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Well Logging
and
Borehole Geophysics
in
Mineral Exploration

by

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Abstract

Both well logging and borehole geophysics are assuming greater importance in mineral exploration and development as targets become deeper, as drilling costs increase, and as solution mining becomes necessary. Resistivity and induced polarization are the most important logs in base metal applications, because they can be used to estimate sulfide content and to aid interpretation of surface surveys. Natural gamma ray logs are used extensively to estimate uranium content; a recently developed cryogenic logging tool measures an early daughter product of uranium in order to avoid disequilibrium problems. Other logging tools, usually in combination, provide information on physical properties such as fracturing, density, and porosity, which are important for solution mining; and on potassium, magnetite, sulfide, and chemically bound water content. Borehole assaying with neutron activation is a promising area of current research. Borehole geophysical techniques such as mise-a-la-masse, induced polarization, resistivity, and electromagnetics greatly increase the amount of information derived from a drill hole, at little additional cost.

Introduction

Well logging is the measurement in boreholes of physical or chemical properties of either the borehole environment or the geological formations surrounding the borehole. It is a significant component of oil and gas exploration and development programs, and most of the available technology has been pioneered by the petroleum industry. It is also important to uranium, coal, geothermal and non-metallic mineral exploration and development. Well logging has been used very little for metallic ore deposits (Dyck et al. 1975; Glenn and Nelson, 1977), where it has been limited mainly to specialized measurements such as magnetic susceptibility and induced polarization. However, the base metals industry has developed tools designed to make measurements between boreholes and between boreholes and the surface. These techniques are commonly called *borehole geophysics*.

The requirements for research in well logging and borehole geophysics for minerals exploration and development have been identified by representatives of the mining industry (Ward et al. 1977) as: 1) determination of physical properties, 2) development of direct assay logging, and 3) expanding the radius of investigation of the borehole. Much research has been done in recent years in direct assay logging methods, particularly radiation techniques (IRT Corporation, 1976; Czubek, 1977; Wilson and Cosby, 1980), but most of the technology is only now at the point where some techniques can be applied routinely. The objectives of a good logging technology are to reduce exploration and development costs and to provide information unobtainable in any other way. Logging becomes important as new mining technologies arise, such as *in situ* or solution mining, and as ore targets become deeper and more expensive to evaluate.

Various logging tools, the quantities they measure and their applications are listed in Table 1. We will illustrate the use of some of these tools and techniques with examples. Table 1 includes an evaluation of each method on the basis of its ability to measure directly or indirectly the physical or chemical property of interest. The data may be either quantitative or qualitative.

Caliper Logging

The *caliper log* is a measurement of borehole diameter and can be obtained separately or in combination with other tools. Various caliper tools are available, the most common tools are one-, three- or four-arm calipers. Many borehole measurements are sensitive to borehole size and can be corrected if caliper data are avaible. Logging tools generally include a caliper, and caliper corrections to other logs are made automatically during the logging process.

The caliper log can be used to locate fractured zones or poorly consolidated formations that sluff material into the borehole. Also, the caliper log, if used first, can alert the logging operator of poor hole conditions and of the potential risks of further logging.

Temperature Logging

Temperature logging is not extensively used by the minerals industry but can be useful in certain situations. One application is to locate zones of fluid flow in a borehole. Also, Guyod (1946) reports that temperature increases of more than 10°F due to oxidation have been noted near pyrite deposits.

Table 1: Logging tools, property measured and mining application

Logging Tool	Property Measured	Application
Caliper	Hole size	Hole completion[1], fractures[3], lithology[3], corrections of other measurements[1].
Temperature	Temperature	Fracturing[3], fluid flow[1,3], oxidation[3], lithology [1,3], corrections of other measurements[1].
Magnetic susceptibility	Magnetic susceptibility	Lithology[1] and correlation[3], magnetite content[1].
Spontaneous polarization	Natural voltage in the earth	Lithology[3], mineralization[4], oxidation-reduction[2,4].
Resistivity/IP	Complex resistivity	Lithology identification[2,3], sulfide and clay content[2,4], correlation[3].
Natural gamma	Natural gamma radiation, count or spectral	Lithology[1,3], correlation[1], U_3O_8[1], K_2O[1] (borehole assaying)[1].
Gamma-Gamma	Scattered gamma-rays	Bulk density[1], porosity[2], lithology[2], borehole assaying[2].
Neutron	Capture gamma-rays; thermal, epithermal, or fission neutrons	Borehole assay[1], porosity[2], chemically bound water[2], lithology[2].
3-component magnetometer	Magnetic field components	Type and location of ore zone[2].
Gravity meter	Gravity field, gradient	Excess mass and location of ore zone[2].

1. Direct quantitative
2. Indirect quantitative
3. Direct qualitative
4. Indirect qualitative

In the absence of temperature logs, bottom-hole temperatures can be recorded while logging with other tools. This information may be needed to correct or interpret other logs, particularly resistivity logs.

Electrical Logging and Borehole Geophysics

Electrical drill hole methods employed by the minerals industry fall into two groups: (1) single-hole methods or conventional well logging, and (2) hole-to-surface and hole-to-hole borehole geophysics. Either of these methods may employ electrodes, loops, or measurement techniques commonly used in surface geophysics. Resistivity, induced polarization (IP), electromagnetics (EM), and spontaneous potential (SP) are all popular techniques. Dyck et al. (1975) have reviewed these various methods.

Spontaneous potential

Spontaneous potential (SP) is usually taken as the measured natural voltage of a downhole electrode relative to a surface electrode. Measurement of SP is routine in conventional well logging and is often a part of combination tools such as resistivity, nuclear and acoustic tools.

The origin of SP in the earth has been discussed extensively in the logging literature (Dyck et al., 1975). Natural voltage variations in a borehole may arise from (1) the diffusion of ions either from the drilling fluid into the formation or the reverse; and (2) oxidation-reduction reactions of minerals in the vicinity of the borehole. The second source of SP is the one commonly observed in minerals logging.

SP can be measured at the surface but, in cases where it is masked by a clay surface layer, borehole measurements are recommended (Telford et al., 1976).

SP logs are commonly obtained in uranium exploration logging in sedimentary environments. The log can be used to identify lithology, and the log may also reflect the redox potential (Eh) in the vicinity of the ore zone.

Resistivity/induced polarization

The measurement of resistivity and/or IP in boreholes, the most popular well logging technique in the minerals industry, can be made in a single hole, between holes, or between a hole and the surface. The instrumentation and techniques used are numerous.

Figures 1a through 1e schematically illustrate the common single-hole electrode configurations and their popular names. The popular hole-to-hole and hole-to-surface electrode systems are sketched in Figure 1f.

The *single point resistance* tool (Figure 1a) routinely included in many mineral logging programs, particularly in uranium exploration, measures downhole electrode impedance. This measurement can be obtained in combination with other measurements and requires only a single cable conductor. Also, SP can be measured simultaneously from the same electrode. The measured resistance can be used for correlation or identification of lithology but seldom provides quantitative information.

The *long- and short-normal and lateral logs* (Figures 1b and 1c) were among the first electrode systems used in oil and gas logging. The measurements are very sensitive to borehole diameter and bed thickness. Minerals industry applications usually include IP with the resistivity log. Both time- and frequency-domain systems are used (Snyder et al., 1977). The electronics may be totally on the surface, partially on the surface and partially downhole, or totally downhole. Placing the electronics entirely downhole, using the time domain method, or shielding cable lines minimizes capacitive and inductive coupling between the transmitter and receiver cable lines.

Glenn and Nelson (1977) discuss borehole and laboratory data which indicate that in disseminated copper sulfide ore a correlation exists between total sulfides and IP phase, ϕ; in veined mineralization the correlation exists between total sulfides and $\sqrt{10\phi/\rho}$, where ρ is resistivity. Results that demonstrate the latter relationship are shown in Figure 2. The sulfide minerals in drill hole A are predominantly on veins. In contrast, in drill hole B (Figure 3) where sulfide minerals are largely dissiminated, the correlation is between total sulfides and phase only. However, the results are unquestionably dependent on lithology, texture, mineralization and porosity of the rocks. Insufficient studies have been made to assess the importance of these factors.

When a current electrode is placed in a borehole in a conducting body, and potential measurements are made with an electrode pair either on the surface or in other boreholes, it is a special case of both a three array hole-to-hole or hole-to-surface technique and of the mise-a-la-masse method (Telford et al., 1976; Ketola, 1972).

Ketola (1972) examines several electrode systems and presents a number of case histories. Figure 1f depicts the measurement system employed by Ketola. Figure 4 shows examples of data obtained with this system at a small nickel ore deposit at Telkkala, Finland. The data in Figure 4a were obtained with current electrode C 10 m deep in bore hole BH1, current electrode D situated .5 km to the west of the deposit, and the fixed potential electrode F situated as shown in the figure. Measurements were made by moving E, the second potential electrode. Ketola (1972) noted that the 10 mv/A contour delineates the limit of sulfide ore fairly accurately. Figures 4b and 4c show a vertical section through x = 4.95 (refer to Figure 4a for location of section) and data obtained in five drill holes. The contours of the mise-a-la-masse potential pattern, Figure 4b, reflect the shape of the deposit; the potential increases rapidly outside the limits of the deposit. The resistivity data in Figure 4c suggest that the ore body occurs in three separate lenses.

