J=1,NP)
  109 CONTINUE
      J=1
      IF(KI-I) 104,103,104
  103 XP(I)=XC(J)
      DP(I)=DC(J)
      I=I+1
      J=J+1
  104 XP(I)=XC(J)
      DP(I)=DC(J)
      R2=(XP(I)-XP(I-1))**2+(DP(I)-DP(I-1))**2
      CC(I)=(XP(I)-XP(I-1))**2/R2
```

```
      CS(I)=(XP(I)-XP(I-1))*(DP(I)-DP(I-1))/R2
      I=I+1
      J=J+1
      IF(KF-I) 106,105,105
  105 IF(J-4) 104,104,110
  110 CONTINUE
      GO TO 100
  106 IF(INF-1) 108,107,108
  107 CC(KI)=COS(PHI)**2
      CS(KI)=COS(PHI)*SIN(PHI)
      GO TO 200
  108 R2=(XP(KI)-XP(KF))**2+(DP(KI)-DP(KF))**2
      CC(KI)=0.0
      CS(KI)=0.0
      IF(R2.EQ.0.0)   GO TO 200
      CC(KI)=(XP(KI)-XP(KF))**2/R2
      CS(KI)=(XP(KI)-XP(KF))*(DP(KI)-DP(KF))/R2
  200 CONTINUE
      IM1=I-1
      WRITE(IPR,516)    (XP(J1),DP(J1),J1=KI,IM1)
  202 CONTINUE
      KK(NB+1)=KK(NB)+NP
      DO 900 M=1,NEL
      READ (IRD,517) E,IPLOT,IINC,IPNCH,IZ1
      IF(IINC.EQ.0)    IINC=1
      IF(IZ1.EQ.0)   GO TO 51
      READ(IRD,580) NZ1
```

```
580 FORMAT(I10)
    READ(IRD,590)  (X1(K1),Z1(K1),K1=1,NZ1)
590 FORMAT(7F10.3,F6.0)
    WRITE(IPR,161)
161 FORMAT(//10X,31HTOPOGRAPHY/FLIGHT ALTITUDE DATA,//10X,
   *  2(5X,5HCOORD,10X,6HX  DIST,10X,8HZ   HEIGHT,3X))    C
WRITE(IPR,160)  (K1,X1(K1),Z1(K1),K1=1,NZ1)
160                                                        FOR-
MAT(11X,I8,5X,F12.3,5X,F12.3,5X,I8,5X,F12.3,5X,F12.3)
 51 CONTINUE
    WRITE(IPR,518)
    X=XOFF
    DO 800  K=1,NLIM
    Y(K)=0.0
    DZ=0.0
    DH=0.0
    DT=0.0
    IF(IZ1.NE.0)  GO TO 820
    ZZ1=E
    GO TO 840
820 NX=0
    DO 830 JJ=1,NZ1
    IF(X.GT.X1(JJ))  NX=JJ
830 CONTINUE
    IF(NX.LT.1.OR.NX.EQ.NZ1)  GO TO 800
    DUM=0.0
    IF(X1(NX).EQ.X1(NX+1))  GO TO 835
```

```
      DUM=(X-X1(NX))/(X1(NX+1)-X1(NX))
  835 CONTINUE
      ZZ1=Z1(NX)+DUM*(Z1(NX+1)-Z1(NX))+E
  840 CONTINUE
      DO 700 N=1,NB
      II=KK(N)
      IE=KK(N+1)-1
      ANGB=ATAN((XP(IE)-X)/(DP(IE)+ZZ1))
      FLRB=0.5*ALOG((XP(IE)-X   )**2+(DP(IE)+ZZ1)**2)
      ZZ=0.0
      ZH=0.0
      JF=IE-II+1
      DO 650 JJ=1,JF
      I=II+JJ-1
      ANGA=ATAN((XP(I)-X   )/(DP(I)+ZZ1))
      DELANG=ANGA-ANGB
      FLRA=0.5*ALOG((XP(I)-X   )**2+(DP(I)+ZZ1)**2)
      ZZ=ZZ+CC(I)*DELANG+CS(I)*(FLRA-FLRB)
      ZH=ZH+CC(I)*(FLRA-FLRB)-CS(I)*DELANG
      ANGB=ANGA
  650 FLRB=FLRA
      DZ=DZ+2.0*ZR(N)*ZZ+2.0*HR(N)*ZH
  700 DH=DH+2.0*ZR(N)*ZH-2.0*HR(N)*ZZ
      DT=SQRT((Z+DZ)**2+(HCS+DH)**2+HSN**2)-T
      WRITE(IPR,519) K,X,DZ,DH,DT,ZZ1
      IF(IOP.LE.0.OR.IOP.GT.3)   IOP=3
      GO TO (701,702,703),IOP
```