Electromagnetics

Induction logging is a second type of borehole electrical measurement; it utilizes current loops to create a magnetic field that induces currents to flow in the adjacent rocks. Measurements may be made with frequency- or time-domain systems. Often the systems are only slightly modified versions of surface instrumentation. The applications are typically in single hole, hole-to-hole and hole-to-surface studies as depicted in Figure 5. Typically only the coils are placed downhole with the majority of the elecronics in surface instruments. Highly sophisticated induction logging (Figure 5c) long popular in the oil and gas industry, has only recently been used by the mining industry. Borehole EM systems typically are operated over the frequency range of 10 to 5000 Hz, although measurements are commonly made at only a few frequencies. Time-domain instruments are designed to operate over an equivalent spectrum. The higher the frequency, the greater the signal attenuation and the smaller the range of investigation, particularly in conductive environments. Model curves have been developed for various dipping conductors adjacent to a borehole (Drinkow and Duffin, 1978).

A hole-to-surface frequency-domain system is shown in Figure 5b (Scintrex, 1978). This system measures both the phase between the transmitted and received fields and also the ratio of the amplitude of the received field to the amplitude of a reference field coil placed near the transmitter at a number of frequencies. The system may be used to 1500 m depth, depending on the host rock conductivity, and over a frequency range of 35 to 5000 Hz. The example in Figure 6 illustrates how a conductor missed by the drill hole was detected by both the phase and the amplitude EM measurements made with this system.

Use of a time-domain system is illustrated in Figure 7 (Crone, 1978). Eight samples of the transient EM secondary field are measured after the primary pulse is turned off such that an equivalent frequency range of 2000 to 16 Hz is covered. Model curves for this Crone PEM system have been developed by Woods (1975). The borehole anomaly is greater than would be expected from the two minor sulfide intercepts in the drill hole. One would suspect a wider zone of sulfides near the borehole. The dual negative peaks in the data, shifted above the sulfide intercepts, are interpreted to mean that the borehole lies below the main sulfide body. On the basis of this borehole and two others, Crone calculated a conductivity-thickness product for the sulfide body of 10 to 18 mhos, well within the expected range for massive sulfides.

Radioactivity Logging

Radioactivity logging techniques, popular for many years in other industries, have been employed only recently by the base metals industry (Czubek, 1977; Glenn and Nelson, 1977).

There are two basic types of radioactive well logs: active and passive. Passive methods measure the natural radioactivity of the rocks using gamma rays. Active methods use a source of radiation, natural or induced, in the logging tool, and observe various kinds of scattered radiation. Many tools are used for qualitative or quantitative examination of rock formations behind casing (Czubek, 1977).

Passive radioactive methods

The most common passive gamma-ray logging tools measure total counts, and the data are used for lithologic identification and qualitative assay of uranium. More sophisticated tools may measure total count above some threshold gamma-ray energy, counts in several selected energy windows, and counts in one thousand to 4000 or more channels.

Undoubtedly, the greatest application of the gamma-ray log by the mining industry is in uranium exploration. Obviously, in addition to uranium daughter products, the total counts will reflect the presence of ^{40}K and thorium. In addition, the uranium series may be in disequilibrium. Hence the total counts measurement is commonly recorded either in equivalent uranium concentration (eU_3O_8) or counts/sec, but it is only a qualitative indicator of possible uranium occurrence.

Four-channel spectral logging, comprising measurements in gamma-ray energy windows for thorium, uranium and potassium and for total counts, has been developed in recent years (Conaway and Killeen, 1980). This technique would minimize the effect of thorium and potassium contributions in the gamma-ray counts attributed to uranium. Many logging companies today use calibrated logging tools and compute eU_3O_8 directly in the field. This calculation may include corrections for dead time, borehole size and fluid, formation moisture content, and casing.

Protactnium-234 is a short half-life daughter of ^{238}U early in the decay chain. A measure of its characteristic spectral peak of gamma-ray emission should provide a more accurate estimate of uranium concentration in disequilibrium situations than would the customary measurement of ^{214}Bi. A tool that employs this technique has been described by Goldman and Marr (1979). The probe contains an intrinsic germanium detector cooled to liquid nitrogen temperatures using frozen propane in a canister, and a 4000-channel analyzer. The logging speed, measurements and data processing are all automated and computer controlled, and the logging speed is controlled to optimize counting statistics and grade accuracy.

Active Radioactive methods

Two basic types of active radioactive logging techniques are used; one uses a source of gamma-rays, commonly Cobalt-60 (1.17 and 1.33 MeV γ-rays) or Cesium-137 (.662 MeV γ-ray), the other uses neutrons either from radioactive emitters or neutron generators.

Gamma-ray density logger: The attenuation and absorption of gamma-rays by elements of low atomic number, Z, is not too different between 1 and 10 MeV and is dominated by Compton scattering. Below this range photoelectric attenuation becomes important and above this range, pair production becomes more important with increasing energy. For elements with atomic number Z greater than about 20 the dominant Compton region shrinks; for example, for lead this region lies between 1 and 3 MeV. Gamma-gamma density tools are designed to operate in the Compton region where gamma-ray scattering is near equal for all elements in the rock. The density tool is very sensitive to borehole size; to minimize this problem the gamma-ray source is placed to one side of the tool with all but this side enclosed by a lead shield. The unshielded side of the tool is held firmly against the side of the hole by one or two arms on the other side of the tool. However, mudcake and hole rugosity can still be serious problems with this design. A two-detector system which is expected to eliminate mudcake effects and minimize borehole rugosity effects has been developed (Wahl et al., 1964). Small scale, heavy mineral variations may generate inappropriate corrections with these systems. A simultaneously recorded caliper log can be used to correct the variations further.

The bulk density can be expressed in terms of the fractions of the densities of the components in the rock:

$$\rho_b = V1\ \rho_{m1} + V2\ \rho_{m2}\ \ell\ .\ .\ .\ +Vn\ \rho_{mn}$$

where Vi and ρ_{mi} are the volume fractions and densities respectively of the mineral fraction i. In cases where the various minerals have nearly equal densities, and relative amounts vary only slightly, one may write

$$\rho_b = \phi\ \rho_f + (1-\phi)\ \rho_{ma}$$

where ϕ is porosity, ρ_{ma} is average matrix mineral density and ρ_f is the fluid density. If the matrix mineral density can be divided into a base metal density, ρ_s, and non-metallic mineral density, ρ_{ma}, this equation becomes

$$\rho_b = \phi\ \rho_f + (1-\phi-x)\ \rho_{ma} + x\ \rho_s$$

where x is volume fraction of base metal minerals. In many igneous and metamorphic rocks the porosity ϕ is very low and fairly constant. Hence, ρ_b variations can reflect base metal mineral concentrations (Glenn and Nelson, 1977).

Gamma-ray assaying: Gamma-ray scattering properties of rock formations can be used for mineral assaying. Most techniques are in the experimental stage (IRT Corporation, 1976), and much of the literature is in Russian. One technique that has been tried successfully is the selective gamma technique (Charbucinski et al., 1977). A measure of scattered gamma-rays in the density region (Compton scattering region) and in the lower energy region is made. A ratio of the two counts can be qualitatively or quantitatively related to Z or Z- equivalent of the rock. Charbucinski et al. were able to assay iron to .8% at the 95% confidence level. They concluded that their system could assay 10 blast holes per shift, and costs compared favorably with those of analytical laboratories. However, their applications were to highly mineralized rocks. Application of this method to lower grade ore bodies such as porphyry copper deposits may be less successful.

Neutron logging: Many papers on neutron logging techniques emphasize a particular process of interaction of neutrons with matter, which is the one being monitored for the particular application, and little mention is made of other processes that are taking place. These other processes, in individual circumstances, can seriously change the measurement being made. Neutrons interact with the nuclei of elements and these interactions involve a number of competing processes that depend on the neutron energy and on the neutron capture and scattering characteristics of the nuclei present.

Neutron porosity logging: The neutron tool was developed initially to measure porosity. In porosity applications of neutron logging, one supposes that most of the interactions involve elastic collisions between the neutrons and hydrogen nuclei. This process is most likely elastic since the neutron and hydrogen nucleus have nearly equal mass. Once the neutrons have been slowed, or moderated, to thermal energies (approximately 0.025ev) they are easily captured by any number of elements in the formation. Neutron tools have been designed to measure either the thermal neutron population or the capture gamma-rays. The assumptions made are that the processes are dominated by hydrogen nuclei in the formation, that the hydrogen is entirely in water, and that the water is entirely in the pore space. However, in many rocks hydrous minerals are quite abundant and the water of hydration can appear as porosity on a neutron log. In many igneous and metamorphic rocks, porosity is commonly very low, and the neutron log responds primarily to the water in hydrous minerals (Nelson and Glenn, 1975). This result can be used to identify particular lithologies.

A second problem is the different moderating or capture properties of the matrix material in the rock. The neutron tool is commonly calibrated in a particular lithology, and where this lithology is encountered during logging the porosity measurement should be quite good. If the lithology is different and has different neutron moderating or capture properties, the log must be corrected to determine the true porosity. Unfortunately, good calibration of commercially available neutron logging tools does not exist for rocks commonly associated with base metal ore deposits. The neutron log may need to be corrected further for borehole size, borehole fluid salinity, temperature and mud cake.

Tools have been designed to measure neutrons in the epithermal energy range 0.4 to 1.0ev, just above the thermal energy. The belief is that the epithermal neutrons reflect the moderating influence of hydrogen in the formation and are less sensitive to neutron capture properties of the formation.

Neutron assaying: Potentially the most important application of neutron logging to minerals exploration is borehole assaying. Although recognition of this use of neutron logging appeared in the literature some years ago, it has been only recently that a number of commercial systems, in each case designed for only a few selected elements, have been available in North America (Seigel and Nargolwalla, 1975; Wilson and Cosby, 1980).

A new tool, developed by Princeton Gamma-Tech for the United States Bureau of Nines is currently being field tested in copper, iron, gold and silver deposits. This tool uses a ^{252}Cf source, and the detector is a 4000-channel gamma-ray spectrometer. Figure 5-8 compares chemical assay data with data obtained using the Bureau of Mines system in an area mineralized with silver near Creed, Colorado. In this case the correlation is good, but the accuracy, calibration, sensitivity and optimum logging techniques have yet to be fully resolved (Wilson and Cosby, 1980).

Acoustic Logging

The logging of acoustic velocity in boreholes is routine in several fields but is seldom applied to base minerals exploration (Glenn and Nelson, 1977). Formation velocity is determined by measuring the time difference in arrival at two or more receivers, separated by one to two meters, of a signal from one or two transmitters several meters distant, all mounted in a single tool. The recorded measurement is interval transit time, and compressional wave velocity is proportional to the reciprocal of this measurement. Wyllie et al. (1956) determined an empirical relationship between porosity and travel time. The sonic (acoustic) travel time log can be used, in conjunction with the density log, to generate synthetic seismograms which are used to interpret surface seismic reflection data (Telford et al., 1976).

The sonic log can be correlated with Rock Quality Designation (RQD) (Nelson and Glenn, 1975), and the full wave form of the received velocity signal can be used to locate fractures (Myung and Helander, 1972). The best acoustic tool for fracture identification is the seisviewer, or borehole televiewer. The tool can be used not only to locate fractures but also to determine their strike and dip: examples of its use in a porphyry copper deposit have been given by Glenn and Nelson (1977) and in a variety of igneous and metamorphic rocks by Keys (1979).

Gravity Logging

Borehole gravity measurements have been suggested and investigated for thirty years (Smith, 1950; Rasmussen, 1975; among others). However, only in the last decade has sufficient progress been made in the design of sensitive, small diameter, rugged gravity meters to allow routine, useful borehole measurements to be made. These tools have been designed by and for the petroleum industry but they have potential use by the minerals industry to determine *in situ* density and to detect mineralization missed by the borehole log. The only serious limitation for minerals use is the tool size, which is 4 3/8 inches (11 cm) in diameter.

Magnetic Logging

Two types of borehole magnetic logging are utilized by the minerals industry: (1) the measurement of three components of the magnetic field (Levanto, 1959; Lantto, 1973) and (2) the measurement of magnetic susceptibility (Zablocki, 1966). The various instruments and techniques that are used have been reviewed by Dyck et al. (1975). The three-component borehole magnetic field measurement has great promise as indicated by theoretical studies made by Silva and Hohmann (1981).

The logical and principal application of borehole magnetic methods is the investigation for iron ore, pyrrhotite-associated massive sulfide, and skarn deposits. The borehole measurement of magnetic susceptibility has been used for lithologic identification (Glenn and Nelson, 1977) and is particularly valuable in rotary drilled holes. Hafen et al. (1976) describe the application of magnetic susceptibility measurements to the identification of uranium ore zones in the Grant district of New Mexico. Magnetite conversion to hematite in ore zones results in reduced magnetic susceptibility.

Cross Plots

The successful application and interpretation of well logs by the petroleum industry has resulted from judicious use of combinations of logs. As indicated in previous sections, many logging tools respond to more than one formation property. Since each tool may respond to a different set of properties or to the same set but in a different manner, a plot of one type of data versus another type can often reveal which properties are dominant. Cross plots of well log data from igneous and metamorphic rock environments can be found in Ritch (1975), Glenn and Hulen (1979), among others. Cross plots can be used to separate matrix and porosity effects in either igneous or metamorphic rocks.

A cross plot, Figure 9, of neutron porosity versus gamma-gamma bulk density from an interval of biotite-hornblende quartz monzonite gneiss in a geothermal well at Roosevelt Hot Springs thermal area, Utah will illustrate this technique. Figure 9 shows that the data follow a trend of increasing density accompanied by an increase in neutron porosity. However, porosity variations would cause a trend different from that observed in Figure 9. An increase in pore porosity actually decreases the bulk density and increases the neutron porosity. In contrast, the water in the hydrous minerals produces an apparent neutron porosity and these minerals, because they are denser than the feldspar and quartz that comprises the bulk of the rock, also increase the rock density. The data trend in Figure 9 is due to dense, hydrous minerals. The grid in Figure 9 was constructed using log response equations and depicts the expected and different data trends due to porosity and hydrous mafic mineral variations. The grid origin is offset from zero because the neutron tool was calibrated in limestone porosity units. Figure 10 shows a plot of estimated volume per cent mafics (estimated from binocular microscope examination of drill chips) plotted versus interval transit time, bulk density and neutron porosity data. The dashed lines trace the correlation between the various log data and the volume per cent hydrous mafic minerals. This correlation demonstrates that these minerals, rather than porosity, dominate the log responses.

The Outlook for Borehole Assaying

Since application of logging to borehole assaying is important in exploration by the minerals industry, Figure 11 lists the various elements in Periodic Table format along with the various radioactivity logging methods used to detect these elements. Sensitivities for assaying of the various elements are also indicated in the figure. Only a few of the techniques have been developed to a stage where commercial tools are available.

Application of magnetic, gravity and resistivity methods in the borehole for quantitative or qualitative estimation of mineralization has been demonstrated and should experience greater use in the future.

Borehole assaying has many advantages. Drilling costs can be substantially lowered since core drilling is not required. Logging tools sample a greater volume of rock and minimize assay errors in ore bodies having highly variable mineralization. The data are available soon after drilling is completed, often with the drill rig still over the hole. Repeat runs are easily made to improve measurement statistics. Assays on core are commonly made on two- to three-meter composite samples, whereas borehole assays are by continuous measurement limited only by source receiver separations, typically less than one meter. Borehole assaying can be done in holes where core recovery is bad and in holes in old prospects where core has been lost or is unavailable. Now that the technology for borehole assaying and the application of other logging tools are routinely available and highly useful, the mineral industry should begin to use borehole logging more effectively. As the use of logging increases, the methods of interpreting log data in minerals exploration will be improved.

Figure Captions

1 Schematic of various popular single hole, hole-to-hole and hole-to-surface electrode configurations used in resistivity/IP logging. As noted, several names may be given to a particular electrode configuration.

2 a) IP resistivity and phase measured in drill hole A in a sulfide veined portion of a porphyry copper deposit in the south western United States. b) Correlation between IP phase divided by resistivity and sulfide analysis on core.

3 IP phase correlation with total sulfides in drill hole B; a disseminated sulfide mineralization area of the same deposit as cited in Figure 2.

4 Mise-a-la-masse measurements about the Telkkala nickel ore body in Finland: (a) measurements on the surface (b) mise-a-la-masse measurements in several boreholes and (c) resistivity measurements in several boreholes (after Ketola, 1972).

5 Hole-to-surface and single-hole electromagnetic logging systems.

6 Example of a multi-frequency drill hole survey (Scintrex Limited).

7 Example of a time domain hole-to-surface measurement in the Flying Doctor Prospect, North Broken Hill Area, Australia (Crone Case Study, 20, Crone Geophysics, Ltd., 1978).

8 Data obtained with United States Bureau of Mines borehole neutron activation tool in a silver mineralized area near Creed, Colorado (Schneider, G. J., 1979, personal communication).

9 A cross plot of bulk density versus neutron porosity well log data illustrating the affect of dense, hydrous mafic minerals on the tool responses.

10 A plot of estimated volume per cent mafic minerals versus well log responses for part of the interval plotted in Figure 9.

11 Periodic Table of the elements and an indication of the various methods that could possibly be used in borehole assay methods and the sensitivity of each method (Schneider, 1979, personal communication).

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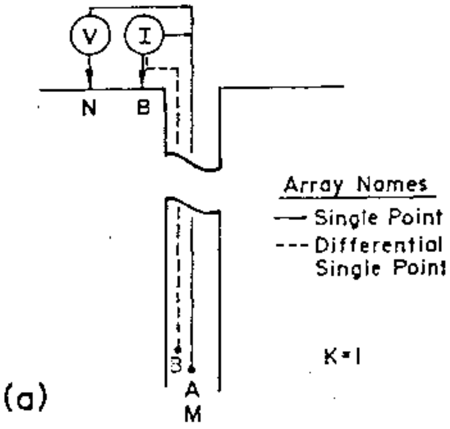
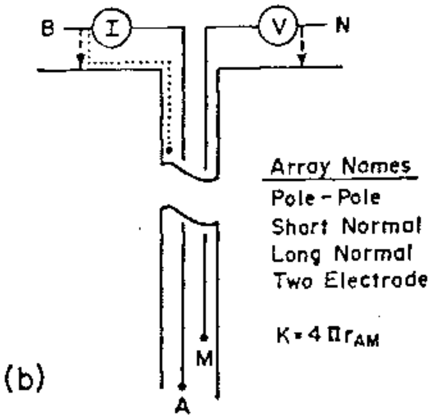
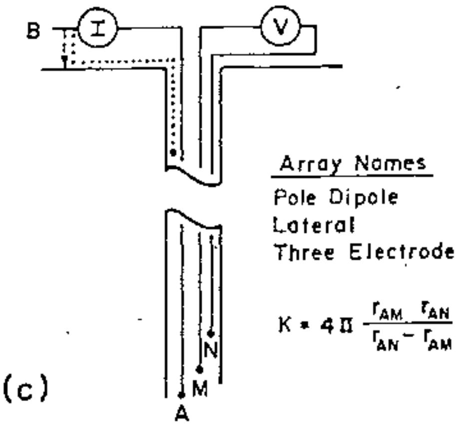
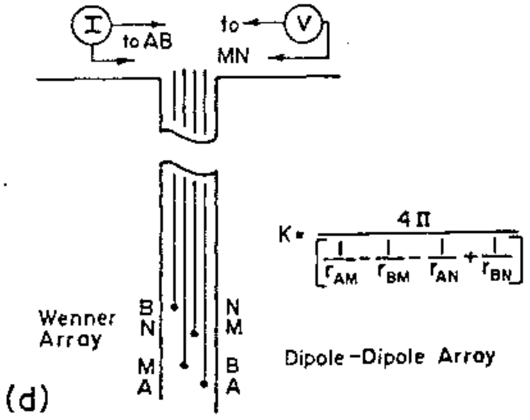
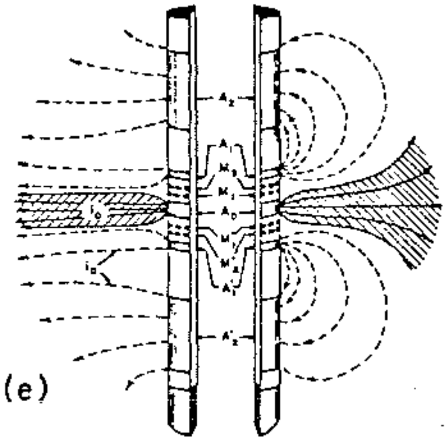