```
701 Y(K)=DZ
    GO TO 800
702 Y(K)=DH
    GO TO 800
703 Y(K)=DT
800 X=X+DX
    IF(IPLOT.EQ.0)  GO TO 1000
    WRITE(IPR,502)  (ALPHM(J),J=1,20)
    READ(5,889)  (FIELD(NFF),NFF=1,NLIM) 889   FORMAT(F5.0)
    B1=FIELD(1)
    B2=FIELD(NLIM)
    SL=(B2-B1)/(NLIM*1.-1)
    DO 890 NFF=1,NLIM
    FIELD(NFF)=FIELD(NFF)-(SL*(NFF-1)+B1)                  890
XF(NFF)=(NFF-1)*.2
    WRITE(6,899)    (FIELD(JJJ),JJJ=1,NLIM)   899     FOR-
MAT(12F7.0)
    CALL PLOT(XF,Y,FIELD,NLIM) C C
1000 CONTINUE
    IF(IPNCH.EQ.0)    GO   TO  1500   C      WRITE(IPN,65)
FORM(1,IOP),FORM(2,IOP),E C   65 FORMAT(45(1H*),2A4,19HFIELD
ANOMALY,ELEV=,F8.2)
    WRITE(IPN,501)  (ALPHM(J1),J1=1,20)
    WRITE(IPN,66)   (Y(K1),K1=1,NLIM)
 66 FORMAT(12F6.0)
1500 CONTINUE
 900 CONTINUE
```

```
999 STOP
501 FORMAT(20A4)
502   FORMAT(1H1,44X,32HTWO DIMENSIONAL   MAGNETIC   PRO-
FILE,//20X,20A4//)
503 FORMAT(I10,3F10.3,I10,F10.3,I10,I10)
505      FORMAT(20X,11HTOTAL      FIELD,F8.0,7H      GAM-
MAS,/20X,11HINCLINATION,
    1F7.1,5H DEG.,/20X,6HSTRIKE,F7.1,5H DEG.)
510 FORMAT( I10,3F10.3,I10,F10.3)
5120FORMAT(17HOBODY        SEGMENT         NO.,I4,4X,I3,7H
POINTS,4X,9HINTENSITY,
    1F12.5,4H                  EMU,4X,11HINCLINATION,F7.1,5H
DEG.,4X,6HSTRIKE,F7.1,
    25H DEG.,//)
513  FORMAT(30H  BODY  EXTENDS  TO  INFINITY   DIP,F7.1,5H
DEG.,//)
5140FORMAT(9X,1HX, 9X,5HDEPTH, 9X,1HX, 9X,5HDEPTH, 9X,1HX,
9X,
    15HDEPTH,/)
515 FORMAT(7F10.3,F6.0)
516 FORMAT(6F12.2)
517 FORMAT(F10.3,5I10)
518 FORMAT(1H ,//,10X,7HSTATION,8X,6HX DIST,14X,5HVERT.,
   1  15X,5HHORIZ,15X,5HTOTAL,8X,17HOBSERVATION LEVEL,/)
519 FORMAT(10X,I5,4(F15.2,5X),5X,F10.3)
    END
```