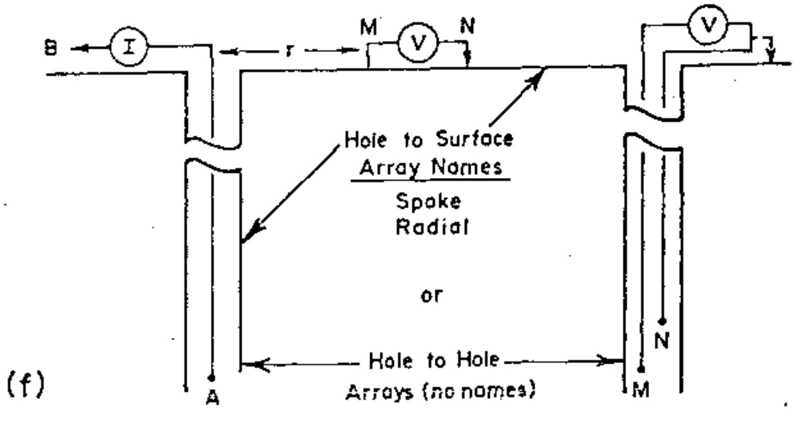


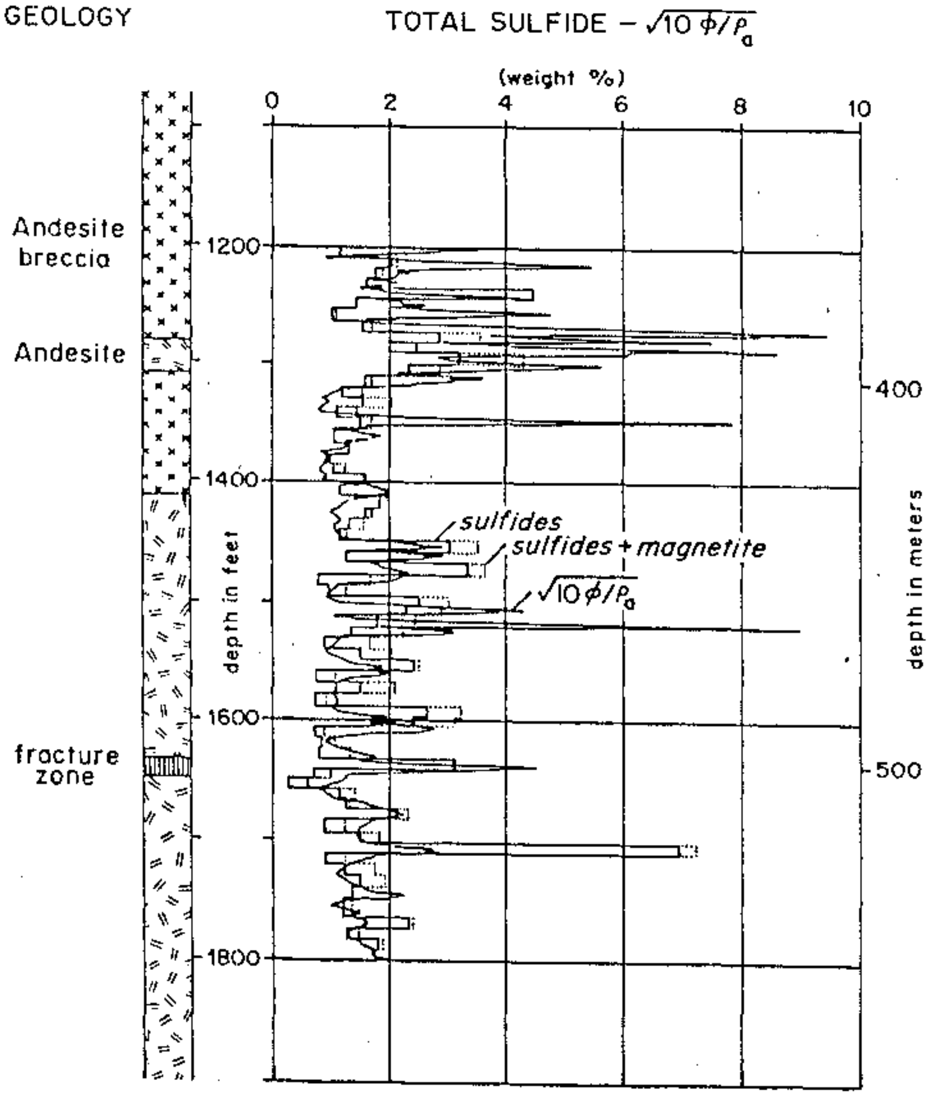






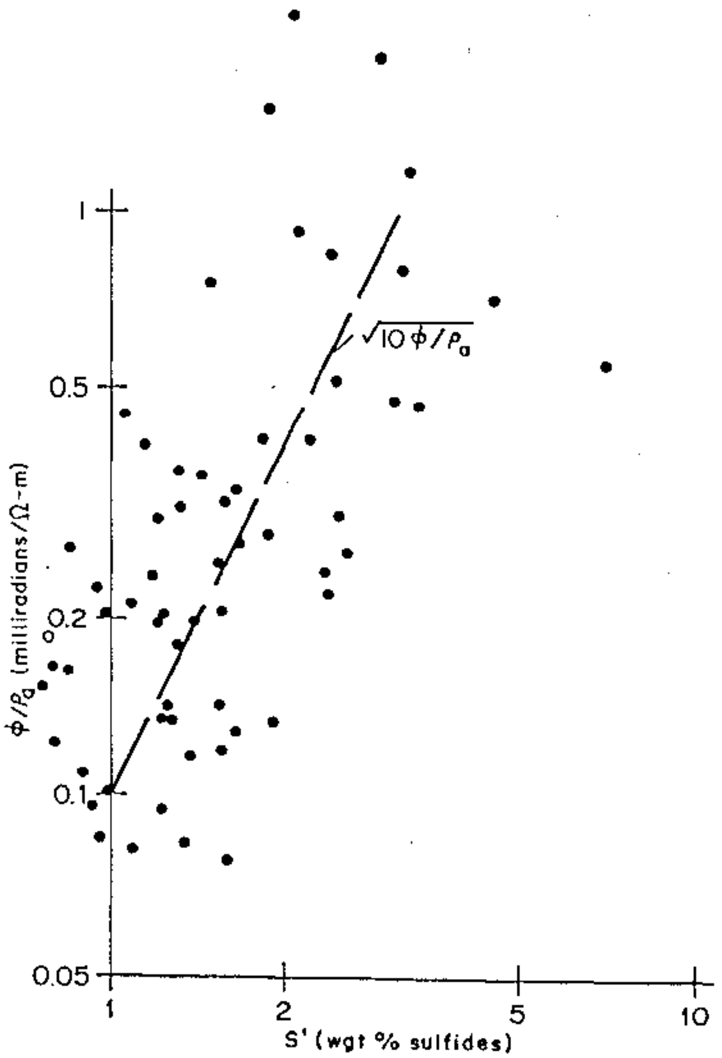
Example of a focused electrode array - dual laterolog (Courtesy of Schlumberger)





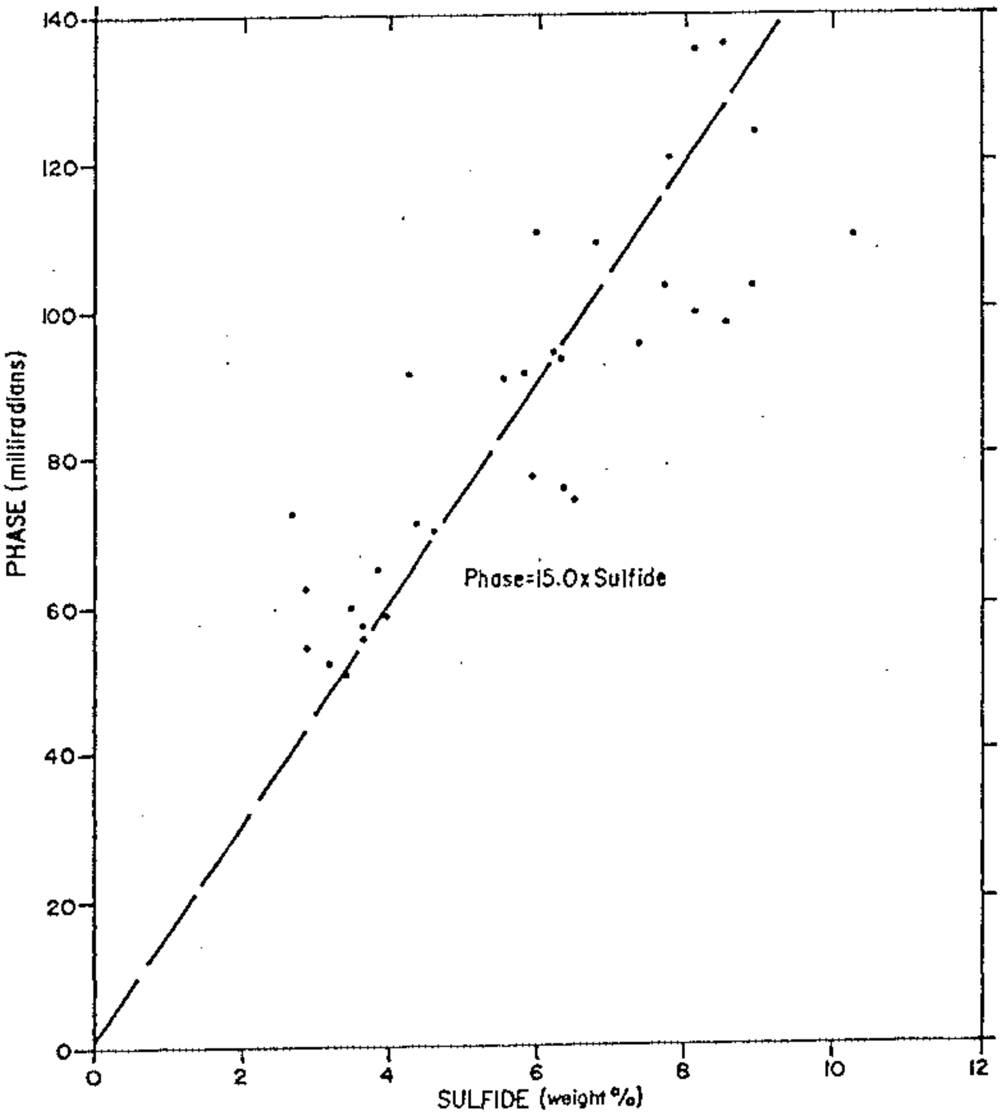
Drill Hole A

5-2a



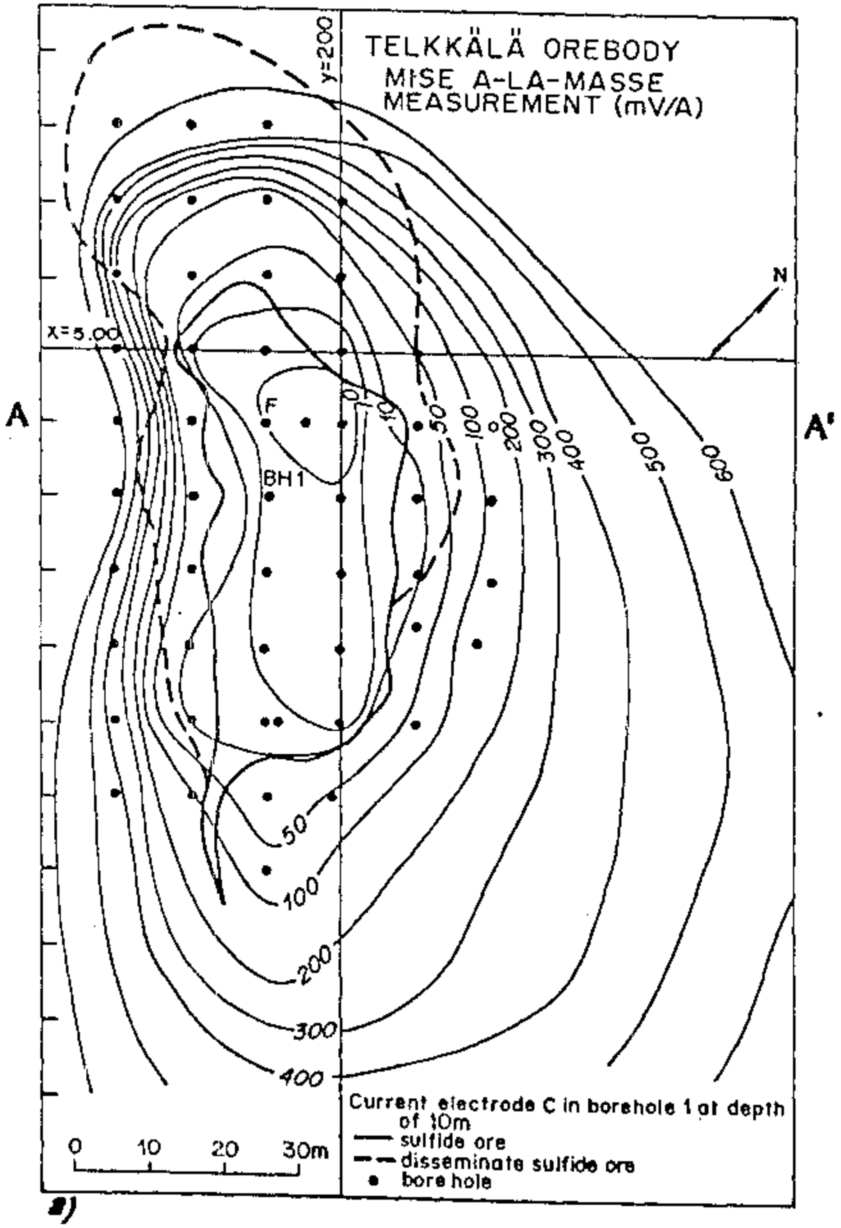
Drill Hole A

5-2b)

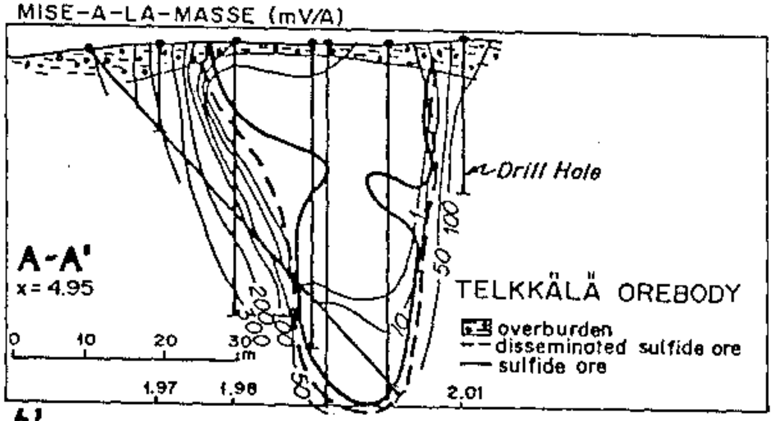


Phase values averaged over 10 foot interval vs. sulfide content.

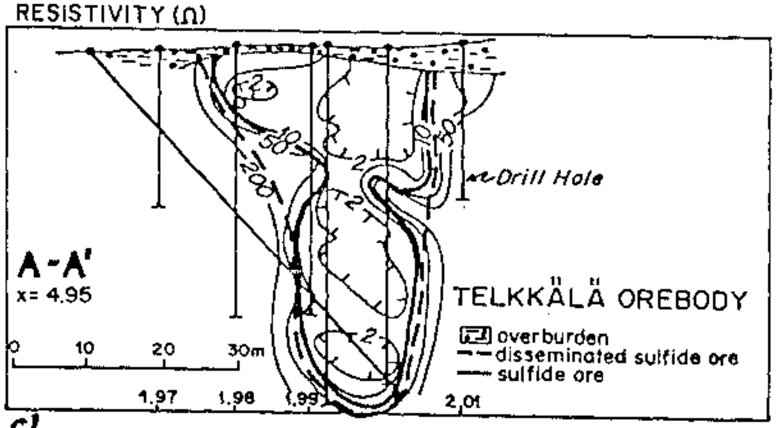
Drill Hole B


TELKKÄLÄ OREBODY
MISE A-LA-MASSE
MEASUREMENT (mV/A)
y=200
X=5.00
N
A
A'
F
BH1
0
10
50
100
200
300
400
500
600
50
100
200
300
400
0
10
20
30m
Current electrode C in borehole 1 at depth of 10m
sulfide ore
disseminate sulfide ore
bore hole

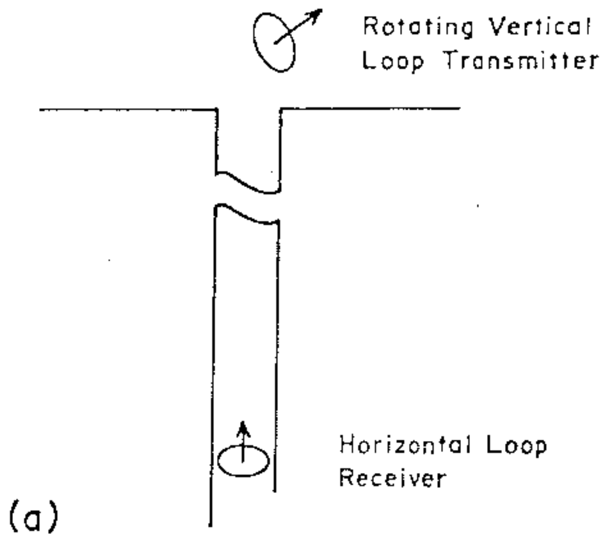
a)