```
      SUBROUTINE PLOT(X,Y1,Y2,NP)    C       USES  SUBROUTINES
AMAX AND AMIN,  SUPPLIED.    C       THIS SUBROUTINE PLOTS ONE
OR TWO FUNCTIONS  ON A LINE PRINTER OR  C       TERMINAL WRI-
TER. THE ORDINATE CONTAINS UP TO 100 DIVISIONS AND C       IS
ACROSS THE PAGE, AND THE ABSCISSA IS OF UNLIMITED LENGTH AND
C       DOWN THE PAGE.  NP IS  THE NUMBER OF POINTS AND THESE
MAY BE          175.0 C        UNEVENLY SPACED ALONG THE ABSCISSA
AND THE ORDINATE.  THE USER  C       SHOULD ENSURE THE DIMEN-
SIONS AND TYPE ARE SUITABLE.  C       QUERIES TO B. W. DARRA-
COTT,  DEPT. OF GEOPHYSICS, NEWCASTLE U.  C
      INTEGER DOT,BLANK,PLUS
      DIMENSION LINE(120),Y1(NP),Y2(NP),X(NP),XX(1200)
      DATA  DOT,BLANK,PLUS/'*   ','    ','+   '/
      WRITE(6,9200) NP
 9200 FORMAT('1',15X,'NO. OF POINTS EQUALS',I4)
      CALL AMAX(Y1,NP,Y1MAX)
      CALL AMIN(Y1,NP,Y1MIN)
      CALL AMAX(Y2,NP,Y2MAX)
      CALL AMIN(Y2,NP,Y2MIN)
      Z1=Y1MAX-Y1MIN
      Z2=Y2MAX-Y2MIN
      YMIN=AMIN1(Y1MIN,Y2MIN)
      AMPL=AMAX1(Z1,Z2)
      IF(AMPL.GT.10.0) GO TO  9218
      DO 9215 M=1,7
```

```
      IF((AMPL.LE.(10.0**(2-M))).AND.(AMPL.GT.(10.0**(1-M))))
 GOTO 9216
 9215 CONTINUE
 9216 YMIN=YMIN*10.0**M
      AMPL=AMPL*10.0**M
      WRITE(6,9213)M
 9213 FORMAT(15X,'INPUT SCALING EXPONENT EQUALS',I3)
      DO 9212 J=1,NP
      Y1(J)=Y1(J)*10.0**M
      Y2(J)=Y2(J)*10.0**M
 9212 CONTINUE
 9218 SCALE=(AMPL/80.0)+1.0
      ISCALE=SCALE
      WRITE(6,9113)ISCALE
 9113   FORMAT(15X,'ORDINATE   DIVISIONS  ARE   DATA   UNITS
TIMES',I4)
      NNP=NP-1
      DO 9104 J=1,NNP
 9104 XX(J)=X(J+1)-X(J)
      CALL AMIN(XX,NNP,XXMIN)
      WRITE(6,9114)XXMIN
 9114   FORMAT(15X,'ABSCISSA  DIVISIONS   EQUAL',F10.3,'DATA
UNITS')
 9120 BASE=-(YMIN/ISCALE)+20.0
 9109 DO 9101 K=1,120
 9101 LINE(K)=DOT
      WRITE(6,9102)(LINE(JJJJJ),JJJJJ=1,115)
```

```
 9102 FORMAT(' ',8X,120A1)
      DO 9103 K=1,120
 9103 LINE(K)=BLANK
      LINE(1)=DOT
      DO 9105 J=1,NP
      K1=BASE+Y1(J)/ISCALE+0.5
      K2=BASE+Y2(J)/ISCALE+0.5
      IF(K2-K1) 9106,9107,9106
 9106 LINE(K1)=PLUS
 9107 LINE(K2)=DOT
      IF(J.NE.1) GOTO 9110
      WRITE(6,9108)LINE
 9108 FORMAT(' ',8X,120A1)
      GOTO 9111
 9110 ISTEP=(X(J)-X(J-1))/XXMIN+0.5
      ISTEP=ISTEP-1
      IF(ISTEP.EQ.0) GOTO 9123
      DO 9112 L=1,ISTEP
 9112 WRITE(6,9108)LINE(1)
 9123 CONTINUE
      WRITE(6,9108)LINE
 9111 LINE(K1)=BLANK
      LINE(K2)=BLANK
      LINE(1)=DOT
 9105 CONTINUE
      RETURN
      END C C
```

```
      SUBROUTINE AMIN (X,N,XMIN) C C      FINDS MINIMUM VALUE
OF ARRAY X C
      DIMENSION X(N) C
      KQ = 1
    5 KP = KQ
    2 IF(KQ-N)3,4,4
    3 KQ = KQ + 1
      IF(X(KP) - X(KQ))2,5,5
    4 XMIN = X(KP)
      RETURN
      END
      SUBROUTINE AMAX (X,N,XMAX)
      DIMENSION X(N) C
      KQ = 1
    2 KP = KQ
    5 IF(KQ -N)3,4,4
    3 KQ = KQ + 1
      IF(X(KP) - X(KQ))2,5,5
    4 XMAX = X(KP)
      RETURN
      END
```

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