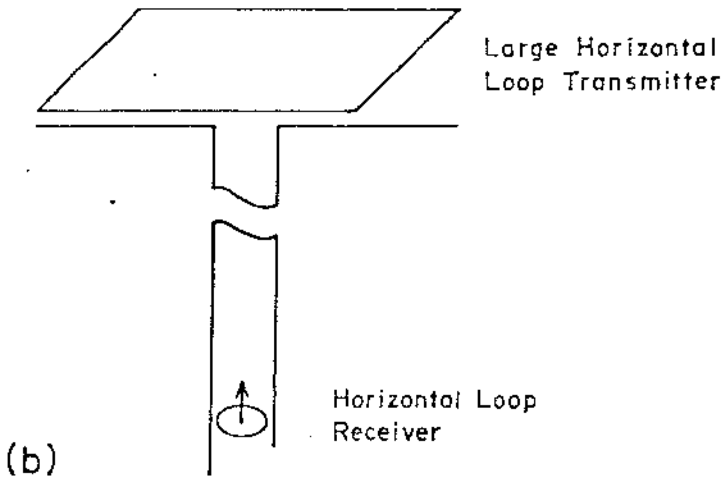

MISE-A-LA-MASSE (mV/A)
Drill Hole
A-A'
x= 4.95
100
50
10
2000
3000
100
50
TELKKÄLÄ OREBODY
overburden
disseminated sulfide ore
sulfide ore
0
10
20
30m
1.97
1.98
2.01

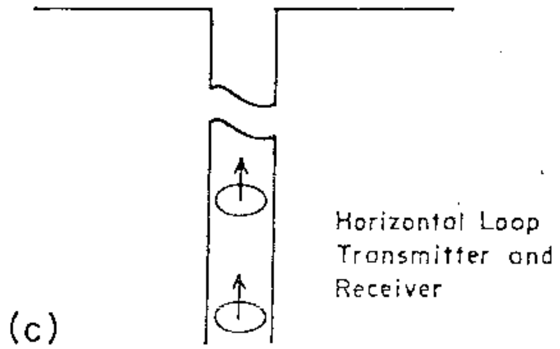
b)

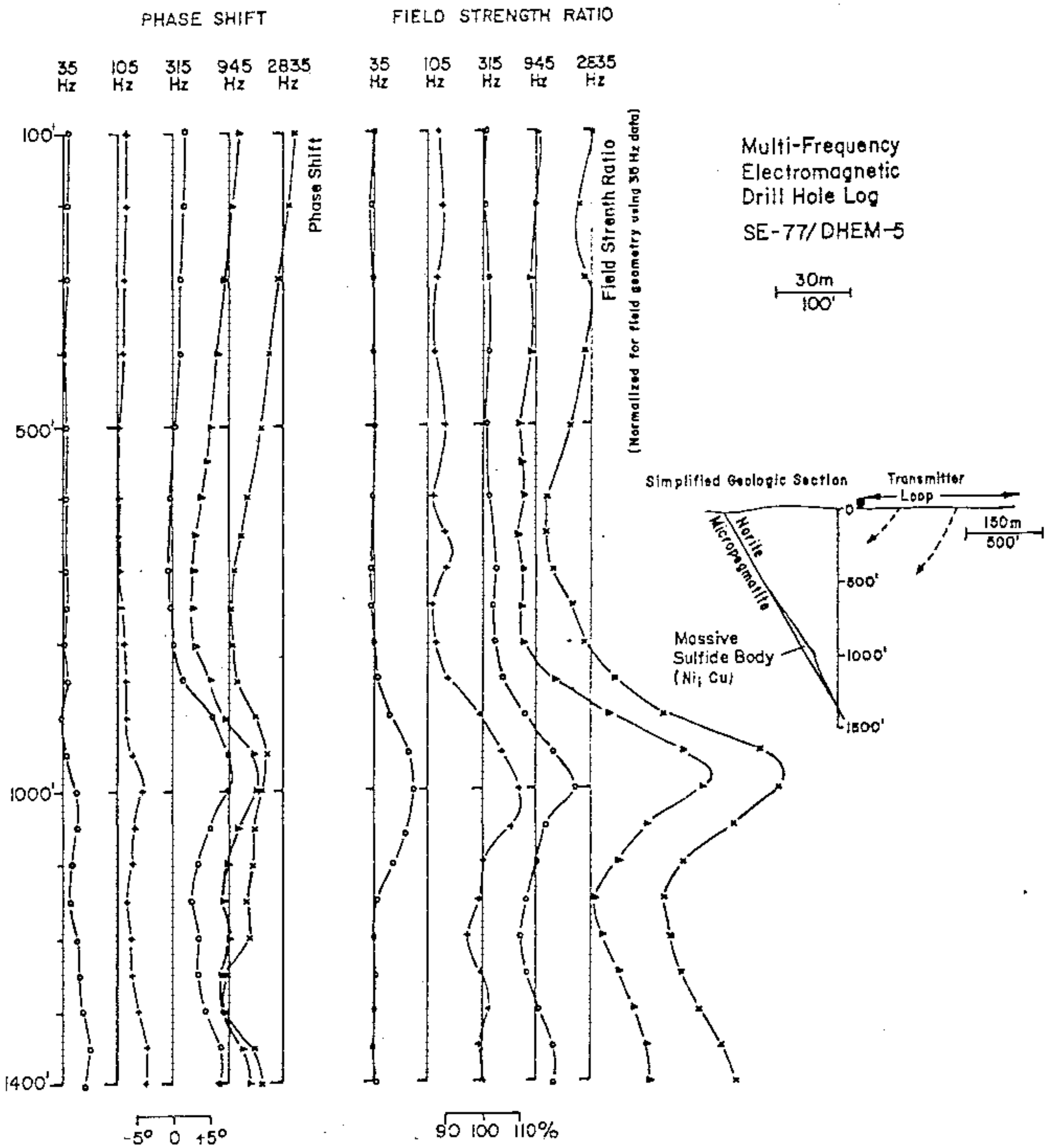

RESISTIVITY (Ω)
2
10
50
200
2
Drill Hole
10
50
2
2
A-A'
x= 4.95
TELKKÄLÄ OREBODY
overburden
disseminated sulfide ore
sulfide ore
0
10
20
30m
1.97
1.98
1.99
2.01

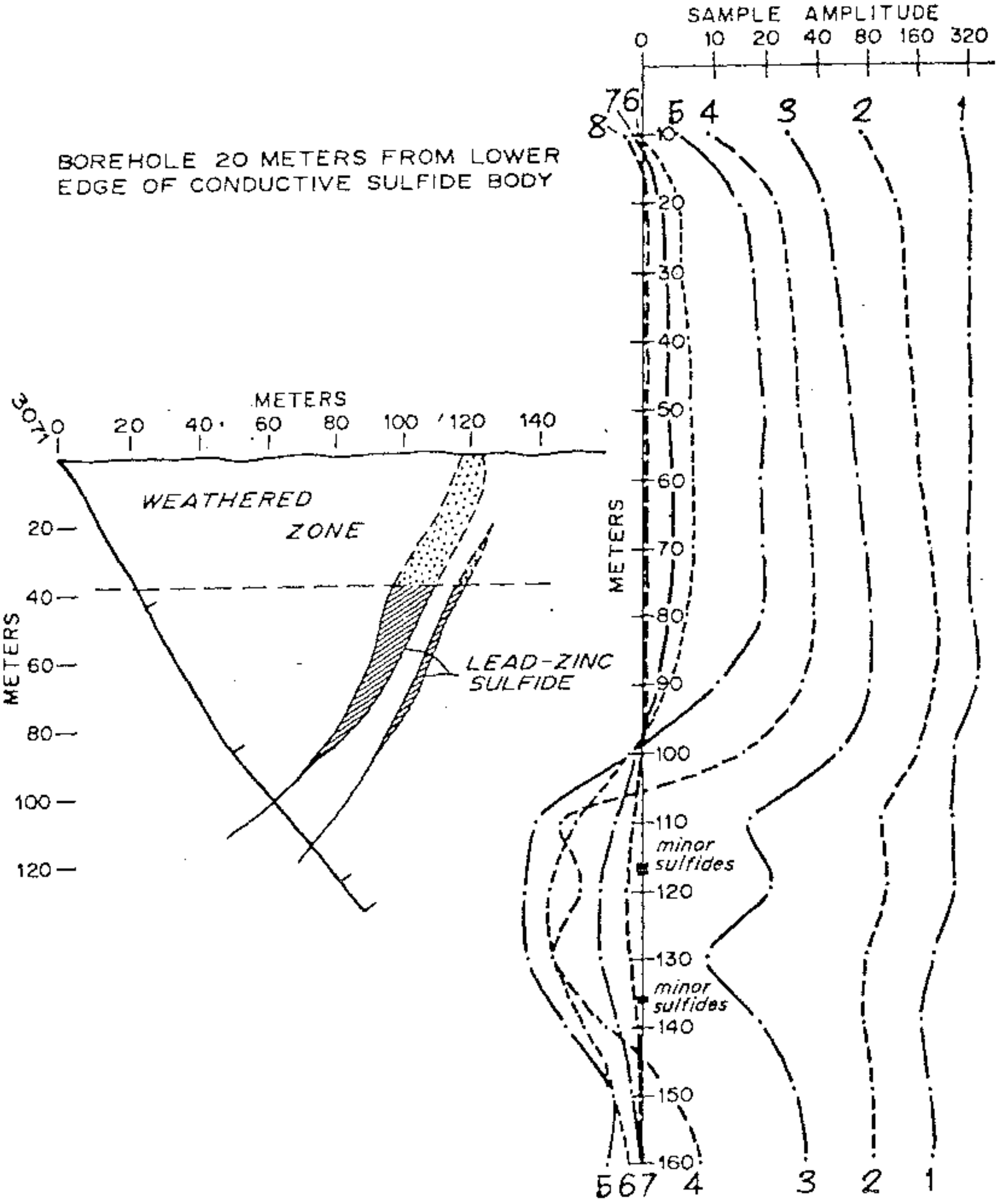
c)


Rotating Vertical Loop Transmitter
Horizontal Loop Receiver
(a)

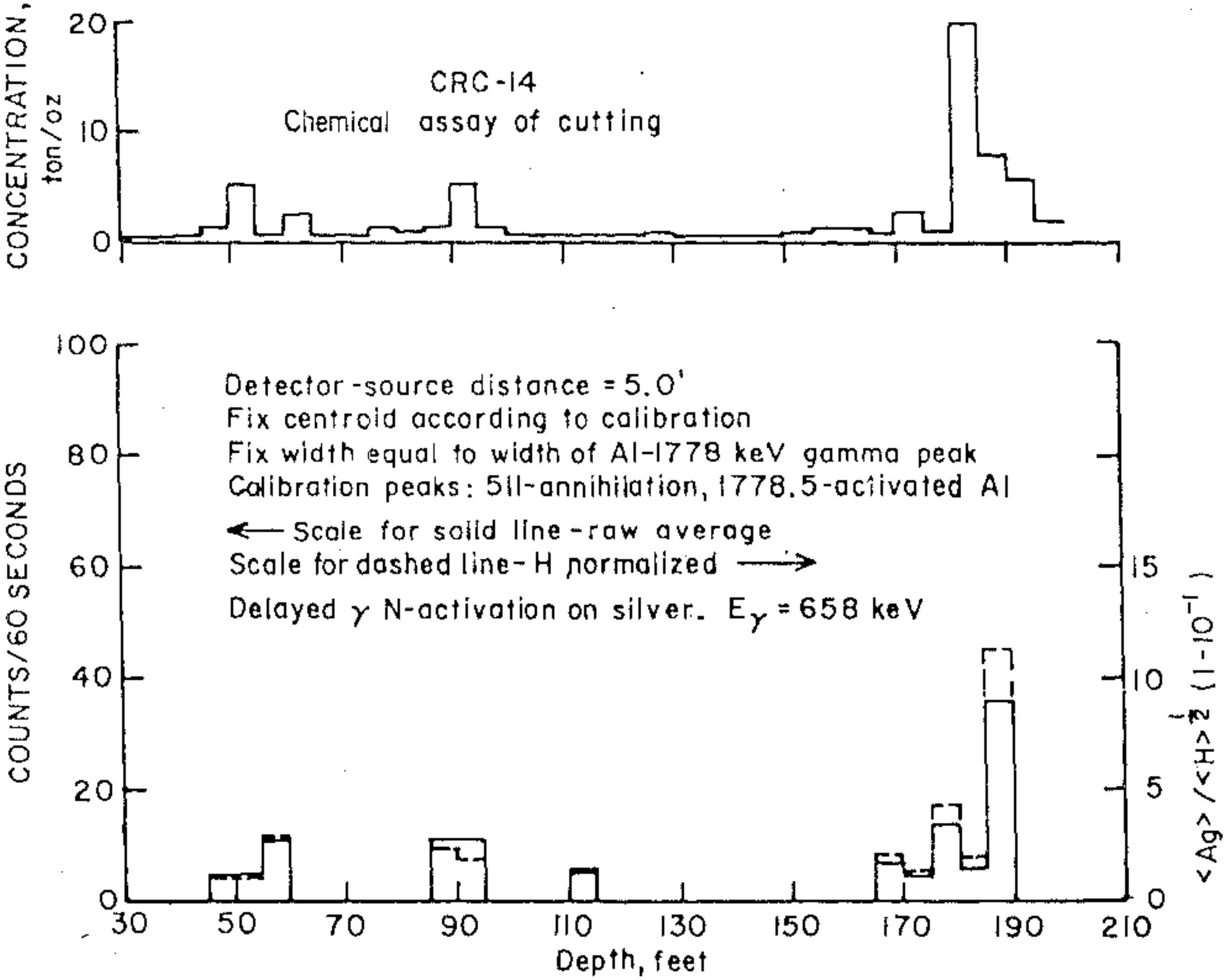

Large Horizontal Loop Transmitter
Horizontal Loop Receiver
(b)


Horizontal Loop Transmitter and Receiver
(c)

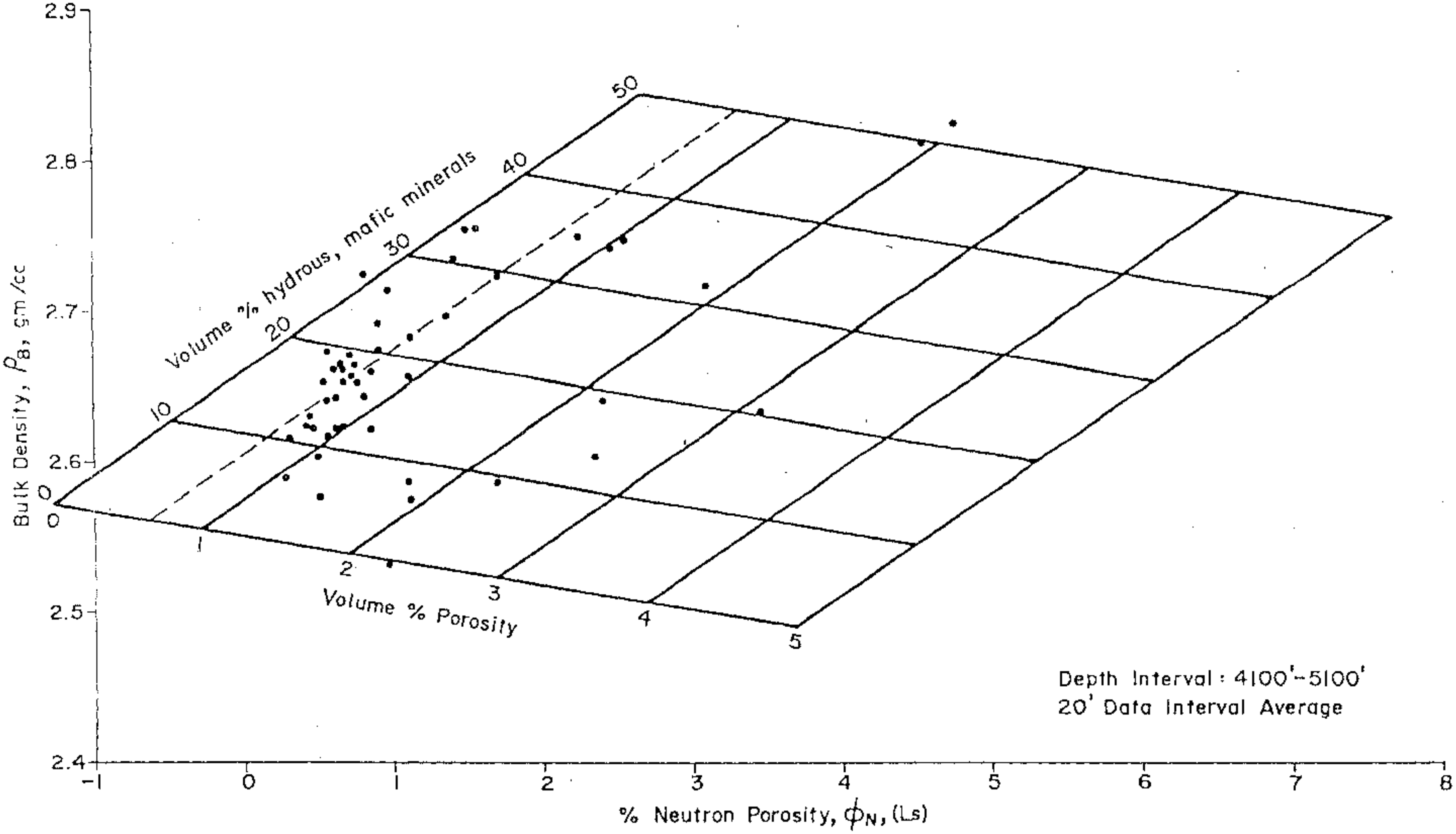

PHASE SHIFT
FIELD STRENGTH RATIO
35 Hz
105 Hz
315 Hz
945 Hz
2835 Hz
35 Hz
105 Hz
315 Hz
945 Hz
2835 Hz
100'
500'
1000'
1400'
Phase Shift
Field Strength Ratio
(Normalized for field geometry using 35 Hz data)
-5° 0 +5°
90 100 110%
Multi-Frequency
Electromagnetic
Drill Hole Log
SE-77/DHEM-5
30m
100'
Simplified Geologic Section
Transmitter Loop
150m
500'
Norite
Micropegmatite
Massive Sulfide Body (Ni, Cu)
0
500'
1000'
1500'



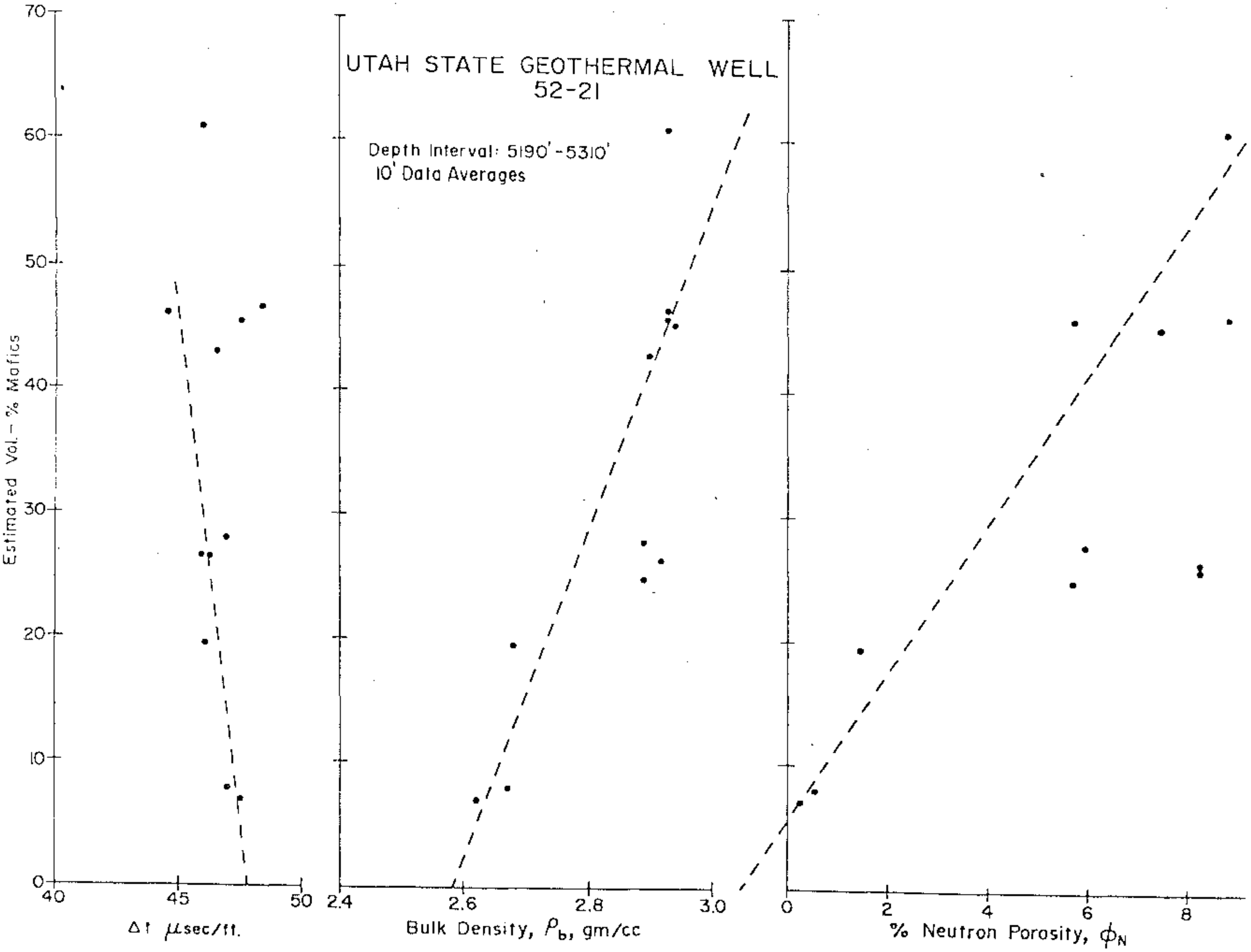
BOREHOLE 20 METERS FROM LOWER EDGE OF CONDUCTIVE SULFIDE BODY


CONCENTRATION, ton/oz
20
10
0
CRC-14
Chemical assay of cutting
COUNTS/60 SECONDS
100
80
60
40
20
0
Detector-source distance = 5.0'
Fix centroid according to calibration
Fix width equal to width of Al-1778 keV gamma peak
Calibration peaks: 511-annihilation, 1778.5-activated Al
← Scale for solid line-raw average
Scale for dashed line-H normalized →
Delayed γ N-activation on silver. Eγ = 658 keV
15
10
5
0
$\langle Ag\rangle/\langle H\rangle^{\frac{1}{2}}$ $(1\text{-}10^{-1})$
30
50
70
90
110
130
150
170
190
210
Depth, feet

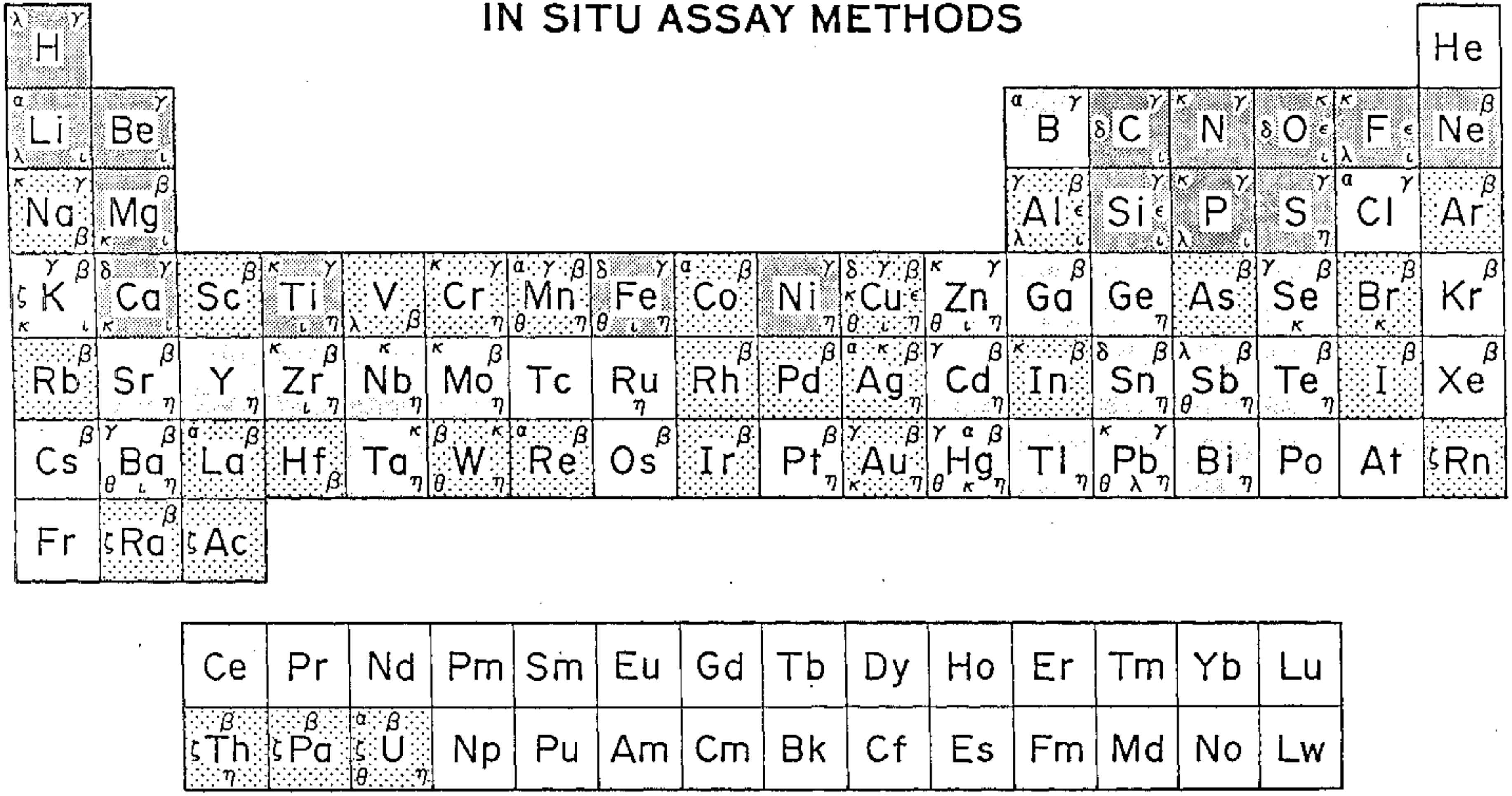
UTAH STATE GEOTHERMAL WELL 52-21



Depth Interval: 4100'–5100'
20' Data Interval Average


UTAH STATE GEOTHERMAL WELL
52-21
Depth Interval: 5190'-5310'
10' Data Averages
Estimated Vol.-% Mafics
70
60
50
40
30
20
10
0
40
45
50
Δt μsec/ft.
2.4
2.6
2.8
3.0
Bulk Density, ρ_b, gm/cc
0
2
4
6
8
% Neutron Porosity, ϕ_N

IN SITU ASSAY METHODS



ESTIMATED MINIMUM SENSITIVITY

▩ < 1%

▨ > 1%

☐ > 100 ppm

░ > 1 ppm

METHODS

α Neutron-fission neutron

β Thermal neutron activation, decay gamma ray spectroscopy

γ Thermal neutron activation, prompt capture gamma ray spectrometry

δ Fast neutron, inelastic scattering

ϵ Fast neutron activation

ζ Natural radioactive decay

η X-ray fluorescence

θ Selective gamma ray spectrometry

ι Photon-activation

κ High energy gamma and charged particle activation

λ Electro Magnetic Resonance